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Simulation-Based Analysis of Three Phase Symmetrical Fault Using Double Ended Impedance Method A Case Study for Otukpo 132kv Transmission Line

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***Abstract-** This study conducts a simulation-based analysis of three-phase (ABC) symmetrical fault location on a 132 kV transmission line using a double-ended impedance-based approach implemented in MATLAB/Simulink. The method is derived from Kirchhoff's Voltage Law and uses synchronized voltage and current measurements from both the sending and receiving ends to remove the dependency on fault-point voltage and directly estimate the fault distance based on apparent impedance. A 160 km distributed-parameter transmission line model, with realistic line and system parameters, is developed in SimPowerSystems to simulate both steady-state and transient fault conditions. Three-phase fault scenarios are tested at various locations (from 10 km to 120 km) with different fault resistances (5 Ω to 100 Ω) and fault inception times to assess the accuracy and robustness of the estimation. The results show that the proposed method gives highly accurate fault location estimates, with percentage errors typically below 1% in all test cases. The approach is resistant to changes in fault resistance and fault inception time, and maintains reliable performance across various fault distances. The study confirms that the double-ended impedance-based technique offers an effective, accurate, and computationally efficient solution for fault location and protection in high-voltage power systems.*

***Keywords:** 132 kV transmission line, Three-phase symmetrical fault, Impedance-based method; MATLAB/Simulink and Kirchhoff's Voltage Law.*

I. INTRODUCTION

Electric power transmission systems are essential for modern power delivery, allowing large amounts of energy to be sent from power plants to where it's needed, all while maintaining high efficiency and reliability. However, these transmission networks, especially high-voltage 132 kV systems, are very sensitive to various types of faults. These faults can happen because of environmental factors, aging equipment, lightning, insulation problems, switching surges, and physical damage. Among all these issues, a three-phase symmetrical fault is the most serious because it causes the highest fault current, significant voltage drops, and places a lot of stress on the electrical equipment (Kundur, 1994; Glover et al., 2017). That's why accurately detecting and precisely locating these faults is crucial for keeping the power system stable and reducing the time the power is off. Traditional methods for locating faults, especially those that rely on impedance measurements from just one end of the line, are commonly used in protective relays.

However, these methods often face challenges like fault resistance, changes in load current, and uncertainty in the line's properties. To address these issues, more advanced methods that use data from both ends of the line have been developed. These double-ended impedance-based techniques make use of synchronized voltage and current data from both ends. With the help of Phasor Measurement Units (PMUs) and wide-area measurement systems, the accuracy and reliability of these fault location methods have greatly improved (Phadke and Thorp, 2017; IEEE PES, 2018; Gopakumar et al., 2015).

Recent research has shown that these double-ended techniques are effective in reducing the impact of remote infeed currents and fault resistance, leading to more accurate fault location, especially in long transmission lines and interconnected power grids (Li and Chen, 2024; Eze et al., 2025).

The use of modern simulation tools like MATLAB/Simulink and Simscape Electrical has also made it possible to model transmission systems under fault conditions in detail, providing a solid environment for developing, testing, and evaluating fault location algorithms (MathWorks, 2024; Swain and Cherukuri, 2021). In this context, this study performs a simulation-based analysis of three-phase symmetrical faults on the Otukpo 132 kV transmission line using a double-ended impedance-based technique. The research uses synchronized measurements and detailed system modeling to assess how accurately faults can be located under different conditions, helping to improve the coordination of protection systems and increase the reliability of high-voltage transmission systems.

1.1 Overview of the Otukpo 132 kV Transmission Line

The Otukpo 132 kV transmission line is a key sub-transmission network operated by TCN, connecting Benue and Enugu States to transfer large amounts of power and support grid stability. It is modeled as a three-phase system where reactance plays a major role, and it is typically represented using a π-equivalent model for analysis. This line is susceptible to both symmetrical and unsymmetrical faults. It is protected using distance relays and overcurrent protection schemes, and fault location has been improved with the use of double-ended impedance methods. Despite challenges like lightning, insulation failure, and interference from vegetation, its electrical behavior makes it suitable for fault analysis and simulation studies.

II. LITERATURE REVIEW

This paper looks at different studies, articles, research papers, and books about one-ended and double-ended methods for finding faults in transmission lines. For example, a 2018 research paper titled "Fault Detection of Transmission Line by Using Single and Double End Method" talks about a double-ended fault location algorithm for high-voltage, overhead transmission lines. This method uses synchronized voltage and current data from both ends of the line. Even though it's similar to a one-terminal method, it improves the accuracy of fault distance measurements by using data from both ends to reduce the impact of fault resistance and remote infeed. Studies show that double-ended methods usually perform better than one-ended ones (Izykowski, 2006). You don't need to identify the fault type to calculate the fault location. Instead of using zero sequence components, you can use positive sequence components, which reduces the effect of zero sequence. The only downside is that it requires a communication system to gather remote data, which can be done with GPS technology. In contrast, the single-end method just needs data collected at the line terminal, relay, or device. Although the double-ended method takes more time, it's still quick enough for human use. Another 2016 journal, "An Overview of Impedance-Based Fault Location Techniques in Electrical Power Transmission Network" by Ganiyu Adedayo Ajenikoko & Segun, Olufemi Sangotola, gives an overview of impedance-based fault location techniques. It reviews methods like the variance-based sensitivity method, one-ended impedance techniques including the Takagi method, Modified Takagi method, Erikson method, and two-ended methods such as synchronized and unsynchronized ones, as well as the unsymmetrical current-only two-ended method. The paper shows that the simple reactance technique is the easiest of all impedance-based methods. A 2014 journal paper by Sushma Ghimire, "Analysis of Fault location methods on transmission lines," discusses how each fault location method is applied and its usefulness. It finds that impedance-based methods are easier and more commonly used than traveling-wave methods. A 2012 journal paper by Steve Turner, "End-To-End testing of double ended fault locators for high voltage, overhead transmission lines," explains how to test double-ended fault locators. It covers fault location and shows one double-ended method. It also talks about classic problems with single-ended fault location methods.

2.1 Three-Phase Symmetrical Faults

A three-phase symmetrical fault affects all three phases equally, so the system stays balanced during the fault, as shown in Figure 1.

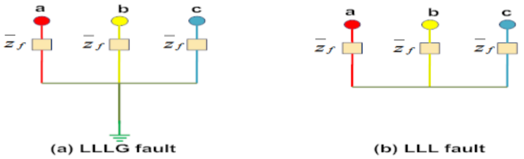

Figure 1: Symmetrical Faults

Recent studies show that symmetrical faults create the highest short-circuit currents and cause big drops in voltage across the network. That's why they are important for designing protective devices and analyzing system stability (Kumar and Singh, 2023). Because they are balanced, three-phase faults can be analyzed using per-phase equivalent circuits, making mathematical modeling and simulations easier (Patel et al., 2024).

2.2 Impedance-Based Fault Location methods

Impedance-based fault location methods are extensively used in power system protection because they are simple, reliable, and work well with existing relay systems. These methods are divided into single-ended and double-ended types.

Single-ended methods calculate the distance to a fault using one end of the transmission line by measuring the apparent impedance between the relay and the fault point. However, their accuracy is limited by issues like remote infeed currents, fault resistance, and changes in line parameters (Sharma et al., 2024). On the other hand, double-ended methods use synchronized voltage and current data from both ends of the line. These methods reduce the impact of unknown parameters, offering better accuracy. The use of PMUs (Phasor Measurement Units) for synchronized data has made double-ended methods more practical in modern power systems (Eze et al., 2025). Recent studies suggest double-ended impedance methods are more accurate than single-ended ones, especially for long transmission lines and high-voltage networks. They effectively handle errors from fault resistance, load flow, and remote sources (Li and Chen, 2024).

III. MATERIALS AND METHOD

(A) Double Ended Impedance Based method:

The double-ended impedance-based model for the Otukpo 132 kV transmission line uses Kirchhoff's Voltage Law from both ends of the line to the fault point. It removes the voltage at the fault point and uses synchronized voltage and current measurements to create a fault location equation based on apparent and total line impedance. This approach reduces reliance on unknown parameters and increases accuracy by reducing the impact of fault resistance and remote infeed. Overall, it offers a precise and dependable framework for transmission line fault location and protection.

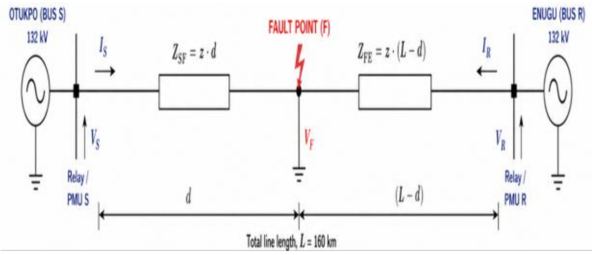

Figure 2: Double-ended impedance-based modelling of the Otukpo 132 kV transmission line using Kirchhoff's voltage law from both ends to the fault point

Consider the 132 kV Otukpo transmission line modeled as a uniform distributed-parameter line of length L, with:

Positive-Sequence Impedance per unit length

$$\boldsymbol{z = r + jwL} \qquad (1)$$

Total line impedance:

$$\boldsymbol{Z_{Line} = zL} \qquad (2)$$

Let a fault occur at a distance dfrom the sending end.

$$\boldsymbol{At\ the\ Sending\ end\ terminal\ (S)}: \quad \boldsymbol{V_S\ I_S}$$

$$\boldsymbol{At\ the\ Receiving\ end\ terminal\ (R)}: \quad \boldsymbol{V_R\ I_R}$$

Let $\boldsymbol{Z_F}$ = Impedance from sending end terminal to fault point

$\boldsymbol{Z_{RF}}$= Impedance from receiving end terminal to fault

Then, $\boldsymbol{Z_F = zd}, \quad \boldsymbol{Z_{RF} = z(L - d)}$

Let the fault point voltage be $\boldsymbol{V_F}$

From the sending end terminal:

$$\boldsymbol{V_F = V_S - I_S Z_F = V_S - I_S(zd)} \qquad (3)$$

From the receiving end terminal:

$$\boldsymbol{V_F = V_R - I_R Z_{RF} = V_R - I_R\{z(L - d)\}} \qquad (4)$$

Therefore, since both expressions equal V_F:

$$V_S - I_S zd = V_R - I_R z(L - d) \quad (5)$$

$$V_S - I_S zd = V_R - I_R zL + I_R zd \quad (6)$$

Rearrange terms involving d to one side:

$$V_S - V_R + I_R zL = I_S zd + I_R zd \quad (7)$$

Factorization (d)

$$V_S - V_R + I_R zL = zd(I_S + I_R) \quad (8)$$

To find fault distance (d):

$$d = \frac{V_S - V_R + I_R zL}{z(I_S + I_R)} \quad (9)$$

Substitute the line impedance $(Z_{Line} = zL)$ into equation (9) we have:

$$d = \frac{V_S - V_R + I_R Z_{Line}}{z(I_S + I_R)} \quad (10)$$

Where;

$V_S = Phase\ Voltage$

$I_S = Phase\ Current$

$V_S, V_R = Phase\ Voltage\ at\ sending\ and\ receiving\ ends$

$I_S, I_R = Phase\ Current\ at\ sending\ and\ receiving\ ends$

$V_F, = Voltage\ at\ fault\ point$

$z = Series\ Impedance\ per\ km\ of\ Line$ L

L $= Total\ Line\ Length\ (160km)$

$Z_{RF} = z(L - d)\ \ is\ \ Impedance\ from\ F\ to\ R$

$Z_F = zd\ \ Impedance\ from\ S\ to\ Fault$

$Z_{Line} = Total\ seriers\ impedance\ of\ the\ transmission\ line$

$d = \ Fault\ distance\ from\ sending\ end$

3.1 Simulation Modelling

The Otukpo 132 kV transmission line was modeled in MATLAB/Simulink using SimPowerSystems with accurate parameters from Tables 1 and 2, allowing for reliable steady-state and transient analysis and effective validation of the double-ended impedance-based fault distance method.

Table I

Line Parameters used for analysis

Parameters of Lines Value	Value
Total Length	160Km
Normal frequency	50 Hz
Voltage phase to phase	132 KV
Zero Sequence Resistance	0.210 Ω/Km
Positive Sequence Resistance	0.075 Ω/Km
Zero Sequence Inductance	0.001267 H/Km
Positive Sequence Inductance	0.003819 H/Km
Positive Sequence Capacitance	12.74e-0.0009 F/Km

Table II

Simulation Parameters used for analysis

Parameters of Lines Value	Value
Time start	0.0s
Time end	0.03s
Solver type	Variable-Step
Solver Algorithm	Ode23td(stiff/TR-BDF2)
Sampling Time	0.25msec
Integration method	discrete
Discrete Sampling Time	0.01sec
Fault inception Time	0.02sec

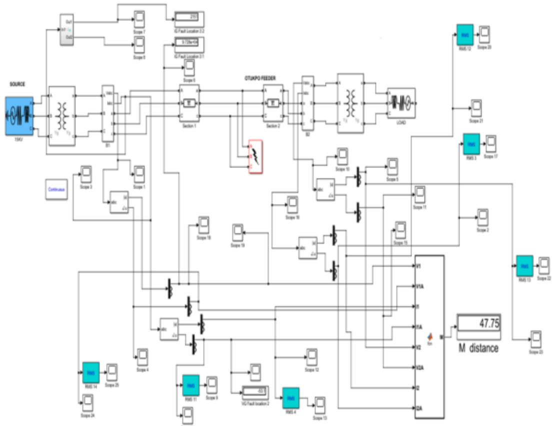

Figure 3: Simulation model for verification of fault distance on Otukpo 132kV transmission line using double-ended method

IV. SIMULATION RESULT AND DISCUSSION

The MATLAB R2018a simulator is used to evaluate the proposed scheme. Figure 3 shows the transmission line model. The results for the Otukpo 132 kV line agree with balanced fault theory.

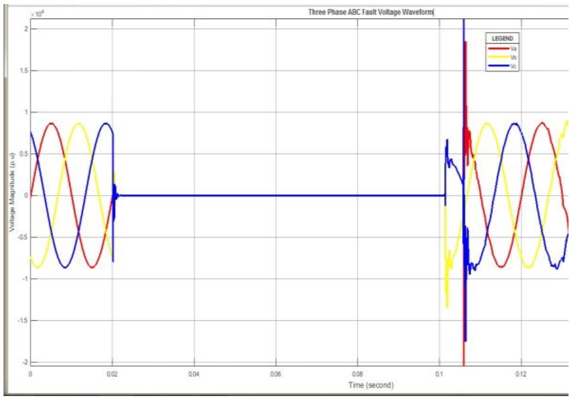

Figure 6: (Relay 1) Three Phase ABC Fault Voltage Waveform measured quantity at the remote side Otukpo transmission line

At fault inception, all phase voltages collapse simultaneously as shown in figure 6. The collapse is uniform across phases A, B, and C. This confirms a perfectly symmetrical fault. It also validates accurate fault modeling. Similarly, in figure 7, the current in all phases rises sharply. The magnitudes are equal in all phases. The 120° phase displacement is maintained. This confirms a balanced three-phase fault condition. High sub-transient currents appear immediately after the fault. The currents then decay gradually to steady-state. This behavior reflects the influence of system reactances.

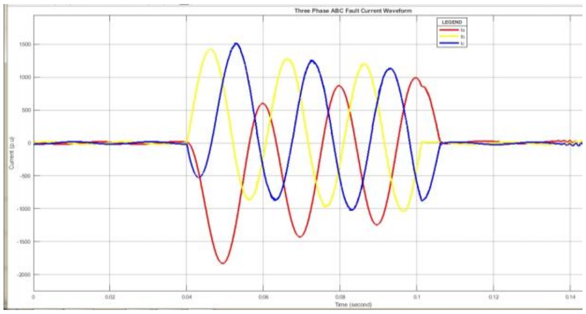

Figure 7: (Relay 1) Three Phase ABC fault Current Waveform, measured quantity at the remote side Otukpo transmission line

Percentage error between the actual and obtained distances is calculated as

$$\%\,Error = \left(\frac{\textbf{Calculated Fault Distance} - \textbf{Actual Fault Distance}}{\textbf{Actual Fault Distance}}\right) x\ 100$$

The simulation results for a three-phase ABC fault are presented in Table III. These results were obtained considering a homogeneous system.

Table III:
FAULT DISTANCE RESULT AND ERROR

Three Phases ABC Fault						
Fault type	Fault location (km)	Fault resistance	fault inception time(s)	Measuring Time	Calculated fault location (km)	Fault location % Error
ABC	10	5	0.02	0.07	9.89	0.2
		10	0.024	0.071	9.95	0.1
		100	0.027	0.075	9.92	0.2
	50	5	0.02	0.07	49.97	0.1
		10	0.024	0.072	50.02	0.1
		100	0.027	0.053	50.28	0.5
	90	5	0.02	0.08	90.09	0.3
		10	0.024	0.076	90.31	0.1
		100	0.027	0.053	90.31	0.1
	120	5	0.024	0.075	121.3	0.6
		10	0.02	0.077	121.6	1
		100	0.024	0.065	121.5	0.5

The results in Table III are analyzed using a double-ended impedance-based fault location method. This method uses synchronized voltage and current data from both ends of the transmission line to accurately estimate where a fault has occurred. For faults at 10 km, the calculated distances range from 9.89 to 9.95 km, which is very close to the actual location. The percentage error is between 0.1% and 0.2%, showing excellent accuracy. Changes in fault resistance (5 to 100 ohms) and the time when the fault starts have little effect on the estimate. At 50 km, the estimated fault locations range from 49.97 to 50.28 km, which aligns well with the real distance. The error is still low, between 0.1% and 0.5%. A small increase in error is seen when the fault resistance is higher (100 ohms), suggesting some sensitivity to fault impedance, but the error remains within acceptable limits. For a fault at 90 km, the calculated distances range from 90.09 to 90.31 km, maintaining high accuracy with errors between 0.1% and 0.3%. The consistent performance across different resistance levels confirms the method's reliability over long distances. At 120 km, the calculated distances range from 121.3 to 121.6 km, showing a slight increase in deviation. The error rises to a maximum of 1%, especially at moderate resistance levels. This suggests that the accuracy decreases slightly for faults near the end of the line, probably due to accumulated line parameters and measurement uncertainties. Overall, the double-ended impedance-based method shows high accuracy and reliability, with errors usually below 1%. The method is not greatly affected by changes in fault resistance or when the fault starts, making it effective for pinpointing faults in transmission networks.

V. CONCLUSION

This study shows that the double-ended impedance-based fault location method, applied to the Otukpo 132 kV transmission line using MATLAB/Simulink, provides highly accurate and reliable fault distance estimates under three-phase symmetrical fault conditions.

The method efficiently uses synchronized measurements from both ends of the line to remove voltage dependence at the fault point, which improves accuracy and reduces the impact of fault resistance and system uncertainties. Simulation results confirm excellent performance with percentage errors usually below 1%, confirming the method's strength and practical use in modern transmission line protection systems.

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