This article has been accepted for publication in IEEE Journal of Emerging and Selected Topics in Industrial Electronics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/JESTIE.2026.3702647

A Robust Differential Energy-Based Fault Detection Method for Renewable-Dominated Distribution Networks

Javeed Bashir, *Student Member, IEEE,* Md. Sajid Alam, and Premalata Jena, *Senior Member, IEEE.*

***Abstract*—The extensive integration of distributed renewable energy systems (DRES) into modern AC distribution networks has significantly modified fault current characteristics and power flow behavior, especially under abnormal operating conditions. Traditional protection schemes, which were originally developed for conventional radial networks, frequently struggle to maintain reliability in these evolving network configurations. The detection of high-impedance faults (HZFs), in particular, remains a major challenge, as they produce weak and nonlinear current responses that are difficult to distinguish. To overcome this issue, the paper presents a unified fault detection approach capable of accurately identifying both low-impedance faults (LZFs) and HZFs in smart AC distribution systems. The proposed method analyzes the energy of the negative-sequence component before and after fault events to differentiate between faulty and healthy operating conditions. By utilizing this energy-based formulation, the technique enhances detection sensitivity and ensures robust performance under diverse network scenarios. Simulation studies on a modified IEEE-34 bus system with multiple DRES configurations demonstrate average detection times of approximately 8 milliseconds for LZFs and 14 milliseconds for HZFs. Furthermore, real-time validation using RTDS and dSPACE DSP-1104 verifies the approach's reliability, speed, and practical suitability for future smart distribution networks.**

***Index Terms*—Distributed renewable energy systems (DRES), fault detection, high impedance fault (HZF), intelligent electronic device (*IED*), and low impedance fault (LZF).**

I. INTRODUCTION

A. Motivation and Literature Review.

DRES have recently attracted a lot of attention in power system protection over the past ten years owing to their increasing penetration in distribution networks. Importantly, these small-scale distributed energy resources (e.g., wind turbines, solar PV, and fuel cells) are adopted at the distribution level, reducing transmission losses, lowering power transfer costs, and improving system reliability. With their proximity to end-users, the grid integrated with these systems serves as a cost-effective alternative to extending central grids to remote areas, while also contributing to reduced carbon emissions. In addition, DRES enhances the reliability of the grid, since in isolated or off-grid environments, they can supply uninterrupted power for local loads and improve power quality [1]-[2]. To ensure secure and coordinated operation, *IEDs* are increasingly deployed to monitor feeder conditions, while communication infrastructure enables the real-time exchange of system data for protection, control, and fault detection [3]. Renewable energy sources are naturally unpredictable and constantly changing, as they depend on weather conditions and varying power demands. This unpredictability creates challenges like bidirectional power flow and fluctuating fault currents, making it essential to develop advanced protection schemes to maintain grid stability [4]. At the same time, microgrids (MG) and multi-microgrid systems (MMGs) have become a hopeful approach to new renewable energy access and growing demand for green energy. Microgrids are self-contained energy systems that combine around DRES, energy storage systems, and loads that enable reliable and economical energy provision in areas that are not served by a centralized electricity grid [5]. They improve resilience and efficiency of the system. MMGs take this concept one step further by interconnecting several small but self-sufficient microgrids, allowing greater flexibility and efficiency in rural electrification [6]. Nevertheless, MMGs give rise to some challenges of their own (e.g., variable fault current contributions, bidirectional power flows, and the intermittency of DRES) that require advanced protection mechanisms to ensure reliable operation [7].

The literature highlights various protection strategies for microgrids, such as directional overcurrent relays [8], adaptive schemes [9], intelligent approaches that employ neural networks [10] and other AI and ML techniques [11]. In addition, several techniques have been proposed to tackle protection challenges in systems augmented with DRES and MMGs. For synchronous DRES, fault current limiters have been applied to control fault current contribution; however, their high impedance and slow time response remain major drawbacks [12]. Communication-assisted schemes, such as voltage harmonic-based detection and overcurrent relay-based methods, have also been introduced, with applications ranging from fault isolation to fuse-saving strategies [13]. Despite these advancements, most existing techniques are ineffective for HZFs, which produce low fault currents with nonlinear and random characteristics [14].

For HZF detection, numerous sophisticated techniques have been proposed such as those derived from sequence components [15], discrete wavelet transform [16], S-transform [17], or mathematical morphology [18]. Although effective, such methods are often ineffective under noise conditions or cannot distinguish well among the fault types. Protection schemes based on fault energy criteria have been proposed for DRES, but these methods have low robustness for handling HZFs in smart distribution systems (SDS) [19]. Moreover, the effects of communication latency and synchronization errors have not been considered in these methods, which can significantly impact the accuracy and reliability of fault detection in practical SDS environments. These factors create a growing demand for protection schemes that are novel in design and tailored to the unique characteristics of DRES and