FAULT LOCATION FOR TWO- AND THREE-ENDED AND MIXED LINES USING SYNCHRONIZED MEASUREMENTS

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I. INTRODUCTION

Transmission lines are exposed to faults due to bad weather (hurricanes, lightning), insulation breakdown, short circuits by birds, and contact by tree branches and other objects. Temporary faults are cleared by tripping then autoreclosing. For permanent faults, the power supply is restored only after the maintenance crew finds and replaces the failed component. For this purpose, precise fault location should be known, else the fault location identification job turns out to be tedious and time consuming for long transmission lines spread across rugged terrains such as hilly areas, mountains, and deserts, etc. Visual inspection techniques are advanced, from road patrols to air patrols and, more recently, to trials with drones and unmanned aerial vehicles, etc. These methods may not be cost effective for long transmission lines. Identification of fault location with high precision on transmission lines is of great value to transmission asset owners and maintenance crews as it helps in expediting maintenance work and achieving quick restoration of the line. Quick restoration of service improves the reliability of power supply and reduces the financial loss for the utilities and end users.

Traveling wave (TW)-based fault locators are used to locate the fault within a 1-2 tower span distance. The performance of TW-based fault location methods depends on accurate detection of wavefront arrival times, sampling rate, and data synchronization. The single-ended TW-based methods use the incident and reflected wave arrival times to locate the fault. The single-ended TW-based techniques pose challenges in identifying the waves reflected from the location of the fault and the remote substation terminals, as well as the waves reflected from the buses of adjacent networks connected to the protected line. Therefore, the practical implementation of the single-ended TW-methods is challenging and limited. Two-ended TW-based methods are more accurate, and these methods are in practical use. However, accuracy of TW-based fault location algorithms depends on traveling wave detection, data synchronization, IED hardware, processing of multiple reflections, filtering of noise, correction of substation secondary cable delays, and wave speed, etc. These data synchronization and wave speed errors can be corrected by conducting experiments such as creating a fault at a known distance and calculating the secondary cable delays and wave speed. This process is difficult, requires more engineering effort and is not cost-effective. Besides, they are not economical solutions for transmission asset owners due to the high cost involved in dedicated hardware and solution tuning efforts.

Present communication technology allows for the use of data from all ends of the line to calculate the location of the fault. This offers an economical alternative to TW-based methods that require high IED sampling rates. For the fault location methods presented in this paper, one IED is required at each end of the line, and each IED must be connected to each other IED via a 2Mbps

communication link. At each line-end, the local currents and voltages are connected to the local IED, which digitizes these inputs to obtain sampled values of the local currents and voltages. Each local IED sends these sampled values to the remote IED/s. Hence all remote IEDs receive the currents and voltages from the local IED as sampled values. The IEDs need to be time coordinated (time synchronized) so that, on receipt of the current and voltage sampled values from a remote IED, the local receiving IED can time coordinate these with its current and voltage sampled values, and interpolate as required to obtain remote values that are time aligned with the local values. Each IED therefore has available to it time aligned sampled values of the local and all remote currents and voltages. It is from these sampled values that the pre- and during-fault positive-sequence phasors are calculated.

II. TRANSMISSION LINE MODELED AS A GENERAL TWO-PORT NETWORK

To characterize transmission lines using ABCD parameters, the line is modeled as a general two-port network. The two-port model of a transmission line has input port PQ (voltage V_1 and current I_1) and output port RS (voltage V_2 and current I_2).

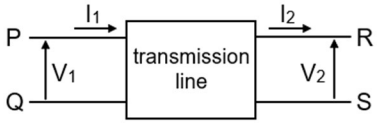


Fig. 1: two-port network

The ABCD parameters of a transmission line give the relationship of the input voltage and current to the output voltage and current, i.e. they link the input and output voltages and currents. The input voltage and current (V_1 and I_1) are derived from the output voltage and current (V_2 and I_2) as follows

$$V_1 = AV_2 + BI_2$$

$$I_1 = CV_2 + DI_2$$

or, in matrix form

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix}$$

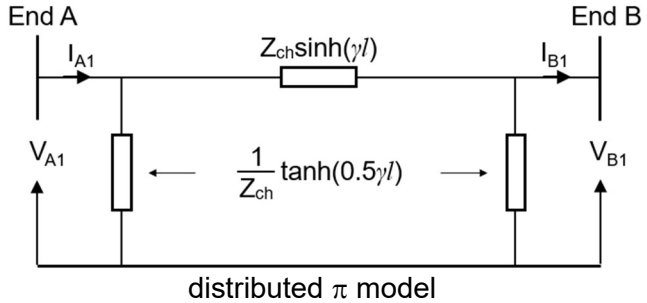
The ABCD parameters for a long line are

$$A = \cosh(\gamma l)$$

$$B = Z_{ch} * \sinh(\gamma l)$$

$$C = \frac{1}{Z_{ch}} * \sinh(\gamma l)$$

$$D = \cosh(\gamma l)$$



distributed π model

$$V_{A1} = AV_{B1} + BI_{B1} = \cosh(\gamma l)V_{B1} + Z_{ch}*\sinh(\gamma l)I_{B1}$$

$$I_{A1} = CV_{B1} + DI_{B1} = \frac{1}{Z_{ch}}*\sinh(\gamma l)V_{B1} + \cosh(\gamma l)I_{B1}$$

where

- l is the length of the line in meters
- $Z_{ch} = \sqrt{Z_{L1}/Y_{L1}}$ is the characteristic impedance of the line
- $\gamma = \sqrt{Z_{L1}*Y_{L1}}$ is the propagation constant of the line
- Z_{L1}, Y_{L1} are, respectively, the positive-sequence series impedance and positive-sequence shunt admittance of the line, per meter of the line length

Note, the output voltage and current (V_2 and I_2) can also be derived from the input voltage and current (V_1 and I_1) follows

$$\begin{bmatrix} V_2 \\ I_2 \end{bmatrix} = \begin{bmatrix} D & -B \\ -C & A \end{bmatrix} \begin{bmatrix} V_1 \\ I_1 \end{bmatrix}$$

i.e.

$$V_2 = DV_1 - BI_1$$

$$I_2 = -CV_1 + AI_1$$

III. TWO-ENDED LINE FAULT LOCATION

The following set line parameters are required

- R_{L1} = the positive-sequence resistance of the line
- X_{L1} = the positive-sequence inductive reactance of the line

  where $Z_{L1} = R_{L1} + jX_{L1}$

- B_{L1} = the positive-sequence susceptance of the line

  where $Y_{L1} = G_{L1} + jB_{L1}$

- l = the length of the line (in kilometers or miles)

The solution does not require source impedance values or fault loop information.

Synchronized (aligned) voltage and current sampled values (all three phases of voltage and current) from both End A and End B are available to both IEDs (i.e. to the IED at each end of the line) from each IED's disturbance recorder (from the record triggered by the fault).

At End A
- local V_{L1} and I_{L1} = V_{A1} and I_{A1}, and
- remote V_{R1} and I_{R1} = V_{B1} and I_{B1}

At End B
- local V_{L1} and I_{L1} = V_{B1} and I_{B1}, and
- remote V_{R1} and I_{R1} = V_{A1} and I_{A1}

Fault location calculation

The fault location method for two-ended lines uses measurements from both line ends. The main idea is that the fault location is derived by equating the fault-point voltage calculated from measurements from both ends of the line.

IED at End A

A fault occurs at distance d_A from End A.

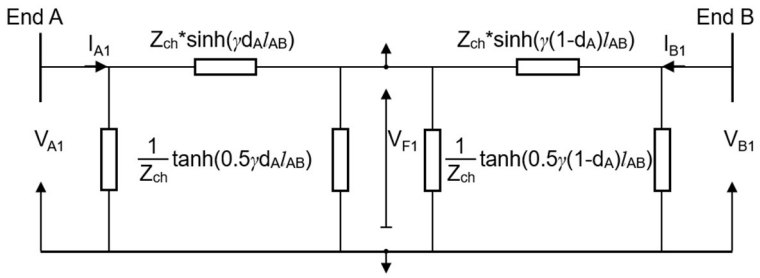


Fig. 2: positive-sequence network during a fault

In Fig. 2
- V_{A1}, I_{A1} are during-fault positive-sequence voltage and current phasors measured at End A
- V_{B1}, I_{B1} are during-fault positive-sequence voltage and current phasors measured at End B
- V_{F1} is the during-fault positive-sequence voltage phasor at the fault-point
- l_{AB} is the length of the line

The during-fault positive-sequence voltage phasor V_{F1} can be calculated from the End A during-fault quantities (V_{A1}, I_{A1} → V_{F1AA}), as well as from the End B during-fault quantities (V_{B1}, I_{B1} → V_{F1BA}). The IED at End A has the measured during-fault quantities from both ends, so can make both calculations.

- d_A is the fault-point as per unit of line length from End A
- $1-d_A$ is the fault-point as per unit of line length from End B
- V_{L1} and I_{L1} = V_{A1} and I_{A1}, i.e. V_{A1} and I_{A1} are the local-end voltage and current V_{L1} and I_{L1}
- V_{R1} and I_{R1} = V_{B1} and I_{B1}, i.e. V_{B1} and I_{B1} are the remote-end voltage and current V_{R1} and I_{R1}

$$V_{F1AA} = \cosh(\gamma d_A l_{AB})*V_{L1} - Z_{ch}*\sinh(\gamma d_A l_{AB})*I_{L1} \quad (1)$$

$$V_{F1BA} = \cosh(\gamma(1-d_A) l_{AB})*V_{R1} - Z_{ch}*\sinh(\gamma(1-d_A) l_{AB})*I_{R1} \quad (2)$$

Expanding (2)

$$V_{F1BA} = (\cosh(\gamma l_{AB})*\cosh(\gamma d_A l_{AB}) - \sinh(\gamma l_{AB})*\sinh(\gamma d_A l_{AB}))*V_{R1} - Z_{ch}*(\sinh(\gamma l_{AB})*\cosh(\gamma d_A l_{AB}) - \cosh(\gamma l_{AB})*\sinh(\gamma d_A l_{AB}))*I_{R1} \quad (3)$$

As $V_{F1AA} = V_{F1BA}$, the distance to fault d_A from End A can be calculated by the End A IED by equating (1) and (3), i.e. by equating (1) and (3) an equation can be derived to calculate d_A that is a *f*(the set parameters and available during-fault measurements).

$$\cosh(\gamma d_A l_{AB})*V_{L1} - Z_{ch}*\sinh(\gamma d_A l_{AB})*I_{L1} = (\cosh(\gamma l_{AB})*\cosh(\gamma d_A l_{AB}) - \sinh(\gamma l_{AB})*\sinh(\gamma d_A l_{AB}))*V_{R1} - Z_{ch}*(\sinh(\gamma l_{AB})*\cosh(\gamma d_A l_{AB}) - \cosh(\gamma l_{AB})*\sinh(\gamma d_A l_{AB}))*I_{R1}$$

from which

$$d_A = \frac{1}{\gamma l_{AB}} * \tanh^{-1}\left(\frac{\cosh(\gamma l_{AB})*V_{R1} + Z_{ch}*\sinh(\gamma l_{AB})*I_{R1} - V_{L1}}{\sinh(\gamma l_{AB})*V_{R1} - Z_{ch}*\cosh(\gamma l_{AB})*I_{R1} - Z_{ch}*I_{L1}}\right)$$

The above equation to calculate d_A is a *f*(the set parameters and available during-fault measurements).

IED at End B

The IED at End B makes a similar calculation.

- d_B (= 1-d_A in Fig. 2) is the fault-point as per unit of line length from End B
- 1-d_B (= d_A in Fig. 2) is the fault-point as per unit of line length from End A
- V_{L1} and I_{L1} = V_{B1} and I_{B1}, i.e. V_{B1} and I_{B1} are the local-end voltage and current V_{L1} and I_{L1}
- V_{R1} and I_{R1} = V_{A1} and I_{A1}, i.e. V_{A1} and I_{A1} are the remote-end voltage and current V_{R1} and I_{R1}

$$V_{F1BB} = \cosh(\gamma d_B l_{AB})*V_{L1} - Z_{ch}*\sinh(\gamma d_B l_{AB})*I_{L1} \quad (4)$$

$$V_{F1AB} = \cosh(\gamma (1-d_B) l_{AB})*V_{R1} - Z_{ch}*\sinh(\gamma (1-d_B) l_{AB})*I_{R1} \quad (5)$$

By equating (4) and (5), i.e. V_{F1BB} (4) = V_{F1AB} (5), an equation can be derived to calculate d_B that is a *f*(the set parameters and available during-fault measurements), where d_B is the distance to fault from End B calculated by the End B IED.

Line parameter estimation

The accuracy of the two-ended fault locator described above depends on the accuracy of the set line parameters R_{L1}, X_{L1} and B_{L1}. As these transmission line parameters are not known with great precision, there can be a significant error between the actual and the set values of the line parameters. Line parameters with little accuracy are sufficient for protection applications, but for accurate fault location precise line parameters are required. Furthermore, these line parameters are not constant as they vary with conditions such as weather, age of the conductor, etc.

The parameter estimation method for two-ended lines uses measurements from both line ends. Synchronized (aligned) pre-fault voltage and current sampled values from both End A and End B

are available to both IEDs (i.e. to the IED at each end of the line) from each IED's disturbance recorder (from the record triggered by the fault).

The method estimates the line parameters using positive-sequence pre-fault phasors and the line length using a two-step approach. The line parameters are first calculated using the lumped parameter π line model in step one, and the distributed parameter π line model in step two. The parameters obtained from step one are given as the initial guess for step two to solve the nonlinear equations.

The following set line parameters are required

- l = the length of the line (in kilometers or miles)

i) step one – initial guess calculation using the lumped π model of the line

Consider the transmission line shown in Fig. 3.

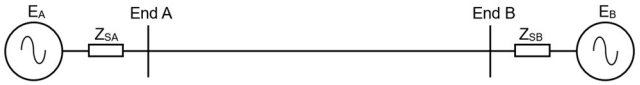


Fig. 3: two-ended transmission line

Fig. 4 shows the lumped π model for the transmission line shown in Fig. 3.

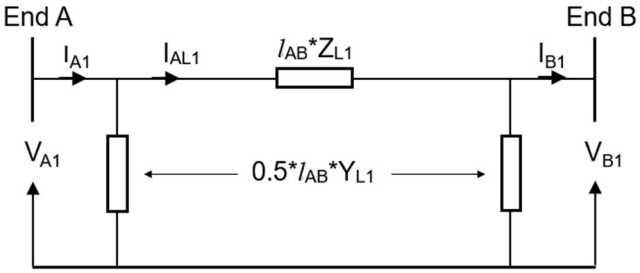


Fig. 4: two-ended transmission line lumped π model

In Fig. 4

- V_{A1}, I_{A1} are pre-fault positive-sequence voltage and current phasors measured at End A
- V_{B1}, I_{B1} are pre-fault positive-sequence voltage and current phasors measured at End B
- I_{AL1} is the pre-fault positive-sequence current flowing through the series impedance l_{AB}*Z_{L1}
- l_{AB} is the length of the line in meters
- Z_{L1}, Y_{L1} are, respectively, the positive-sequence series impedance and positive-sequence shunt admittance of the line, per meter of the line length

The pre-fault positive-sequence current phasor I_{AL1} can be calculated from the End A pre-fault quantities (V_{A1}, I_{A1}), as well as from the End B pre-fault quantities (V_{B1}, I_{B1}). As the IED at each end of the line has the measured pre-fault quantities from both ends, both IEDs make the same calculations.

IED at End A

- V_{L1} and I_{L1} = V_{A1} and I_{A1}
- V_{R1} and I_{R1} = V_{B1} and I_{B1}

From Fig. 4

$$I_{AL1AA} = I_{L1} - 0.5*l_{AB}*Y_{L1}*V_{L1} \quad (6)$$

$$I_{AL1BA} = I_{R1} + 0.5*l_{AB}*Y_{L1}*V_{R1} \quad (7)$$

As I_{AL1AA} calculated from End A measured values = I_{AL1BA} calculated from End B measured values, Y_{L1} can be calculated from (6) and (7) by equating them, i.e.

$$I_{L1} - 0.5*l_{AB}*Y_{L1}*V_{L1} = I_{R1} + 0.5*l_{AB}*Y_{L1}*V_{R1}$$

from which

$$Y_{L1} = \frac{2}{l_{AB}} \left(\frac{I_{L1} - I_{R1}}{V_{L1} + V_{R1}}\right) \quad (8)$$

Again from Fig. 4

$$V_{L1} - V_{R1} = I_{AL1AA}*l_{AB}*Z_{L1} \quad (9)$$

Substitute I_{AL1AA} from (6) into (9)

$$V_{L1} - V_{R1} = (I_{L1} - 0.5*l_{AB}*Y_{L1}*V_{L1})*l_{AB}*Z_{L1} \quad (10)$$

Then substitute Y_{L1} from (8) into (10)

$$V_{L1} - V_{R1} = \left(I_{L1} - \left(\frac{I_{L1} - I_{R1}}{V_{L1} + V_{R1}}\right)*V_{L1}\right)*l_{AB}*Z_{L1}$$

from which

$$Z_{L1} = \frac{1}{l_{AB}} \left(\frac{(V_{L1})^2 - (V_{R1})^2}{V_{L1}I_{R1} + V_{R1}I_{L1}}\right) \quad (11)$$

From (8) and (11)

$$R_{L1} = \text{real}(Z_{L1});\ L_{L1} = \frac{\text{imag}(Z_{L1})}{2\pi f};\ C_{L1} = \frac{\text{imag}(Y_{L1})}{2\pi f}$$

R_{L1}, L_{L1}, and C_{L1} are, respectively, the positive-sequence resistance, inductance, and capacitance per meter of the transmission line length. f is the system frequency in Hz. These parameters obtained using the simplified lumped π model of the line are used as the initial guess in the next step.

IED at End B

The IED at End B makes a similar calculation with

- V_{L1} and I_{L1} = V_{B1} and I_{B1}
- V_{R1} and I_{R1} = V_{A1} and I_{A1}

ii) step two – estimated line parameter calculation using the distributed π model of the line

The estimated line parameters are calculated using the distributed π model of the line as shown in Fig. 5.

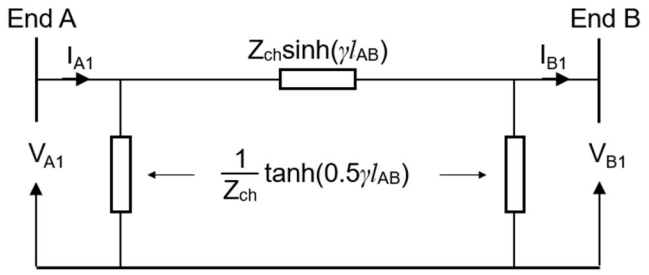


Fig. 5: two-ended transmission line distributed π model

In Fig. 5

- V_{A1}, I_{A1} are the pre-fault positive-sequence voltage and current phasors measured at End A
- V_{B1}, I_{B1} are the pre-fault positive-sequence voltage and current phasors measured at End B
- Z_{L1}, Y_{L1} are, respectively, the positive-sequence series impedance and positive-sequence shunt admittance of the line, per meter of the line length
- l_{AB} = length of the line in meters
- $Z_{ch} = \sqrt{Z_{L1}/Y_{L1}}$ = characteristic impedance of the line = $\sqrt{\frac{R_{L1} + j\omega L_{L1}}{j\omega C_{L1}}}$
- $\gamma = \sqrt{Z_{L1}*Y_{L1}}$ = propagation constant of the line = $\sqrt{(R_{L1} + j\omega L_{L1})*(j\omega C_{L1})}$

IED at End A

- V_{L1} and I_{L1} = V_{A1} and I_{A1}
- V_{R1} and I_{R1} = V_{B1} and I_{B1}

From the two-port network shown in Fig. 5

$$V_{L1} = \cosh(\gamma l_{AB})*V_{R1} + Z_{ch}*\sinh(\gamma l_{AB})*I_{R1} \quad (12)$$

$$I_{L1} = \frac{1}{Z_{ch}}*\sinh(\gamma l_{AB})*V_{R1} + \cosh(\gamma l_{AB})*I_{R1} \quad (13)$$

The non-linear equations (12) and (13) are solved by using the least squares method to obtain the actual parameters of the line. The initial guess required for this solution is obtained from the previous step.

The final parameters are determined using the following relationships

$$Z_{L1} = Z_{ch} * \gamma = R_{L1} + jX_{L1} \quad (14)$$

$$Y_{L1} = \frac{\gamma}{Z_{ch}} = G_{L1} + jB_{L1} \quad (15)$$

From (14) and (15)

$$R_{L1} = \text{real}(Z_{L1});\ L_{L1} = \frac{\text{imag}(Z_{L1})}{2\pi f};\ C_{L1} = \frac{\text{imag}(Y_{L1})}{2\pi f}$$

R_{L1}, L_{L1}, and C_{L1} are, respectively, the positive-sequence resistance, inductance, and capacitance per meter of the transmission line length, which are estimated using the pre-fault voltage and current measured at both ends of the line. These estimated parameters can be used as input to the fault location calculation.

When fault location is calculated using the estimated parameters, just the line length and during-fault positive-sequence phasors are needed. No set line parameters are required other than the line length.

IED at End B

The IED at End B makes a similar calculation with

- V_{L1} and I_{L1} = V_{B1} and I_{B1}
- V_{R1} and I_{R1} = V_{A1} and I_{A1}

IV. THREE-ENDED LINE FAULT LOCATION

There has been a huge growth in the number of multi-ended tapped lines mainly due to increased renewable integration into the grid. To transmit power from a renewable energy source, or supply power to bulk industrial loads, multi-ended or tapped lines provide an attractive solution at minimum cost. This is true in cases of solar parks and wind farms where the power transmitted to the main grid is done through short lines. New transmission lines connecting new generation sources or loads are directly connected to an existing transmission line. To make the setup more cost-effective, building a substation or installing measurement transformers at the tap/junction point is avoided.

The fault location method for multi-ended tapped lines uses positive-sequence voltage and current quantities from all ends. The approach on which this is based is to estimate the currents flowing from all three sections into the junction as a function of the unknown distance to the fault. Since the sum of currents at the junction must be equal to zero, the fault location is obtained by equating the sum of the three estimated currents to zero and solving for the unknown.

The following set line parameters are required

- R_{L11} = the positive-sequence resistance of line section 1
- X_{L11} = the positive-sequence inductive reactance of line section 1
- B_{L11} = the positive-sequence susceptance of line section 1
- l_1 = the length of line section 1 (in kilometers or miles)

- R_{L12} = the positive-sequence resistance of line section 2
- X_{L12} = the positive-sequence inductive reactance of line section 2
- B_{L12} = the positive-sequence susceptance of line section 2
- l_2 = the length of line section 2 (in kilometers or miles)

- R_{L13} = the positive-sequence resistance of line section 3
- X_{L13} = the positive-sequence inductive reactance of line section 3
- B_{L13} = the positive-sequence susceptance of line section 3
- l_3 = the length of line section 3 (in kilometers or miles)

The fault location method does not require source impedance values or fault loop information.

The three-ended line shown in Fig. 6 is used to describe the fault location method.

The ends of the three-ended line shown in Fig. 6 are labelled End A, End B, and End C. J is the junction between the three sections.

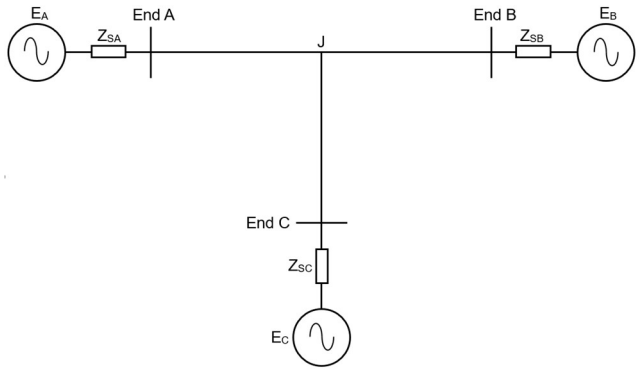


Fig. 6: three-ended transmission line

The line section between End A and junction J is designated section AJ. Similarly, the line section between End B and junction J is designated section BJ, and the line section between End C and junction J is designated section CJ.

The respective line lengths of the sections AJ, BJ and CJ are l_{AJ}, l_{BJ} and l_{CJ}.

Synchronized (aligned) voltage and current sampled values (all three phases of voltage and current) from End A, End B and End C are available to all IEDs (i.e. to the IED at each end of the line) from each IED's disturbance recorder (from the record triggered by the fault).

As each IED has available to it time aligned sampled values of the local and both remote currents and voltages, the during-fault positive-sequence phasors are calculated by each IED, i.e. each IED calculates V_{A1}, I_{A1}, V_{B1}, I_{B1}, V_{C1} and I_{C1}.

At End A
- local V_{L1} and I_{L1} = V_{A1} and I_{A1},
- remote V_{R11} and I_{R11} = V_{B1} and I_{B1}, and
- remote V_{R12} and I_{R12} = V_{C1} and I_{C1}

At End B
- local V_{L1} and I_{L1} = V_{B1} and I_{B1},
- remote V_{R11} and I_{R11} = V_{C1} and I_{C1}, and
- remote V_{R12} and I_{R12} = V_{A1} and I_{A1}

At End C
- local V_{L1} and I_{L1} = V_{C1} and I_{C1},
- remote V_{R11} and I_{R11} = V_{A1} and I_{A1}, and
- remote V_{R12} and I_{R12} = V_{B1} and I_{B1}

From the two-port network for each line section

- A_{AJ}, B_{AJ}, C_{AJ} and D_{AJ} are, respectively, the A, B, C and D positive-sequence parameters of section AJ
- A_{BJ}, B_{BJ}, C_{BJ} and D_{BJ} are, respectively, the A, B, C and D positive-sequence parameters of section BJ
- A_{CJ}, B_{CJ}, C_{CJ} and D_{CJ} are, respectively, the A, B, C and D positive-sequence parameters of section CJ

After a fault has been detected, the fault location function is initiated. The fault can be in any of the three sections. A separate calculation is made for each of the three line sections, AJ, BJ and CJ, with the calculation for each section assuming the fault is in its section. The IED at each end has the measured fault quantities from all ends, so all IEDs make the same calculations for all three sections.

Consider that the fault is in section AJ d_A from End A as shown in Fig. 7 (d_A is a length of section AJ < l_{AJ}).

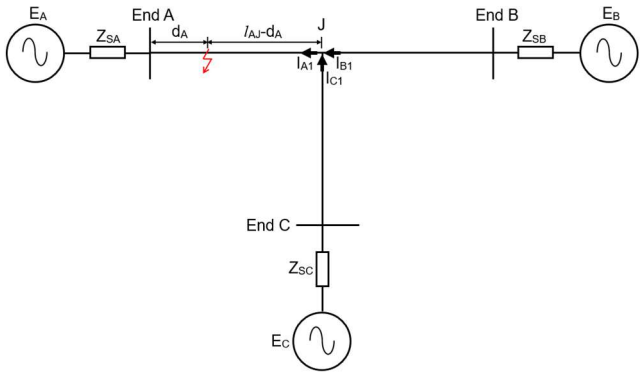


Fig. 7: three-ended line with fault in section AJ

IED at End A

- local V_{L1} and I_{L1} = V_{A1} and I_{A1}, i.e. V_{A1} and I_{A1} are the local-end voltage and current V_{L1} and I_{L1}
- remote V_{R11} and I_{R11} = V_{B1} and I_{B1}, i.e. V_{B1} and I_{B1} are the remote-end voltage and current V_{R11} and I_{R11}
- remote V_{R12} and I_{R12} = V_{C1} and I_{C1}, i.e. V_{C1} and I_{C1} are the remote-end voltage and current V_{R12} and I_{R12}

Section AJ calculation

This calculation assumes that the fault is in section AJ (which in this case it is). For a fault in section AJ, as shown in Fig. 7, d_A is the unknown distance to the fault from End A.

Calculate I_{B1BA} and I_{C1CA} (IED at End A calculation), the positive-sequence currents flowing into junction J from, respectively, sections BJ and CJ (which in this case are the two healthy sections).

From the two-port network defined between End B and the junction J

$$I_{B1BA} = -C_{BJ}V_{R11} + A_{BJ}I_{R11} \quad (16)$$

where

$$C_{BJ} = \frac{1}{Z_{chBJ}} * \sinh(\gamma_{BJ} l_{BJ})$$

$$A_{BJ} = \cosh(\gamma_{BJ} l_{BJ})$$

Z_{chBJ} is the characteristic impedance and γ_{BJ} the propagation constant of section BJ.

Similarly, from the two-port network defined between End C and the junction J

$$I_{C1CA} = -C_{CJ}V_{R12} + A_{CJ}I_{R12} \quad (17)$$

where

$$C_{CJ} = \frac{1}{Z_{chCJ}} * \sinh(\gamma_{CJ} l_{CJ})$$

$$A_{CJ} = \cosh(\gamma_{CJ} l_{CJ})$$

Z_{chCJ} is the characteristic impedance and γ_{CJ} the propagation constant of section CJ.

For the fault in section AJ, calculate now the current I_{A1A}, the positive-sequence current flowing from the junction-end of section AJ.

Note that neither of the above equations for I_{B1BA} or I_{C1CA} contain the unknown d_A.

To obtain an equation for I_{A1A} as a $f(d_A)$, from the two-port network defined between End A and the fault location F, calculate the voltage V_{F1AA} at the fault-point F using the voltage and current measured at End A. This will be a function of the unknown distance to the fault d_A.

$$V_{F1AA} = D_{dA}V_{L1} - B_{dA}I_{L1} \quad (18)$$

where

$$D_{dA} = \cosh(\gamma_{AJ}d_A)$$

$$B_{dA} = Z_{chAJ}*\sinh(\gamma_{AJ}d_A)$$

D_{dA} and B_{dA} are *f*(the section AJ parameters from End A to the fault).

Similarly, from the two-port network defined between junction J and the fault-point F, calculate the voltage V_{F1JA} at the fault-point F using the voltage V_{J1A} and current I_{A1A} at the junction J.

$$V_{F1JA} = D_{lAJ\text{-}dA}V_{J1A} - B_{lAJ\text{-}dA}I_{A1A} \quad (19)$$

where

$$D_{lAJ\text{-}dA} = \cosh(\gamma_{AJ}(l_{AJ}-d_A))$$

$$B_{lAJ\text{-}dA} = Z_{chAJ}*\sinh(\gamma_{AJ}(l_{AJ}-d_A))$$

$D_{lAJ\text{-}dA}$ and $B_{lAJ\text{-}dA}$ are *f*(the section AJ parameters from junction J to the fault).

Note (18) and (19) are both calculations for the positive-sequence voltage at the fault-point F, hence V_{F1AA} (18) = V_{F1JA} (19).

Once more, in a similar way, from the two-port network defined between End B and the junction J, calculate the voltage V_{J1BA} at the junction J using the voltage V_{B1} and current I_{B1} measured at End B.

$$V_{J1BA} = D_{BJ}V_{R11} - B_{BJ}I_{R11} \quad (20)$$

where

$$D_{BJ} = \cosh(\gamma_{BJ}l_{BJ})$$

$$B_{BJ} = Z_{chBJ}*\sinh(\gamma_{BJ}l_{BJ})$$

Note (19) includes the positive-sequence voltage V_{J1A} at the junction J, and (20) calculates the positive-sequence voltage V_{J1BA} at junction J.

Substitute V_{J1BA} from (20) for V_{J1A} in (19)

$$V_{F1JA} = D_{lAJ\text{-}dA}(D_{BJ}V_{R11} - B_{BJ}I_{R11}) - B_{lAJ\text{-}dA}I_{A1A} \quad (21)$$

As noted above, (18) and now (21) are both calculations for the positive-sequence voltage at the fault-point F, hence V_{F1AA} (18) = V_{F1JA} (21). By equating (18) and (21) an equation can be derived to calculate I_{A1A} that is a *f*(d_A, the set parameters and available during-fault measurements), i.e.

$$D_{dA}V_{L1} - B_{dA}I_{L1} = D_{lAJ\text{-}dA}(D_{BJ}V_{R11} - B_{BJ}I_{R11}) - B_{lAJ\text{-}dA}I_{A1A}$$

from which

$$I_{A1A} = \frac{D_{dA}V_{L1} - B_{dA}I_{L1} - D_{lAJ\text{-}dA}(D_{BJ}V_{R11} - B_{BJ}I_{R11})}{-B_{lAJ\text{-}dA}} \qquad (22)$$

Since the sum of currents at the junction must be equal to zero, the fault location is obtained by equating the sum of the three estimated currents to zero and solving for the unknown, i.e. from (22), (16) and (17)

$$I_{A1A} + I_{B1BA} + I_{C1CA} = 0$$

and simplifying further, the distance to the fault d_A from End A is obtained as

$$d_A = \frac{1}{\gamma_{AJ}} \tanh^{-1}\left[\frac{K_1}{K_2}\right]$$

where

K_1 and K_2 are *f*(the set parameters and available during-fault measurements), so therefore

d_A is a *f*(the set parameters and available during-fault measurements).

Section BJ calculation

Although in this case the fault is in section AJ, exactly the same calculations as described above for section AJ are made for section BJ, with the calculations for section BJ assuming the fault to be within this section.

$$I_{C1CA} = -C_{CJ}V_{R12} + A_{CJ}I_{R12} \qquad I_{A1AA} = -C_{AJ}V_{L1} + A_{AJ}I_{L1}$$

$$V_{F1BA} = D_{dB}V_{R11} - B_{dB}I_{R11} \qquad V_{F1JA} = D_{lBJ\text{-}dB}V_{J1A} - B_{lBJ\text{-}dB}I_{B1A} \qquad V_{J1CA} = D_{CJ}V_{R12} - B_{CJ}I_{R12}$$

From these calculations, and again by equating the sum of the three estimated currents to zero, the distance to the fault d_B from End B is obtained.

Section CJ calculation

Although in this case the fault is in section AJ, exactly the same calculations as described above for section AJ are made for section CJ, with the calculations for section CJ assuming the fault to be within this section.

$$I_{A1AA} = -C_{AJ}V_{L1} + A_{AJ}I_{L1} \qquad I_{B1BA} = -C_{BJ}V_{R11} + A_{BJ}I_{R11}$$

$$V_{F1CA} = D_{dC}V_{R12} - B_{dC}I_{R12} \qquad V_{F1JA} = D_{lCJ\text{-}dC}V_{J1A} - B_{lCJ\text{-}dC}I_{C1A} \qquad V_{J1AA} = D_{AJ}V_{L1} - B_{AJ}I_{L1}$$

From these calculations, and again by equating the sum of the three estimated currents to zero, the distance to the fault d_C from End C is obtained.

Selection of actual fault location

Selection of the final accurate fault location from the three possible estimates is the final step. When the actual fault is in a particular section, say section AJ, the fault location estimates from the section BJ and section CJ calculations would yield non-feasible values, i.e. they would be negative or greater than the length of the particular section. For example, if the actual fault is in section AJ, the fault location estimate d_A from the section AJ calculation would be such that $0<d_A<l_{AJ}$. The fault location estimate d_B from the section BJ calculation would be such that either $d_B<0$ or $d_B>l_{BJ}$, and the estimate d_C from the section CJ calculation would be such that either $d_C<0$ or $d_C>l_{CJ}$. Hence, these conditions can be used to identify the correct fault location from the three probable estimates.

IED at End B

The IED at End B makes exactly the same calculations with

- local V_{L1} and I_{L1} = V_{B1} and I_{B1}, i.e. V_{B1} and I_{B1} are the local-end voltage and current V_{L1} and I_{L1}
- remote V_{R11} and I_{R11} = V_{C1} and I_{C1}, i.e. V_{C1} and I_{C1} are the remote-end voltage and current V_{R11} and I_{R11}
- remote V_{R12} and I_{R12} = V_{A1} and I_{A1}, i.e. V_{A1} and I_{A1} are the remote-end voltage and current V_{R12} and I_{R12}

IED at End C

The IED at End C makes exactly the same calculations with

- local V_{L1} and I_{L1} = V_{C1} and I_{C1}, i.e. V_{C1} and I_{C1} are the local-end voltage and current V_{L1} and I_{L1}
- remote V_{R11} and I_{R11} = V_{A1} and I_{A1}, i.e. V_{A1} and I_{A1} are the remote-end voltage and current V_{R11} and I_{R11}
- remote V_{R12} and I_{R12} = V_{B1} and I_{B1}, i.e. V_{B1} and I_{B1} are the remote-end voltage and current V_{R12} and I_{R12}

V. MIXED LINE FAULT LOCATION

A mixed line is a line with both overhead line (OHL) and underground cable (UGC) sections.

Two-ended line

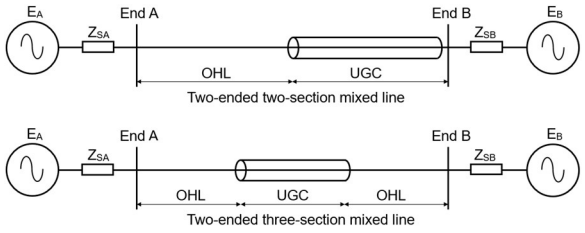


Fig. 8: two-ended mixed lines

The positive-sequence line parameters for each section are entered as settings. The fault location method does not require source impedance values or fault loop information.

The two-ended line shown in Fig. 9 is used to describe the fault location method.

The ends of the two-ended line shown in Fig. 9 are labelled End A and End B. J is the junction between the two sections.

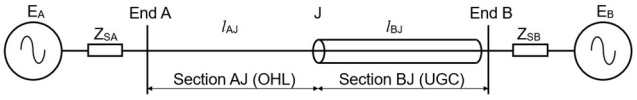


Fig. 9: two-ended mixed transmission line

The line section between End A and junction J is designated section AJ. Similarly, the line section between End B and junction J is designated section BJ.

The respective line lengths of the sections AJ and BJ are l_{AJ} and l_{BJ}.

Synchronized (aligned) voltage and current sampled values (all three phases of voltage and current) from both End A and End B are available to both IEDs (i.e. to the IED at each end of the line) from each IED's disturbance recorder (from the record triggered by the fault).

As each IED has available to it time aligned sampled values of both the local and remote currents and voltages, the during-fault positive-sequence phasors are calculated by each IED, i.e. each IED calculates V_{A1}, I_{A1}, V_{B1} and I_{B1}.

At End A
- local V_{L1} and I_{L1} = V_{A1} and I_{A1}, and
- remote V_{R1} and I_{R1} = V_{B1} and I_{B1}

At End B
- local V_{L1} and I_{L1} = V_{B1} and I_{B1}, and
- remote V_{R1} and I_{R1} = V_{A1} and I_{A1}

From the two-port network for each line section

- A_{AJ}, B_{AJ}, C_{AJ} and D_{AJ} are, respectively, the A, B, C and D positive-sequence parameters of section AJ
- A_{BJ}, B_{BJ}, C_{BJ} and D_{BJ} are, respectively, the A, B, C and D positive-sequence parameters of section BJ

After a fault has been detected, the fault location function is initiated. The fault can be in any of the two sections. The faulted section is identified as step one, after which the location of the fault within that section is determined as step two. The IED at each end has the measured fault quantities from both ends, so both IEDs make the same calculations.

i) step one – identify the faulted section

Fig. 10 shows a two-ended mixed line with OHL section AJ (length l_{AJ}) and UGC section BJ (length l_{BJ}). Step one determines whether the fault is in the OHL section (F_{AJ}) or UGC section (F_{BJ}).

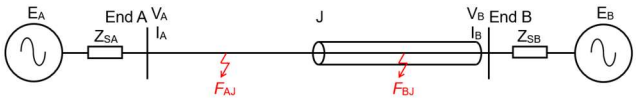


Fig. 10: two-ended mixed line with fault

IED at End A

- local V_{L1} and I_{L1} = V_{A1} and I_{A1}, i.e. V_{A1} and I_{A1} are the local-end voltage and current V_{L1} and I_{L1}
- remote V_{R1} and I_{R1} = V_{B1} and I_{B1}, i.e. V_{B1} and I_{B1} are the remote-end voltage and current V_{R1} and I_{R1}

A summary of the calculations is
- calculate the junction voltage from both ends
- calculate the junction current from both ends
- calculate the ratio (= K) of the difference between the junction voltages to the sum of the junction currents
- determine the angle of K – if < 0, the fault is in the first section (i.e. F_{AJ} within section AJ, the OLH) – if not < 0, the fault is in the second section (i.e. F_{BJ} within section BJ, the UGC).

The IED at End A assumes the fault to be in the section immediately connected to End A, i.e. fault F_{AJ}.

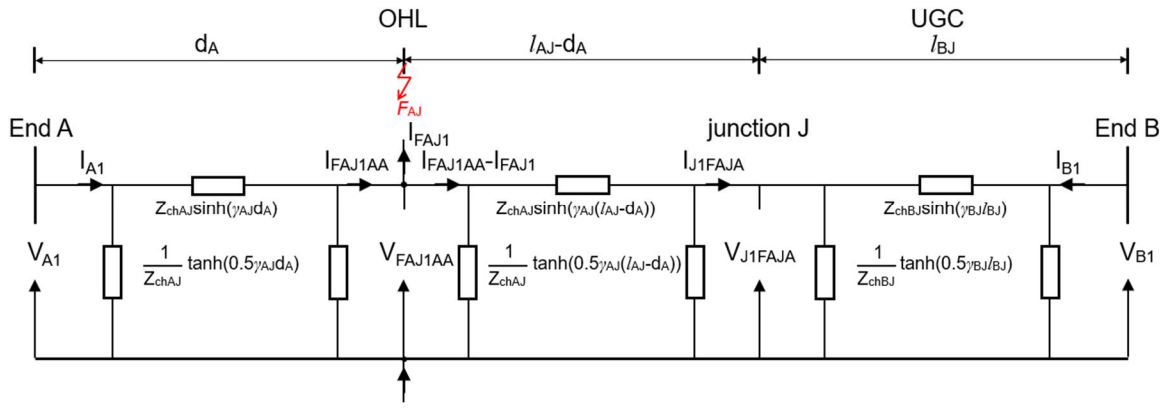


Fig. 11: positive-sequence transmission line distributed π model for F_{AJ} fault

The fault-point voltage and current can be calculated as follows from the measured End A positive-sequence voltage and current V_{L1} and I_{L1}.

$$V_{FAJ1AA} = \cosh(\gamma_{AJ}d_A)V_{L1} - Z_{chAJ}*\sinh(\gamma_{AJ}d_A)I_{L1} \quad (23)$$

$$I_{FAJ1AA} = -\frac{1}{Z_{chAJ}}*\sinh(\gamma_{AJ}d_A)V_{L1} + \cosh(\gamma_{AJ}d_A)I_{L1} \quad (24)$$

The voltage and current at the junction J can be calculated as follows from the calculated values for the fault-point positive-sequence voltage and current.

$$V_{J1FAJA} = \cosh(\gamma_{AJ}(l_{AJ}-d_A))V_{FAJ1AA} - Z_{chAJ}*\sinh(\gamma_{AJ}(l_{AJ}-d_A))(I_{FAJ1AA}-I_{FAJ1}) \quad (25)$$

$$I_{J1FAJA} = -\frac{1}{Z_{chAJ}}*\sinh(\gamma_{AJ}(l_{AJ}-d_A))V_{FAJ1AA} + \cosh(\gamma_{AJ}(l_{AJ}-d_A))(I_{FAJ1AA}-I_{FAJ1}) \quad (26)$$

Substitute (23) and (24) into both (25) and (26) to get

$$V_{J1FAJA} = \cosh(\gamma_{AJ}l_{AJ})V_{L1} - Z_{chAJ}*\sinh(\gamma_{AJ}l_{AJ})I_{L1} + Z_{chAJ}*\sinh(\gamma_{AJ}(l_{AJ}-d_A))I_{FAJ1} \quad (27)$$

$$I_{J1FAJA} = -\frac{1}{Z_{chAJ}}*\sinh(\gamma_{AJ}l_{AJ})V_{L1} + \cosh(\gamma_{AJ}l_{AJ})I_{L1} - \cosh(\gamma_{AJ}(l_{AJ}-d_A))I_{FAJ1} \quad (28)$$

The voltage and current at the junction J can also be calculated as follows from the measured End B positive-sequence voltage and current V_{R1} and I_{R1}.

$$V_{J1BA} = \cosh(\gamma_{BJ}l_{BJ})V_{R1} - Z_{chBJ}*\sinh(\gamma_{BJ}l_{BJ})I_{R1} \quad (29)$$

$$I_{J1BA} = -\frac{1}{Z_{chBJ}}*\sinh(\gamma_{BJ}l_{BJ})V_{R1} + \cosh(\gamma_{BJ}l_{BJ})I_{R1} \quad (30)$$

Consider voltage first. J is a point on the line. Therefore, the voltage at that point calculated from End A is equal to the voltage at that point calculated from End B, i.e. V_{J1FAJA} (27) = V_{J1BA} (29), from which

$$\cosh(\gamma_{AJ}l_{AJ})V_{L1} - Z_{chAJ}*\sinh(\gamma_{AJ}l_{AJ})I_{L1} + Z_{chAJ}*\sinh(\gamma_{AJ}(l_{AJ}-d_A))I_{FAJ1} = \cosh(\gamma_{BJ}l_{BJ})V_{R1} - Z_{chBJ}*\sinh(\gamma_{BJ}l_{BJ})I_{R1}$$

or, re-arranging

$$\cosh(\gamma_{AJ}l_{AJ})V_{L1} - Z_{chAJ}*\sinh(\gamma_{AJ}l_{AJ})I_{L1} - (\cosh(\gamma_{BJ}l_{BJ})V_{R1} - Z_{chBJ}*\sinh(\gamma_{BJ}l_{BJ})I_{R1}) = - Z_{chAJ}*\sinh(\gamma_{AJ}(l_{AJ}-d_A))I_{FAJ1} \quad (31)$$

The voltage at the junction J can also be calculated as follows from the measured End A positive-sequence voltage and current V_{L1} and I_{L1}.

$$V_{J1AA} = \cosh(\gamma_{AJ}l_{AJ})V_{L1} - Z_{chAJ}*\sinh(\gamma_{AJ}l_{AJ})I_{L1} \quad (32)$$

From (32) and (29), (31) can be re-written as

$$V_{J1AA} - V_{J1BA} = - Z_{chAJ}*\sinh(\gamma_{AJ}(l_{AJ}-d_A))I_{FAJ1} \quad (33)$$

where both V_{J1AA} and V_{J1BA} are *f*(the set parameters and available during-fault measurements).

Consider now the current. J is a point on the line. Therefore, the current at that point calculated from End A is equal to minus the current at that point calculated from End B, i.e. I_{J1FAJA} (28) = - I_{J1BA} (30), from which

$$-\frac{1}{Z_{chAJ}}*\sinh(\gamma_{AJ}l_{AJ})V_{L1} + \cosh(\gamma_{AJ}l_{AJ})I_{L1} - \cosh(\gamma_{AJ}(l_{AJ}-d_A))I_{FAJ1} = -(-\frac{1}{Z_{chBJ}}*\sinh(\gamma_{BJ}l_{BJ})V_{R1} + \cosh(\gamma_{BJ}l_{BJ})I_{R1})$$

or, re-arranging

$$-\frac{1}{Z_{chAJ}}*\sinh(\gamma_{AJ}l_{AJ})V_{L1} + \cosh(\gamma_{AJ}l_{AJ})I_{L1} + (-\frac{1}{Z_{chBJ}}*\sinh(\gamma_{BJ}l_{BJ})V_{R1} + \cosh(\gamma_{BJ}l_{BJ})I_{R1}) = \cosh(\gamma_{AJ}(l_{AJ}-d_A))I_{FAJ1} \quad (34)$$

The current at the junction J can also be calculated as follows from the measured End A positive-sequence voltage and current V_{L1} and I_{L1}.

$$I_{J1AA} = -\frac{1}{Z_{chAJ}}*\sinh(\gamma_{AJ}l_{AJ})V_{L1} + \cosh(\gamma_{AJ}l_{AJ})I_{L1} \quad (35)$$

From (35) and (30), (34) can be re-written as

$$I_{J1AA} + I_{J1BA} = \cosh(\gamma_{AJ}(l_{AJ}-d_A))I_{FAJ1} \quad (36)$$

where both I_{J1AA} and I_{J1BA} are *f*(the set parameters and available during-fault measurements).

Divide (33) by (36) to get

$$K = (\frac{V_{J1AA} - V_{J1BA}}{I_{J1AA} + I_{J1BA}}) = -Z_{chAJ}*\tanh(\gamma_{AJ}(l_{AJ}-d_A))$$

$$= Z_{chAJ}*\tanh(\gamma_{AJ}(d_A-l_{AJ}))$$

If the fault occurred in the first line section, i.e. F_{AJ} on section AJ, $d_A < l_{AJ}$, so that $(d_A - l_{AJ}) < 0$. Therefore, an angle of $K < 0$ indicates that the fault is in the first section.

As already stated above, the IED at End A assumes the fault to be in the section immediately connected to End A, i.e. fault F_{AJ} in section AJ, and the calculations made by the IED at End A are based on this assumption. However, the fault could be in the next section, i.e. fault F_{BJ} in section BJ. The IED at End A will still make the same calculations, which now do not represent the actual system condition as the fault is not in the first section. This non-representative calculation for a fault F_{BJ} in the next section BJ will always give the result $d_A > l_{AJ}$, i.e. the angle of K will be > 0 indicating that the fault is not in the first section AJ.

An angle of $K < 0$ indicates that the fault is in the first section, whereas if the angle of K is not < 0 this indicates that the fault is not in the first section, i.e. the polarity of the angle of K identifies if the fault is in section AJ or BJ.

Simulation example to illustrate

- Total line length 120km
- OHL section 100km
- UGC section 20km

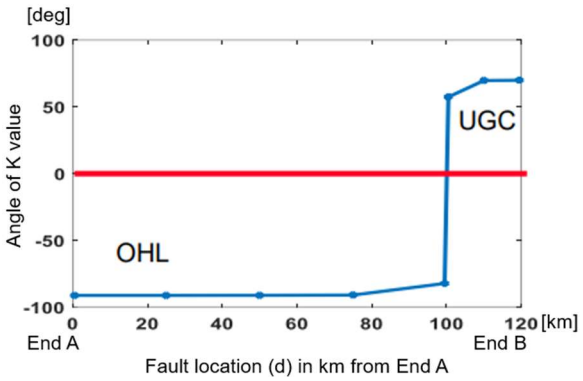


Fig. 12: Angle of K as calculated by the IED at End A for faults at different locations d along the line

IED at End B

The IED at End B assumes the fault to be in the section immediately connected to End B, i.e. fault F_{BJ}.

The IED at End B makes exactly the same calculations with

- local V_{L1} and I_{L1} = V_{B1} and I_{B1}, i.e. V_{B1} and I_{B1} are the local-end voltage and current V_{L1} and I_{L1}
- remote V_{R1} and I_{R1} = V_{A1} and I_{A1}, i.e. V_{A1} and I_{A1} are the remote-end voltage and current V_{R1} and I_{R1}

When the IED at End A calculates the angle of K < 0, the IED at End B will calculate the angle of K > 0, and vice versa.

ii) step two – calculate the fault location

IED at End A

If the fault is in section AJ, section AJ becomes equivalent to a two-ended line with known voltages and currents from both ends (V_{L1} and I_{L1} (= V_{A1} and I_{A1}), and V_{J1BA} and I_{J1BA}. Likewise, if the fault is in section BJ, section BJ becomes equivalent to a two-ended line with known voltages and currents from both ends (V_{R1} and I_{R1} (= V_{B1} and I_{B1}), and V_{J1AA} and I_{J1AA}. To determine the fault location within the faulty section the two-ended fault location method described in Section III is now used.

IED at End B

As for the IED at End A, but from the perspective of the IED at End B.

Three-ended line

The positive-sequence line parameters for each section are entered as settings. The fault location method does not require source impedance values or fault loop information.

The three-ended line shown in Fig. 13 is used to describe the fault location method.

The ends of the three-ended line shown in Fig. 13 are labelled End A, End B and End C. J is the junction between the three sections.

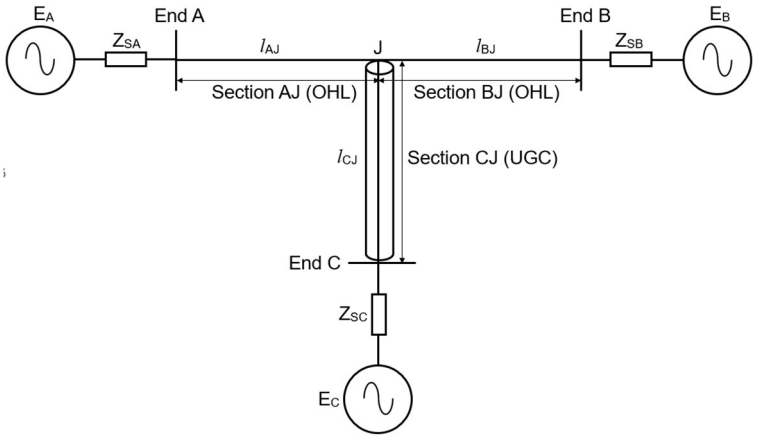


Fig. 13: three-ended mixed transmission line

The line section between End A and junction J is designated section AJ. Similarly, the line section between End B and junction J is designated section BJ, and between End C and junction J is designated section CJ.

The respective line lengths of the sections AJ, BJ and CJ are l_{AJ}, l_{BJ} and l_{CJ}.

Synchronized (aligned) voltage and current sampled values (all three phases of voltages and currents) from End A, End B and End C are available to all IEDs (i.e. to the IED at each end of the line) from each IED's disturbance recorder (from the record triggered by the fault).

As each IED has available to it time aligned sampled values of the local and both remote currents and voltages, the during-fault positive-sequence phasors are calculated by each IED, i.e. each IED calculates V_{A1}, I_{A1}, V_{B1}, I_{B1}, V_{C1} and I_{C1}.

At End A
- local V_{L1} and I_{L1} = V_{A1} and I_{A1},
- remote V_{R11} and I_{R11} = V_{B1} and I_{B1}, and
- remote V_{R12} and I_{R12} = V_{C1} and I_{C1}

At End B
- local V_{L1} and I_{L1} = V_{B1} and I_{B1},
- remote V_{R11} and I_{R11} = V_{C1} and I_{C1}, and
- remote V_{R12} and I_{R12} = V_{A1} and I_{A1}

At End C
- local V_{L1} and I_{L1} = V_{C1} and I_{C1},
- remote V_{R11} and I_{R11} = V_{A1} and I_{A1}, and
- remote V_{R12} and I_{R12} = V_{B1} and I_{B1}

From the two-port network for each line section

- A_{AJ}, B_{AJ}, C_{AJ} and D_{AJ} are, respectively, the A, B, C and D positive-sequence parameters of section AJ
- A_{BJ}, B_{BJ}, C_{BJ} and D_{BJ} are, respectively, the A, B, C and D positive-sequence parameters of section BJ
- A_{CJ}, B_{CJ}, C_{CJ} and D_{CJ} are, respectively, the A, B, C and D positive-sequence parameters of section CJ

After a fault has been detected, the fault location function is initiated. The fault can be in any of the three sections. The faulted section is identified as step one, after which the location of the fault within that section is determined as step two. The IED at each end has the measured fault quantities from all ends, so all IEDs make the same calculations.

i) step one – identify the faulted section

IED at End A

- local V_{L1} and I_{L1} = V_{A1} and I_{A1}, i.e. V_{A1} and I_{A1} are the local-end voltage and current V_{L1} and I_{L1}
- remote V_{R11} and I_{R11} = V_{B1} and I_{B1}, i.e. V_{B1} and I_{B1} are the remote-end voltage and current V_{R11} and I_{R11}
- remote V_{R12} and I_{R12} = V_{C1} and I_{C1}, i.e. V_{C1} and I_{C1} are the remote-end voltage and current V_{R12} and I_{R12}

Calculate

- the estimated voltage at End B $V_{B1AAcalc}$ using voltage and current measured at End A and current measured at End B

$$V_{J1AA} = D_{AJ}V_{L1} - B_{AJ}I_{L1} \quad \text{from which} \quad V_{B1AAcalc} = D_{BJ}V_{J1AA} - B_{BJ}I_{R11}$$

- the estimated voltage at End C $V_{C1BAcalc}$ using voltage and current measured at End B and current measured at End C

$$V_{J1BA} = D_{BJ}V_{R11} - B_{BJ}I_{R11} \quad \text{from which} \quad V_{C1BAcalc} = D_{CJ}V_{J1BA} - B_{CJ}I_{R12}$$

- the estimated voltage at End A $V_{A1CAcalc}$ using voltage and current measured at End C and current measured at End A

$$V_{J1CA} = D_{CJ}V_{R12} - B_{CJ}I_{R12} \quad \text{from which} \quad V_{A1CAcalc} = D_{AJ}V_{J1CA} - B_{AJ}I_{L1}$$

Having calculated the estimated voltage for each end, subtract the calculated estimated voltage magnitude from the measured voltage magnitude for the same end.

$$|\Delta V_{B1AA}| = |V_{B1AAcalc} - V_{R11}|$$

$$|\Delta V_{C1BA}| = |V_{C1BAcalc} - V_{R12}|$$

$$|\Delta V_{A1CA}| = |V_{A1CAcalc} - V_{L1}|$$

The line section with the fault is identified by which of $|\Delta V_{B1AA}|$, $|\Delta V_{C1BA}|$, $|\Delta V_{A1CA}|$ has minimum magnitude.

If

- $|\Delta V_{B1AA}|$ has minimum magnitude, the fault is in section CJ
- $|\Delta V_{C1BA}|$ has minimum magnitude, the fault is in section AJ
- $|\Delta V_{A1CA}|$ has minimum magnitude, the fault is in section BJ

IED at End B

The IED at End B makes exactly the same calculations with

- local V_{L1} and I_{L1} = V_{B1} and I_{B1}, i.e. V_{B1} and I_{B1} are the local-end voltage and current V_{L1} and I_{L1}
- remote V_{R11} and I_{R11} = V_{C1} and I_{C1}, i.e. V_{C1} and I_{C1} are the remote-end voltage and current V_{R11} and I_{R11}
- remote V_{R12} and I_{R12} = V_{A1} and I_{A1}, i.e. V_{A1} and I_{A1} are the remote-end voltage and current V_{R12} and I_{R12}

IED at End C

The IED at End C makes exactly the same calculations with

- local V_{L1} and I_{L1} = V_{C1} and I_{C1}, i.e. V_{C1} and I_{C1} are the local-end voltage and current V_{L1} and I_{L1}
- remote V_{R11} and I_{R11} = V_{A1} and I_{A1}, i.e. V_{A1} and I_{A1} are the remote-end voltage and current V_{R11} and I_{R11}
- remote V_{R12} and I_{R12} = V_{B1} and I_{B1}, i.e. V_{B1} and I_{B1} are the remote-end voltage and current V_{R12} and I_{R12}

ii) step two – calculate the fault location

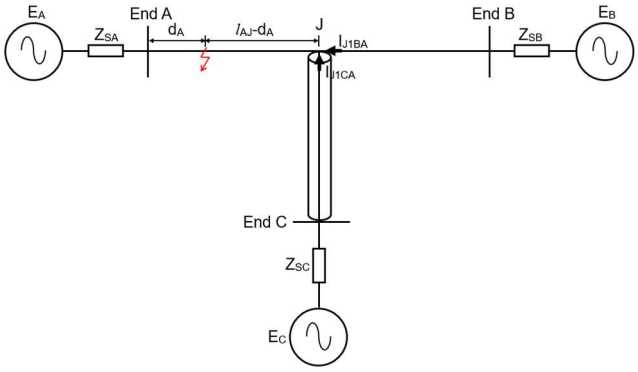


Fig. 14: three-ended mixed line with fault in section AJ

Calculate the current flowing towards the junction in the healthy line sections (e.g. if the fault is in section AJ as shown in Fig. 14)

$$I_{J1BA} = -C_{BJ}V_{R11} + A_{BJ}I_{R11}$$

$$I_{J1CA} = -C_{CJ}V_{R12} + A_{CJ}I_{R12}$$

Calculate also the junction voltage from one of the healthy line ends (e.g. End B)

$$V_{J1BA} = D_{BJ}V_{R11} - B_{BJ}I_{R11}$$

Line section AJ is now equivalent to a two-ended line with known voltages and currents from both ends (V_{L1} and I_{L1} (= V_{A1} and I_{A1}), and V_{J1BA} and I_{J1A} (= I_{J1BA} + I_{J1CA}). To determine the fault location within the faulty section the two-ended fault location method described in Section III is now used.

Similar calculations apply for faults in section BJ or section CJ.

IEDs at Ends B and C

As for the IED at End A, but from the perspective, respectively, of the IEDs at End B and End C.

VI. SIMULATION RESULTS AND ANALYSIS

Two-ended line

To evaluate and validate the fault location method, EMTDC/PSCAD was used to simulate the faults on a 220kV, 50Hz, 240km two-ended transmission line. The simulations were done in EMTDC software with frequency dependent transmission line models. The fault data was recorded in COMTRADE99 format and Discrete Fourier Transform (DFT) was applied to obtain the current and voltage phasors. The main inputs to the algorithm are synchronized pre- and during-fault voltage and current phasors, and line length – calculated (estimated) line parameters are used, so set line parameters are not required.

The following figures and tables illustrate the effect variation in power system and fault parameters have on the accuracy of the calculated fault location.

$$\%\text{Error} = \left| \frac{\text{Actual fault location - Calculated Fault Location}}{\text{Total line length}} \right| * 100 \qquad (37)$$

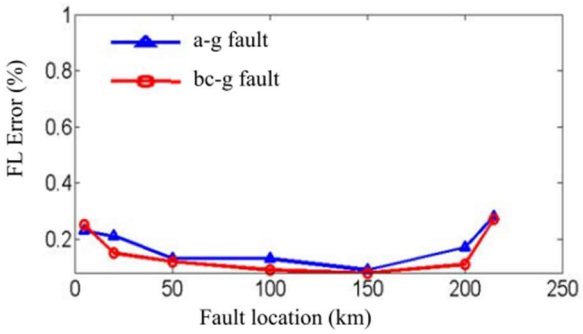


Fig. 15: fault location errors for different fault locations
fault inception angle: 60°
fault resistance: 10Ω

Fault Type	R_F (Ω)	Max.FL Error (%)	Avg.FL Error (%)
a-g	0.01	0.19	0.09
	5	0.18	0.10
	10	0.23	0.10
	50	0.31	0.11
	100	0.37	0.12
bc-g	0.01	0.14	0.07
	5	0.13	0.09
	10	0.17	0.10
	50	0.27	0.10
	100	0.31	0.11

Table I: fault location errors for different fault resistances
fault locations every 10km in range 10-240km

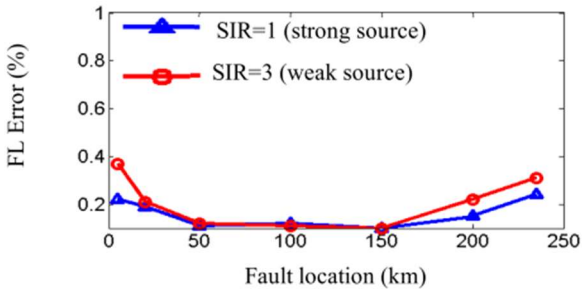


Fig. 16: fault location errors for different SIR values

fault type: a-g
fault inception angle: 60°
fault resistance: 20Ω

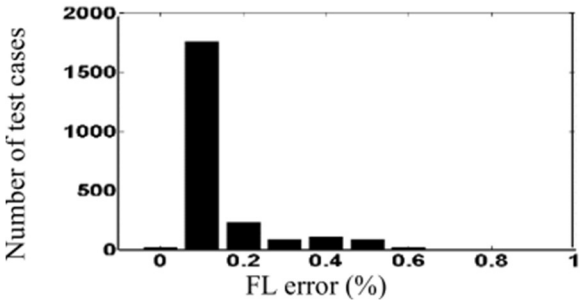


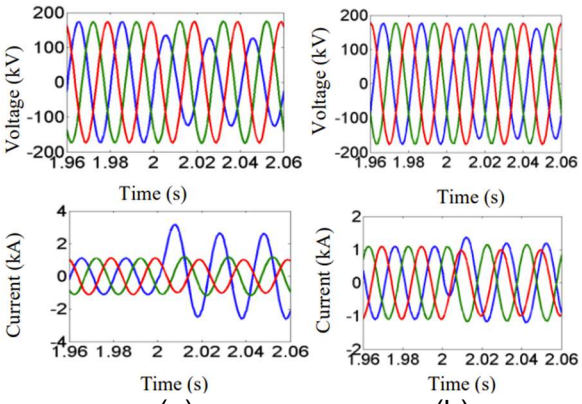
Fig. 17: fault location performance for various test conditions

Test Cases	Test conditions
Fault Location (km)	1, 60, 120, 100 180 and 235
Fault Type	a-g, ab, bc-g and abc-g
Fault Inception Angle	0^0 and 90^0
Fault resistance (Ω)	0.01, 10, 20 and 50
SIR (EndA:EndB)	0.1:1, 1:2, 2:3 and 5:2
Load	No load (0%), 100 % and 125%

Table II: test conditions for simulation study

i) illustrative case 1 – line connected with conventional sources

AG fault at 60km from End A (see Fig. 3) (line length = 240km) with fault resistance = 25Ω, fault inception angle = 0°, and source to line impedance ratio (SIR) = 1.0.



(a) (b)

TABLE III
CALCULATED LINE PARAMETERS USING LUMPED MODEL

Method	R^1 (Ω/KM)	L^1(mH/KM)	C^1 (NF/KM)
Actual	0.1879	1.03870	16.18147
Proposed	0.1838	1.02739	16.27543
Error (%)	2.18	1.10	0.58

TABLE IV
ESTIMATED LINE PARAMETERS USING DISTRIBUTED LINE MODEL

Method	R^1 (Ω/KM)	L^1(mH/KM)	C^1 (NF/KM)
Actual	0.1879	1.03870	16.18147
Proposed	0.1880	1.03878	16.18532
Error (%)	0.02	0.01	0.02

Fig. 18: pre- and during-fault voltage and current signals measured at (a) End A and (b) End B for an AG fault at 60km from End A

Table III and Table IV

The calculated (lumped model – step one, line parameter estimation, section III) and estimated (distributed model – step two, line parameter estimation, section III) line parameters, with corresponding errors compared to the actual line parameters for this case, are provided in Tables III and IV respectively. From Tables III and IV, the calculated and estimated parameters are close to the actual parameters. The estimated parameters are more accurate than the calculated ones and these parameters are used for the fault location calculation.

The calculated fault location using the estimated line parameters and during-fault phasors is 59.85km. The absolute percentage of fault location error calculated using (37) is 0.06% for this 240km transmission line.

ii) illustrative case 2 – line connected with renewable (IBR) source at one end of the line

Two-ended line with wind type IV renewable power plant connected at End A, and with End B connected to the power grid as shown in Fig. 19. For this simulation, type IV wind turbine generator (full converter model) was modeled as 200 units of 2MW each in compliance with various grid codes. The FRT characteristics were modelled for the study.

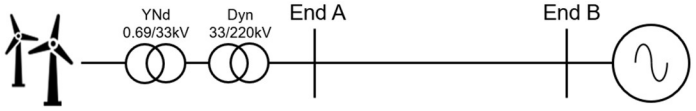


Fig. 19: two-ended line with renewable power plant connected at End A (wind type IV)

AG fault at 48km from End A (line length = 240km) with fault resistance = 50Ω, and fault inception angle = 0°.

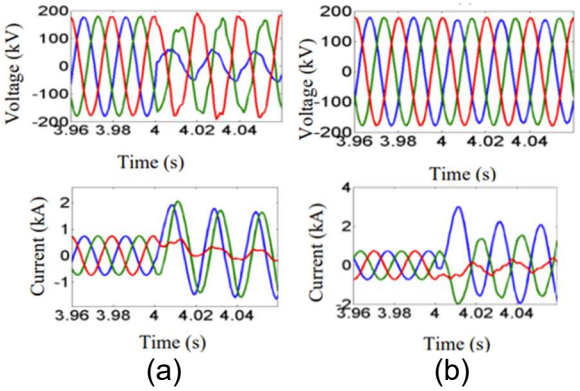


TABLE V
CALCULATED LINE PARAMETERS USING Π MODEL

Method	R^1 (Ω/KM)	L^1(mH/KM)	C^1 (NF/KM)
Actual	0.1879	1.03870	16.18147
Proposed	0.1812	1.02750	16.26191
Error (%)	3.59	1.08	0.49

TABLE VI
ESTIMATED LINE PARAMETERS USING DISTRIBUTED LINE MODEL

Method	R^1 (Ω/KM)	L^1(mH/KM)	C^1 (NF/KM)
Actual	0.1879	1.03870	16.18147
Proposed	0.1852	1.03891	16.17192
Error (%)	1.43	0.02	0.06

Fig. 20: pre- and during-fault voltage and current signals measured at (a) End A and (b) End B for an AG fault at 48km from End A

Table V and Table VI

The calculated (lumped model) and estimated (distributed model) line parameters, with corresponding errors compared to the actual line parameters for this case, are provided in Tables V and VI respectively. From Tables V and VI, the calculated and estimated parameters are close to the actual parameters. The estimated parameters are used for the fault location calculation.

The calculated fault location using the estimated line parameters and during-fault phasors is 48.24km. The absolute percentage of fault location error calculated using (37) is 0.1% for this 240km transmission line. This verifies that the presented method is not affected by renewable integration.

iii) illustrative case 3 – line connected with renewable (IBR) sources at both ends of the line

Two-ended transmission line with wind type IV power plant connected at End A, with End A also connected to the power grid, and solar PV power plant connected to End B, as shown in Fig. 21.

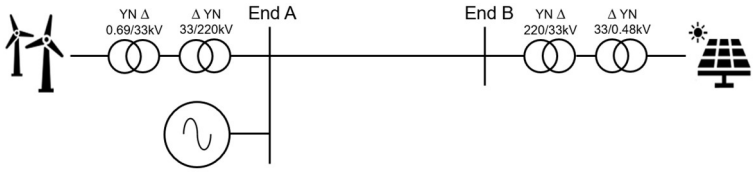


Fig. 21: two-ended line with renewable power plant connected at End A (wind type IV) and End B (solar PV)

AB fault at 180km from End A (line length = 240km) with fault resistance = 10Ω, and fault inception angle = 60°.

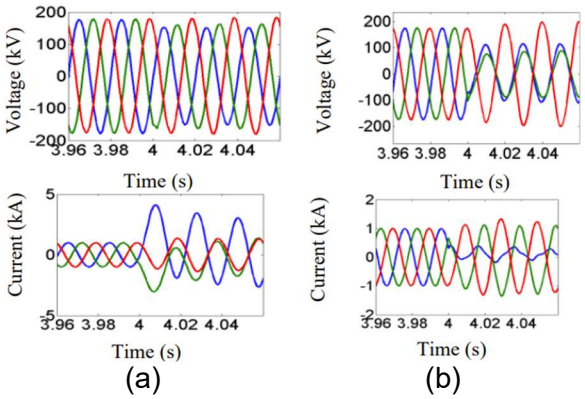


TABLE VII
CALCULATED LINE PARAMETERS USING Π MODEL

Method	R^1 (Ω/KM)	L^1(mH/KM)	C^1 (NF/KM)
Actual	0.1879	1.03870	16.18147
Proposed	0.1834	1.02722	16.25737
Error (%)	2.41	1.10	0.47

TABLE VIII
ESTIMATED LINE PARAMETERS USING DISTRIBUTED LINE MODEL

Method	R^1 (Ω/KM)	L^1(mH/KM)	C^1 (NF/KM)
Actual	0.1879	1.03870	16.18147
Proposed	0.1875	1.03862	16.16746
Error (%)	0.21	0.01	0.08

Fig. 22: pre- and during-fault voltage and current signals measured at (a) End A and (b) End B for an AB fault at 180km from End A

Table VII and Table VIII

The calculated (lumped model) and estimated (distributed model) line parameters, with corresponding errors compared to the actual line parameters for this case, are provided in Tables VII and VIII respectively. From Tables VII and VIII, the calculated and estimated parameters are close to the actual parameters. The estimated parameters are used for the fault location calculation.

The calculated fault location using the estimated line parameters and during-fault phasors is 179.48km. The absolute percentage of fault location error calculated using (37) is 0.2% for this 240km transmission line. This verifies that the presented method is not affected by renewable integration at both line ends and is suitable for future renewable energy configurations.

Three-ended line

To evaluate and validate the fault location method, EMTP/PSCAD was used to simulate the faults on a 220kV three-ended tapped transmission line. The main line AB has a length of 120km, with section AJ having a length of 80km and section BJ a length of 40km. Various fault scenarios, including different fault resistances, fault types, fault inception angles and source to line impedance ratios were simulated at different fault locations. For each case, the resultant voltages and currents from the simulation were transferred to MATLAB where the fault location method had been implemented.

The absolute error was calculated as a percentage of the length of line (37).

The fault location method was tested

- for several different values of fault resistance, including 0.01, 10 and 50 ohms – the results are shown in Fig. 23
- for all different fault types – the results are shown in Fig. 24
- to determine any influence of source to line impedance ratios – the results are shown in Fig. 25
- to determine any influence of fault inception angle – the results are shown in Fig. 26

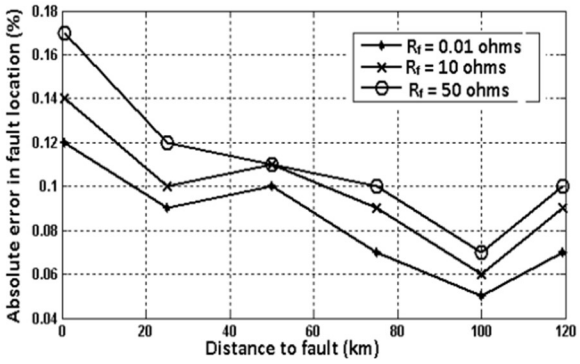


Fig. 23: absolute % error vs. fault location for different values of fault resistance

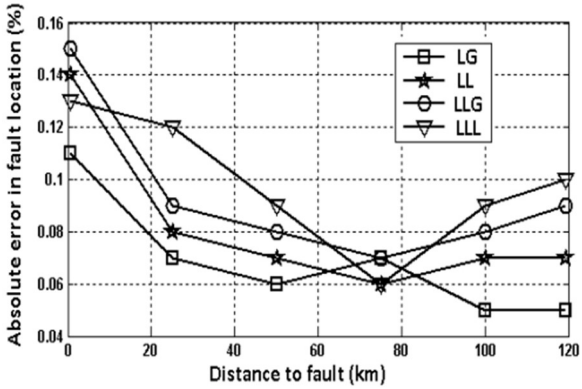


Fig. 24: absolute % error vs. fault location for for different fault types

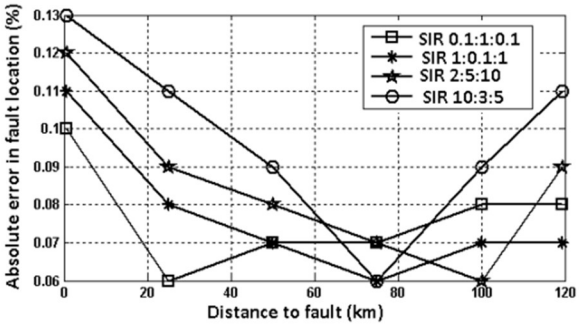


Fig. 25: absolute % error vs. fault location for different values of SIR

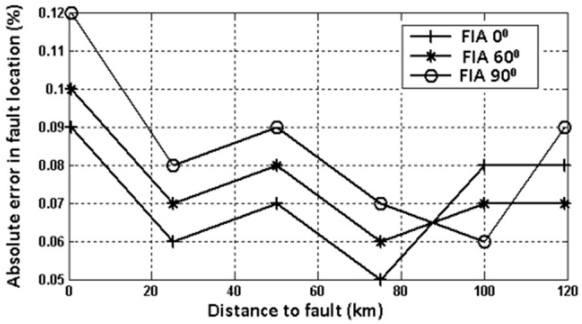


Fig. 26: absolute % error vs. fault location for for different values of fault inception angle

VII. FIELD INSTALLATIONS

Two-ended line

The two-ended fault location method was implemented in an IED and evaluated in the laboratory. After success in the laboratory evaluation, IEDs with the fault location method implemented were installed on a 400kV, 233km line in the Indian POWERGRID network, and on a 220kV, 265.6km line in the Swedish utility Svenska Kraftnät network.

In each case, an IED with the two-ended fault location method was installed at each end of the line. The IEDs were connected via a 2Mbps communication link. At each end, the local currents and voltages were connected to the IED, which digitized these inputs to obtain sampled values of the local currents and voltages. Each local IED sent these values to the remote IED. Each remote IED received the currents and voltages from the local IED as sampled values. The IEDs were time coordinated (time synchronized) so that, on receipt of the current and voltage sampled values from the IED at the other end of the line, they could be time coordinated with the local current and voltage samples, and interpolated in order to be comparable with the local samples. Each IED then had available to it time coordinated values, as sampled values, of both the local and remote currents and voltages.

a) pilot 1 – Indian pilot installation

A 400kV, 233km transmission line in Power Grid Corporation of India (POWERGRID) was chosen as a pilot installation.

CG fault (fault 1):

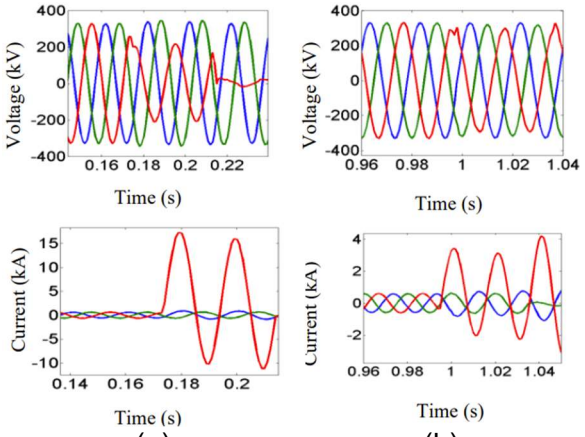


TABLE IX
ESTIMATED LINE PARAMETERS USING PROPOSED METHOD

IED Location	R (Ω)	X(Ω)	B (MS)
STATION A	5.269	68.830	901.105
STATION B	5.288	68.795	900.621

TABLE X
CALCULATED FAULT LOCATION USING PROPOSED METHOD

IED Location	Calculated Fault Location (Km)	Actual Fault Location (Km)	Error (%)
STATION A	32.87	33.00	0.04
STATION B	200.78	200.00	0.34

Fig. 27: pre- and during-fault voltage and current signals measured at (a) Station A and (b) Station B for a CG fault at 33km from Station A
Table IX and Table X

The line positive-sequence parameters (resistance (R), reactance (X), and susceptance(B)) and fault location calculated by the IED at Stations A and B are provided in Tables IX and X respectively.

The estimated fault distances using the two-ended fault location method are 32.87km from Station A and 200.78km from Station B. When the line crew patrolled the line they found the fault at 33km from Station A. The difference of actual to estimated fault location is 130 meters (within a one tower span for Station A fault location for this case).

CG fault (fault 2)

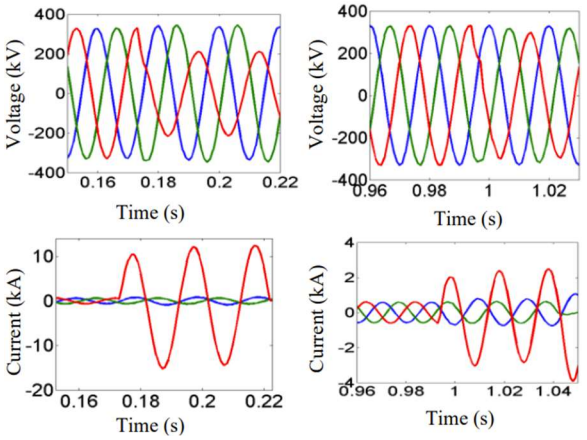


TABLE XI
ESTIMATED LINE PARAMETERS USING PROPOSED METHOD

IED Location	R (Ω)	X(Ω)	B (mS)
STATION A	5.026	68.721	901.658
STATION B	5.025	68.721	901.662

TABLE XII
CALCULATED FAULT LOCATION USING PROPOSED METHOD

IED Location	Calculated Fault Location (Km)	Actual Fault Location (Km)	Error (%)
STATION A	33.23	33.00	0.10
STATION B	200.80	200.00	0.34

Fig. 28: pre- and during-fault voltage and current signals measured at (a) Station A and (b) Station B for a CG fault at 33km from Station A
Table XI and Table XII

The line positive-sequence parameters (resistance (R), reactance (X), and susceptance(B)) and fault location calculated by the IED at Stations A and B are provided in Tables XI and XII respectively.

The estimated fault distances using the two-ended fault location method are 33.23km from Station A and 200.80km from Station B. When the line crew patrolled the line they found the fault at 33km from Station A. The difference of actual to estimated fault location is 230 meters (within a one tower span for Station A fault location for this case).

b) pilot 2 – Swedish pilot installation

A 220kV, 265.6km transmission line in the Swedish utility Svenska Kraftnät was also chosen as a pilot installation.

AB fault:

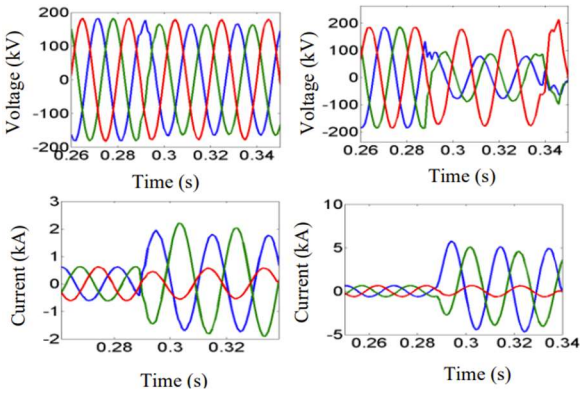


TABLE XIII
ESTIMATED LINE PARAMETERS USING PROPOSED METHOD

IED Location	R (Ω)	X(Ω)	B (MS))
STATION A	14.166	84.85	1000.548
STATION B	14.482	84.85	1000.865

TABLE XIV
CALCULATED FAULT LOCATION USING PROPOSED METHOD

IED Location	Calculated Fault Location (Km)	Actual Fault Location (Km)	Error (%)
STATION A	226.82	226.60	0.08
STATION B	38.69	39.00	0.11

Fig. 29: pre- and during-fault voltage and current signals measured at (a) Station A and (b) Station B for an AB fault at 226.6km from Station A
Table XIII and Table XIV

The line positive-sequence parameters (resistance (R), reactance (X), and susceptance(B)) and fault location calculated by the IED at Stations A and B are provided in Tables XIII and XIV respectively.

The estimated fault distances using the two-ended fault location method are 226.82km from Station A and 38.69km from Station B. When the line crew patrolled the line they found the fault at 226.6km from Station A (39km from Station B). The difference of actual to estimated fault location is 220 and 310 meters (within a one tower span for both Station A and Station B fault location for this case).

VIII. CONCLUSIONS

Two-ended, three-ended, and mixed transmission line fault location methods were presented. The sources connected to the transmission line can be either conventional synchronous generation or renewable power plants, i.e. the accuracy of the calculated fault location is not affected by renewable integration. The parameters of the line are required to be entered as settings. However, the two-ended fault location method permits estimated line parameters to be calculated, requiring just the line length to be entered as a setting. The source impedances at the line ends are not required to be known.

The voltage and current signals from all line ends are required as time aligned sampled values.

The performance of the fault location methods was evaluated using EMTDC simulations.

The described fault location methods have been implemented in an existing line protection IED using 1kHz sampling rate. The fault location methods do not require any additional hardware beyond what is required for a modern line differential protection, i.e. a 2Mbps communication link.

IEDs with the two-ended fault location method were installed in the Indian and Swedish power systems. The early field results confirm the validity of the method. The field experimental results

are matching with simulation results. In the pilot installations the fault locations were calculated to be within one tower span of the actual fault location. These geographically diverse pilot installation results stand as testimony to the accuracy of the developed fault location method.

In more general testing, where different fault conditions were considered, the fault location error in the majority of cases was ~0.1%. Based on these results and confirmation from the pilot installations, it is expected that the fault location accuracy will be within two tower spans even in more problematic situations with higher fault resistances and different fault types.

The achieved accuracy levels are comparable to the TW-based fault locator technology that uses 1000 times higher sampling frequency, more costly hardware and commissioning process.