Implementation of Voltage Sag Based Fault Localization Algorithm in Nepalese Distribution System Considering the Impact of Fault Resistances

Awnish Kumar Thakur [1]; Sagar Dharel [2]; Nikee Thakur [3]; Raunak Ghimire [4]; Rojina Sharma [5]; Sher Singh Bhat [6]
Nepal Energy Foundation[1-6]
Lalitpur, Nepal[1-6]

Abstract:- Reliability is a significant challenge in the Nepalese distribution system, primarily due to the extensive lengths of distribution feeders, some of which span over 100 km, including all branches. In such long feeders, fault localization, particularly in cases of insulator puncture or tree contact, takes considerable time, delaying fault clearance and service restoration. This paper proposes a novel voltage sag-based fault localization algorithm tailored for the Nepalese distribution system. The algorithm utilizes both synchronized and non-synchronized time measurement devices to compare calculated and measured voltage sag errors for accurate fault distance estimation. The method was validated using simulations of a real Nepalese distribution system in OpenDSS and Python. Results demonstrate that the maximum error in calculated fault distances compared to actual fault locations was 3.01% for bolted faults. This approach provides a reliable and efficient solution for fault localization, significantly enhancing system reliability and fault response times in the Nepalese context.

Keywords:- *Fault Location, Open Source Software, Synchronised Time Meaurement, OpenDSS, Voltage Sag.*

I. INTRODUCTION

Identifying fault locations in distribution systems is challenging due to the inherent characteristics of these networks, such as short and heterogeneous line segments, the presence of laterals and load taps, and the relatively limited deployment of measurement instruments [1].

Fault localization approaches can be broadly classified into several categories based on the underlying characteristics of faults that are exploited for measurement and analysis. The first category is superimposed component methods, which analyze the transient components generated during fault events to determine the fault location. The second category comprises intelligent system methods, which leverage advanced techniques such as artificial intelligence and machine learning to enhance the accuracy and efficiency of fault detection. The third category includes impedance-based methods, where the fault location is estimated using the impedance of the distribution line as a key parameter. The fourth category is traveling wave-based methods, which utilize the propagation characteristics of fault-induced traveling waves along the line to pinpoint the fault. Lastly, voltage sag-based methods focus on identifying fault locations by analyzing the voltage sag patterns caused by faults, providing a reliable approach, especially in systems with limited measurement devices. These methods collectively offer a diverse range of solutions for fault localization in power distribution systems [2].

Several fault detection and localization algorithms have been presented, with a novel method proposed for fault localization in distribution systems utilizing fuzzy logic and neural networks, as discussed in [3].

Smart meter-based real-time data, including voltage and current measurements, are utilized for fault detection and localization. During fault events, changes in the current and voltage waveforms, as well as their magnitudes, are captured. These changes are analyzed to determine a weighted matrix, as described in [4].

Reference [1] proposes a fault localization algorithm using voltage sag data gathered from selected nodes. Tested on the IEEE 123-node system using ATPS, the algorithm includes functions for voltage sag characterization, fault resistance estimation, load variations, and implementation. It requires fewer smart meters compared to impedance-based methods, making it cost-effective. By analyzing voltage magnitude, phase angle changes, and load variations, the algorithm identifies faulted nodes efficiently with minimal data transfer to the distribution center.

Reference [5] proposes a decision tree-based fault localization method that significantly reduces computational time by 90%. However, it requires training an artificial neural network (ANN) with a large number of scenarios to enhance its decision-making capabilities.

Reference [6] proposes a novel fault localization method in distribution systems based on voltage sag calculations. This method requires only a small number of synchronized and non-synchronized measurement units for accurate fault detection.

The objective of this paper is to develop and test the accuracy of a fault localization algorithm for the Nepalese distribution system. For this purpose, the fault localization algorithm presented in [6] is used as a reference. A combination of OpenDSS is employed to provide pre-fault and fault system electrical operational parameters, while Python is utilized for the analysis of the system.

The number of metering unit required for fault localization in this paper is less than that of [2] and [4]. This is because this method requires only two synchronized time measurement unit at substation node and any of another node. In non-synchronized time measurement unit is placed at the end of the subsystems. Other advantages of this method over [3] and [5] that it does not require historical load profile data and training the ANN. The direct circuit analysis method is used.

The paper is organized as follow. Section II consists of proposed approach for fault localization method. Section III consists of modeling of system for verification of methodology. Section IV present's fault localization result and discussion. Conclusion and future scope of this research is presented in section V.

II. FAULT LOCALIZATION APPROACH

A. Assumptions

- In distribution system, first, and last nodes should be equipped with synchronized measurement unit. The synchronize measurement unit is such type of intelligent electronic measurement devices, that can transmit data in synchronized time. These devices may be micro phasor measurement unit, power quality meter having capability of transmitting transient data, other some sensors.
- Another end nodes of distribution line should be equipped with non-synchronized time measurement unit. Thus, voltage sag at particular nodes should be compared between actual measured and compared one.
- Distribution line should be equipped with fault point indicator. The fault point indicator measure function is to detect presence of fault in distribution system. Then after fault localization algorithm will run to identify faulted node.

B. Formation of Subsystem of Full Network

Fig 1 illustrates a sample 7-bus distribution system with three branches. This method does not require the optimal placement of measurement units throughout the distribution network. Instead, it necessitates only two synchronized time measurement units, which can be either Phasor Measurement Units (PMUs) or Intelligent Electronic Devices (IEDs) capable of transmitting transient data to a central processing unit. One synchronized time device must be installed at the substation node, while the other can be placed at any end of system. Additionally, non-synchronized time measurement units are required at the endpoints of each subsystem.

As shown in the figure, the entire system must be decomposed into subsystems, each spanning from the source node to the end node. During this decomposition, other branches are neglected to simplify the analysis, enabling the impedance matrix for each subsystem to be determined accurately.

When a fault occurs on line 2-3, all subsystems are affected, as illustrated in Figure 1, even though the fault section is not physically present in subsystems 2 and 3. This occurs because a fault in one branch significantly impacts the electrical parameters of other interconnected branches.

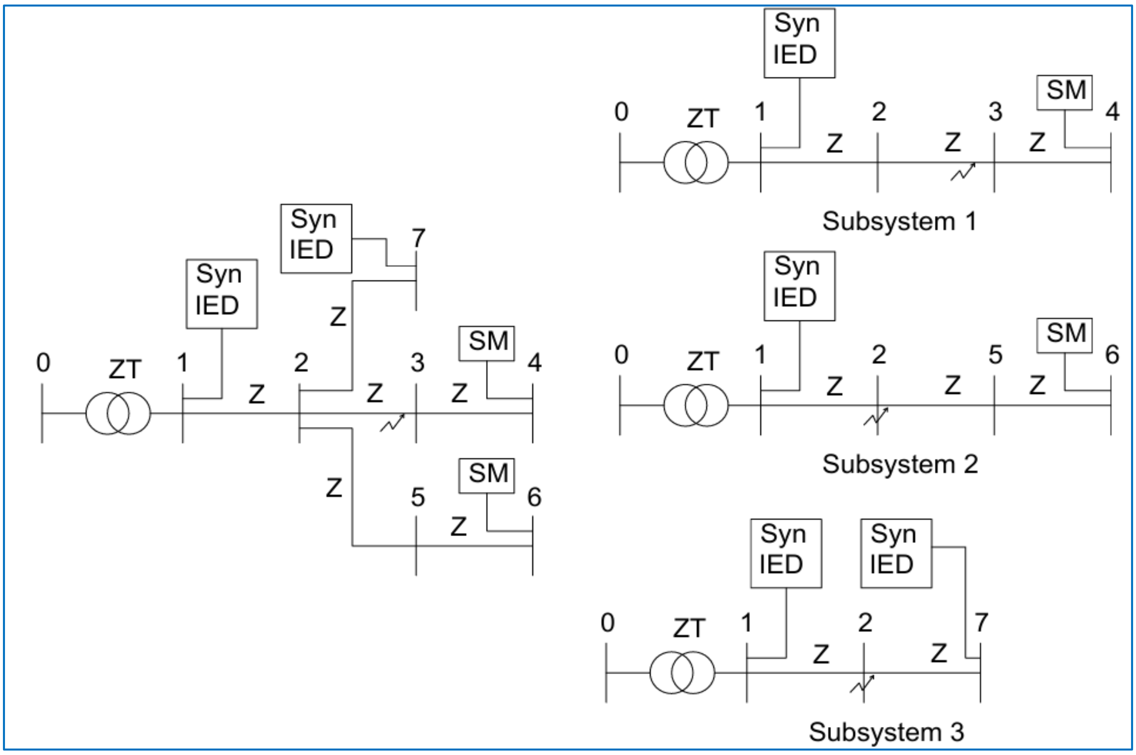


Fig 1: Sample 7 Bus System

C. Fault Current Calculation

During fault current calculation, the magnitude and angle of the pre-fault and during-fault voltages must be known. The fault current I is thus determined using the data obtained from the subsystem equipped with a micro-PMU at its terminal bus.

The voltage sags at buses 1 and 7 are obtained to compose a (6×1) voltage sag vectors. The voltage sag at each bus is calculated by (1), where $v_n^{abc,pf}$ and $v_n^{abc,f}$ represents pre fault and during fault voltages.

$$\Delta V_n^{abc} = \begin{bmatrix} V_n^{a,pf} - V_n^{a,f} \\ V_n^{b,pf} - V_n^{b,f} \\ V_n^{c,pf} - V_n^{c,f} \end{bmatrix} \qquad 1$$

The three-phase impedance matrix of the subsystem 3 is built from the topology [7]. By multiplying inverse of the impedance matrix by the voltage sag vector, a current vector is obtained as described in (2).

$$\begin{bmatrix} i_1^{abc} \\ i_7^{abc} \end{bmatrix} = inv \begin{bmatrix} Z_T & Z_T \\ Z_T & Z_T + 2Z \end{bmatrix}_{6\times 6} * \begin{bmatrix} \Delta V_1^{abc} \\ \Delta V_7^{abc} \end{bmatrix}_{6\times 1} \qquad 2$$

Finally, the fault current is calculated by summing up all its components, as expressed in Equation (3). For different fault types, the fault current exhibits varying characteristics: it has one non-zero element for single-phase faults, two non-zero elements for double-phase faults, and three non-zero elements for three-phase faults.

$$i_f^{abc} = i_1^{abc} + i_7^{abc} \qquad 3$$

The effect of Distributed Generation (DG) is inherently incorporated into this method, as the voltage measurements obtained from the micro-PMU already account for the impact of DG on the system.

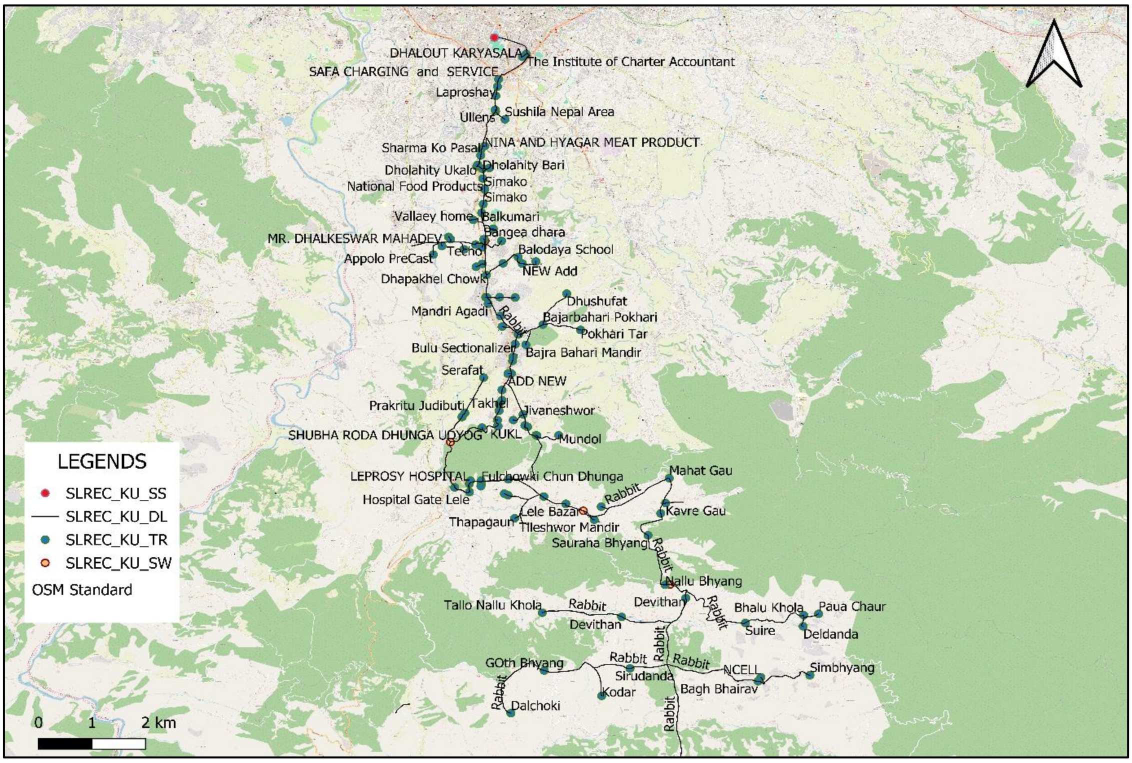
D. Fault Bus Localization

After calculating the fault current using Equation (3) through the subsystem equipped with micro-PMUs, the fault location process is carried out by analyzing the magnitude of the voltage sag at the terminal bus of each subsystem. The voltage sag error, candidate bus error calculation, pin pointing the fault location is adopted similar as [6].

III. MODELING OF SYSTEM

This section provides information about the selected distribution feeder, including the configuration of load centers within the system and the process used for system formation. Additionally, it describes the methods employed for visualizing the results effectively.

A. Distribution Feeder



Fie 2: Chapagaun Distribution Feeder

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Fie 2 illustrates the distribution feeder selected for validation purposes. The feeder comprises a total of 104 load centers. The total length of the distribution feeder, including its laterals, is approximately 110 km, with the longest distance from the substation to a single load center being 36.22 km.

While creating subsystems within the system, branch lengths of up to 700 meters are neglected. This approach is adopted because, in practical implementations, considering smaller branches as subsystems would significantly increase the number of smart meters required, leading to substantial investment in metering units. As a result, a total of 32 subsystems are formed for this validation.

B. OpenDSS System Modeling

The complete distribution system is simulated in OpenDSS to provide pre-fault and during-fault voltages under different loading conditions. OpenDSS allows the export of the full admittance matrix, which accounts for the presence of loads and is further utilized to develop the system's impedance matrix. Similarly, each subsystem is individually simulated in OpenDSS to obtain its admittance matrix, enabling the derivation of the impedance matrix for each phase through appropriate manipulations.

C. Python Manupulation and User Interface

OpenDSS and Python are interfaced using the COM interface, allowing full control of OpenDSS through Python. The admittance matrix for each subsystem is inverted to derive the system's impedance matrix. Pre-fault and fault voltages are computed and stored in variables, which are then used to calculate the fault current and the error between measured and sag voltages. Through this implementation of mathematical computations in Python, the fault-affected buses are identified. Subsequently, the weight matrix is calculated, and the precise fault location is determined. Also, various tests commands are provided form the Python.

Since OpenDSS lacks built-in GIS visualization capabilities, a user interface for displaying fault locations is developed using the Folium [8] package in Python. This process involves identifying the faulted buses through Python computations and linking them to the bus data set used for visualizing the distribution system. When faulted buses are identified, they are marked in red on the GIS map to clearly indicate their locations.

IV. RESULT AND DISCUSSION

A. Fault Localization Users Interface

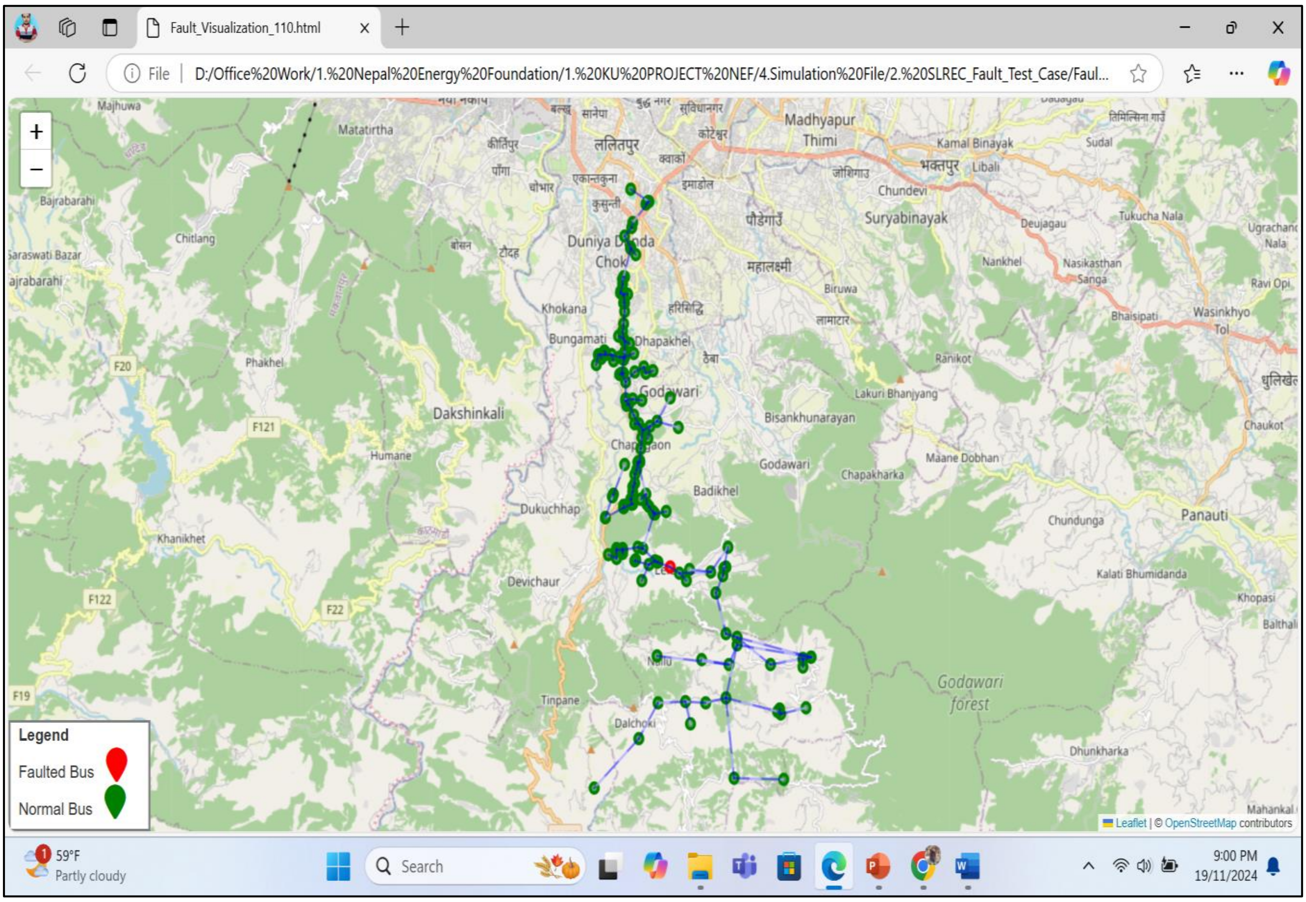

Fig 3: Fault Localization Users Interface

Fig 3 Figure 3 illustrates the developed user interface for identifying faulted points in the distribution system. In this scenario, a fault was simulated at bus number 112, and the calculated fault location was also determined to be at bus 112. This result is displayed in the interface, with the faulted bus highlighted in red to provide a clear visual indication.

Similarly, a total number of 156 node fault was simulated and the result found as satisfactory.

Table 1: Fault Localization Result with Bolted Fault

S.N.	Simulated Distance (km)	Calculated Distance (km)			
		LLLG	LLG	LL	LG
1	1.37	1.37	1.37	1.37	1.37
2	6.13	6.13	6.13	6.13	6.127
3	6.51	5.85	5.85	5.85	5.847
4	8.53	8.53	8.53	8.53	8.533
5	10.85	10.45	10.45	10.45	10.854
6	13.54	13.54	13.54	13.54	13.541
7	15.81	15.15	15.15	15.15	15.146
8	17.93	16.65	16.65	16.65	16.652
9	21.85	21.85	21.85	21.85	21.845
10	24.80	24.80	24.80	24.80	24.8

A bolted fault was simulated at various points along the distribution system, and the results obtained from the program were recorded. Table 1 presents a sample of these results. For instance, in S.N. numbers 3 and 8, deviations of 10.13% and 7.14% were observed, respectively. In most other cases, the error in the calculated fault distances was negligible. The observed deviations were due to the absence of subsystem creation for certain branches, causing faults to be attributed to the beginning of laterals.

B. Impact of Fault Resistances

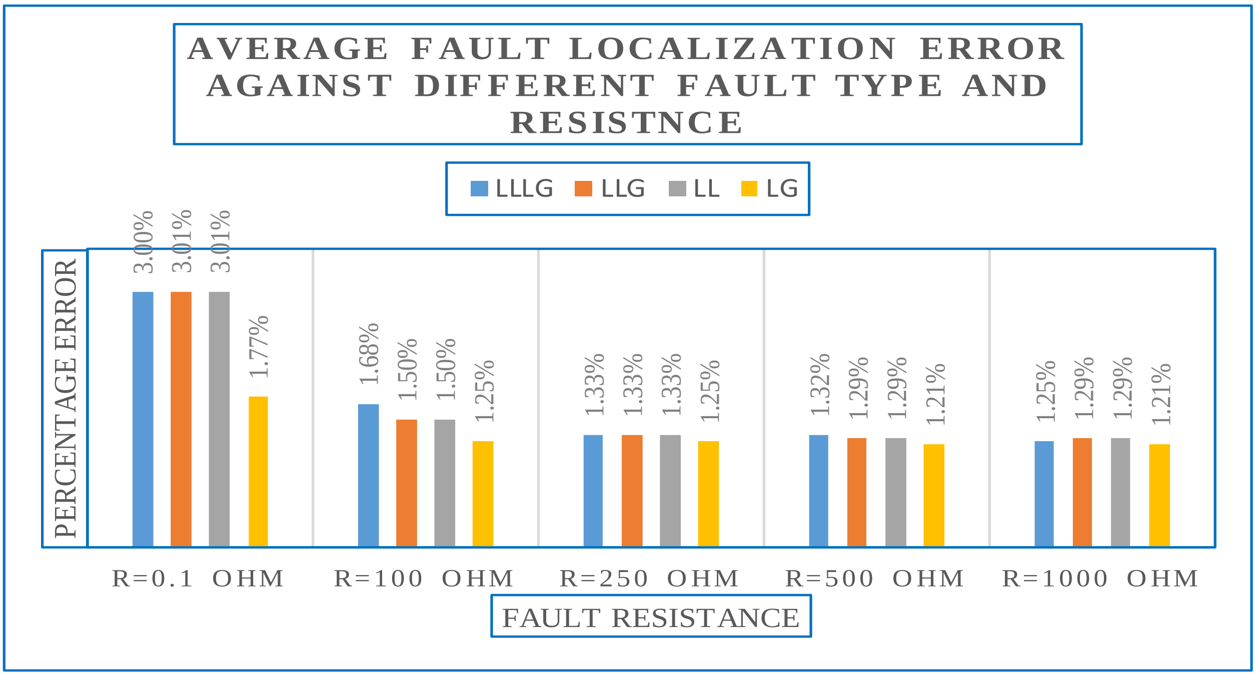

Fig 4: Average Fault Localization Error Against Variation of Resistances

Fig 4 illustrates the impact of fault resistance on the accuracy of fault localization. The maximum error observed was 3.01% in cases of very low fault resistance. When a fault with low resistance occurs, it causes a significant voltage drop in the system, leading to higher localization errors. As the fault resistance increases, the error decreases, with a minimum error of 1.25% observed for higher fault resistance values. This trend highlights the inverse relationship between fault resistance and localization error.

C. Impact of Distributed Generation

Table 2: Accuracy of Developed Approach in Presence of DGs

Resistance	LLLG	LLG	LL	LG
R=0.1 ohm	1.53%	1.46%	1.46%	1.55%
R=100 ohm	1.21%	1.21%	1.21%	1.36%
R=250 ohm	1.37%	1.37%	1.37%	1.36%
R=500 ohm	1.27%	1.37%	1.37%	1.35%
R=1000 ohm	1.27%	1.37%	1.37%	1.35%

Table 2 presents the results obtained in the presence of distributed generators (DGs). Although the current distribution feeder does not include DGs, a DG was hypothetically placed at a random position, such as bus 50, to evaluate the impact of the developed methodology. The inclusion of DGs improved the accuracy of the fault localization results. For instance, in the case of a very low fault resistance of 0.1 ohms, the error reduced significantly from 3.01% to 1.53%, demonstrating the positive influence of DGs on fault localization accuracy.

V. CONCLUSION

The developed fault localization approach has proven to be effective for the Nepalese distribution system, even when faced with challenges such as heterogeneity in network topology, the presence of laterals and multiple load taps, and variations in load. Despite these complexities, the maximum error observed was 3.01% in the absence of distributed generation (DG). The inclusion of DG further enhanced the accuracy, reducing the error to as low as 1.53% under specific scenarios.

One of the most significant advantages of the proposed methodology is its ability to minimize the number of smart meters required, which directly lowers the cost of practical implementation. By leveraging synchronized and non-synchronized measurement devices strategically placed across the network, the approach ensures cost-effectiveness without compromising performance.

These results demonstrate that the methodology is well-suited for application in real-world scenarios, making it a promising solution for enhancing the reliability and efficiency of fault management in Nepalese distribution networks. Future work could explore integrating additional features, such as real-time data analysis and scalability for larger systems, to further improve its effectiveness.

The developed GIS-based user interface significantly aids distribution system operators by providing a clear visualization of fault locations. This tool enhances the efficiency of system restoration, expedites damage repairs, and accelerates fault clearance processes. Its intuitive design allows operators to quickly identify faulted buses and take appropriate corrective actions, ultimately minimizing downtime and improving the reliability of the distribution network.

For future work, we plan to pilot the proposed methodology on an 11 kV distribution feeder to evaluate its performance and effectiveness in reducing system downtime. Additionally, this approach can be extended to identify fault locations using smart meters installed at the household level and distribution transformers, further enhancing the precision and scalability of the fault localization process.

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