Research Article

Application of Composite Method for Determining Fault Location on Electrical Power Distribution Lines

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Distribution line is one of the most important components of the distribution system. Troubleshooting faults on these lines are often a tedious task requiring service vehicles and personnel moving from one place to another in order to locate the fault and fix the problem. The study, therefore, is on how a composite fault location technique can be applied to predict the location of faults on the distribution lines. The calculations for the estimation of the fault location are performed using one terminal voltage and current data of the distribution line. A composite method that combines the impedance-based method and the fuzzy inference system method is used in the fault location algorithm. The presented algorithm has been extensively tested using the MATLAB-Simulink model of a 33 KV 40-kilometer distribution line. The simulation result demonstrates good accuracy and robustness of the algorithm.

1. Introduction

In developing countries, inadequate provision of social amenities abound which undoubtedly include poor electricity supply. Distribution of electricity in these areas has been haunted by continuous malfunctions of electrical equipment especially distribution lines. So far, corrective maintenance is often done by the usual method; that is, personnel patrol around in a service van from place to place in an effort to locate the fault [1]. Responding to this situation in this manner is unarguably inefficient as the patrol team spends time locating the fault and, in some cases, may mistake the place where the fault occurred for another place. This has led to lengthened downtime and hence has made power delivery unreliable. Therefore, there is a need for a timely, effective, and efficient method of locating faults. This paper discusses a technique in the maintenance of electricity distribution infrastructure by bringing about on-time location of faults.

Maintenance is defined in [2] as the combination of all technical and administrative actions with the intention of retaining an equipment in (or restore it to) an operating state in order for it to perform its required functions. It is also defined as any work undertaken in order to keep or restore a facility to any acceptable standard. As stated in [2], there are two broad types of maintenance, namely, preventive maintenance and corrective maintenance. While preventive maintenance includes condition monitoring and servicing, as well as planned outages, corrective maintenance involves modifying faulted equipment so as to restore normal operation. This paper addresses the problem of corrective maintenance on distribution lines.

According to [3], faults can be caused by short-circuits, faulty equipment, disoperation, overload, growing vegetation, aging, etc. Based on statistics, line faults happen to be the commonest faults in power systems [3]. Line faults that occur in power systems include single line-to-ground, line-to-line, double line-to-ground, and balanced three-phase faults [4]. Faults may be temporary (if the fault is cleared after the circuit breaker closes back) or permanent (if the fault is not cleared after opening and closing of the circuit breaker) [5]. Permanent faults can lead to loss of service lines.
2. Literature Review

In all the methods studied in the course of this work, there is similarity in their overall design. They all include a fault locating system and a means of communicating the location to the repairs people. Several works have been done in a bid to design an accurate fault locator. The various methods designed include impedance-based method, travelling wave method, noncontact magnetic field measurement method, fuzzy inference system method, and artificial neural networks method [3, 6]. These methods are by default used for transmission lines but can also be used for distribution lines [3–9]. If Global Positioning System (GPS) capability is added to the setup, the method is said to be synchronized, but if not, it is said to be unsynchronized [6]. The impedance method is the commonest one. It can be one-ended, two-ended, or multiended [3]. It leverages on the assumption that the line is uniform; that is, the line parameters are distributed evenly throughout the line and therefore they can be obtained by ordinary methods for analyzing transmission line [3]. The prefault and postfault voltages and currents and their symmetrical components are obtained and, together with the line parameters, are used to estimate the fault location. It is for a fact that uneven spacing between the phase conductors causes line inductance to vary; temperature of the day affects line resistance and the amount of sag of conductors (due to thermal expansion) which in turn affects line capacitance [4]. This method has been revised in the “modified” impedance method [7]. By way of illustration, for simplicity, suppose that the algorithm gives a fault point, \( Y \), for an input current, \( X \), and the algorithm can be tested using example cases of known fault points. A pattern in the error may be discovered after which the algorithm is improved [7]. In the travelling wave method, either the disturbance created by the fault on the line is detected and analyzed or impulse voltages are injected into the line and the reflected wave is observed using time-domain reflectometry (TDR) in order to determine the impedance characteristics of the line [3, 8]. Like the impedance method, it can be one-ended, double-ended, or multiended [3]. The wave captured usually contains noise that must be filtered out. A signal processing method using wavelet transform is employed to do this [9]. The noncontact magnetic field measurement method involves the use of a magnetometer (which contains a magnetic sensor) to sense the magnetic field produced by a fault current and relay the data so gotten to a central unit for processing [3]. The fuzzy inference system formulates mappings between fault currents and voltages (inputs) and the location of the fault (output). It does this using a series of fuzzy if-then rules. A merit of this method is that it follows human intuition and takes advantage of the fact that results are not always exact. A limitation of the fuzzy inference system is that it is only useful when its parameters are well tuned. The artificial neural network (ANN) method uses a network of nodes or objects whose output depends on the input(s) and an internal mechanism that can be modified on training. This gives the network the property of being able to learn. An artificial neural network, which is one of the soft computing techniques, requires a model to be trained with actual fault data. The data need to be up-to-date to take into account changes happening on the line with time and have to be unbiased so that the model will be accurate [9]. A demerit of the ANN method is that the accuracy of the model increases with increase in its complexity (i.e., depth of the network) and with the amount of data it is trained with [9]. Sometimes, more than one of these methods is employed in parallel, in which case they are called composite methods, in an effort to minimize error that ensues [10, 11].

A new and state-of-the-art method is the smart fault location method. This is a feature of major electric power systems of the world today [3]. This makes use of intelligent electronic devices (IEDs) installed throughout the power system to monitor it around-the-clock [5]. The IEDs act as sensors and relay sensor data, for example, temperature of component and line current, to a control station [12]. This has been made possible with advances in Big Data and radio silicon and wireless sensor network technologies [12]. There is incentive to adopt this method because of the flexibility and scalability it affords, especially for smart power systems. An advantage of a smart power system is the economy in power supply it provides through efficient energy management systems and support for distributed generation to augment the conventional power generation [10]. It also makes static var control and “self-healing” in power system networks possible through coordinated transmission and distribution of electric power [10]. But the infrastructure to put this in place is expensive, although there has been progressive decrease in costs as a result of advancements in integrated circuit (IC) technologies, information and communications technologies (ICT), and battery production technologies [11]. As stated in [5], a smart fault location system will use knowledge of the network parameters, current topology, and type of data to determine the fault location method that best suits the situation.

There are different software tools and associated hardware in use today with the fault location methods to monitor transmission and distribution systems and hence faults in them. Traditionally, remote terminal units collect measurements (bus voltages, currents flowing in the lines, frequency, breaker status, transformer tap position, etc.) called supervisory control and data acquisition (SCADA) from monitored equipment using field devices like sensors and measuring instruments [13]. Control action is carried out using on-site programmable logic controllers or remote terminal units [13]. This arrangement incorporates a software application that provides a graphical user interface for monitoring of the system [13].

In the work of [14], the identification methodology of main distribution line faults in OV MV BPL networks was presented and assessed. Result of the work shows that the identification of main distribution line faults is based on the coupling reflection coefficients derived from the original and
the extended TM2 methods as well as their differences. Federico and Tonello in their paper [15] used two monitoring techniques, namely, the symbol level sensing and mains level sensing, which allow monitoring different types of anomalies. The results show that correctly identifying and locating an anomaly does not depend much on the size of the network or on the noise but rather on the topology of the network and how it is taken into account by the detection and localization algorithms.

In the methods described so far, impedance method is the cheapest and simplest method to implement. A combination of the impedance method with any of the artificial intelligence methods of fault location will give good precision of the fault location. In this paper, the impedance-based method and the fuzzy inference system are used.

3. Methodology

A composite method combining the impedance method and the fuzzy inference system method is used as the fault location algorithm.

3.1. Impedance-Based Method. A single-ended impedance-based method is employed as measurements will be obtained at the substation. In the impedance-based method, first the symmetrical components of the fault currents are obtained by evaluating the analysis equation as follows:

\[
\begin{bmatrix}
I_0 \\
I_1 \\
I_2
\end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix}
I_a \\
I_b \\
I_c
\end{bmatrix}. \tag{1}
\]

On the basis of the result, the fault type can be ascertained as different fault types have different effects on the line. In order to draw the equivalent sequence network, the sequence impedances of the sequence networks must be determined. To do this, the line impedances have to be transposed so that self-impedances of the line become equal and mutual impedances of the line become equal. Then the sequence impedances are found by the following:

\[
[V_{abc}] = [Z_{abc}] [I_{abc}] = \begin{bmatrix}
Z_s & Z_m & Z_m \\
Z_m & Z_s & Z_m \\
Z_m & Z_m & Z_s
\end{bmatrix} \begin{bmatrix}
I_a \\
I_b \\
I_c
\end{bmatrix}. \tag{2}
\]

For a transposed line, the phase-impedance matrix is transformed into the sequence-impedance matrix using the following equation:

\[
[A]^{-1} [Z_{abc}] [A] = [Z_{012}], \tag{3}
\]

where \([A]\) is the symmetrical components transformation matrix:

\[
[Z_{012}] = \begin{bmatrix} (Z_s + 2Z_m) & 0 & 0 \\ 0 & (Z_s - Z_m) & 0 \\ 0 & 0 & (Z_s - Z_m) \end{bmatrix}. \tag{4}
\]

Or

\[
[Z_{012}] = \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix}. \tag{5}
\]

\[Z_0, Z_1, \text{and } Z_2 \text{ are the zero, positive, and negative sequence impedances, respectively. } Z_0, Z_1, \text{ and } Z_2 \text{ are calculated as follows:}
\]

\[
Z_1 = Z_2 = Z_S + Z_T + Z_L, \tag{6}
\]

\[
Z_0 = Z_T + Z_{10}, \tag{7}
\]

\[
Z_{10} = K_0 Z_L. \tag{8}
\]

\[Z_T \text{ is the transformer impedance. } Z_L \text{ is a function of distance along the feeder to the fault point:}
\]

\[
Z_L = s \left[ r_f + jw_L D_{eq} D_s \right], \tag{9}
\]

where \(s = \text{length of line, } r_f = \text{line resistance, } D_{eq} = \text{equivalent spacing } = (D_{12} D_{30} D_{03})^{1/3}, D_s = \text{self GMD of conductor, and } K_0 = \text{Earth and ground wire condition.}
\]

Use

\[
Z_B = \frac{V_{B-L1}^2}{S_{B-30}} = \frac{V_{B-LN}^2}{S_{B-10}}. \tag{10}
\]

So we get \(Z_L\) in pu as

\[
Z_{L,pu} = \frac{Z_L}{Z_B} \tag{11}
\]

The fault impedance \(Z_f\) is

\[
Z_f = \frac{R_{FLT}}{Z_B}, \tag{12}
\]

where \(R_{FLT}\) is the arcing fault resistance in ohms.

Thus, the fault currents are as follows:

\[
I_{f-30} = \frac{V_f}{Z_s + Z_T + Z_L + Z_f} \tag{13}
\]

\[
I_{f-11} = \frac{\sqrt{3} V_f}{2(Z_s + Z_T + Z_L) + Z_f} \tag{14}
\]

\[
I_{f-SLG} = \frac{3 V_f}{2Z_s + 3Z_T + (2 + K_0)Z_L + 3Z_f}. \tag{15}
\]

As can be observed, the sequence impedances are functions of the distance \(s\) from the substation to the fault point. Since the parameter of interest is "s" and all other
parameters are known or can be calculated, “s” can be easily computed.
For 3-∅ fault,
\[
s = \frac{\left( V_f/I_f \right) - Z_s - Z_T - Z_f}{r_L + jwln\left( D_{eq}/D_s\right)}
\]
(17)

For line-to-line fault,
\[
s = \frac{\left( \sqrt{3} V_f/2I_f \right) - \left( Z_f/2 \right) - Z_s - Z_T}{r_L + jwln\left( D_{eq}/D_s\right)}
\]
(18)

For single-line-to-ground fault,
\[
s = \frac{\left( 3V_f/(2+K_0)I_f \right) - \left( 2Z_s + 3Z_T + 3Z_f/(2+K_0) \right)}{r_L + jwln\left( D_{eq}/D_s\right)}
\]
(19)

The flow chart for the impedance method is shown in Figure 1.

The Simulink model of the distribution system used for the impedance-based method is as follows.

The algorithm for the impedance-based method is done in the embedded MATLAB function of Figure 2. In Figure 3, the faults are placed at an interval of 10 km on the line. At any time, only one of the three-phase fault blocks is switched on.

3.2. Fuzzy Inference System. The structure of the fuzzy inference system is as shown in Figure 4.

The output of the system is the weighted average of the inputs based on the fuzzy logic if-then rules. The “if” statements are the antecedent blocks, while the “then” statements are the consequent blocks. The type of fuzzy inference system is the Mamdani fuzzy inference system because it gives fuzzy outputs, an indication that the result is an approximation. MATLAB’s fuzzy logic toolbox is used to model the fuzzy inference system (FIS) and Simulink is used to test the system using SimPowerSystems library and fuzzy logic controller block. Two fuzzy inference systems were created. The first fuzzy inference system determines whether the fault is single-line-to-ground, line-to-line, double-line-to-ground, or line-to-line-to-line, while the second fuzzy inference system determines the location of the fault.

3.2.1. Fault Classifier FIS. The fault classifier identifies a fault as either single-line-to-ground fault, line-to-line fault, double-line-to-ground fault, three-phase-clear-of-ground fault, or three-phase-to-ground fault. Postfault currents of the phases after the transient period are used since at that time the fault currents would have attained their highest values. The ratios \( R_1, R_2, \) and \( R_3 \) are calculated first and normalized to get \( R_{1n}, R_{2n}, \) and \( R_{3n} \) of \( R_1, R_2, \) and \( R_3, \) respectively, followed by the differences \( \Delta_1, \Delta_2, \) and \( \Delta_3. \) This is as follows:

\[
R_1 = \frac{|I_a|}{|I_b|}
\]
(20)

\[
R_2 = \frac{|I_b|}{|I_c|}
\]
(21)

\[
R_3 = \frac{|I_c|}{|I_a|}
\]
(22)

\[
R_{1n} = \frac{R_1}{\text{maximum}(R_1, R_2, R_3)}
\]
(23)

\[
R_{2n} = \frac{R_2}{\text{maximum}(R_1, R_2, R_3)}
\]
(24)

\[
R_{3n} = \frac{R_3}{\text{maximum}(R_1, R_2, R_3)}
\]
(25)

\[
\Delta_1 = R_{1n} - R_{2n},
\]
(26)

\[
\Delta_2 = R_{2n} - R_{3n},
\]
(27)
\[ \Delta_3 = R_{3n} - R_{1n}. \]  

The ratios \( R_1, R_2, \) and \( R_3 \) determine the relative magnitude of the current in each phase with respect to another phase; it is expected that the phase (or phases) where the fault has occurred is the phase (or phases) with the largest current(s). Dividing the ratios by their maximum normalizes the ratios so that they have values between one and zero. \( \Delta \)s determine the phases that are connected in a line-to-line fault; a small value for delta implies that the phases are connected in a line-to-line fault. If all three \( \Delta \)s are small, a three-phase fault exists between the three phases. In the event that a fault to ground occurs, the neutral current is no more zero, which implies that the zero-sequence current is not zero. The zero-sequence current is given as
where \( I_a, I_b, \text{ and } I_c \) represent phase ’a,’ phase ’b,’ and phase ’c’ currents, respectively, and \( I_0 \) and \( I_N \) are zero-sequence and neutral currents, respectively. To take into account the zero-sequence current, \( \Delta_4 \) is computed using the following equation:

\[
\Delta_4 = |I_0|
\]

A large value for \( \Delta_4 \) shows the presence of a ground fault. The values of \( \Delta_1, \Delta_2, \Delta_3, \text{ and } \Delta_4 \) show what type of fault occurred. \( \Delta_1 \) is calculated for fault classification; the phase differences between positive and negative sequence currents of each of the unbalanced current phasors have to be found. These are represented by angle A for phase “a,” angle B for phase “b,” and angle C for phase “c.” The angles can be determined bearing in mind that the negative sequence is the positive sequence reversed. For a single-line-to-ground fault, phase “a” currents of the sequence networks are in phase; therefore,

\[
\text{angle A} = |\arg(I_{a1}) - \arg(I_{a2})| = 0\degree
\]

\[
\text{angle B} = |\arg(I_{b1}) - \arg(I_{b2})| = 120\degree
\]

\[
\text{angle C} = |\arg(I_{c1}) - \arg(I_{c2})| = 120\degree
\]

where \( \arg(I_{a1}) \) and \( \arg(I_{a2}) \) are the arguments of the positive and negative sequence components of current in phase ’a’; \( \arg(I_{b1}) \) and \( \arg(I_{b2}) \) are the arguments of the positive and negative sequence components of current in phase ’b’; and \( \arg(I_{c1}) \) and \( \arg(I_{c2}) \) are the arguments of the positive and negative sequence components of current in phase ’c.’ The absolute value sign clears any negative that may arise from taking the difference. For three-phase faults, \( \arg(I_{a2}), \arg(I_{b2}), \text{ and } \arg(I_{c2}) \) have no significance, since the fault is a balanced fault.

\( a) \) Fuzzification. The inputs \( \Delta_1, \Delta_2, \Delta_3, \Delta_4, \text{ angle A, angle B, and angle C have to be converted to fuzzy variables. The process of doing so is called fuzzification. Membership functions are used to generate grades for the variables depending on their actual values. The triangular membership function is used. There is no rule for assigning membership functions to the inputs; rather membership functions are selected by trial and error with the aim of improving the result.

\( b) \) Fuzzy if-then rules. The fuzzy if-then rules for the FIS are as shown in Appendix A.

\( c) \) Defuzzification. To defuzzify the output, the centroid method is used. The outputs are the fault types: single-line-to-ground, double-line-to-ground, line-to-line, and three-phase faults.

3.2.2. Fault Location FIS. This takes as inputs the fault type from the first FIS and the fault currents detected by the CTs. Given the fault type and values of fault current, it outputs a distance \( s \) that corresponds to the pair. In the simulation, the faults are placed at intervals of 10 km in a 40 km line. With the knowledge of the maximum fault current that can flow on the line (when the fault occurs very close to the substation) for a given fault type, the fault location FIS is able to predict the location of the fault by associating different fault positions to different faults types. The if-then rules are listed in Appendix B.

The Simulink model for the entire setup is shown in Figure 5.

The Simulink model for the distribution subsystem of Figure 5 is shown in Figure 6.

4. Simulation and Results

In the MATLAB simulation, three-phase faults were placed at intervals of 10 km on a 40 km distribution line and the

Figure 5: Simulink model for the fuzzy inference system method.
impedance-based method and fuzzy inference system method were used to estimate the location. The results of the simulation are shown in Figure 7.

As seen from the graph, taking the average is more accurate than using the result obtained from any of the two methods alone. If the error is estimated and added to the average fault distance, a better result will be obtained.

4.1. Application of the Proposed Method in the Underground Distribution System. The proposed methods were applied to a 40 km underground distribution system. The simulation results are shown in Figure 8.

5. Conclusion

In this work, an algorithm for calculating distance to the fault location on the distribution lines using impedance-based method and fuzzy inference system method was developed and applied on three-phase overhead and underground distribution systems. The algorithm can be implemented using information from a microprocessor-based relay, a microcontroller, and a simple spreadsheet, making both methods accessible tools for the small utility. The fuzzy inference system method should provide improvement over the impedance-based method for faults when the parameters are well tuned. Although the
A. The Fuzzy If-Then Rules for Fuzzification

(1) If $\Delta 1$ is high and $\Delta 2$ is moderate and $\Delta 3$ is low and $\Delta 4$ is high and angle $A$ is approx. 30° and angle $B$ is approx. 150° and angle $C$ is approx. 90° then fault type is phase “a” to ground.

(2) If $\Delta 1$ is low and $\Delta 2$ is high and $\Delta 3$ is moderate and $\Delta 4$ is high and angle $A$ is approx. 90° and angle $B$ is approx. 30° and angle $C$ is approx. 150° then fault type is phase “b” to ground.

(3) If $\Delta 1$ is moderate and $\Delta 2$ is low and $\Delta 3$ is high and $\Delta 4$ is high and angle $A$ is approx. 150° and angle $B$ is approx. 90° and angle $C$ is approx. 30° then fault type is phase “c” to ground.

(4) If $\Delta 1$ is low and $\Delta 2$ is high and $\Delta 3$ is low and $\Delta 4$ is high and angle $A$ is approx. 30° and angle $B$ is approx. 90° and angle $C$ is approx. 150° then fault type is phase “a” to phase “b” to ground.

(5) If $\Delta 1$ is low and $\Delta 2$ is low and $\Delta 3$ is high and $\Delta 4$ is high and angle $A$ is approx. 150° and angle $B$ is approx. 30° and angle $C$ is approx. 90° then fault type is phase “c” to phase “b” to ground.

(6) If $\Delta 1$ is high and $\Delta 2$ is low and $\Delta 3$ is low and $\Delta 4$ is high and angle $A$ is approx. 90° and angle $B$ is approx. 150° and angle $C$ is approx. 30° then fault type is phase “a” to phase “c” to ground.

(7) If $\Delta 1$ is low and $\Delta 2$ is high and $\Delta 3$ is low and $\Delta 4$ is low and angle $A$ is approx. 30° and angle $B$ is approx. 90° and angle $C$ is approx. 150° then fault type is phase “b” to phase “c” to ground.

(8) If $\Delta 1$ is low and $\Delta 2$ is low and $\Delta 3$ is high and $\Delta 4$ is low and angle $A$ is approx. 150° and angle $B$ is approx. 30° and angle $C$ is approx. 90° then fault type is phase “c” to phase “b” to ground.

(9) If $\Delta 1$ is high and $\Delta 2$ is low and $\Delta 3$ is low and $\Delta 4$ is low and angle $A$ is approx. 90° and angle $B$ is approx. 150° and angle $C$ is approx. 30° then fault type is phase “b” to phase “a” to phase “c.”

(10) If $\Delta 1$ is moderate and $\Delta 2$ is moderate and $\Delta 3$ is low and $\Delta 4$ is low and angle $A$ is none and angle $B$ is none and angle $C$ is none then fault type is phase “a” to phase “b” to phase “c.”

(11) If $\Delta 1$ is moderate and $\Delta 2$ is low and $\Delta 3$ is moderate and $\Delta 4$ is low and angle $A$ is none and angle $B$ is none and angle $C$ is none then fault type is phase “a” to phase “b” to phase “c.”

(12) If $\Delta 1$ is low and $\Delta 2$ is moderate and $\Delta 3$ is moderate and $\Delta 4$ is low and angle $A$ is none and angle $B$ is none and angle $C$ is none then fault type is phase “a” to phase “b” to phase “c.”

(13) If $\Delta 1$ is moderate and $\Delta 2$ is low & $\Delta 3$ is low and $\Delta 4$ is low and angle $A$ is none & angle $B$ is none and angle $C$ is none then fault type is phase “a” to phase “b” to phase “c.”

(14) If $\Delta 1$ is low and $\Delta 2$ is moderate and $\Delta 3$ is low and $\Delta 4$ is low and angle $A$ is none and angle $B$ is none and angle $C$ is none then fault type is phase “a” to phase “b” to phase “c.”

(15) If $\Delta 1$ is low and $\Delta 2$ is low and $\Delta 3$ is moderate and $\Delta 4$ is low and angle $A$ is none and angle $B$ is none and angle $C$ is none then fault type is phase “a” to phase “b” to phase “c.”

B. The Fuzzy If-Then Rules for Defuzzification

(i) If fault type is $a$-$g$ and $I_a$ is low then location is far

(ii) If fault type is $a$-$g$ and $I_a$ is medium then location is middle

(iii) If fault type is $a$-$g$ and $I_a$ is high then location is near

(iv) If fault type is $b$-$g$ and $I_b$ is low then location is far

(v) If fault type is $b$-$g$ and $I_b$ is medium then location is middle

(vi) If fault type is $b$-$g$ and $I_b$ is high then location is near

(vii) If fault type is $c$-$g$ and $I_c$ is low then location is far

(viii) If fault type is $c$-$g$ and $I_c$ is medium then location is middle

(ix) If fault type is $c$-$g$ and $I_c$ is high then location is near

(x) If fault type is $a$-$b$ and $I_a$ is low and $I_b$ is low then location is far

(xi) If fault type is $a$-$b$ and $I_a$ is medium and $I_b$ is medium then location is middle

(xii) If fault type is $a$-$b$ and $I_a$ is high and $I_b$ is high then location is near

(xiii) If fault type is $b$-$c$ and $I_b$ is low and $I_c$ is low then location is far

(xiv) If fault type is $b$-$c$ and $I_b$ is medium and $I_c$ is medium then location is middle

(xv) If fault type is $b$-$c$ and $I_b$ is high and $I_c$ is high then location is near

(xvi) If fault type is $c$-$a$ and $I_c$ is low and $I_a$ is low then location is far

(xvii) If fault type is $c$-$a$ and $I_c$ is medium and $I_a$ is medium then location is middle
(xviii) If fault type is c-a and $I_c$ is high and $I_a$ is high then location is near

(xix) If fault type is a-b-g and $I_a$ is low and $I_b$ is low then location is far

(xx) If fault type is a-b-g and $I_a$ is medium and $I_b$ is medium then location is middle

(xxi) If fault type is a-b-g and $I_a$ is high and $I_b$ is high then location is near

(xxii) If fault type is b-c-g and $I_b$ is low and $I_c$ is low then location is far

(xxiii) If fault type is b-c-g and $I_b$ is medium and $I_c$ is medium then location is middle

(xxiv) If fault type is b-c-g and $I_b$ is high and $I_c$ is high then location is near

(xxv) If fault type is c-a-g and $I_c$ is low and $I_a$ is low then location is far

(xxvi) If fault type is c-a-g and $I_c$ is medium and $I_a$ is medium then location is middle

(xxvii) If fault type is c-a-g and $I_c$ is high and $I_a$ is high then location is near

(xxviii) If fault type is a-b-c and $I_a$ is medium and $I_b$ is medium and $I_c$ is low then location is far

(xxix) If fault type is a-b-c and $I_a$ is high and $I_b$ is high and $I_c$ is high then location is middle

(XXX) If fault type is a-b-c and $I_a$ is very high and $I_b$ is very high and $I_c$ is very high then location is near

Data Availability
The data used for this research are available and can be provided upon request to the corresponding author.

Conflicts of Interest
The authors declare that they have no conflicts of interest.

References
[1] C. A. Awosope, *Nigerian Electricity Industry: Issues, Challenges and Solution*, Covenant University 38th Public Lecture, Ota, Nigeria, 2014.
[2] T. Covington, T. Stankiewicz, R. Anderson, L. Wright, and B. Cockerham, "A simple method for determining fault location on distribution lines," in *Proceedings of the 71st Annual Georgia Tech Protective Relaying Conference*, Atlanta, Georgia, May 2017.
[3] M. Kezunovic, “Smart fault location for smart grids,” *IEEE Transactions on Smart Grid*, vol. 2, no. 1, 2011.
[4] A. Swetapadma and A. Yadav, "Fuzzy inference system approach for locating series, shunt, and simultaneous series-shunt faults in double circuit transmission lines," *Computational Intelligence and Neuroscience*, vol. 2015, Article ID 620360, 12 pages, 2015.
[5] S. Das, S. Santos, A. Gaikwad, and M. Patel, *Impedance-based Fault Location in Transmission Networks: Theory and Application*, IEEE, Piscataway, NJ, USA, 2014.
[6] S. F. Alwash and V. K. Ramachandaramurthy, "New impedance-based fault location method for unbalanced power distribution systems power quality research group," *International Transactions on Electrical Energy Systems*, vol. 25, no. 6, 2014.
[7] F. Yan, W. Liu, and L. Tian, *Fault Location for 10kV Distribution Line Based on Traveling Wave and ANN Theory*, Electrical Engineering Department, North China Electric Power University, Wuhan, China, 2011.
[8] Q. Huang, W. Zhen, and P. W. T. Pong, "A novel approach for fault location of overhead transmission line with noncontact magnetic-field measurement," *IEEE Transactions on Power Delivery*, vol. 27, no. 3, pp. 1186–1195, 2012.
[9] L. H. Tsoukas and R. E. Uhrig, *Fuzzy and Neural Approaches in Engineering*, John Wiley and Sons Inc., Hoboken, NJ, USA, 1997.
[10] B. Tahar, *Artificial Neural Network-Based Fault Location in EHV Transmission Lines*, University of Science and Technology of Oran, Oran, Algeria, 2000.
[11] A. E. Adel, *Fault Detection and Classification in Transmission Lines Using ANFIS*, IEEJ Transactions on Industry Applications, Berlin, Germany, 2009.
[12] G. Lin, B. Brown, D. Alphenaar et al., *Wireless Sensor Network for Electric Transmission Line Monitoring*, University of Louisville, Genscape Inc., Louisville, KY, USA, 2010.
[13] Wikipedia, “SCADA”, https://en.m.wikipedia.org/wiki/SCADA.
[14] A. Lazaropoulos, “Main line fault localization methodology in smart grid - Part 1: extended TM2 method for the overhead medium-voltage broadband over power lines networks case,” *Trends in Renewable Energy*, vol. 3, no. 3, pp. 2–25, 2017.
[15] F. Passerini and A. M. Tonello, “Smart grid monitoring using power line modems: anomaly detection and localization,” *IEEE Transactions on Smart Grid*, vol. 10, no. 6, pp. 6178–6186, 2019.