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Efficient Fault Localization in Smart Grid Distribution Systems using Smart Discrete Fourier Transform and Dg Sources

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Abstract: *This paper presents an accurate and efficient technique for fault section identification and fault distance estimation in electrical distribution networks operating within a Smartgrid environment integrated with Distributed Generation (DG) sources, including solar and wind farm. Accurate determination of fault locations based on impedance methods relies heavily on the precise calculation of transmission line impedances. Faults occurring on distribution lines pose a significant challenge, as they impact system reliability, service stability, and power quality. Improving the accuracy of fault location greatly simplifies maintenance activities, motivating the development of advanced approaches for precise fault localization. When a fault occurs, it generates a broad range of signals that contain critical information about the fault distance. Fault location algorithms typically process voltage and current phasors measured at both ends of the protected zone. Synchronized sampling of voltage and current at both terminals enables accurate fault distance computation, with the characteristic impedance and propagation constants derived from line parameters. This paper introduces a method based on the Smart Discrete Fourier Transform (SDFT), designed to mitigate system noise and measurement errors. By accurately extracting the fundamental frequency components, the SDFT-based approach enhances the reliability of fault location calculation. Simulation results confirm that the proposed method is effective for distribution networks with DG sources even under conditions of frequency deviation and distortion. All simulations were conducted using MATLAB, and the outcomes demonstrate that the proposed method achieves high efficiency and accuracy across various fault scenarios in typical distribution systems.*

Keywords: Smart Discrete Fourier Transform (SDFT), Smart Grid, Distribution System, Distributed Generation (DG), MATLAB, and Fault Location Estimation.

I. Introduction

High-voltage transmission and distribution lines serve as critical lifelines that ensure continuous delivery of electricity from generation stations to end-users. While service continuity remains a top priority for utilities, faults are inevitable and often lead to service interruptions. This issue is particularly pronounced in distribution networks, where lines are typically overhead and spread across wide geographic areas, exposing them to adverse weather, equipment malfunctions, and external impacts such as vehicular accidents. Identifying the exact location of faults swiftly is essential for utilities to maintain high service reliability.

Although fault location on transmission lines has been extensively studied—primarily due to their balanced operation that supports analysis through symmetrical components-the same cannot be said for distribution systems. Distribution networks are inherently unbalanced because of the combined use of single-phase and three-phase laterals and loads. Consequently, traditional methods, such as symmetrical component analysis, lose effectiveness, and direct three-phase circuit analysis, although possible, becomes cumbersome and computationally intensive. Therefore, research into fault location methods specifically for distribution systems remains relatively limited.

Nonetheless, the growing need for improved service quality and cost-efficiency is making precise fault location increasingly important. Traditional visual inspection methods are time-consuming and labour-intensive, while accurate fault localization significantly eases maintenance, repair, and service restoration. Minimizing downtime reduces customer dissatisfaction, financial losses, and operational costs.

Faults in three-phase systems occur when two or more conductors come into contact with each other or the ground. They are typically classified as single line-to-ground, line-to-line, double line-to-ground, or three-phase faults. Such events expose system components to high mechanical and thermal stresses, risking severe equipment damage and degrading overall power quality. Common causes include lightning strikes, bird activity, wind, snow, ice accumulation, and mechanical degradation of insulators. Statistically, the occurrence of various fault types is distributed approximately as follows:

- Single line-to-ground faults: 70–80%
- Double line-to-ground faults: 10–17%
- Line-to-line faults: 8–10%
- Three-phase faults: 2–3%

Fault events typically manifest as abrupt changes in electrical quantities, including current, voltage, power, impedance, and frequency.

Although significant progress has been made in fault location for transmission systems, the transition from traditional electromechanical and static relays to digital protective devices has further enhanced capabilities through built-in fault recording features. Predominant methods for transmission systems include traveling wave-based, harmonic-based, and impedance-based techniques—each relying on either single-ended or double-ended measurements. While double-ended methods offer superior accuracy, they demand complex communication infrastructure, prompting wider adoption of single-ended techniques augmented by accuracy enhancements.

Distribution systems, due to inherent complexities like unbalanced loading, non-uniform line parameters, and uncertain fault resistances, present unique challenges for fault localization. Nonetheless, the core principle remains the estimation of impedance based on voltage and current measurements, whether using the fundamental frequency component or harmonics. Existing transmission system methods cannot be directly applied, and thus, specialized techniques tailored to distribution systems have been developed. These approaches primarily fall into two categories: impedance-based and traveling wave-based methods.

The transformation of today's conventional electric grid into a highly efficient and resilient Smart Grid necessitates the deployment of advanced computational algorithms, intelligent devices, and communication technologies. A Smart Grid decentralizes the traditional structure into microgrids, each integrating distributed generation (DG) sources. However, integrating DGs introduces new challenges, notably the substantial increase in fault current levels and the risk of islanding—a situation where DGs continue supplying power to a faulted network.

Initiatives by governmental agencies, industry, and research institutions under various programs aim to address these challenges. It will support a diversity of generation sources, ensure high power quality, and maintain market flexibility, while providing consumers with greater empowerment and engagement.

Given the predominance of periodic sine and cosine voltage and current waveforms in power systems under normal conditions, distance relays and fault location algorithms often utilize phasor-based analysis. Even under fault conditions, extracting the fundamental frequency component remains crucial. Phasor measurement techniques, particularly the Synchronized Phasor Measurement (Synchrophasor) technology enhanced by GPS-based timing, now allow for accurate, real-time system monitoring at rates up to 20 samples per second.

However, achieving high accuracy in fault detection, especially in the presence of harmonic distortion and decaying DC components, demands more sophisticated analysis. Traditional Discrete Fourier Transform (DFT) techniques, while widely used, suffer from issues like spectral leakage, limited speed, and sensitivity to harmonics and noise. Although recursive DFT-based filters offer improvements, they can still be adversely affected by DC offsets, resulting in relay maloperations.

To overcome these limitations, a Smart Discrete Fourier Transform (SDFT) method is proposed in this study. SDFT provides rapid and highly accurate frequency estimation even under off-nominal frequency conditions and maintains robustness against harmonics and inter-harmonics. It achieves faster computation while improving fault detection reliability. Simulation results validate the SDFT method's effectiveness for real-time monitoring and protection in modern smart grids.

II. Literature Review

Fault location techniques for power systems have evolved significantly, with many approaches being proposed in recent years. One such method is the Maximum Power Point Tracking (MPPT) technique, which is widely used in photovoltaic (PV) systems to optimize the energy output under varying conditions. MPPT techniques ensure that the PV system operates at its maximum efficiency, especially under variable environmental conditions, such as changing sunlight and temperature. Walker [1] evaluates MPPT converter topologies using a MATLAB PV model. The MATLAB model provides an efficient means for simulating PV systems and optimizing their performance. By evaluating various topologies, Walker's work offers insights into improving the efficiency of energy conversion and provides a foundation for future developments in PV system optimization. Patel and Agarwal [2] further develop an MPPT scheme for PV systems operating under partially shaded conditions, a scenario often seen in large-scale installations. These shaded conditions can result in significant losses in power output. The algorithm developed by Patel and Agarwal uses a modified MPPT scheme that ensures the system remains near the global maximum power point, despite partial shading effects.

In power systems, fault location algorithms are critical for ensuring efficient fault management. Efficient fault location not only aids in reducing system downtime but also improves overall system reliability and safety. Istrate et al. [3] assess fault location algorithms for transmission grids, which are often complex due to the large number of interconnected components. These algorithms are designed to quickly and accurately identify the location of faults, minimizing the impact on the overall system. Luxin and Seung Ho [4] introduce a new method for fault location in distribution systems within a smart grid environment. This method takes advantage of real-time data and modern communication technologies, which are key features of smart grids. The integration of smart grid technologies allows for faster fault detection and more accurate fault location, improving the overall resilience of the power distribution system. Liu et al. [5] apply synchronized phasor measurements for fault location in two-terminal multi-section compound transmission lines. Phasor measurements provide real-time information on the system's electrical parameters, enabling fault location with higher precision and reliability. Similarly, Sadeh et al. [6] propose a nodal analysis-based fault location algorithm for radial distribution systems, which can handle various fault conditions. The algorithm's ability to process different types of faults makes it highly adaptable to a range of operational scenarios, which is crucial for managing the diverse fault conditions that can occur in radial distribution systems.

Choi et al. [7] present a direct circuit analysis-based method for fault location in distribution systems. This method is particularly useful for systems with complex configurations, where traditional fault location techniques may not be as effective. By analyzing the circuit directly, Choi et al. provide a more flexible and robust approach that can be applied to a variety of distribution network structures. Chen et al. [8] use the half-cycle Discrete Fourier Transform (DFT) method to locate sub-cycle faults in distribution networks. The DFT method is known for its ability to quickly process fault signals, allowing for the detection of transient faults that may not be immediately apparent through traditional analysis. This is particularly important in distribution networks, where transient faults can often go undetected but can still cause significant disruptions. Patil and Singh [9] explore synchrophasor measurement techniques for fault location analysis on transmission lines. Synchrophasor measurements provide highly accurate time-synchronized data, which is essential for determining the exact fault location in transmission lines. Patil and Singh's work highlights the advantages of using synchrophasor data, which provides enhanced visibility and real-time monitoring capabilities. Sadhu et al. [10] investigate superconducting fault current limiters for microgrid applications. The integration of superconducting fault current limiters (SFCLs) in microgrids has the potential to significantly improve fault management by limiting the magnitude of fault currents, preventing damage to sensitive equipment, and improving the overall stability of the system.

Several approaches rely on the comparison of simulation models and real-world measurements. Nouri et al. [11] compare ATP simulations and microprocessor-based fault location using DFT. ATP simulations are commonly used for power system studies, and by comparing them with real-world microprocessor-based fault location systems, Nouri et al. provide insights into the effectiveness of fault location algorithms in practical applications. The comparison also highlights potential discrepancies between theoretical models and real-world systems, which can be crucial for improving the accuracy and reliability of fault location techniques. Hinge and Dambhare [12] focus on ground fault location using synchrophasors. Ground faults are one of the most common types of faults in power systems, and their detection is essential for maintaining system stability. By using synchrophasors, Hinge and Dambhare improve the precision of ground fault location, allowing for faster identification and isolation of faults. Chen and Tang [13] examine the optimal allocation of flux-coupling-type superconducting fault current limiters (SFCLs) for microgrids with wind-PV hybrid generation and battery storage. This study explores how SFCLs can be strategically placed in microgrids to enhance fault protection while integrating renewable energy sources and energy storage systems. The use of hybrid systems, which combine wind and solar power with battery storage, presents unique challenges in fault detection and location, making the role of SFCLs even more critical.

In real-time fault detection, Costa et al. [14] evaluate impedance-based fault location algorithms. Impedance-based techniques are commonly used for fault location in transmission lines and have the advantage of being relatively simple and cost-effective. Costa et al. evaluate the performance of these algorithms under various fault conditions, providing valuable information on their accuracy and reliability. The IEEE standard C37.114™-2014 [15] provides guidelines for determining fault location on AC transmission and distribution lines. This standard offers a comprehensive framework for fault location, which is widely accepted and used in the power industry. The standard provides a common reference for engineers and researchers, helping to ensure consistency and accuracy in fault location methods. Aly and El-Sayed [16] propose a smart grid fault detection and classification method based on multi-distributed generation. The increasing integration of distributed generation in smart grids introduces new complexities in fault detection. Aly and El-Sayed's method takes into account the various types of distributed generation, improving the accuracy of fault classification and detection. Zhang et al. [17] discuss fault detection and classification of short-circuit faults in distribution networks using a Fortescue approach and Softmax regression. Short-circuit faults are among the most severe faults in distribution networks, and the ability to quickly detect and classify them is critical for minimizing their impact. The Fortescue approach, combined with machine learning techniques like Softmax regression, enhances the system's ability to accurately detect and classify short-circuit faults, leading to faster response times and reduced damage.

Recent studies continue to explore advanced fault detection and resilience in smart grids. Kulkarni et al. [18] review grid resiliency and islanding detection methods. Grid resiliency is a key concern in modern power systems, particularly with the increasing number of distributed energy resources. Kulkarni et al. discuss various methods for detecting and mitigating islanding, a situation where a portion of the grid becomes electrically isolated from the rest of the system, often due to faults. Islanding detection is essential for preventing damage to equipment and ensuring system stability. Sharma and Verma [19] propose an SDFT-based fault detection technique for distribution systems in smart grids with distributed generation. The SDFT (Synchronized Discrete Fourier Transform) method provides high-resolution fault detection, particularly in systems with distributed generation, where the traditional fault detection methods may not be as effective. Li et al. [20] introduce an adaptive fault detection method based on belief rule base for smart grids. The belief rule base approach incorporates expert knowledge into the fault detection process, allowing the system to adapt to different fault conditions and improve detection accuracy.

Additional works on islanding detection and smart grid management have been proposed to examine fault location techniques, fault detection parameters, and methods for reducing fault location time through component reliability. These works highlight the importance of improving fault detection in the context of the growing complexity of modern power systems, particularly with the integration of renewable energy sources. Renewable energy integration in smart grids, emphasizing the need for efficient fault location and detection techniques in systems that incorporate a high proportion of renewable energy sources. The variability and intermittent nature of renewable generation, such as wind and solar power, present challenges for fault detection and location, making it essential to develop new methods that can account for these uncertainties. Energy storage systems, such as batteries and flywheels, play a crucial role in stabilizing microgrids and ensuring reliable power supply during faults. Smith et al. explore how energy storage can be integrated with fault detection and management systems to enhance the resilience of microgrids.

For comprehensive energy storage and fault management, Sukhatme [21] offers a detailed examination of solar energy principles and thermal storage solutions. Solar energy and thermal storage have significant potential for improving grid reliability and fault management, particularly in regions with high solar resource availability. Sukhatme's work emphasizes the role of thermal storage systems in balancing supply and demand during fault events and in enhancing overall system resilience.

III. SDFT and The Fault Localization Technique

A. Smart Discrete Fourier Transform (SDFT)

SDFT is an advanced signal processing technique developed to improve the accuracy of frequency and phasor estimation, especially under conditions where the signal frequency deviates from its nominal value. Initially, SDFT follows the same basic steps as the conventional DFT, thereby retaining advantages like efficient recursive computation. In the conventional method, small deviations in frequency are often neglected, which introduces errors in the calculation of the signal's frequency and phase. However, SDFT addresses this by incorporating additional terms that account for these deviations, ensuring greater precision.

SDFT operates by sampling the input signal at a higher rate, analysing the samples, and expressing the signal in phasor form. When the frequency of the input signal deviates, the conventional DFT method approximates results, leading to inaccuracies. SDFT refines this by considering the effects of both the fundamental component and its conjugate, capturing the real behaviour of the signal more accurately. Through careful manipulation of the recursive relations between consecutive Fourier coefficients, it derives an exact expression for the frequency deviation.

Moreover, SDFT can estimate the exact phasor once the accurate frequency is determined. This method also extends to scenarios where harmonics are present in the input signal. In such cases, additional recursive equations are established, allowing SDFT to simultaneously handle the fundamental and harmonic components. By solving a system of multiple equations, SDFT can extract precise information about the signal even in distorted environments. Overall, SDFT significantly enhances the reliability of signal analysis, making it particularly useful in applications where small frequency deviations and harmonic distortions cannot be ignored [19].

B. Fault Location Method

The proposed fault locator integrates a SDFT based approach, a line parameter estimation algorithm, and a robust fault location index. An SDFT algorithm is developed to process voltage and current measurements obtained from both ends of the transmission line. To validate the effectiveness of the fault location technique, simulated voltage and current waveforms are treated as synchronized samples from the sending and receiving terminals. The SDFT method is then employed to accurately extract the fundamental phasors of these signals. Following this, the estimation of line parameters is carried out, enabling the generation of accurate modal components necessary for calculating the fault location index.

This method is versatile, capable of fault location in both transmission and distribution networks. Its recursive nature makes it particularly well-suited for real-time monitoring applications. Figure 1 illustrates a single-circuit, transposed transmission line model, where the total line length between the sending (S) and receiving (R) buses is denoted as L, and the synchronized voltage and current phasor measured on sending and receiving end buses are V_s, I_s, V_R, and I_R, respectively [5].

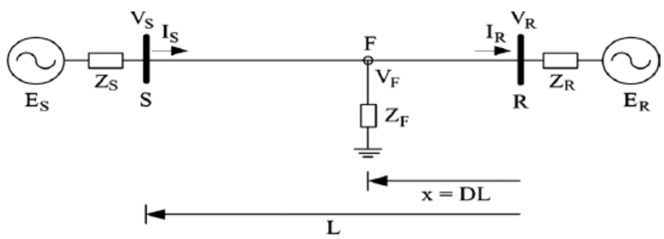

Figure 1: Line with a fault [5].

The relation between the voltages and currents at a distance x away from bus R can be expressed by the following sequence equations,

$$\frac{dV}{dx} = Z\,I \quad (1)$$

$$\frac{dI}{dx} = Y\,V \quad (2)$$

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where, Z and Y are the per-unit length sequence impedance (Ohm/km) and admittance (Mho/km) of the transmission line, respectively.

The synchronized voltage and current phasors measured at the respective ends are represented as [5],

$$V_{xi} = [\, A_i \exp(\tau_i x) + B_i \exp(-\tau_i x) \,] \quad (3)$$

$$I_{xi} = \frac{1}{Z_{Ci}} [\, A_i \exp(\tau_i x) - B_i \exp(-\tau_i x) \,]$$
(4)

where, $Z_{Ci} = \sqrt{\frac{Z_i}{Y_i}}$ denotes the characteristic impedance, and $\tau_i = \sqrt{Z_i Y_i}$ is the propagation constant. The constants A_i and B_i can be obtained by the boundary conditions of voltages and currents measured at bus R and bus S, respectively. Therefore, voltage (3) can be further rewritten as [5],

$$V_{xi,R} = \frac{(V_{xi,R} + Z_{Ci} I_{i,R})}{2} e^{\tau_i x} + \frac{(V_{xi,R} - Z_{Ci} I_{i,R})}{2} e^{-\tau_i x}$$
(5)

$$V_{xi,S} = \frac{1}{2} e^{-\tau_i L} (V_{i,S} + Z_{Ci} I_{i,S}) e^{\tau_i x} + \frac{1}{2} e^{\tau_i L} (V_{i,S} - I_{i,S}) e^{-\tau_i x}$$

(6)

A fault is assumed to occur at point F with a distance x = DL km away from the receiving end R on a transmission line shown in Fig. 3, where D is termed as the per-unit fault location index. Using the relationship $V_{F,R} = V_{F,S}$ and equating (5) to (6), the index can be solved as follows [5],

$$D = \frac{\ln\left(\frac{N}{M}\right)}{2\tau L}$$
(7)

Where M and N are given by,

$$M = \frac{1}{2} (V_S + Z_C I_S) e^{-\tau L} - \frac{1}{2} (V_R + Z_C I_R)$$
(8)

$$N = \frac{1}{2} (V_R - Z_C I_R) - \frac{1}{2} (V_R - Z_C I_S) e^{\tau L}$$
(9)

The index D typically lies between 0 and 1 for faults occurring along the line section between buses S and R. In cases of no fault or external faults, D becomes undefined. Notably, the derivation of D does not depend on assumptions about source impedance, load variations, fault resistance, fault inception angle, or fault type, enhancing the method's robustness.

The accuracy of fault location estimation is quantified by the percentage error calculated as [5],

$$\text{Error (\%)} = \frac{|\text{Estimated location in km} - \text{actual location in km}|}{\text{Total line length in km}} \times 100$$

IV. Modelling, Simulation and Results

The power system model is developed and implemented using MATLAB/Simulink along with its SimPowerSystem toolbox. This platform was chosen due to its distinct advantages over other contemporary simulation tools. A comprehensive smart grid network was modeled, covering generation, transmission, and distribution systems, and incorporating both a wind farm and a solar farm. Figure 2 illustrates that microgrid integrates a 6 MVA wind farm and a 300 kW solar farm within the system. The overall setup includes a conventional 100 MVA grid connected through a 132 kV transmission line extending 200 km, and a distribution network at 33 kV which is divided into several sections for fault localization purpose.

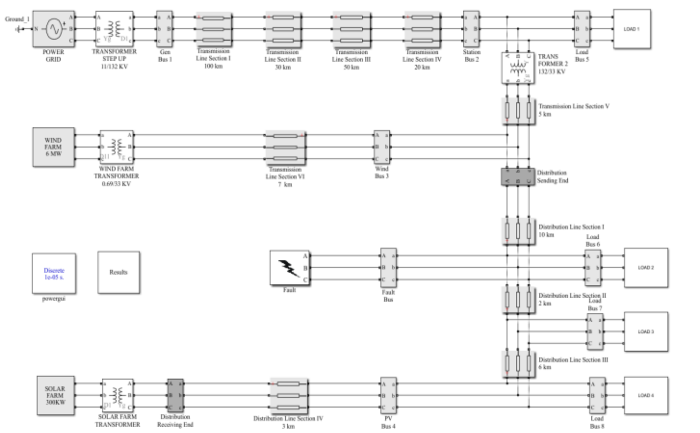

Figure 2: MATLAB / Simulink model with DG sources, transmission and distribution network with SDFT based fault localization [22].

The simulation outcomes, summarized in Table 1 and evaluated using the error metric defined, cover various fault types including three-phase faults (ABC), three-phase-to-ground faults (ABC-G), double-line-to-ground faults (AB-G), and single line-to-ground faults (A-G) at multiple distances. The estimation errors ranged from -0.2864% to 1.5269%, with the minimum error recorded at 0.2864%, which is effectively negligible. These results confirm that the proposed method offers a highly reliable approach to fault location in transmission networks.

Table 1: Estimated Distribution Line Fault Locations from Sending End and Corresponding Percentage Errors for Various Fault Types.

Distance (Actual) km	ABC (SC) fault distance localized (km)	Error (%)	ABC-G fault distance localized (km)	Error (%)	A-G fault distance localized (km)	Error (%)	AB-G fault distance localized (km)	Error (%)
0	00.2806	1.3361	000.2806	1.3361	0.1028	0.4897	0.1282	0.6107
10	10.0999	0.4755	10.0999	0.4755	10.2368	1.1277	10.2012	0.9580
12	12.1118	0.5322	12.1118	0.5322	12.2520	1.1999	12.2320	0.9632
18	18.1152	0.5486	18.1152	0.5486	18.3207	1.5269	18.2031	0.9673
21	20.9398	-0.2864	20.9398	-0.2864	20.9021	-0.4662	20.8565	-0.6835

V. Conclusion

In this paper, a fault location method for smart grids incorporating distributed generation (DG) sources has been presented. Unlike conventional approaches, the proposed fault location index operates without relying on prior assumptions, resulting in a highly robust and versatile solution. Additionally, a parameter estimation technique and a specialized filtering method based on the SDFT have been formulated to enhance fault location accuracy.

Extensive MATLAB-based simulations were carried out to rigorously assess the performance of the proposed scheme under a variety of fault conditions. The SDFT-based filtering technique demonstrated superior capability in accurately extracting the system's true frequency and fundamental phasors, which directly contributes to improving fault location precision. In numerous simulation scenarios, the method achieved fault location accuracies reaching around 99%. By integrating the robust fault index, parameter estimation algorithm, SDFT filtering method, and standard calculation method, the overall system emerges as a high-performance fault localization solution.

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