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# Algorithmic Approach to Transmission Line Fault Distance Estimation Using Impedance Based Method

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## ABSTRACT

The necessity of power and its dependency has grown exponentially over the years. The tremendous demand has increased the focus on minimizing power losses. One of the major problems in transmission lines is the occurrence of fault that affects the quality of electricity supply. Fault location detection is therefore the key to reliable operation of power equipments and satisfactory service delivery with minimum interruption. This need has given rise to fault location techniques so that the economic impact of fault occurrences can be mitigated with appropriate corrective measures. A numerous methods have been developed and used over the years for transmission line fault locations. This paper opts for the applicability of impedance based fault distance estimation on transmission lines. This was achieved by modelling the transmission line and simulating it using Simulink while the algorithm was written using MATLAB codes. The experimental studies indicated that this approach is reliable for rapid and correct identification of various fault locations.

## 1. Introduction

Protection System deals with detection of proximity of system to unstable operating region and consequent control actions to restore stable operating point and/or prevent damage to equipments. Loss of system stability can lead to partial or complete system blackouts. Power supply to consumer must be reliable, adequate and of acceptable quality at a minimum cost. However, this is not easily achievable as the reliability of supply and adequacy is being truncated by incessant faults along the line, which reduces the efficiency of the system (Zhang and Bollen, 1998).

A fault in the power system is any abnormal flow of current in a power system's components. Faults are unavoidable because a portion of these faults occur due to the environmental and natural factors which are beyond the control of human beings. There is no universal fault location technique for all of these faults. As a result, it becomes very important to have a well-organized and coordinated system of power protection that can detect any kind of fault and also locate the faults accurately in the power system. Quick fault detection and location can help in protecting power equipment by ensuring fast diconnection of faulted sections before any significant damage occurs. Reliable algorithms for the analysis of faults on overhead transmission lines have become an essential part of modern transmission line protection schemes (Z. M. Radojevic, C. H. Kim, M. Popov, G. Preston and V. Terzija, 2009). An integral part of such algorithms is the fault locator, which determines the distance to the fault from the local line terminal(s).

Accurate estimation of fault location is very useful when lines are long and run through inaccessible areas where patrolling is difficult and time-consuming (Ratan Das and Damir Novosel, 2000). In addition, visual inspection is difficult during adverse weather conditions. Fault locators provide estimate for both sustained and transient faults. Generally, transient faults cause minor damage that is not easily visible on inspection. Fault locators help identify those locations for early repairs to prevent recurrence and consequent major damages. The subject of fault location has been of considerable interest to electric power utility engineers and researchers for over twenty years. Several methods of locating transmission line faults have been developed to achieve this objective. The primitive method of fault location was to visually inspect the line (T.W. Stringfield, D. J. Marihart and R. F. Stevens, 1957). The procedure involved patrolling the line by foot or automobile and inspecting the line with or without the aid of binoculars. Sectionalizing the line and energizing it in parts has been used to reduce the length of the line that must be inspected. These procedures are slow, inaccurate and expensive, and are unsafe during adverse weather conditions.

Prompt location of faults can enhance the system's reliability greatly. The quicker the power is restored the more the valuable time and money that will be saved. Hence the need and relevance of this research work. The techniques of fault location can be classified into these categories: travelling-wave based methods, intelligence based method, impedance measurement based methods and high frequency components of currents and voltages generated by faults based methods (Kurt, 2007). This work, however, focuses on the location of fault on transmission line using impedance measurement based method.

## 2. Fault Locators Verse Relays

Formulated to provide protection from faults in the transmission lines, there exist some important differences between fault locators using algorithms and the conventional fault location by relays. The under-listed are vital to the development of fault location techniques and fault locators as

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they highlight the insufficient nature of the conventional line protection devices and relay.

- **Accuracy -** Protective relays usually define a general area known as a protective zone where the fault might have occurred. Fault locators pinpoint these areas with a certain percentage of error if any.
- **Speed -** Protective relays require high-speed operations to mitigate the spreading of faulty current to other parts of the power network, making use of circuit breaker and high speed communication devices, sometimes, sacrificing the relay system security and selectivity. Fault locators on the other hand use algorithms that calculate fault locations in several seconds.
- **Data Window -** Relays use a fault interval between the inception of the fault and the clearing by a breaker, which takes several frequencies, resulting in a wide data window. Fault locators use the most compatible data windows to minimize the scope of errors in calculations. However, this is of a considerable importance as it may affect the results of the algorithm.
- **Complexity of Calculation -** The high-speed operation of protective relays render the calculations simpler. Fault locators do not pose any limitation of complexity. They can be relatively simple (based on impedance or travelling wave methods) and may even increase in their complexity to incorporate a more versatile operation.

## 3. Impedance-Based Fault Location Methods

The algorithm used in this paper follows the work of (D. Novosel, D. G. Hart, E. Udren, and J. Garitty, 1996). This method uses fault voltage and current from both terminal ends of transmission lines.

### 3.1. One-End Positive Sequence Reactance Method

One-end positive-sequence-reactance method is based on the symmetrical component model the transmission of the transmission Line. It is assumed that the transmission line is ideally transposed and the phase wires have equal spacing. This results in the equal mutual coupling between phases. The principle of positive-sequence-reactance method can be explained by using fault analysis for a single-line-to-ground fault. Figure1 gives the symmetrical component circuit model of a phase-to-ground fault on phase A at a distance $\boldsymbol{m}$ from the sending end.

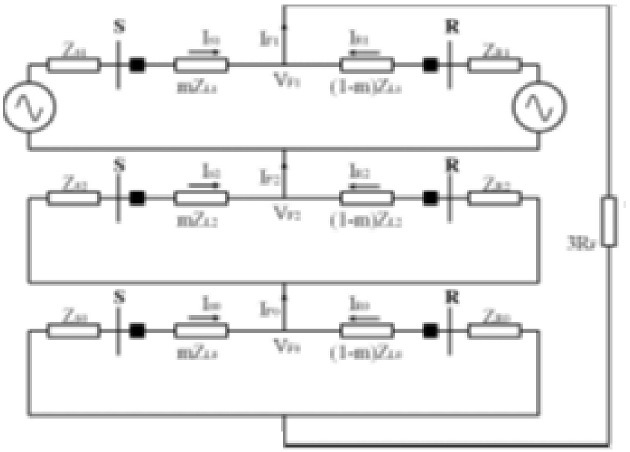

**Figure1. Symmetrical Component Circuits For Phase A-G Fault.**

The voltage drop from the sending terminal to the fault location can be expressed as;

$$V_{S1} = mZ_{L1}I_{S1} + V_{F1} \quad (1)$$

$$V_{S2} = mZ_{L2}I_{S2} + V_{F2} \quad (2)$$

$$V_{S0} = mZ_{L0}I_{S0} + V_{F0} \quad (3)$$

The summation of the three equations results in;

$$V_{Sa} = mZ_{L1}I_{S1} + mZ_{L2}I_{S2} + mZ_{L0}I_{S0} + V_{Fa} \quad (4)$$

Since $Z_{L1}, Z_{L2}$ is assumed to be equal and $I_{S1} = I_{S2} = I_{S0} = \frac{1}{3}I_F$ for phase to ground fault, $V_{Fa} = R_F I_F$. Equation (4) can be rewritten as:

$$V_{Sa} = mZ_{L1}[I_{Sa} + kI_{S0}] + R_F I_F \quad (5)$$

Where factor $k = \frac{Z_{L0} - Z_{L1}}{Z_{L1}}$

The sending voltage and current $V_S$ and $I_S$ is defined as;

$$V_S = V_{Sa} \quad (6)$$

$$I_S = I_{Sa} + kI_{S0} \quad (7)$$

So equation (5) can be expressed as

$$V_S = mZ_{L1}I_S + R_F I_F \quad (8)$$

The selection of $V_S$ and $I_S$ depends on the fault type, as given in Table1.

**Table1. Selection of measurements for different fault types.**

| **Fault Type** | $\boldsymbol{V_S}$ | $\boldsymbol{I_S}$ |
|---|---|---|
| **A-G** | $\boldsymbol{V_a}$ | $\boldsymbol{I_a + k \,.\, I_0}$ |
| **B-G** | $\boldsymbol{V_b}$ | $\boldsymbol{I_b + k \,.\, I_0}$ |
| **C-G** | $\boldsymbol{V_c}$ | $\boldsymbol{I_c + k \,.\, I_0}$ |
| **A-B or A-B-G** | $\boldsymbol{V_{ab}}$ | $\boldsymbol{I_{ab}}$ |
| **B-C or B-C-G** | $\boldsymbol{V_{bc}}$ | $\boldsymbol{I_{bc}}$ |
| **C-A or C-A-G** | $\boldsymbol{V_{ca}}$ | $\boldsymbol{I_{ca}}$ |
| **A-B-C or A-B-C-G** | Any of $\boldsymbol{V_{ab}, V_{bc}, V_{ca}}$ | Any of $\boldsymbol{I_{ab}, I_{bc}, I_{ca}}$ |

The apparent reactance measured at terminal S can be obtained by dividing equation (8) by $I_S$.

$$\frac{V_S}{I_S} = mZ_{L1} + R_F \frac{I_F}{I_S} \quad (9)$$

To compensate the effect of fault resistance, only the imaginary part of equation (9) is computed.

$$Im\left(\frac{V_S}{I_S}\right) = m \,.\, Im(Z_{L1}) + Im\left(R_F \frac{I_F}{I_S}\right) \quad (10)$$

If complex number $I_f$ and $I_s$ have the same phase angle or $R_F$ is negligible, we will obtain,

$$m = \frac{Im\left(\frac{V_S}{I_S}\right)}{X_{L1}} \quad (11)$$

### 3.2. One-End Takagi Method

The Takagi method introduced superposed current $I_{sup}$ to eliminate the effect of power flow on fault location accuracy. Therefore, this method assumes constant current load model and requires both pre-fault and post-fault data.

$$I_{sup} = I_s - I_{pre} \quad (12)$$

Where $I_{pre}$ is the pre-fault current. If we multiply equation (8) by the conjugate of $I_{sup}$ and extract the imaginary part, we will obtain,

$$\boldsymbol{Im\left(V_s \,.\, I_{sup}^*\right) = m \,.\, Im\left(Z_{L1} \,.\, I_s \,.\, I_{sup}^*\right) + Im\left(R_F \,.\, I_s \,.\, I_{sup}^*\right)} \quad (13)$$

If complex number $I_F$ and $I_{sup}$ have the same angle or $R_F$ is negligible, we will obtain,

$$\boldsymbol{m = \frac{Im\left(V_s \,.\, I_{sup}^*\right)}{Im\left(Z_{L1} \,.\, I_s \,.\, I_{sup}^*\right)}} \quad (14)$$

### 3.3. Two-End Negative-Sequence Method

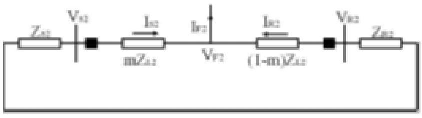

**Figure 2. Negative-sequence circuit of a faulted transmission line.**

Two-end negative-sequence method uses data at both terminals of the transmission line.

By using negative-sequence component, the effects of pre-fault power flow and fault resistance are eliminated. Unlike one-end methods, negative-sequence method requires source impedance to perform fault location estimation. Figure 2 shows the negative sequence circuit of a faulted transmission line.

At source S, (sending end)

$$V_{F2} = -I_{S2} \,.\, (Z_{S2} + m \,.\, Z_{L2}) \qquad (15)$$

At source R, (receiving end)

$$V_{F2} = I_{R2} \,.\, [Z_{S2} + (1 - m) \,.\, Z_{L2}] \qquad (16)$$

By equalizing equation (15) and (16), we can obtain,

$$I_{F2} = I_{R2} \,.\, \frac{Z_{S2} + m \,.Z_{L2}}{Z_{S2} + (1-m)\,.Z_{L2}} \qquad (17)$$

Taking the magnitude of both sides and simplifying the equation, a quadratic equation can be obtained to calculate the fault location estimation.

### 3.4. Two-End Three Phase Impedance Matrix Method

A fault location algorithm based on the three-phase line impedance matrix method is developed and implemented in this paper. This method is not only applicable to transmission lines, but also distribution feeders. Using Figure 2 as the one-line diagram, the voltage at two terminals of the line can be expressed as;

At source S,

$$V_{sabc} = m \,.\, Z_{Labc} \,.I_{sabc} + V_{fabc} \qquad (18)$$

At source R,

$$V_{rabc} = (1 - m) \,.\, Z_{Labc} \,.I_{rabc} + V_{fabc} \qquad (19)$$

Where;

$V_{sabc} = \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix}$ is the three phase terminal voltage measured at source S,

$I_{sabc} = \begin{bmatrix} I_{sa} \\ I_{sb} \\ I_{sc} \end{bmatrix}$ is the three phase terminal current measured at source S,

$V_{rabc} = \begin{bmatrix} V_{ra} \\ V_{rb} \\ V_{rc} \end{bmatrix}$ is the three phase terminal voltage measured at source R,

$I_{rabc} = \begin{bmatrix} I_{ra} \\ I_{rb} \\ I_{rc} \end{bmatrix}$ is the three phase terminal current measured at source R,

$Z_{Labc} = \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{bmatrix}$ is the three phase line impedance matrix

$V_{fabc} = \begin{bmatrix} V_{fa} \\ V_{fb} \\ V_{fc} \end{bmatrix}$ is the three phase voltage at the fault location.

Subtracting equation (18) from (19), we can obtain,

$$V_{sabc} - V_{rabc} + Z_{Labc} \,.\, I_{rabc} = m \,.Z_{Labc}(I_{sabc} + I_{rabc}) \qquad (20)$$

$V_{sabc}$, $I_{sabc}$, $V_{rabc}$, $I_{rabc}$ are measured quantities and is known if line configuration data is available. Let

$$Y = V_{sabc} - V_{rabc} + Z_{Labc} \,.\, I_{rabc} \qquad (21)$$

and

$$D = Z_{Labc}(I_{sabc} + I_{rabc}) \qquad (22)$$

Equation (20) becomes equation (23), which contains three complex equations and six real equations.

$$Y = m \,.D \qquad (23)$$

Least-square estimation can be applied to determine the only unknown parameter m. #Suppose fault occurs at some point which is m distance away from terminal A. $V_f$ is fault voltage, the fault voltage is given

$$\left(V_f\right)_i = (V_A)_i - mZ_i * (I_A)_i \qquad (24)$$

$$\left(V_f\right)_i = (V_B)_i - (1 - m)Z_i * (I_B)_i \qquad (25)$$

Where, i =0,1,2 for zero, positive and negative sequence respectively.

$Z_s$= source impedance

m=fault distance (in km) from bus A on transmission line

$V_A$, $V_B$= Three phase fault voltages at buses A and B respectively

$I_A$, $I_B$= Three phase fault currents at buses A and B respectively

Z= line impedance which is equal to R + jX

Equating equation (24) and (25)

$$(V_A)_i - (V_B)_i + Z_i(I_B)_i = m * Z_i(I_{Ai} + I_{Bi}) \qquad (26)$$

Data from bus A and bus B are not synchronized.

So, synchronization angle, δ is added to equation (26) to make the two terminals synchronized. So, bus voltages at bus A and terminal B become

$$(V_A)_i = (V_A)_i\angle \alpha_i + \delta \qquad (27)$$

$$(V_B)_i = (V_B)_i\angle \beta_i \qquad (28)$$

Similarly, equation for current is

$$(I_A)_i = (I_A)_i\angle \gamma_i + \delta \qquad (29)$$

$$(I_B)_i = (I_B)_i\angle \theta_i \qquad (30)$$

Where,

α, β, γ, θ = measured angles

Equation (26) can be written as

$$(V_A)_i e^{j\delta} - (V_B)_i + Z_i(I_B)_i = m * Z_i * \left(I_{Ai}e^{j\delta} + I_{Bi}\right) \quad (31)$$

Synchronization angle, δ can be expressed as cos(δ) + jsin(δ). Equation (31) is expressed into real and imaginary components as:

$$Re(V_A)_i \sin\delta + Im(V_A)_i \cos\delta - Im(V_B)_i + (C_4)_i = m((C_1)_i \sin\delta + (C_2)_i \cos\delta + (C_4)_i) \qquad (32)$$

$$Re(V_A)_i \cos\delta + Im(V_A)_i \sin\delta - Re(V_B)_i + C_{3_i} = m((C_1)_i \cos\delta - (C_2)_i \sin\delta + (C_3)_i) \qquad (33)$$

Where,

$$(C_1)_i = R_i * Re(I_A)_i - X_i * Im(I_A)_i \qquad (34)$$

$$(C_2)_i = R_i * Im(I_A)_i - X_i * Re(I_A)_i \qquad (35)$$

$$(C_3)_i = R_i * Re(I_B)_i - X_i * Im(I_B)_i \qquad (36)$$

$$(C_4)_i = R_i * Im(I_B)_i - X_i * Re(I_B)_i \qquad (37)$$

To find δ, equation (32) is divided by (33) and removing a number of terms, the following equations are developed:

$$a_i * \sin\delta + b_i \cos\delta + C_i = 0 \qquad (38)$$

Where,

$$a_i = (C_3)_i Re(V_A)_i - (C_4)_i Im(V_A)_i - (C_1)_i Re(V_B)_i - (C_2)_i Im(V_B)_i + (C_1)_i (C_3)_i + (C_2)_i (C_4)_i \qquad (39)$$

$$b_i = (C_4)_i Re(V_A)_i - (C_3)_i Im(V_A)_i - (C_2)_i Re(V_B)_i + (C_1)_i Im(V_B)_i + (C_2)_i (C_3)_i + (C_1)_i (C_4)_i \tag{40}$$

$$c_i = -(C_2)_i Re(V_A)_i - (C_1)_i Im(V_A)_i - (C_4)_i Re(V_B)_i + (C_3)_i Im(V_B)_i \tag{41}$$

The synchronization angle, $\delta$ is determined by an iterative Newton - Raphson Method. The equations for the iteration are

$$\delta_{k+1} = \delta_k - \frac{F(\delta_k)}{\acute{F}(\delta_k)} \tag{42}$$

$$F(\delta_k) = b_i * \cos\delta_k + a_i * \sin\delta_k + C_i \tag{43}$$

$$\acute{F}(\delta_k) = b_i * \cos\delta_k - b_i * \sin\delta_k \tag{44}$$

This method requires initial guess for δ. The iteration is terminated when the difference between $\delta_{k+1}$ and δ is smaller than the specified tolerance. Once the synchronization angle is determined, fault location m is calculated from equations (32) and (33).

If equation (32) is used, fault distance is:

$$m = \frac{Re(V_A)_i \sin\delta + Im(V_A)_i \cos\delta - Im(V_B)_i + (C_4)_i}{(C_1)_i \sin\delta + (C_2)_i \cos\delta + (C_4)_i)} \tag{45}$$

If equation (33) is used, fault distance is:

$$m = \frac{Re(V_A)_i \cos\delta - Im(V_A)_i \sin\delta - Re(V_B)_i + (C_3)_i}{(C_1)_i \cos\delta - (C_2)_i \sin\delta + (C_3)_i)} \tag{46}$$

## 4. Description of the Simulation Model

The transmission line has been modelled with distributed parameters so that it accurately describes a long transmission line. A snapshot of the model used for obtaining the data sets is as shown in Figure3. In this Figure 3, Z1 and Z2 are the source impedances of the generators on both sides. The transmission line (Line 1 and Line 2 together) is 100km long and three-phase fault block is used to inject different fault types at varying location along the transmission line. The three-phase V - I measurement block is used to measure the voltage and current samples at the terminal B. When faults are initiated, phasor currents and voltages are taken from both ends of the transmission line and sent to MATLAB workspace as inputs to the algorithm

## 5. Simulations

Simulations were done in Simulink environment under the applications of different fault types at various locations on the transmission line model of Figure 3. All the fault types were simulated between 0.05s and 0.08s at 30 kilometers away from Bus 2 in the first instance. The measured fault voltage and fault current values were sampled and sent to MATLAB workspace from where the impedance based algorithm compute the fault distance.

## 6. Results

The fault distance calculations from MATLAB analysis, which formed the basis for various fault types at 30 kilometers away from Bus 2 are as shown in Table 1. To further examine the performance accuracy of impedance based method algorithm, similar calculations were done for the same fault types at these locations (15, 25, 35, 45, 55, 65, 75 and 85 km) away from Bus 2 on the transmission lines and the results obtained are thus, presented in Table 2.

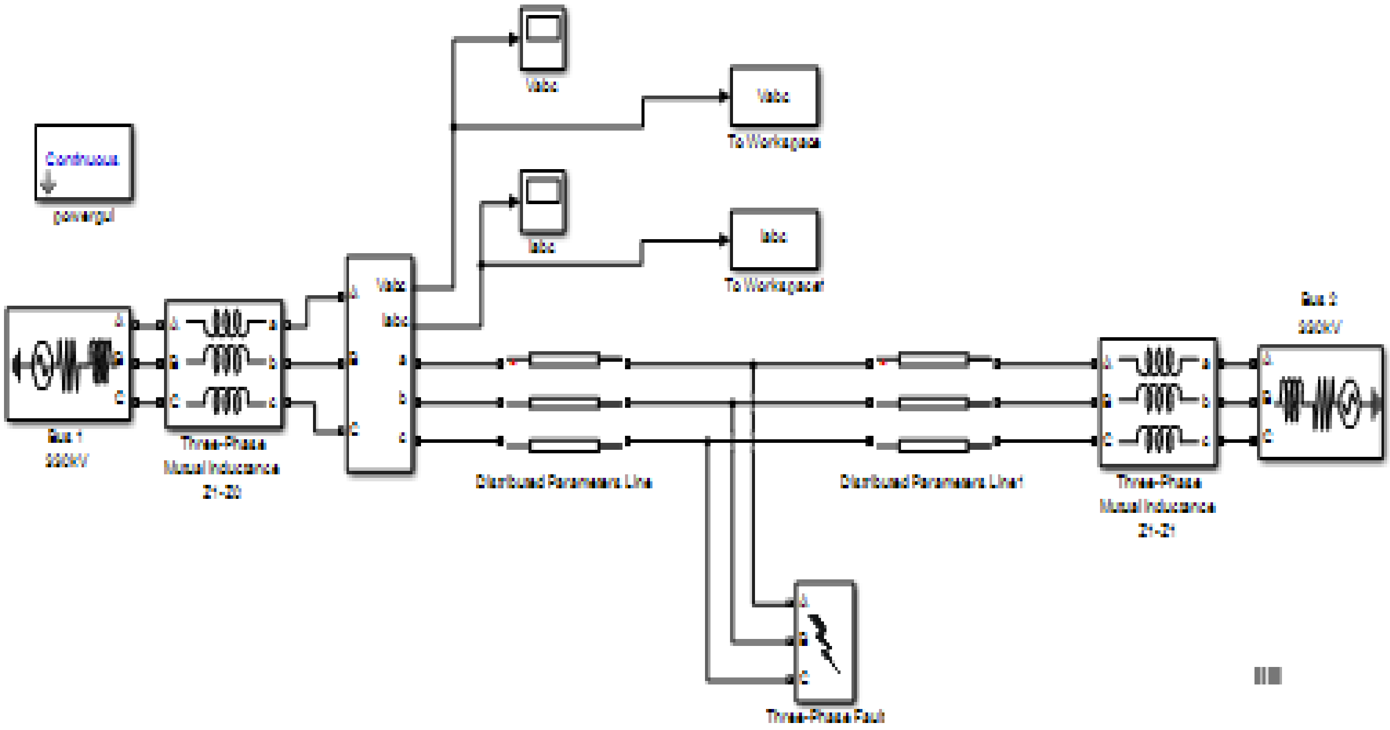

**Figure 3. Simulink Model of Faulted Three-Phase Transmission Line.**

**Table 1. Voltage and current values of both buses 1 and 2 for various fault types at 30km away from bus 2 using impedance based method.**

| Types of Fault | BUS 1 | | | | BUS 2 | | | | Actual Location (km) | Estimated Fault Distance (km) |
|---|---|---|---|---|---|---|---|---|---|---|
| | Current | | Voltage | | Current | | Voltage | | | |
| | Phase Angle | Magnitude | Phase Angle | Magnitude | Phase Angle | Magnitude | Phase Angle | Magnitude | | |
| Phase A to Ground | 2.3381 | 222.4294 | 1.7763 | 2.6522 | 2.5358 | 123.9437 | 1.4590 | 1.4397 | 30 | 30.61 |
| Phase B to Ground | 2.2735 | 222.8659 | 1.8424 | 2.5907 | 2.5954 | 121.8612 | 1.3884 | 1.5078 | 30 | 30.59 |
| Phase C to Ground | 2.2083 | 223.2474 | 1.9080 | 2.5285 | 2.6544 | 119.7486 | 1.3174 | 1.5755 | 30 | 30.80 |
| Phase AB to Ground | 2.1426 | 223.5739 | 1.9732 | 2.4656 | 2.7127 | 117.6065 | 1.2461 | 1.6429 | 30 | 30.38 |
| Phase AC to Ground | 2.0763 | 223.8452 | 1.9423 | 2.4022 | 2.7703 | 115.4354 | 1.1746 | 1.7098 | 30 | 30.15 |
| Phase BC to Ground | 2.0379 | 224.0612 | 1.8746 | 2.3381 | 2.8835 | 113.2357 | 1.1027 | 1.7763 | 30 | 30.83 |
| Phase AB | 2.0096 | 224.2220 | 1.8064 | 2.2735 | 2.9390 | 111.0082 | 1.0305 | 1.8424 | 30 | 30.28 |
| Phase AC | 2.1020 | 224.3275 | 1.7377 | 2.2083 | 2.9938 | 108.7532 | 1.0992 | 1.9080 | 30 | 30.77 |
| Phase BC | 2.1657 | 224.3775 | 1.6687 | 2.1426 | 2.8272 | 106.4715 | 1.0270 | 1.9732 | 30 | 30.64 |
| Phase ABC to Ground | 2.2288 | 224.3723 | 1.5992 | 2.0763 | 0.6663 | 104.1634 | 0.9546 | 2.0379 | 30 | 30.38 |

**Table 2. Fault location estimations for four types of fault at different locations on the transmission line using impedance based method algorithm**.

| Fault Types | Actual Fault Location from Bus 2 (km) | Calculated Fault Distance (km) | Percentage Error |
|---|---|---|---|
| Single phase to ground fault (on phase A) | 15 | 14.06 | 0.94 |
| | 25 | 25.68 | 0.68 |
| | 35 | 35.87 | 0.87 |
| | 45 | 45.53 | 0.53 |
| | 55 | 55.92 | 0.92 |
| | 65 | 66.02 | 1.02 |
| | 75 | 75.82 | 0.82 |
| | 85 | 86.54 | 1.54 |
| Double phase to ground fault (on phase A & B) | 15 | 16.00 | 1.00 |
| | 25 | 25.55 | 0.55 |
| | 35 | 35.87 | 0.87 |
| | 45 | 45.67 | 0.67 |
| | 55 | 55.31 | 0.31 |
| | 65 | 65.91 | 0.91 |
| | 75 | 75.63 | 0.63 |
| | 85 | 86.01 | 1.01 |
| Double phase fault (on phase B & C) | 15 | 14.22 | 0.78 |
| | 25 | 25.89 | 0.89 |
| | 35 | 35.79 | 0.79 |
| | 45 | 45.71 | 0.71 |
| | 55 | 55.31 | 0.31 |
| | 65 | 65.42 | 0.42 |
| | 75 | 75.45 | 0.45 |
| | 85 | 85.64 | 0.64 |
| Three Phase fault (on phase A, B and C) | 15 | 14.24 | 0.76 |
| | 25 | 25.81 | 0.81 |
| | 35 | 35.67 | 0.67 |
| | 45 | 45.43 | 0.43 |
| | 55 | 56.03 | 1.03 |
| | 65 | 65.32 | 0.32 |
| | 75 | 76.12 | 1.12 |
| | 85 | 85.87 | 0.87 |

Table 2 shows the fault location accuracy (i.e. the percentage errors) in fault estimations for various types of fault at various locations. In the tabulated results, it is glaring that the percentage errors are slightly above unity at 65km and 85km of single phase to ground fault. The same occurrence was observed at 15km of double phase to ground fault as well as at 55km and 75km of balance three-phase fault. However, most of the estimated fault distances have very infinitesimal error margins, which indicate the level of accuracy of this method.

## 7. Conclusion

Faults may lead to considerable economic losses in power systems. This paper gives general overview of fault distance estimation on transmission line using impedance-based method. The technique was tested in MATLAB using data generated by simulating different faults. The results obtained provide a good reference for the adoption of this technique since fault location accuracy (percentage errors) for all fault types regarding the power system network are small and approximately the same. Thus, the developed algorithm can be used to determined fault location within a couple of seconds after fault occurrence if properly implemented.

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