Remote End Fault Diagnosis of Microgrid-Based Power Distribution Network

Abstract

The rapid growth in the integration of Distributed Energy Resources (DERs)—including photovoltaic (P–V) systems, battery storage units, and small diesel generators—has significantly altered the topology and behavior of modern power systems. This transformation has led to the evolution of microgrids, which are localized, self-contained clusters of distributed generation, storage, and controllable loads operating within defined electrical boundaries. Microgrids can function either in grid-connected mode, exchanging power with the main grid, or in islanded mode, operating autonomously to serve local loads. Their ability to enhance system reliability, resilience, efficiency, and sustainability makes them a critical component of future energy infrastructure.

However, the introduction of microgrids also presents new technical challenges, particularly in the areas of protection, fault detection, and coordination. Unlike traditional power systems that are radial and passive, microgrids are active and non-radial in nature, with bidirectional power flows, distributed sources, and frequent switching between operating modes. These characteristics complicate the protection mechanism, rendering conventional fault detection schemes inadequate. The non-stationary and transient nature of current and voltage signals during faults further challenges traditional techniques, necessitating the development of new, adaptive approaches.

Traditional protection strategies rely on over-current relays and impedance-based schemes that operate on fixed current or voltage thresholds. Such methods are designed for large, centralized power systems with unidirectional power flow. In a microgrid, however, variability in DER output, bidirectional current flow, and low fault levels make conventional approaches unreliable. Additionally, the Fast Fourier Transform (FFT), commonly used for fault analysis, fails to handle non-stationary signals effectively, leading to inaccurate fault identification and delayed response. These limitations highlight the need for a robust, adaptive, and voltage/current-independent fault detection framework capable of accurately determining fault location and type under all operating conditions.

The overall goal of this research is to design and validate an intelligent, Digital Signal Processing (DSP)-based statistical framework for detection of location and type of fault in microgrid systems. The specific objectives are:

- To frame a protection scheme using digital signal processing based statistical parameter analysis for microgrid networks which will be faster than existing schemes and also be able to distinguish fault type and identify the location of the fault.
- The proposed protection scheme must be independent of the values of voltage and currents.
- It must not be affected by variation of fault resistance i.e. the protection scheme should be well suited to successfully identify ground faults in short lines.

Two DSP-based approaches are developed and examined: one based on the Discrete Wavelet Transform (DWT) and the other on the Stockwell Transform (S-Transform). The DWT-based method uses multi-resolution wavelet decomposition to analyze transient current signals, extracting statistical features like skewness and kurtosis. These features form the basis of a rule-based system for identifying fault types and locations, integrated with an Artificial Neural Network (ANN) and fog computing architecture to enable real-time processing and scalability.

The S-Transform-based method, in contrast, delivers a continuous, high-resolution time–frequency representation of current signals without requiring a predefined mother wavelet, offering enhanced adaptability across diverse operating conditions. By analyzing statistical parameters derived from S-Transform matrices, the method identifies characteristic patterns associated with various fault types, enabling precise classification of both symmetrical (L–L–L, L–L–L–G) and unsymmetrical (L–G, L–L, L–L–G) faults.

The proposed algorithms were evaluated through extensive simulations on the IEEE Standard 14-bus microgrid system. Various fault scenarios, including Line-to-Ground (L–G), Double-Line (L–L), Double-Line-to-Ground (L–L–G), and Three-Line (L–L–L) faults, were simulated under different pre-fault conditions. Current measurements from generator buses were processed using the S-Transform method. The algorithm accurately identified fault locations and types, with results closely matching known fault conditions. The study also explored uncertainties related to DERs, such as P–V cells, batteries, and diesel generators, by varying their generation levels at 100%, 80%, and 50%. While harmonic component magnitudes varied, the skewness values from S-Transform matrices remained stable, demonstrating the robustness of the algorithm, to DER output fluctuations and fault resistance variations.

Comparative analysis showed that both DSP-based methods outperform conventional FFT-based approaches in addressing non-stationary fault signals.

- The DWT-based approach offers faster computation and is suitable for real-time fault detection applications within fog or edge computing frameworks.
- The S-Transform-based approach delivers superior fault localization accuracy and maintains consistent performance under variable DER output and complex multi-fault scenarios.

This thesis establishes a comprehensive, data-driven approach to fault detection and protection in microgrid networks. By combining Digital Signal Processing (DSP) techniques, statistical analysis, and intelligent computation, it delivers a fast, accurate, and mode-independent protection mechanism suited for modern distributed energy systems. Overall, this work contributes a robust and adaptive protection framework that bridges the gap between theoretical signal processing and practical power system applications. It lays the foundation for next-generation intelligent protection architectures, enhancing the reliability, scalability, and resilience of future microgrid and smart grid systems.