New fault location scheme for four-circuit untransposed transmission lines

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ARTICLE INFO

Keywords:
Four-circuit transmission line
Fault location
Phasor measurement unit (PMU)

ABSTRACT

This paper introduces a new fault location scheme for two-terminal four-circuit untransposed transmission line using synchronized measurements. The current phasors at both line terminals and the voltage phasor at only one terminal are needed to formulate the fault location equation. The proposed scheme is developed based on theory of transmission lines and expansion of Taylor series for the distributed line model parameters. The mutual coupling between all phases and the untransposition of the line are considered to obtain precise results. Faulty phases are determined using Kirchhoff’s current law (KCL) and all fault types including normal shunt and inter-circuit faults can be located. DigiSILENT Power Factory software is used to simulate the power system and the fault location calculations are carried out using MATLAB. The proposed scheme is investigated under different fault locations, fault inception angles, fault types, and fault resistances. The influence of soil resistivity variation, measurement and synchrophasors errors, errors in line parameters, various line lengths, non-linear time-varying arc resistance, and complex fault impedance is also investigated. The simulation results confirm the validity of the fault location scheme for all test cases.

1. Introduction

Transmission lines are vital components for reliability of power supply. Transmission lines are permanently suffered from different fault types, the precise fault location is desired to restore the normal conditions and reduce the outage time. Fundamental principles and different fault location methods for various transmission lines configurations are presented in [1]. Generally, fault location schemes can be classified into four categories. The first one utilizes the power frequency components measurements [2–8]. The second category comprises schemes based on traveling waves [9–15]. The third one uses artificial intelligent techniques such as genetic algorithm [16], combined wavelet-fuzzy [17,18], artificial neural network [19,20], and adaptive neural-fuzzy [21]. The last one is based on fault-generated transient analysis of high frequency signals [22,23].

Single- and double-circuit transmission lines are vastly utilized in many countries. However, some countries, such as India, Malaysia, Kuwait, and China, utilize multi-circuit transmission lines for power transfer [24,25]. Fault location techniques are well discussed for Single-[3,8–11,13–21] and double-circuit [2,4–7,12,22] transmission lines. However, the author has found that only three papers [26–28] discussed fault location for multi-circuit transmission lines. Fault location estimation for multi-circuit transmission lines is more complicated than single- and double-circuit transmission lines because the high phase order transmission lines increase the mutual coupling between the lines. In addition, transposition in transmission lines is implemented to balance impedance and admittance matrices of the network. However, the transposed line becomes untransposed during fault because each section on each side of the fault point becomes untransposed. The two sections are assumed to be transposed during fault so that the symmetrical components transformation can be applied which impacts negatively on the accuracy of fault location. In [26], two-terminal voltage and current measurements are completely decoupled into independent 12-sequence components. The fault location is estimated considering that the voltage components calculated form both line sides at fault point are equal to each other. However, this method is only suitable for transposed transmission lines because it utilize 12-sequence component analysis. Also, the fault location is obtained using lump parameter model. In [27], a fault location scheme is introduced for untransposed four-circuit transmission lines employing only one end measurements. The scheme considers the distributed parameter line model and the mutual coupling between all phases to obtain precise results. However, the scheme cannot be applied if the fault type is unknown. In addition, the equivalent source impedance at one terminal is required and the estimated fault location is sensitive to source impedance variations and inaccuracies in line parameters. In [28], a new fault location technique for series compensated untransposed four-circuit transmission line has been proposed utilizing voltage and current measurements from both terminals of the line. The scheme is formulated based on the fact that the currents of healthy phases on the two sides at fault point are equal. However, multiple values of estimated fault distances can satisfy this fact at fault point. In addition, this
scheme cannot be applied when all phases are faulted or the fault type is unknown.

In this paper, a new fault location scheme is developed for two-terminal four-circuit transmission line. The current phasors from both line terminals and the voltage phasor from only one terminal are required to estimate the fault location. The main features of the proposed scheme include:

- Distributed line model parameters are considered.
- The mutual coupling between all phases and untransposition of the line are considered.
- Locations of inter-circuit faults can be obtained.

2. Proposed fault location scheme for four-circuit untransposed transmission line

2.1. Faulty phase identification

Consider the four-circuit transmission line (S-R) shown in Fig. 1 with line length \( L \) and assume that the synchronized current phasors from both line terminals and synchronized voltage phasor at terminal S are available. The voltage and current in phase-coordinates at point N which is \( D_{N,S} \) in per unit away from terminal S can be obtained from \([29]\):

\[
\begin{bmatrix}
V_N
\end{bmatrix} = H(D_{N,S}L) \begin{bmatrix}
V_S
\end{bmatrix} - I_{S,R}
\]

(1)

\[
H(D_{N,S}L) = \begin{bmatrix}
H_{11}(D_{N,S}L) & H_{12}(D_{N,S}L) \\
H_{21}(D_{N,S}L) & H_{22}(D_{N,S}L)
\end{bmatrix}
\]

(2)

where \( V_N \) and \( V_S \) are \( 12 \times 1 \) voltages vectors at point N and terminal S, respectively. \( I_{N,S} \) and \( I_{S,R} \) are \( 12 \times 1 \) currents vectors at point N and terminal S, respectively. The \( H_{11}, H_{12}, H_{21}, \) and \( H_{22} \) are \( 12 \times 12 \) line parameters matrices and they can be written in infinite series \([30]\):

\[
H_{11}(D_{N,S}L) = 1 + \frac{(ZY)^1(D_{N,S}L)^2}{2!} + \frac{(ZY)^2(D_{N,S}L)^3}{4!} + \ldots
\]

(3)

\[
H_{12}(D_{N,S}L) = ZD_{N,S}L + \frac{(ZY)^1Z(D_{N,S}L)^3}{3!} + \frac{(ZY)^2Z(D_{N,S}L)^4}{5!} + \ldots
\]

(4)

\[
H_{21}(D_{N,S}L) = Z^{-1}(ZY)^1Z(D_{N,S}L)^3 + \frac{Z^{-1}(ZY)^2Z(D_{N,S}L)^4}{3!} + \ldots
\]

(5)

\[
H_{22}(D_{N,S}L) = 1 + \frac{Z^{-1}(ZY)^1Z(D_{N,S}L)^2}{2!} + \frac{Z^{-1}(ZY)^2Z(D_{N,S}L)^4}{4!} + \ldots
\]

(6)

where \( Z \) is the series impedance matrix per unit length and \( Y \) is the shunt admittance matrix per unit length. Only four terms of \( H_{11}, H_{12}, H_{21}, \) and \( H_{22} \) are enough because the fault location accuracy will not improve by expansion of more terms \([30]\). In normal conditions, the following equation is applicable.

\[
[I_{F,S}^R] = [H_{21}(L)V_{F} - H_{22}(L)I_{F,R}]
\]

(7)

where \( I_{F,S}^R \) is the estimated current vector at terminal \( R \) in the direction from terminal \( R \) to terminal \( S \).

Let consider that:

\[
[I_{m}] = [\text{abs}(I_{S,R} - I_{F,S}^R)]
\]

(8)

where \( I_{S,R} \) is the measured current at terminal \( R \) as shown in Fig. 1 and the dimensions of \( I_{m} \) are \( 12 \times 1 \). In normal conditions, \( I_{F,S}^R = I_{S,R} \) and therefore, the elements of \( I_{m} \) for all phases are ideally equal to zero based on KCL. In faults conditions, Eq. (7) is not applicable and consequently Eq. (8) is not applicable. Therefore, the elements of \( I_{m} \) corresponding to faulty phases will be higher than zero. In practice, the errors in measurement devices and calculations should be considered. Therefore, threshold value is set at 0.1 per unit instead of zero. As a result, the faulty phases are recognized employing the elements of \( I_{m} \).

The elements of \( I_{m} \) corresponding to faulty phases will be higher than 0.1 per unit and the elements of \( I_{m} \) corresponding to healthy phases will be less than 0.1 per unit.

2.2. Proposed fault location scheme

Let a fault occurred at distance \( D_p \) in per unit away from terminal \( R \). Again, the synchronized current phasors from both line terminals and synchronized voltage phasor at terminal S are available. The voltage and current at fault point \( F \) (\( V_F \) and \( I_{F,S} \)) are equal to:

\[
\begin{bmatrix}
V_F
\end{bmatrix} = H((1-D_p)L) \begin{bmatrix}
V_S
\end{bmatrix} - I_{S,R}
\]

(9)

Also, the current at terminal \( R (I_{F,R}) \) is equal to:

\[
[I_{F,R}] = [H_{21}(D_pL)V_F - H_{22}(D_pL)I_{F,S}]
\]

(10)

\( I_{F,R} \) is known, \( V_F \) is function of \( D_p \) and the current \( I_{F,S} \) is unknown. Eq. (10) is rearranged:

\[
[I_{F,S}] = [H_{21}(D_pL)]^{-1}[H_{22}(D_pL)V_F - I_{F,R}]
\]

(11)

The total fault current at point \( F \) (\( I_F \)) is equal to:

\[
[I_F] = -[I_{F,S} + I_{F,R}]
\]

(12)

At fault point \( F \), the fault impedance is considered purely resistant (\( R_p \) \([7,27]\). The fault network topology for four-circuit lines is shown in Fig. 2 \([27]\). \( R_{1a}, R_{1b}, R_{2a}, R_{2b}, R_{3a}, R_{3b}, R_{4a}, R_{4b}, \) and \( R_{4c} \) refer to the twelve phases transition resistances at fault point. The transition resistances values are considered infinite for healthy phases. \( R_g \) denotes grounded resistance and it is equal to infinite for ungrounded faults. The relation between current and voltage at fault point
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