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Research Article

A Frequency-Domain Differential Protection Scheme Based on Discrete Laplace Transform Considering the Effects of Voltage and Current Transformers in Transmission Lines

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Extended Abstract:

The reliable and secure operation of modern power transmission networks is critically dependent on the accuracy and speed of protective relaying schemes. Among these, differential protection stands as a cornerstone for the safeguarding of critical assets such as transmission lines, transformers, and generators. However, conventional time-domain differential protection schemes are increasingly challenged by the dynamic complexities of contemporary power systems. A primary source of this challenge lies in the frequency-dependent behavior of instrument transformers—specifically, Voltage Transformers (VTs) and Current Transformers (CTs)—whose frequency response characteristics can introduce significant transient errors, particularly during external faults or system disturbances. These errors can manifest as spurious differential currents that mimic internal faults, leading to maloperation and false tripping, thereby compromising system security and reliability.

This paper addresses this critical vulnerability by proposing a novel frequency-domain differential protection scheme that is fundamentally robust against the distorting effects of VT and CT dynamics. The core innovation of the proposed method is its foundation in the Discrete Laplace Transform (DLT), which enables a direct and efficient analysis of the transient components of voltage and current signals in the complex frequency domain. Unlike conventional methods that operate solely in the time domain or rely on computationally intensive time-frequency transforms like the Wavelet Transform or Hilbert-Huang Transform, the DLT offers a mathematically elegant and computationally lean framework for extracting the essential fault signatures while inherently filtering out non-fault transients.

The proposed methodology is implemented in a two-stage process. In the first stage, a First-Order Differential Average (FODA) criterion is applied to the secondary-side voltage or current signals from either terminal of the transmission line. This criterion serves as a highly sensitive and fast-acting fault detection trigger, capable of identifying the inception of a fault with minimal delay. The FODA threshold is computed adaptively from the statistical properties of the signal under normal operating conditions, ensuring robustness against varying load patterns and measurement noise. Once a fault is detected, the scheme transitions to the second, more critical stage: fault discrimination.

For fault discrimination, the proposed scheme leverages a new metric termed the Congruence Criterion (CC). The derivation of the CC is based on a rigorous mathematical model of the transmission line under both internal and external fault conditions. By applying a modal transformation to decouple the three-phase system into its symmetrical components and then subjecting the resulting modal signals to the DLT, the scheme isolates the high-frequency transient components associated with the fault. The CC is then formulated as a specific combination of these transformed voltage and current components from both line terminals. The theoretical analysis demonstrates a fundamental and critical property: for an

external fault, the CC is identically zero, while for an internal fault, the CC is a non-zero value. This clear dichotomy provides a definitive and unambiguous basis for discrimination.

A key strength of the proposed scheme is its explicit and systematic consideration of the transfer functions of the VTs and CTs. The mathematical model from which the CC is derived incorporates these transfer functions directly, ensuring that the criterion remains valid even under the distorted secondary-side signals caused by the resonant and attenuation characteristics of real-world instrument transformers. This is a significant departure from traditional approaches, which often assume ideal transformer behavior and thus fail under practical conditions.

Furthermore, the protection scheme exhibits several compelling practical advantages:

- Power-Level Independence: The CC is a normalized metric that is independent of the absolute magnitude of the fault current or the pre-fault load level, making it equally effective for high- and low-magnitude faults.
- High-Impedance Fault Sensitivity: By focusing on the transient characteristics rather than the steady-state current magnitude, the scheme is inherently more sensitive to high-impedance faults, which are notoriously difficult for conventional overcurrent or impedance-based relays to detect.
- Low Computational Burden: The DLT, being a direct integral transform, is computationally less demanding than multi-resolution or iterative decomposition methods like the Wavelet Transform, making it well-suited for real-time, online implementation in digital relays.
- Low Sampling Rate Requirement: The reliance on transient features, rather than high-frequency traveling waves, allows the scheme to operate effectively with a lower sampling rate, reducing hardware costs and data throughput requirements.

The efficacy and robustness of the proposed scheme have been thoroughly validated through comprehensive MATLAB/Simulink simulations on a 200-km, 100-kV, 60-Hz transmission line model equipped with realistic VT and CT models. The performance was evaluated under a wide array of challenging scenarios, including various internal and external fault types (e.g., single-line-to-ground, double-line-to-ground, three-phase), fault resistances ranging from 10 Ω to 500 Ω, different fault inception angles (0°, 45°, 120°), and varying levels of measurement noise (SNR from 30 dB to 70 dB). The results consistently demonstrate that the proposed scheme achieves 100% accuracy in both fault detection and internal/external fault discrimination across all tested conditions. The CC for external faults was found to be on the order of 10^{-10} to 10^{-12}, effectively zero for practical purposes, while for internal faults, it exhibited a robust, non-zero value, clearly separable from the external fault case.

A comparative analysis with other state-of-the-art protection schemes highlights the superiority of the proposed method. Unlike adaptive impedance or machine learning-based approaches that can be computationally heavy and require extensive training data, the proposed DLT-based scheme is model-based, deterministic, and requires no offline training. Its computational simplicity and inherent robustness to instrument transformer dynamics make it a highly practical and reliable solution for modern digital protective relaying.

In conclusion, this paper presents a powerful and practical solution to a long-standing problem in transmission line protection. By shifting the protection paradigm from the time domain to the frequency domain and leveraging the Discrete Laplace Transform, the proposed scheme achieves a unique combination of high accuracy, robustness, computational efficiency, and practical feasibility. The explicit modeling of instrument transformer effects ensures its reliability in real-world deployments, where these effects are a major source of relay misoperation. This work paves the way for a new generation of intelligent, frequency-domain protection algorithms that are better equipped to handle the dynamic complexities of future power grids.

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