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COMPARATIVE ANALYSIS OF TRANSFORMATION-BASED FAULT DETECTION TECHNIQUES IN RENEWABLE ENERGY-INTEGRATED DISTRIBUTION NETWORKS

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Abstract: Faults in transmission and distribution networks can significantly affect the reliability, stability, and continuity of electrical power supply, potentially resulting in service interruptions and large-scale blackouts. Rapid fault detection, accurate fault classification, and precise estimation of fault location are therefore essential for improving power-system protection, reducing restoration time, and enhancing network reliability. The increasing integration of renewable energy sources, such as solar photovoltaic and wind energy systems, introduces distributed generation (DG) into conventional distribution networks and significantly changes their electrical characteristics and fault behavior. The bidirectional power flow, variable generation, and altered fault-current characteristics associated with DG can also influence the performance of conventional protection and fault-detection schemes. This paper presents a comparative analysis of transformation-based fault detection techniques for renewable energy-integrated distribution networks. Various signal transformation methods are investigated for extracting significant time-domain and frequency-domain characteristics from electrical signals during normal and fault conditions. The study considers the applicability of transformation techniques for detecting and distinguishing different types of power-system faults under changing network conditions. The extracted features are further analyzed using suitable decision-based fault detection approaches to improve the identification of fault events. The comparative evaluation highlights the capabilities and limitations

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of the investigated transformation techniques in terms of fault detection accuracy, sensitivity, and suitability for renewable-integrated distribution systems. The study demonstrates that transformation-based signal analysis can provide an effective approach for reliable and rapid fault detection in modern distribution networks with distributed renewable energy generation.

Keywords: Distribution Network; Hilbert Transform; Power Quality; Solar Energy; Stockwell Transform; Rule Based Decision Tree; Wind Energy.

I. INTRODUCTION

Faults are unavoidable in modern electrical power systems and can adversely affect system performance, equipment efficiency, and overall network reliability. In severe cases, faults may result in equipment damage, service interruptions, or even widespread power outages. Faults can arise due to various factors, including external disturbances, component degradation, insulation failure, and abnormal variations in electrical signals [1]. Consequently, rapid fault detection, accurate fault classification, and precise fault-location estimation are essential for maintaining the reliability and stability of power networks. Fault detection and localization in overhead power transmission and distribution lines have been extensively investigated over the years. Fault diagnosis in power systems involves the detection of fault occurrence, identification of the fault type and affected phase, and estimation of the fault location. Several signal-processing and intelligent techniques, including wavelet transform (WT), artificial neural networks (ANNs), and fuzzy-logic-based methods, have been widely employed for power-system fault detection, classification, and localization [2]. A comprehensive survey of intelligent-system applications for fault diagnosis in electric power transmission networks was presented in [3], highlighting the importance of intelligent techniques in improving the reliability and accuracy of fault detection. In [4], an alternative fault-location algorithm for multi-terminal transmission lines was proposed using synchronized measurements. A data-synchronization protocol was developed to identify the faulted section before estimating the fault location. The proposed algorithm was designed to be less sensitive to variations in fault resistance and source impedance. Its performance was evaluated under different major fault conditions and high fault-resistance scenarios. The results demonstrated that the proposed multi-terminal fault-location algorithm provided

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fast and accurate fault-location estimation while maintaining robustness against power-system transients. In [5], a wavelet-transform-based method was proposed for the detection, classification, and localization of transmission-line faults. Voltage and current signals measured at both ends of the transmission line were synchronized using a Global Positioning System (GPS) clock. Information coefficients derived from the current signals at both ends were used to determine fault indices. These indices were compared with predefined threshold values for fault detection and classification. Artificial neural networks were subsequently employed for fault-location estimation using approximate wavelet decompositions of the voltage and current signals measured at the local end. The results demonstrated the effectiveness of combining wavelet-based signal processing with artificial intelligence for transmission-line fault analysis.

The increasing integration of distributed generation (DG), particularly renewable energy sources, has introduced significant changes in the operating characteristics of modern distribution networks. DG units can alter power-flow patterns, fault-current levels, and the overall electrical behavior of distribution systems. Consequently, their integration can significantly influence the performance of conventional protection and fault-detection equipment. Since the number, location, and operating conditions of DG units can vary considerably, the protection requirements of distribution networks become more complex. Therefore, conventional fault-detection techniques may require modification or enhancement to maintain reliable operation in DG-integrated networks [6].

These developments highlight the need for reliable and computationally efficient fault-detection techniques capable of operating under the changing conditions of modern distribution networks. In particular, signal-transformation-based techniques provide useful time-domain and frequency-domain information from transient electrical signals and can therefore support the rapid identification and classification of faults. A comparative analysis of such transformation-based techniques is consequently important for evaluating their suitability for renewable-energy-integrated distribution networks.

Faults in Power Systems

Faults in power systems are undesirable electrical disturbances that can cause abnormal operating conditions, equipment damage, protective-device operation, and interruption of power supply over a localized or wide area. Power-system faults are broadly classified into symmetrical faults and unsymmetrical faults.

In a symmetrical fault, the currents and voltages in all three phases are affected equally, and the system remains electrically balanced during the fault condition. In contrast, an unsymmetrical fault produces unequal changes in the voltages and currents of the three phases, resulting in an unbalanced system. During an unsymmetrical fault, the currents in the three phases are generally unequal, and their phase-angle relationships are also altered. Although the fault causes an unbalanced condition, the source voltages and the principal system elements, such as generators, transformers, and transmission lines, are normally considered symmetrical under healthy operating conditions.

Unsymmetrical faults can occur in the following forms:

Single Line-to-Ground Fault (SLG): This fault occurs when one phase conductor comes into contact with the ground. It is one of the most common types of faults in power systems.

Double Line Fault (LL): This fault occurs when two phase conductors come into contact with each other without involving the ground.

Double Line-to-Ground Fault (LLG): This fault occurs when two phase conductors simultaneously come into contact with each other and the ground.

The symmetrical faults generally include the following:

Three-Phase Fault (LLL): All three phase conductors are simultaneously involved in the fault, producing balanced fault currents.

Three-Phase-to-Ground Fault (LLLG): All three phase conductors are simultaneously connected to ground. This is also a symmetrical fault because the three phases are affected equally.

Among these fault types, unsymmetrical faults occur more frequently in practical power systems, whereas symmetrical three-phase faults are generally more severe in terms of fault-current magnitude. Therefore, rapid detection and accurate classification of different fault types are essential for reliable power-system protection and operation.

II. LITERATURE REVIEW

Chothani et al. (2026) [7] proposed a wavelet transform-based approach for fault detection and classification in transmission lines. The study employed a bi-orthogonal 5.5 wavelet for signal decomposition and analyzed detailed coefficients to distinguish faulted phases from healthy phases. A 400 kV transmission system with a 300 km transmission line was modeled in MATLAB to evaluate the proposed method. Faults were identified using carefully selected threshold values, and the performance was compared with conventional FFT, DFT, and Stockwell Transform-based approaches. The method was tested under different operating conditions, including current inversion, CT saturation, nonlinear MOV effects, series compensation, fault resistance, and fault location. The results demonstrated that the proposed bi-orthogonal wavelet-based technique could effectively detect and classify different fault conditions with good reliability and robustness. However, the study mainly considered a conventional transmission-line model, while systems with high penetration of inverter-based renewable energy sources such as solar and wind were identified as an area for future investigation.

Xiao et al. (2026) [8] developed a multistage fault-diagnosis framework for smart distribution networks using an adaptive multiresolution Stockwell Transform (MST) and a MCNN. The adaptive MST was first used to detect the initiation and recovery times of feeder faults. The resulting fault waveforms were then converted into two-dimensional feature images using equal-interval sampling. A modified CNN with a parallel network structure was subsequently employed for fault classification. The proposed approach was validated using both simulated IEEE-system data and field data obtained from a practical power system. The average fault-detection accuracy reached 94.8%, while the 10-fold cross-validation accuracy of the MCNN model was 97.3% for simulation data and 95.6% for field data. The results demonstrated that the combination of adaptive MST and MCNN provides accurate and efficient fault detection and classification. The study also highlighted the importance of data augmentation techniques for improving the generalization capability of deep learning-based fault-diagnosis models.

Anwar et al. (2025) [9] proposed a ML based approach for fault detection and classification in transmission lines using voltage and current measurements. The study evaluated several ML algorithms, including RF, KNN and LSTM networks. An ensemble approach combining RF,

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LSTM, and tuned KNN was developed to improve classification performance. The proposed ensemble model achieved an accuracy of approximately 99.96% for multi-label fault classification, outperforming individual RF and KNN models. For binary classification, KNN and RF also achieved high accuracies of approximately 99.85% and 99.72%, respectively. Confusion matrices and ROC curves were used to further evaluate model performance. The study demonstrated that combining conventional machine learning with deep learning techniques can significantly improve the accuracy and robustness of power-system fault classification. However, the approach primarily focused on machine learning-based classification and provides scope for further investigation under changing network configurations and renewable-energy penetration conditions.

Rao et al. (2025) [10], proposed a DWT-DNN based approach for fault detection and classification in hybrid renewable-energy-based, multi-area grid-connected microgrids. The DWT was used to extract relevant features from current signals measured at the point of common coupling, and the extracted features were subsequently provided as inputs to a DNN for fault detection and classification. The proposed method was implemented in MATLAB/Simulink 2022a and its performance was compared with the Wavelet Packet Transform (WPT). The results showed that the DNN-based approach provided better fault-detection and classification performance than the WPT-based method. The study also examined the effects of network architecture and data augmentation on classification accuracy. However, the authors identified feature extraction, data preprocessing, and real-time implementation as major challenges. Future improvements were suggested through optimized feature selection, parameter tuning, and hybrid machine learning approaches.

Bhaumik et al. (2025) [11], developed a fault detection and classification method for renewable-energy-integrated standalone microgrids. The proposed method used only current signals obtained from the generator buses of the microgrid. A DWT was applied up to the ninth decomposition level, and the detailed and approximate coefficients were used to generate kurtosis-based features for fault detection. PCA was employed for dimensionality reduction, while a SVM was used to classify different fault types. The proposed approach was implemented and evaluated using PSCAD simulations under different fault conditions and renewable-generation variations. The results demonstrated that the method could detect and classify faults effectively while remaining relatively independent of fault location and partial fault impedance. The study highlighted the potential of DWT-based feature extraction combined with PCA-SVM for fast and reliable fault diagnosis in renewable-energy-based microgrids.

Saiprakash et al. (2024) [12], proposed a Stockwell Transform (ST) and ML based approach for fault detection and classification in photovoltaic (PV) array systems. The Stockwell Transform was used to extract time-frequency features from PV operational signals, enabling the identification of fault-related characteristics. Different machine learning algorithms, including SVM, DT, RF and KNN, were evaluated for fault classification. The proposed method was tested for different PV faults, including short-circuit, open-circuit, partial-shading, and degradation conditions. The ST-RF approach achieved an accuracy of 99.61% for simulation data, while an accuracy of 98.12% was obtained using experimental data. The method also demonstrated good performance under noisy conditions. The study concluded that combining Stockwell Transform-based feature extraction with machine learning provides an effective and reliable solution for early fault detection and classification in PV systems.

Bhagwat et al. (2024) [13], developed a customized CANN architecture by integrating the up-pyramid and down-pyramid structures of conventional neural networks into a unified custom-pyramid model. Fault-related transient signals generated from a reconfigured IEEE 33-bus distribution system were processed using spectral kurtosis to extract relevant features. These features were subsequently supplied to the CANN for simultaneous identification of fault type and location. The proposed approach achieved 95.43% accuracy in fault-location identification and 96.08% accuracy in fault-type classification. The findings further indicated that selecting a reduced set of significant input features can lower the computational burden while maintaining satisfactory classification performance. However, the model showed lower performance for certain fault locations and fault types and was found to be application-specific. The authors suggested using larger datasets, real-system data, and further model optimization to improve the generalization and reliability of the proposed approach.

Gogula et al. (2023) [14], presented a DWT-NNRBF based method for detecting high-impedance faults in power systems integrated with solar photovoltaic and wind generation. An IEEE 13-bus distribution system was modeled in MATLAB/Simulink to represent the renewable-energy-integrated network. The three-phase current signals were decomposed using the Daubechies-4 (db4) mother wavelet, and the resulting detail and approximation coefficients were analyzed to extract fault-related features. The maximum wavelet coefficients were then provided as inputs to the Radial Basis Function Neural Network for fault detection. The proposed method was evaluated under different operating conditions, including normal operation, transformer inrush current, load switching, capacitor switching, and different fault types such as LG, LL, LLG, LLLG, and high-impedance faults. The simulation results demonstrated that the proposed approach could reliably detect high-impedance faults and remained relatively insensitive to variations in fault type, fault initiation angle, and transition resistance. The study demonstrated the effectiveness of combining wavelet-based signal analysis with neural networks for fault detection in renewable-energy-integrated distribution systems.

Gupta et al. [15], proposed a hybrid protection scheme for utility grids with high penetration of wind and solar energy. The proposed method was tested on an IEEE 13-bus system with 50% renewable-energy penetration under different fault impedances, fault occurrence angles, fault locations, and noise conditions. The results showed that the method effectively detected and classified faults and distinguished fault events from switching operations. The proposed approach achieved lower maximum and mean detection errors of 1.89% and 0.978%, respectively, compared with the alienation coefficient-based method. The study demonstrated the effectiveness of hybrid signal-processing techniques for reliable fault protection in renewable-energy-integrated power systems.

Mahela et al. (2022) [16], proposed a hybrid protection scheme for fault detection and classification in renewable-energy-integrated hybrid power systems. The method combines WDF and ST based fault indices to develop a HFI. The proposed scheme was tested for SPG, TP, TPG, and APG faults under different conditions, including noise, fault impedance, fault location, fault incidence

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angle, overhead and underground lines, and transformer operation. The results showed that the proposed method could accurately identify and classify faults within approximately one-quarter of a cycle and effectively distinguish faults from switching events. It also demonstrated better performance and faster detection than conventional WESE-, DWT-, and ST-based protection schemes.

III. STOCKWELL TRANSFORM METHOD

The Stockwell transform is a hybrid of the short time Fourier transform and the wavelets (WT), but it belongs to a different family of transforms. In 1996, R. G. Stockwell was the first to suggest this method. This method analyses multi-resolution signals with disturbances while keeping the phase of the each frequency variable in the signal. The frequency of this technique is proportional to the length of the window used. As a result, obtain higher time resolution at higher frequencies while also providing higher frequency resolution at low frequency is extremely beneficial.

The short time Fourier Transform of a signal h is defined by the following relationship (t).

$$STFT(\tau,f)=\int_{-\infty}^{+\infty}h(t)g(\tau-t)e^{-j2\pi ft}dt \quad (1)$$

Where spectral localization time and Fourier frequency are denoted by τ and f, respectively, and g(t) is a window function. The S transform can be derived from the above equation by substituting the Gaussian function for the window function g(t).

$$g(t)=\frac{|f|}{\sqrt{2\pi}}e^{-\frac{f^2t^2}{2}} \quad (2)$$

& S-Transform is defined as:

$$S(\tau,f)=\int_{-\infty}^{+\infty}h(t)\frac{|f|}{\sqrt{2\pi}}e^{\frac{f^2(\tau-t)^2}{2}}e^{-j2\pi ft}dt \quad (3)$$

The S transform is thus a variant of the STFT with a Gaussian window function. If the time domain window of the S-transform is larger, it can provide higher frequency resolution for lower frequencies. Even though the window is smaller, it can provide better time resolution for higher frequencies. The S-transform produces an S-matrix, which is a matrix. The S-matrix can be used to extract knowledge about the signal's frequency and amplitude.

IV. CONCLUSIONS

This study presented a comparative analysis of transformation-based fault detection techniques for renewable-energy-integrated distribution networks. The increasing penetration of distributed generation, particularly solar and wind energy, changes the operating

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characteristics, power-flow patterns, and fault-current behavior of distribution systems, thereby creating challenges for conventional protection and fault-detection techniques. The review and analysis of existing techniques indicate that signal-transformation methods such as Wavelet Transform (WT), Stockwell Transform (ST), and other time-frequency analysis techniques can effectively extract transient characteristics associated with power-system faults. Wavelet-based approaches have demonstrated good performance in fault detection and classification, particularly when combined with artificial intelligence techniques such as neural networks, support vector machines, and decision-based classifiers. Similarly, Stockwell Transform provides useful time-frequency information while maintaining phase information and offering high time resolution at higher frequencies and improved frequency resolution at lower frequencies.

The comparative studies reviewed in this work demonstrate that transformation-based techniques can successfully identify different fault conditions, including single line-to-ground, line-to-line, double line-to-ground, and three-phase faults. Hybrid approaches that combine signal transformations with machine-learning or decision-based methods have also shown promising performance under variations in fault location, fault resistance, noise, switching conditions, and renewable-generation operating conditions. Among the investigated approaches, the Stockwell Transform is particularly attractive for modern distribution networks because of its localized time-frequency representation and its ability to characterize transient disturbances. Its S-matrix provides valuable information regarding the frequency and amplitude characteristics of electrical signals, which can be utilized for fault identification and classification. Overall, the study establishes that transformation-based fault-detection techniques provide an effective foundation for improving the speed, reliability, and sensitivity of fault identification in renewable-energy-integrated distribution networks. However, the performance of individual techniques depends on network configuration, renewable-energy penetration, fault characteristics, noise, and operating conditions. Therefore, the development of robust hybrid transformation-based methods, combined with intelligent decision-making techniques, can provide further

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improvements in the reliable protection and monitoring of modern distribution power systems.

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