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Research Article

Detection of High Impedance Faults in Electrical Distribution Systems Based on the RF-ICEEMDAN Approach

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Extended Abstract:

High Impedance Faults (HIFs) represent one of the most insidious and hazardous anomalies in low- and medium-voltage electrical distribution networks. Unlike conventional short-circuit faults that generate large, easily detectable currents, HIFs—typically caused by downed conductors contacting high-resistance surfaces such as asphalt, soil, or vegetation—produce fault currents that are often comparable in magnitude to normal load currents. This deceptive similarity renders HIFs virtually invisible to conventional overcurrent relays and other legacy protection schemes, creating a dangerous blind spot that can persist for hours or even days. The consequences are severe: sustained arcing at the fault point can ignite wildfires, cause electrocution hazards to humans and animals, damage equipment, and trigger cascading outages. Compounding the challenge, HIF current waveforms exhibit highly nonlinear, non-stationary, and stochastic characteristics, including high-frequency transients, current notching, and intermittent arcing. These features closely resemble benign system transients such as load switching, capacitor bank energization, or transformer inrush currents, making reliable discrimination an exceptionally difficult pattern recognition problem.

To address this critical gap in distribution system protection, this paper proposes a novel, data-driven HIF detection methodology that synergistically combines an advanced signal decomposition technique—Improved Complete Ensemble Empirical Mode Decomposition with Adaptive Noise (ICEEMDAN)—with a powerful machine learning classifier—Random Forest (RF). The core innovation of the proposed RF-ICEEMDAN framework lies in its ability to first isolate the subtle, fault-specific signatures embedded within the complex, noisy current signal and then leverage a robust, interpretable classifier to make a highly accurate binary decision: HIF present or absent.

The methodology begins with the acquisition of three-phase current signals from the feeder head using standard, commercially available measurement infrastructure (e.g., CTs with a sampling rate of 7,680 Hz, as used in the study). The raw current signal, which is a superposition of the fundamental load current and any superimposed HIF transients, is processed independently for each phase. The ICEEMDAN algorithm is then applied to decompose this complex signal into a finite set of Intrinsic Mode Functions (IMFs). ICEEMDAN is a significant evolution over traditional Empirical Mode Decomposition (EMD) and its predecessor, CEEMDAN. Its key advantages are its adaptive noise injection mechanism, which tailors the added white noise to the signal's local characteristics, and its ensemble averaging process, which mitigates mode mixing and residual noise. This results in a cleaner, more physically meaningful decomposition that can effectively separate the high-frequency, fault-induced oscillations from the underlying load current.

Through a detailed empirical analysis of the decomposed IMFs, the study identifies IMF-2 as the most discriminative component for HIF detection. IMF-2 captures the mid-frequency oscillatory behavior that is characteristic of the erratic arcing in HIFs, while filtering out both the high-frequency measurement noise (IMF-1) and the low-frequency load variations (IMF-3 and beyond). From this critical IMF-2, a comprehensive set of six robust statistical and energetic features is extracted:

1. Mean Amplitude, which quantifies the average magnitude of the oscillations;

2. Energy, defined as the sum of squared signal values, which measures the overall power of the transient activity;
3. Standard Deviation, which captures the variability or "spread" of the signal around its mean;
4. Peak-to-Peak Value, which measures the total excursion between the signal's maximum and minimum;
5. Skewness, which indicates the asymmetry of the signal's probability distribution, a key marker of the unidirectional nature of arcing;
6. Kurtosis, which quantifies the "tailedness" or presence of sharp spikes in the signal, directly linked to the impulsive nature of HIF arcs.

This carefully engineered 6-dimensional feature vector serves as the input to the Random Forest classifier. RF was chosen for its renowned strengths: high accuracy, robustness to noisy and irrelevant features, resistance to overfitting, intrinsic feature importance ranking, and computational efficiency. The classifier is trained on a large, diverse dataset generated from detailed electromagnetic transient simulations of the IEEE 34-bus distribution test system using EMTP-RV software. The dataset encompasses a wide range of scenarios, including various HIF locations, fault impedances (90–8000 Ω), and arc models (based on the well-established Emanuel model), alongside numerous non-fault events like load switching and capacitor bank operations. This ensures the model's generalizability and resilience to real-world operational variations.

The performance of the RF-ICEEMDAN approach is rigorously evaluated using standard machine learning metrics derived from the confusion matrix, including Accuracy, Sensitivity (Recall), Specificity, Precision, F1-Score, and Dice Coefficient. The results are striking. The proposed method achieves an overall accuracy of 97.47%, with a sensitivity of 94.66% (correctly identifying true HIFs) and a remarkably high specificity of 98.77% (correctly rejecting non-HIF events). This high specificity is crucial in a protection context to avoid costly and disruptive false alarms.

To validate the superiority of the ICEEMDAN decomposition, the study conducts a controlled comparison against the widely used CEEMDAN method. When the same RF classifier is fed features extracted from CEEMDAN's IMF-2, its performance degrades significantly, achieving an accuracy of only 91.60% and a specificity of 90.50%. This direct comparison conclusively demonstrates that the adaptive noise mechanism of ICEEMDAN provides a cleaner, more discriminative signal representation, which is the primary driver of the proposed method's enhanced performance.

In conclusion, this paper presents a highly effective, practical, and robust solution for the long-standing challenge of HIF detection. By marrying the advanced time-frequency analysis capabilities of ICEEMDAN with the powerful classification prowess of Random Forest, the RF-ICEEMDAN framework offers a significant leap forward in reliability and accuracy. Its ability to operate on standard current measurements and its high immunity to false positives make it a prime candidate for deployment in real-world distribution automation systems, thereby enhancing public safety, grid resilience, and operational reliability. Future work will focus on validating the approach on field data from utility distribution feeders and exploring its integration with real-time edge computing platforms for immediate fault response.

Keywords: High impedance fault, Random forest, Load switching, Fault current, ICEEMDAN method

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