An Iterative Parameter-Free Fault Location Method on Three-Terminal Untransposed Transmission Lines

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***Abstract*—This paper proposes an iterative parameter-free fault location algorithm on three-terminal untransposed transmission lines. Three phase voltage and current synchrophasor measurements at three terminals of the line before and during the fault are typically required. The proposed method considers the lumped shunt capacitance and does not require any assumption on the tower structure. The method first builds the transmission line models before and during faults, which describe all the physical laws that the line should obey. Meanwhile, the parameters of transmission line as well as the location of the fault are introduced as unknown variables. Afterwards, the fault location is obtained using the Newton-Raphson iterative method. Numerical experiments in PSCAD/EMTDC validate the fault location accuracy of the proposed method, which is independent of fault locations, fault types and fault impedances.**

***Index Terms*—Fault Location, Parameter-Free, Untransposed Line, Three-terminal lines, Synchrophasors**

I. INTRODUCTION

With the growing demand of electricity in modern power system, the reliable operation of power system is of increasing importance. When faults occur in transmission lines, accurate fault location technique is vital since it can minimize the time spent in searching for the fault, minimize the outage time, reduce operating costs, and improve the reliability of the power system [1-4]. Among different methods of fault location, the most widely adopted methods in practice are the fundamental frequency phasor based methods, since they can be simply implemented using available recording devices in substations.

Based on available measurements, fundamental frequency phasor based approaches can be further classified into one-terminal methods and two/multi-terminal methods. For one-terminal methods, they only utilize the available measurements at local terminals to calculate the distance between the fault and the local terminal. No communication channels are required. The accuracy of these methods could be influenced by the fault impedances, the source impedances and the load current [7]. To obtain higher accuracy of the fault location, researchers also proposed the two/multi-terminal methods, to find the location of fault using additional measurements from the remote ends of the line. Proper communication channels among terminals of the transmission lines are required. The fault location accuracy can usually be improved compared to one-terminal methods [5-7]. With the development of time synchronization, these methods can be further categorized according to whether the synchronized phasor measurements are available at terminals of the transmission line. The synchronization can usually be achieved through common time signals from satellites such as the global positioning system (GPS) [8-9]. Specifically, compared to two-terminal transmission lines, there could be additional challenges for fault location in multi-terminal transmission lines. The faulted section may need to be found first in multi-terminal line cases [10-11]. Moreover, to ensure fault location accuracy, sequence line models [12-13] for transposed lines as well as three phase models [14-15] for untransposed lines are also considered in existing literatures. However, above methods usually require accurate parameters of the transmission line, which may not be available. The line parameters may even vary due to weather and loading conditions, resulting compromised fault location accuracy.

Parameter-free fault location approaches could be promising to solve the above issues. Literature [16] uses the Newton-Raphson method to obtain the fault location by means of the unsynchronized voltage and current phasors of the two terminals during the fault. Literature [17] proposes a method using dual-ended synchronized voltage and current phasors during the fault to find the fault location, which neglects shunt capacitance currents of the transmission line. Literature [18] utilizes the model of the sequence network to build equations, which can be solved to obtain fault location. However, literatures [16-18] all assume transposed transmission lines (the transmission line is geometrically symmetrical). Literature [19] introduces a parameter-free fault location for two-terminal untransposed lines. A closed-form solution obtained only using the synchronized measurements at both terminals before and during faults. However, the method is with the assumption of a specific structure. The idea about parameter-free is feasible for three-terminal lines as well. Literature [20] proposes a parameter-free fault location method for three-terminal circuits. However, it assumes the line is fully transposed and the shunt capacitance of the line is neglected.

In this paper, an iterative three-terminal parameter-free fault location on untransposed transmission line is proposed. Synchronized current and voltage phasor measurements at three terminals of the transmission line are typically required. The proposed method fully considers the lumped shunt capacitance of the transmission line and has no assumption on the tower structure. The proposed method first establishes the model of the three-terminal untransposed line by considering

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the physical laws of the transmission line before and during the fault. The model includes the fault location as well as the transmission line parameters as unknown variables. Afterwards, the location of fault is determined using the Newton-Raphson iterative method. The rest of the paper is arranged as follows. Section II introduces the proposed fault location method, including the procedure of modeling the three-terminal untransposed transmission line before and during the fault, and the solution of the equation using the Newton-Raphson method. Section III demonstrates the numerical experiments to validate the fault location accuracy of the proposed method with different fault types, locations and impedances. Section IV concludes the paper.

II. Proposed Fault Location Approach

This section derives the proposed parameter-free fault location method in detail. First, the model of a three-terminal untransposed transmission line is built before and during the fault. Afterwards, the parameter-free fault location algorithm using the Newton-Raphson iterative method is derived.

A. Model of Three-Terminal Transmission Line

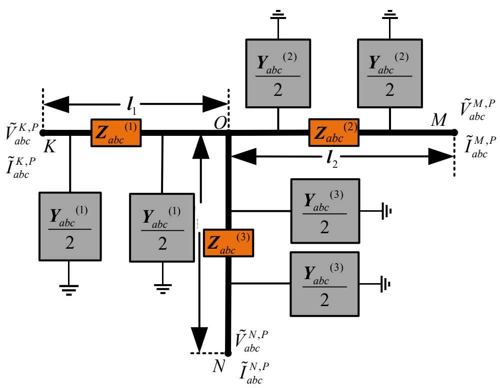

Figure 1. The three-terminal line model before the fault

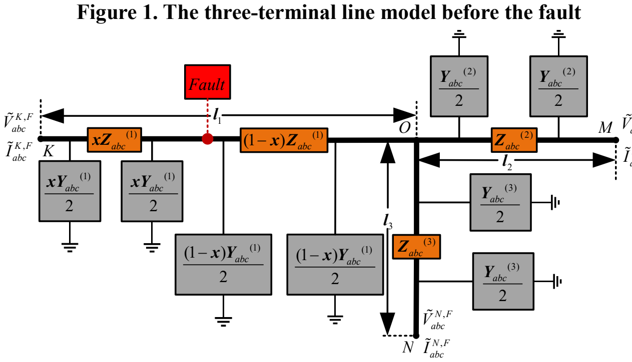

Figure 2. The three-terminal line model during the fault

Figure 1 and Figure 2 demonstrate the three-terminal line models before and during the fault. The three phase circuit is displayed in a single line view. Three phase voltage and current synchronized phasors at each terminal of the line before and during the fault are measured, including $\tilde{\boldsymbol{V}}_{abc}^{K,P}$, $\tilde{\boldsymbol{V}}_{abc}^{M,P}$, $\tilde{\boldsymbol{V}}_{abc}^{N,P}$, $\tilde{\boldsymbol{V}}_{abc}^{K,F}$, $\tilde{\boldsymbol{V}}_{abc}^{M,F}$, $\tilde{\boldsymbol{V}}_{abc}^{N,F}$, $\tilde{\boldsymbol{I}}_{abc}^{K,P}$, $\tilde{\boldsymbol{I}}_{abc}^{M,P}$, $\tilde{\boldsymbol{I}}_{abc}^{N,P}$, $\tilde{\boldsymbol{I}}_{abc}^{K,F}$, $\tilde{\boldsymbol{I}}_{abc}^{M,F}$ and $\tilde{\boldsymbol{I}}_{abc}^{N,F}$. The superscripts ‘K’, ‘M’ and ‘N’ denote the terminals with the available measurements. The superscript ‘P’ and ‘F’ denote the measurements before and during the fault. $\boldsymbol{Z}_{abc}^{(1)}$, $\boldsymbol{Z}_{abc}^{(2)}$, $\boldsymbol{Z}_{abc}^{(3)}$, $\boldsymbol{Y}_{abc}^{(1)}$, $\boldsymbol{Y}_{abc}^{(2)}$ and $\boldsymbol{Y}_{abc}^{(3)}$ are the series impedance and shunt admittance matrices of the transmission lines. Assume the tower of three lines are same. The impedance and the shunt admittance matrices of the **KO** transmission lines are given as,

$$\boldsymbol{Z}_{abc}^{(1)} = \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ab} & Z_{bb} & Z_{bc} \\ Z_{ac} & Z_{bc} & Z_{cc} \end{bmatrix}, \boldsymbol{Y}_{abc}^{(1)} = \begin{bmatrix} Y_{aa} & Y_{ab} & Y_{ac} \\ Y_{ab} & Y_{bb} & Y_{bc} \\ Y_{ac} & Y_{bc} & Y_{cc} \end{bmatrix} \quad (1)$$

Define l_1, l_2 and l_3 as the lengths of the three transmission line sections, respectively. Therefore, $\boldsymbol{Z}_{abc}^{(2)}$, $\boldsymbol{Z}_{abc}^{(3)}$, $\boldsymbol{Y}_{abc}^{(2)}$ and $\boldsymbol{Y}_{abc}^{(3)}$ can be represented using $\boldsymbol{Z}_{abc}^{(1)}$ and $\boldsymbol{Y}_{abc}^{(1)}$,

$$\boldsymbol{Z}_{abc}^{(2)} = l_2/l_1 \cdot \boldsymbol{Z}_{abc}^{(1)} = a\boldsymbol{Z}_{abc}^{(1)}, \boldsymbol{Z}_{abc}^{(3)} = l_3/l_1 \cdot \boldsymbol{Z}_{abc}^{(1)} = b\boldsymbol{Z}_{abc}^{(1)} \quad (2)$$

$$\boldsymbol{Y}_{abc}^{(2)} = l_2/l_1 \cdot \boldsymbol{Y}_{abc}^{(1)} = a\boldsymbol{Y}_{abc}^{(1)}, \boldsymbol{Y}_{abc}^{(3)} = l_3/l_1 \cdot \boldsymbol{Y}_{abc}^{(1)} = b\boldsymbol{Y}_{abc}^{(1)} \quad (3)$$

Take the $\boldsymbol{Z}_{abc}^{(1)}$, $\boldsymbol{Y}_{abc}^{(1)}$, a and b as the unknowns (6 + 6 + 1 + 1 =14 unknowns). In Figure 1, the following equations hold,

$$\begin{aligned} &\tilde{\boldsymbol{V}}_{abc}^{K,P} - \boldsymbol{Z}_{abc}^{(1)}\left(\tilde{\boldsymbol{I}}_{abc}^{K,P} - 1/2\cdot\boldsymbol{Y}_{abc}^{(1)}\tilde{\boldsymbol{V}}_{abc}^{K,P}\right) \\ &= \tilde{\boldsymbol{V}}_{abc}^{M,P} - a\boldsymbol{Z}_{abc}^{(1)}\left(\tilde{\boldsymbol{I}}_{abc}^{M,P} - a/2\cdot\boldsymbol{Y}_{abc}^{(1)}\tilde{\boldsymbol{V}}_{abc}^{M,P}\right) \end{aligned} \quad (4)$$

$$\begin{aligned} &\tilde{\boldsymbol{V}}_{abc}^{K,P} - \boldsymbol{Z}_{abc}^{(1)}\left(\tilde{\boldsymbol{I}}_{abc}^{K,P} - 1/2\cdot\boldsymbol{Y}_{abc}^{(1)}\tilde{\boldsymbol{V}}_{abc}^{K,P}\right) \\ &= \tilde{\boldsymbol{V}}_{abc}^{N,P} - b\boldsymbol{Z}_{abc}^{(1)}\left(\tilde{\boldsymbol{I}}_{abc}^{N,P} - b/2\cdot\boldsymbol{Y}_{abc}^{(1)}\tilde{\boldsymbol{V}}_{abc}^{N,P}\right) \end{aligned} \quad (5)$$

$$\begin{aligned} &\tilde{\boldsymbol{I}}_{abc}^{K,P} - 1/2\cdot\boldsymbol{Y}_{abc}^{(1)}\tilde{\boldsymbol{V}}_{abc}^{K,P} - 1/2\cdot\boldsymbol{Y}_{abc}^{(1)}\Big[\tilde{\boldsymbol{V}}_{abc}^{K,P} - \boldsymbol{Z}_{abc}^{(1)} \\ &\cdot\left(\tilde{\boldsymbol{I}}_{abc}^{K,P} - 1/2\cdot\boldsymbol{Y}_{abc}^{(1)}\tilde{\boldsymbol{V}}_{abc}^{K,P}\right)\Big] + \tilde{\boldsymbol{I}}_{abc}^{M,P} - a/2\cdot\boldsymbol{Y}_{abc}^{(1)}\tilde{\boldsymbol{V}}_{abc}^{M,P} \\ &- a/2\cdot\boldsymbol{Y}_{abc}^{(1)}\Big[\tilde{\boldsymbol{V}}_{abc}^{M,P} - \boldsymbol{Z}_{abc}^{(1)}\left(\tilde{\boldsymbol{I}}_{abc}^{M,P} - a/2\cdot\boldsymbol{Y}_{abc}^{(1)}\tilde{\boldsymbol{V}}_{abc}^{M,P}\right)\Big] \\ &+ \tilde{\boldsymbol{I}}_{abc}^{N,P} - b/2\cdot\boldsymbol{Y}_{abc}^{(1)}\tilde{\boldsymbol{V}}_{abc}^{N,P} - b/2\cdot\boldsymbol{Y}_{abc}^{(1)}\Big[\tilde{\boldsymbol{V}}_{abc}^{N,P} - \boldsymbol{Z}_{abc}^{(1)} \\ &\left(\tilde{\boldsymbol{I}}_{abc}^{N,P} - b/2\cdot\boldsymbol{Y}_{abc}^{(1)}\tilde{\boldsymbol{V}}_{abc}^{N,P}\right)\Big] = 0 \end{aligned} \quad (6)$$

Assume that a fault occurs on the **KO** transmission line. Define the fault location (distance between the fault and the terminal **K)** is m (1 additional unknown variable, $0 < m < 1$). In Figure 2, the following equations hold,

$$\begin{aligned} &\tilde{\boldsymbol{V}}_{abc}^{N,F} - b\boldsymbol{Z}_{abc}^{(1)}(\tilde{\boldsymbol{I}}_{abc}^{N,F} - b/2\cdot\boldsymbol{Y}_{abc}^{(1)}\tilde{\boldsymbol{V}}_{abc}^{N,F}) \\ &= \tilde{\boldsymbol{V}}_{abc}^{M,F} - a\boldsymbol{Z}_{abc}^{(1)}(\tilde{\boldsymbol{I}}_{abc}^{M,F} - a/2\cdot\boldsymbol{Y}_{abc}^{(1)}\tilde{\boldsymbol{V}}_{abc}^{M,F}) \end{aligned} \quad (7)$$

$$\begin{aligned} &\tilde{\boldsymbol{V}}_{abc}^{N,F} - b\boldsymbol{Z}_{abc}^{(1)}\left(\tilde{\boldsymbol{I}}_{abc}^{N,F} - b/2\cdot\boldsymbol{Y}_{abc}^{(1)}\tilde{\boldsymbol{V}}_{abc}^{N,F}\right) - (1-m)\boldsymbol{Z}_{abc}^{(1)} \\ &\cdot\Big\{\tilde{\boldsymbol{I}}_{abc}^{N,F} - b/2\cdot\boldsymbol{Y}_{abc}^{(1)}\tilde{\boldsymbol{V}}_{abc}^{N,F} - b/2\cdot\boldsymbol{Y}_{abc}^{(1)}\Big[\tilde{\boldsymbol{V}}_{abc}^{N,F} - b\boldsymbol{Z}_{abc}^{(1)} \\ &\left(\tilde{\boldsymbol{I}}_{abc}^{N,F} - b/2\cdot\boldsymbol{Y}_{abc}^{(1)}\tilde{\boldsymbol{V}}_{abc}^{N,F}\right)\Big] + \tilde{\boldsymbol{I}}_{abc}^{M,F} - a/2\cdot\boldsymbol{Y}_{abc}^{(1)}\tilde{\boldsymbol{V}}_{abc}^{M,F} \\ &- a/2\cdot\boldsymbol{Y}_{abc}^{(1)}\Big[\tilde{\boldsymbol{V}}_{abc}^{M,F} - a\boldsymbol{Z}_{abc}^{(1)}\left(\tilde{\boldsymbol{I}}_{abc}^{M,F} - a/2\cdot\boldsymbol{Y}_{abc}^{(1)}\tilde{\boldsymbol{V}}_{abc}^{M,F}\right)\Big] \\ &- (1-m)/2\cdot\boldsymbol{Y}_{abc}^{(1)}\Big[\tilde{\boldsymbol{V}}_{abc}^{N,F} - b\boldsymbol{Z}_{abc}^{(1)}\left(\tilde{\boldsymbol{I}}_{abc}^{N,F} - b/2\cdot\right. \\ &\left.\left.\boldsymbol{Y}_{abc}^{(1)}\tilde{\boldsymbol{V}}_{abc}^{N,F}\right)\Big]\Big\} = \tilde{\boldsymbol{V}}_{abc}^{K,F} - m\boldsymbol{Z}_{abc}^{(1)}\left(\tilde{\boldsymbol{I}}_{abc}^{K,F} - m/2\cdot\boldsymbol{Y}_{abc}^{(1)}\tilde{\boldsymbol{V}}_{abc}^{K,F}\right) \end{aligned} \quad (8)$$

For these equations, (4), (5), (7), (8) describes the Kirchhoff’s Voltage Laws (KVLs), while (6) descries the Kirchhoff’s Current Laws (KCLs). There are 15 equations and 15 unknowns to be solved. The parameters of transmission line are included in the equations as unknowns. Here we do not have any assumptions on the tower structures of the transmission line, and only use the measurements of three terminals to find the fault location m. Hence the proposed method is a parameter-free method.

B. Finding the Fault Location by Newton-Raphson Method

The basic idea of the Newton-Raphson method is to approximate the roots of an objective function in an iterative way. According to above unknowns, define,

$$\boldsymbol{x}=\left[Z_{aa},Z_{ab},Z_{ac},Z_{bb},Z_{bc},Z_{cc},Y_{aa},Y_{ab},Y_{ac},Y_{bb},Y_{bc},Y_{cc},a,b,m\right]^T \quad (9)$$

where $\boldsymbol{x}$ is a vector of unknown variables, and $[\cdot]^T$ means the transposition of the matrix $[\cdot]$.

Here we take (4) as an example. It can be expanded into the following form,

$$\begin{aligned} f_1(\boldsymbol{x}) &= \tilde{V}_a^{K,P}-\tilde{V}_a^{M,P}+Z_{aa}\left(a\tilde{I}_a^{M,P}-\tilde{I}_a^{K,P}\right)+Z_{ab}\left(a\tilde{I}_b^{M,P}\right. \\ &\left.-\tilde{I}_b^{K,P}\right)+Z_{ac}\left(a\tilde{I}_c^{M,P}-\tilde{I}_c^{K,P}\right)+Z_{aa}\left[Y_{aa}\left(1/2\cdot\tilde{V}_a^{K,P}\right.\right. \\ &\left.-a^2/2\cdot\tilde{V}_a^{M,P}\right)+Y_{ab}\left(1/2\cdot\tilde{V}_b^{K,P}-a^2/2\cdot\tilde{V}_b^{M,P}\right) \\ &\left.+Y_{ac}\left(1/2\cdot\tilde{V}_c^{K,P}-a^2/2\cdot\tilde{V}_c^{M,P}\right)\right]+Z_{ab}\left[Y_{ab}\left(1/2\cdot\tilde{V}_a^{K,P}\right.\right. \\ &\left.-a^2/2\cdot\tilde{V}_a^{M,P}\right)+Y_{bb}\left(1/2\cdot\tilde{V}_b^{K,P}-a^2/2\cdot\tilde{V}_b^{M,P}\right) \\ &\left.+Y_{bc}\left(1/2\cdot\tilde{V}_c^{K,P}-a^2/2\cdot\tilde{V}_c^{M,P}\right)\right]+Z_{ac}\left[Y_{ac}\left(1/2\cdot\tilde{V}_a^{K,P}\right.\right. \\ &\left.-a^2/2\cdot\tilde{V}_a^{M,P}\right)+Y_{bc}\left(1/2\cdot\tilde{V}_b^{K,P}-a^2/2\cdot\tilde{V}_b^{M,P}\right) \\ &\left.+Y_{cc}\left(1/2\cdot\tilde{V}_c^{K,P}-a^2/2\cdot\tilde{V}_c^{M,P}\right)\right]=0 \end{aligned} \quad (10)$$

In this way, all 15 equations from formula (4), (5), (6), (7) and (8) could be expanded respectively, resulting in,

$$F(\boldsymbol{x})=0 \quad (11)$$

where $F(\boldsymbol{x})=[f_1(\boldsymbol{x}),f_2(\boldsymbol{x}),f_3(\boldsymbol{x}),f_4(\boldsymbol{x}),f_5(\boldsymbol{x}),f_6(\boldsymbol{x}),f_7(\boldsymbol{x}),$ $f_8(\boldsymbol{x}),f_9(\boldsymbol{x}),f_{10}(\boldsymbol{x}),f_{11}(\boldsymbol{x}),f_{12}(\boldsymbol{x}),f_{13}(\boldsymbol{x}),f_{14}(\boldsymbol{x}),f_{15}(\boldsymbol{x})]^T$.

The unknown variables can be solved through the following iterative method until convergence,

$$\boldsymbol{x}^{\nu+1}=\boldsymbol{x}^{\nu}-[\boldsymbol{J}(\boldsymbol{x}^{\nu})]^{-1}F(\boldsymbol{x}^{\nu}) \quad (12)$$

where $\boldsymbol{x}^{\nu}$ is value of $\boldsymbol{x}$ at iteration ν, and the Jacobian matrix $\boldsymbol{J}(\boldsymbol{x}^{\nu})$ is defined as $\boldsymbol{J}(\boldsymbol{x}^{\nu})=\partial F(\boldsymbol{x})/\partial\boldsymbol{x}\big|_{\boldsymbol{x}=\boldsymbol{x}^{\nu}}$.

Actually, the above calculations have an assumption: the fault occurs inside the section '**KO**' of the three terminal transmission line. Next, the way to find the faulted line section is presented. Define the variables m_K, m_M and m_N as the distance between the fault location and corresponding terminal if the faulted section is **KO**, **MO** and **NO**, respectively. Three different transmission line models are built, where each model corresponds to one possible faulted section, with the fault location m_K, m_M and m_N as unknown variables, respectively. Afterwards, three models are solved simultaneously. Among the solutions of the three variables m_K, m_M and m_N, if one of the fault location variables is realistic (within the range of 0 to 1), this fault location variable corresponds to the actual faulted section.

III. NUMERICAL EXPERIMENTS

To verify the effectiveness of the proposed parameter-free fault location method, an example test system of a three-terminal untransposed three phase transmission line is built in PSCAD/EMTDC. The transmission line is a 500 kV transmission line, with the total length of 180 km. The definitions of variables are the same as in Figure 1 and 2. The lengths of section **KO**, **MO** and **NO** are 50 km, 60 km and 70 km, respectively. The nominal frequency of the transmission line is 50 Hz. The tower structure is shown in Figure 3. Three phase voltage and current synchrophasor measurements are installed at all terminals of the transmission line. Note that the distributed parameter transmission line model with frequency dependent parameters is utilized in PSCAD/EMTDC to ensure the practicability of the voltage and current measurements before and during faults.

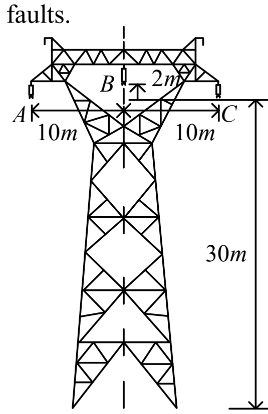

Figure 3. The tower structure of the untransposed transmission line

Next, a large number of fault events are studied in the simulation. Here the fault events on **KO** line section are studied as examples (the fault location results are similar in **MO** and **NO** line sections). The fault events include single phase to ground faults, phase to phase faults, phase to phase to ground faults and three phase faults. For low impedance faults, the fault impedances are chosen to be 0.01 ohm, 1 ohm, 5 ohm and 10 ohm for different fault types. For single phase to ground high impedance faults, the fault impedances are selected to be 100 ohm, 200 ohm, 300 ohm and 500 ohm. The absolute error (in percentage) of the fault location is defined as,

$$Error(\%)=\left|\frac{Estimated\ Fault\ Location-Actual\ Fault\ Location}{Line\ Length}\right| \quad (13)$$

In formula (13), the *Line Length* represents the length of faulted section.

A. Test case 1: low impedance phase A to ground faults with different fault locations and fault impedances

This test case studies a group of low impedance phase A to ground faults with different fault locations L (every 5 km through the **KO** line) and different fault impedances R_f (0.01 ohm, 1 ohm, 5 ohm, 10 ohm). The absolute fault location errors (in percentage) of the proposed method are depicted in Figure 4. It can be observed that the maximum error is 0.0199%. The average absolute fault location errors with 0.01 ohm, 1 ohm, 5 ohm, 10 ohm fault impedances are 0.0037%, 0.0074%, 0.0057%, 0.0072%, respectively.

B. Test case 2: low impedance phase B to C faults with different fault locations and fault impedances

This test case studies a group of low impedance phase B to C faults with different fault locations L (every 5 km through the **KO** line) and different fault impedances R_f (0.01 ohm, 1 ohm, 5 ohm, 10 ohm). The absolute fault location errors (in percentage) of the proposed method are depicted in Figure 5. It can be observed that the maximum error is 0.0049%. The average absolute fault location errors with 0.01 ohm, 1 ohm, 5 ohm, 10 ohm fault impedances are 0.0019%, 0.0022%, 0.0023%, 0.0023%, respectively.

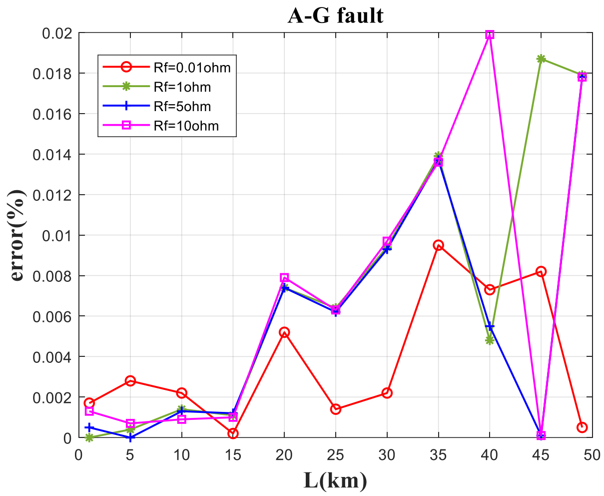

Figure 4. Results of the absolute fault location errors (in percentage), low impedance phase A to ground faults with different fault locations and fault impedances

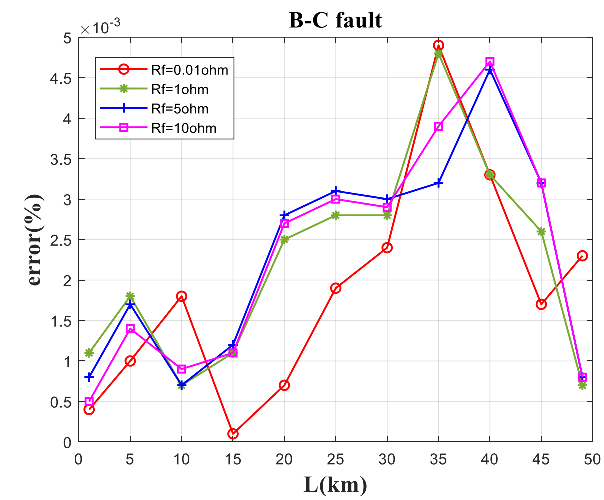

Figure 5. Results of the absolute fault location errors (in percentage), low impedance phase B to C faults with different fault locations and fault impedances

C. Test case 3: low impedance phase BC to ground faults with different fault locations and fault impedances

This test case studies a group of low impedance phase BC to ground faults with different fault locations L (every 5 km through the **KO** line) and different fault impedances R_f (0.01 ohm, 1 ohm, 5 ohm, 10 ohm). The absolute fault location errors (in percentage) of the proposed method are depicted in Figure 6. It can be observed that the maximum error is 0.0162%. The average absolute fault location errors with 0.01 ohm, 1 ohm, 5 ohm, 10 ohm fault impedances are 0.0050%, 0.0054%, 0.0042%, 0.0047%, respectively.

D. Test case 4: low impedance three phase faults with different fault locations and fault impedances

This test case studies a group of low impedance symmetrical three phase faults with different fault locations L (every 5 km through the **KO** line) and different fault impedances R_f (0.01 ohm, 1 ohm, 5 ohm, 10 ohm). The absolute fault location errors (in percentage) of the proposed method are depicted in Figure 7. It can be observed that the maximum error is 0.0385%. The average absolute fault location errors with 0.01 ohm, 1 ohm, 5 ohm, 10 ohm fault impedances are 0.0156%, 0.0071%, 0.0071%, 0.0130%, respectively.

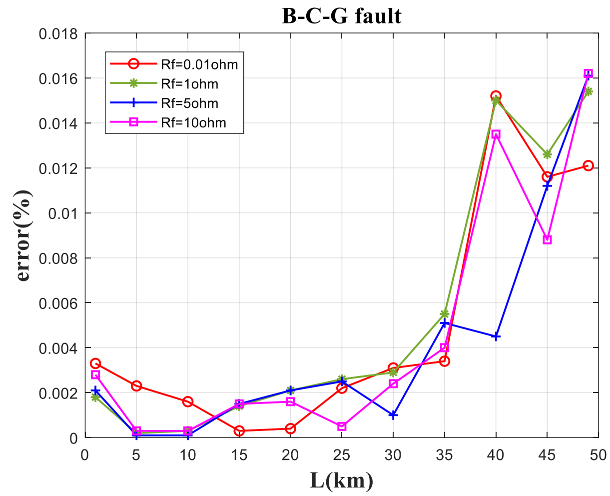

Figure 6. Results of the absolute fault location errors (in percentage), low impedance phase BC to ground faults with different fault locations and fault impedances

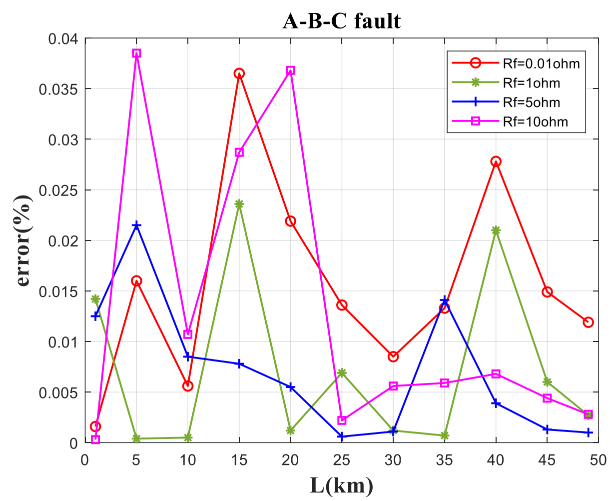

Figure 7. Results of the absolute fault location errors (in percentage), low impedance phase ABC faults with different fault locations and fault impedances

E. Test case 5: high impedance phase A to ground faults with different fault locations and fault impedances

This test case studies a group of high impedance phase A to ground faults with different fault locations L (every 5 km through the **KO** line) and different fault impedances R_f (100 ohm, 200 ohm, 300 ohm, 500 ohm). The absolute fault location errors (in percentage) of the proposed method are depicted in Figure 8. It can be observed that the maximum error is 0.0759%. The average absolute fault location errors with 0.01 ohm, 1 ohm, 5 ohm, 10 ohm fault impedances are 0.0088%, 0.0113%, 0.0187%, 0.0327%, respectively.

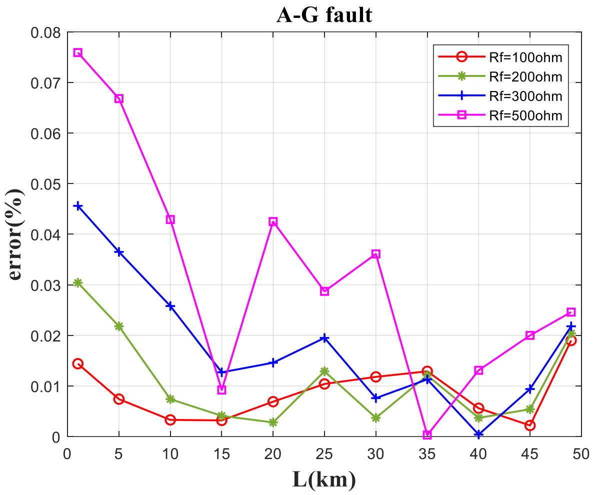

Figure 8. Results of the absolute fault location errors (in percentage), high impedance phase A to ground faults with different fault locations and fault impedances

F. Discussion

One limitation of the Newton-Raphson iterative method is the issues of convergence and proper selections of initial values. For all above test cases, we select the initial values of the state vector $\boldsymbol{x}$ as follows. For all parameters to be estimated (all entries except the fault location m inside $\boldsymbol{x}$), the initial values are selected as 90% of the true values. To ensure convergence, the initial values of fault location m are selected from 0 to 1, with 1% as the incremental step. Among all the initial values of m, the calculated fault location converges to the reported fault location results or simply diverge to unrealistic values (fall outside of the range from 0 to 1). Therefore, the aforementioned accurate fault location results can be achieved. Nevertheless in practice, if the transmission line parameters are extremely inaccurate, there might still be convergence issues. In this case, non-iterative parameter-free algorithms are preferred.

IV. Conclusion

This paper proposes an iterative parameter-free fault location method on three-terminal untransposed transmission lines. It has no assumptions on the structure of the tower. Three phase voltage and current synchrophasor measurements at each terminal of the lines before and during the fault are utilized. The proposed method first builds the untransposed transmission line models before and during the fault by considering the physical laws of the untransposed transmission line. The parameters of the line as well as the fault location are introduced as unknown variables to be solved. Afterwards, the Newton-Raphson iterative method is applied to solve the problem. Numerical experiments prove the accuracy of the proposed method, independent of fault types, fault locations and fault impedances.

In fact, the convergence of the Newton-Raphson method is highly dependent on the the initial values as well as the characteristics of the problem. The model used in the method is the lumped shunt admittance matrices instead of fully distributed parameters, which may generate fault location errors especially in long transmission lines. These problems of the parameter-free fault location method on three-terminal untransposed transmission lines will be studied in future publications.

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