Fault Detection in Transmission Lines of Grid-Connected Power Systems Using Empirical Mode Decomposition

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ABSTRACT

In power system engineering, transmission lines play a crucial role in delivering electricity from generation stations to various distribution units. They serve as the essential link between power producers and end users. Since these lines are often exposed to outdoor conditions, they are more susceptible to faults. Detecting and addressing these faults quickly is vital to ensure the reliable and continuous operation of the power system.

To tackle such disturbances, advanced signal processing techniques like Discrete Wavelet Transform (DWT) and Empirical Mode Decomposition (EMD) are employed for fault detection and analysis. DWT is particularly effective in analyzing fault transients, as it provides insights into both the time and frequency characteristics of the signal. On the other hand, EMD is used to break down the voltage signals of transmission lines into a series of components known as Intrinsic Mode Functions (IMFs), which help in identifying fault patterns.

In this study, four types of transmission line faults are simulated within a grid-connected power system environment using MATLAB/Simulink. These simulations help in understanding the behavior of faults and validating the effectiveness of the proposed detection methods.

Keyword: Transmission Line Faults, Empirical Mode Decomposition (EMD), Discrete Wavelet Transform (DWT), Grid-Connected Power System, Fault Detection and Diagnosis

1. INTRODUCTION

Transmission Line Fault Detection Techniques: A Review

Transmission lines are a vital component of the power system infrastructure. Their primary role is to deliver electrical energy to consumers efficiently and without interruptions. However, due to unpredictable natural events, faults often occur, which are beyond human control. These faults can be categorized into several types: phase-to-phase (line-line), phase-to-ground (line-ground), three-phase (line-line-line), and three-phase-to-ground (line-line-line-ground) faults.

To detect and classify these faults accurately, various modern techniques have been developed. Some of the prominent methods include Wavelet Packet Transform (WPT), Phasor Measurement Units (PMU), Short Time Fourier Transform (STFT), Decision Trees (DT), Fuzzy Logic, Artificial Neural Networks (ANN), Wavelet Transform (WT), and hybrid models combining ANN and Fuzzy Logic.

Wavelet Packet Transform (WPT)

WPT is particularly effective for two-terminal transmission lines. It offers four major functionalities: fault detection, classification of fault types, differentiation between temporary and permanent faults, and identification of arc initiation. This makes it a comprehensive tool for fault analysis.

Phasor Measurement Units (PMU)

PMUs help in identifying faults by observing abrupt changes in voltage levels. The detection process involves two key stages: the first stage pinpoints the region of the fault using a matching index, while the second stage accurately identifies the faulted line and the distance to the fault location. Though this method is well-suited for long transmission lines, it struggles when the fault resistance is high.

Artificial Neural Network (ANN)

ANNs are widely employed for fault classification and location. These systems rely on a backpropagation learning algorithm and utilize various fault-related parameters, including energy decomposition and peak values of fault currents. ANN-based methods offer high accuracy and robustness, often exceeding 90% accuracy, but they require significant computational resources and expertise.

Wavelet Transform (WT)

WT is used to analyze transient signals in both time and frequency domains. One major advantage of WT over the traditional Fourier Transform is its ability to localize disturbances in time. However, the selection of an appropriate "mother wavelet" is crucial, as different wavelets can yield varied results from the same signal. WT is also extensively used in image processing and power signal analysis.

Adaptive Network-Based Fuzzy Inference System (ANFIS)

ANFIS combines neural networks with fuzzy logic to detect faults in both underground and overhead lines. A typical configuration may involve up to ten ANFIS units: one for fault detection, another for locating the fault, and the remaining for fault classification. ANFIS models, when integrated with multi-resolution analysis, can effectively address conventional issues in voltage and current-based fault detection.

Hybrid Techniques: WT with Fuzzy Logic and ANN

Integrating WT with fuzzy logic helps enhance feature extraction and fault classification. Multi-resolution analysis further supports fault categorization. Likewise, combining WT with ANN enables better handling of tasks like load forecasting, fault diagnosis, and location by decomposing voltage and current signals for analysis.

Emerging Technique: EMD and DWT

A promising approach in fault diagnosis is the combination of Empirical Mode Decomposition (EMD) and Discrete Wavelet Transform (DWT).

Empirical Mode Decomposition (EMD):

EMD is particularly suited for analyzing non-linear and non-stationary signals. It decomposes these signals into simpler, symmetric components called Intrinsic Mode Functions (IMFs) without relying on predefined basis functions, as required in DWT.

Discrete Wavelet Transform (DWT):

DWT excels in identifying fault locations, especially when faults involve multiple phases. It analyzes signals in both time and frequency domains, offering detailed insights for accurate fault detection.

2. TECHNIQUES USED

In the proposed approach, Empirical Mode Decomposition (EMD) is employed to facilitate effective fault detection in transmission lines. EMD works by decomposing the input signal into a set of Intrinsic Mode Functions (IMFs), which represent the underlying oscillatory modes inherent in the signal. To further analyze these components, the Hilbert Transform (HT) is applied specifically to the first four IMFs, as they typically contain the most significant information related to fault events.

In addition to EMD, Discrete Wavelet Transform (DWT) is utilized for its capability to detect transient signals, which are often indicative of faults within the transmission system. A comparative evaluation between EMD and DWT is carried out, focusing on statistical metrics such as mean and standard deviation derived from fault-related parameters. This comparison helps in assessing the performance and reliability of both techniques in accurately identifying and classifying transmission line faults.

A. Block diagram of proposed system

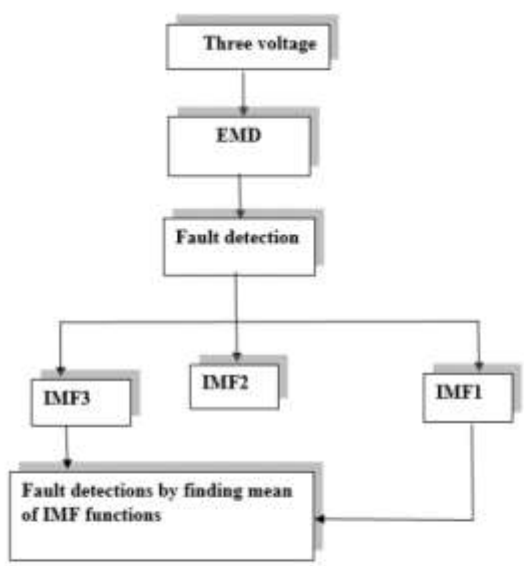

Fig -1 Block diagram for fault detection using EMD

B. Empirical Mode Decomposition (EMD)

The Empirical Mode Decomposition (EMD) technique is an adaptive analytical approach specifically designed for processing signals that are nonlinear and non-stationary. Unlike traditional methods such as Fourier Transform (FT) or standard wavelet analysis, EMD does not rely on predefined basis functions. Instead, it allows the data itself to dictate the basis, thereby enabling a more intuitive and data-driven decomposition of complex signals.

When EMD is integrated with Hilbert Spectral Analysis, the combined technique is referred to as the Hilbert Transform (HT). This enhanced method enables the decomposition of any time-domain signal into a set of modulated components known as Intrinsic Mode Functions (IMFs). Each IMF represents a simple oscillatory mode with zero mean and a well-defined instantaneous frequency, which makes them particularly useful in analyzing transient events such as faults in transmission lines.

The main objective of EMD is to empirically identify and extract the intrinsic oscillatory modes embedded within the original signal, categorized by their characteristic time scales. This process, known as sifting, involves iteratively removing riding waves or oscillations that lack zero crossings between local extrema. Through this sifting process, the signal is effectively broken down into IMFs, each representing a distinct component of the original data.

A key advantage of EMD lies in its ability to retain temporal resolution while decomposing the signal, making it superior in many cases to FT and wavelet-based methods for time-domain analysis. For a given signal

f(t), the EMD process begins by identifying the mean of the upper and lower envelopes, typically denoted as m1, which is then subtracted from the signal to initiate the decomposition.

The 1st component 1 imf is calculated as:

$imf_1 = f(t) - m_1$ (1)

imf_1 Is taken as the data and mean of imf_1 is m_1 in the next sifting process,

$imf_2 = imf_{1-m1}$ (2)

The sifting process continues iteratively until all the Intrinsic Mode Functions (IMFs) are extracted, or until the remaining signal, known as the residue, becomes a monotonic function from which no further IMFs can be derived. At the end of this process, the original signal can be represented as the sum of all the extracted IMFs along with the final residue. This decomposition offers a clear and structured representation of the underlying oscillatory modes present in the signal, making it particularly useful for analyzing complex, non-stationary data such as fault signals in transmission lines.

C. Discrete Wavelet Transform (DWT)

The Discrete Wavelet Transform (DWT) is a mathematical tool used to analyze signals at multiple resolutions by scaling and shifting a basic function known as the mother wavelet. Unlike traditional methods that focus solely on either time or frequency, DWT allows simultaneous observation of both, making it particularly effective for identifying and analyzing transient events in signals.

Through this technique, a signal is broken down into components that reveal different frequency contents over time. By applying filters at various levels, DWT separates the signal into approximation and detail coefficients. Higher scale levels correspond to wavelets that are stretched over longer durations, capturing slower-changing components of the signal, while lower scales detect rapid variations. This multiscale decomposition enables precise detection, enhancement, or suppression of signal features depending on their frequency and time characteristics.

D. Fault Detection Using Discrete Wavelet Transform (DWT)

The Discrete Wavelet Transform (DWT) serves as an effective technique for identifying faults in transmission lines, particularly those that manifest as transient disturbances. DWT offers rapid and precise analysis, with reduced computational demands when compared to methods like the Continuous Wavelet Transform (CWT).

In this approach, voltage or current signals from a three-phase transmission system are used as input. These signals are processed through DWT to extract relevant features across multiple decomposition levels. Specifically, five levels of detail coefficients are analyzed, capturing both high-frequency and low-frequency components of the signal.

At each level, the signal is broken down into various directional details—such as horizontal, vertical, and diagonal components—allowing for a comprehensive assessment of the waveform characteristics. The combination of the wavelet and scaling functions yields the wavelet coefficients, which are especially useful in detecting abnormalities.

Typically, level 4 reveals the most significant variations (maximum detail), while level 5 highlights subtler changes (minimum detail). A fault is indicated when the values of these coefficients exceed the thresholds observed during normal operating conditions. This method enables early and accurate detection of faults in real time.

3. SIMULINK MODEL

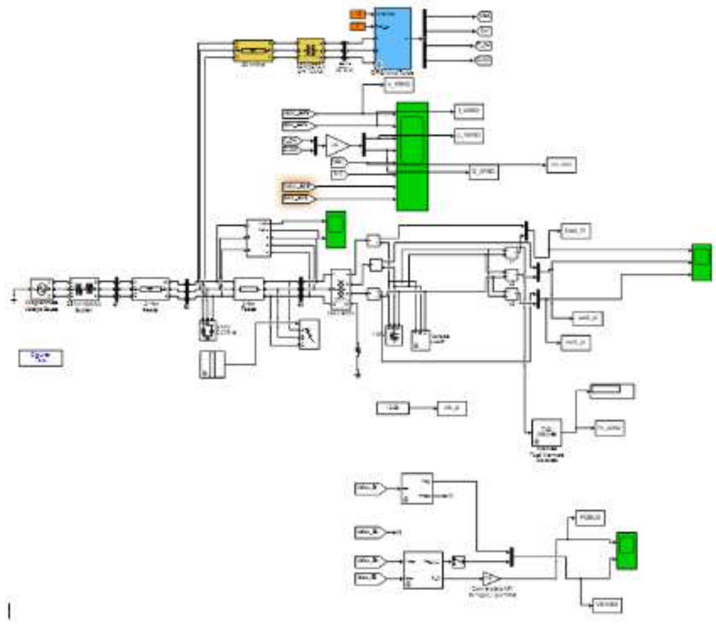

Figure 1 Simulation Model

The designed simulation framework for fault detection integrates Empirical Mode Decomposition (EMD) and Discrete Wavelet Transform (DWT), as illustrated in Figure 3. A 30 km transmission line, rated at 25 kV and 100 MVA, is modeled along with a 21 km feeder connected to a voltage source. Three-phase loads are distributed across the network, and the generator is linked to two distinct buses.
Various fault scenarios are introduced at multiple locations along the transmission line using MATLAB/Simulink. During these simulations, voltage and current signals from each phase are captured for analysis. Both normal and fault conditions are evaluated by applying EMD and DWT techniques to the recorded signals.
EMD is employed to extract Intrinsic Mode Functions (IMFs) from the voltage signals. These IMFs, once normalized, are compared with predefined threshold values. If the values exceed the thresholds, a fault condition is confirmed. This approach enables accurate identification and classification of faults within the system using the developed algorithm.

4. RESULTS

4.1 Normal Condition

EMD: IMFs show low-frequency content.
DWT: Coefficient values remain below threshold.

4.2 Fault Conditions

(a) Phase-Phase Fault

EMD: IMFs exceed threshold values (>350).
DWT: Maximum detail coefficient at level 4.

(b) Phase-Ground Fault

Distinct high-frequency IMFs identified.
DWT analysis reveals abrupt transient signature.

(c) Three-Phase Fault

IMF values show largest amplitude variations.
Mean value in EMD: 17,508; SD: 22,362.

(d) Three-Phase Ground Fault

Most severe case: highest wavelet coefficient variance.

4.3 Comparative Analysis

Table 1 Comparative Analysis

Fault Type	Mean (EMD)	SD (EMD)	Mean (DWT)	SD (DWT)
Normal	4.5480	35.3011	282.4088	52882.00
L-L Fault	3431.3	7617.5	238.4229	50036.00
L-G Fault	22745.0	25481.0	1.7338	53590.00
3L Fault	17508.0	22362.0	216.8012	47159.00
3L-G Fault	2182.9	21168.0	237.5379	47163.00

5. CONCLUSION

This study introduces a robust method for detecting and diagnosing faults in transmission lines by combining Empirical Mode Decomposition (EMD) and Discrete Wavelet Transform (DWT). The complete system is modeled and tested using MATLAB/Simulink. In this approach, voltage signals from all three phases are captured and analyzed. EMD is applied to extract Intrinsic Mode Functions (IMFs), while DWT is used to obtain approximation and detail coefficients across five decomposition levels.

To identify fault conditions, the extracted features are normalized and compared against a predefined threshold. It was observed that under normal operating conditions, the normalized IMF values remain below this threshold. However, during fault events, these values surpass the threshold, confirming the presence of abnormalities. The method achieved an impressive accuracy rate of 98.9% and proved effective for detecting various fault types at multiple locations along the transmission line.

Looking ahead, the individual strengths of EMD and DWT suggest promising potential for developing advanced hybrid approaches. Such systems could further enhance the accuracy and speed of fault classification, particularly for different short-circuit fault scenarios in complex power networks.

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