Transient Frequency Spectrum Analysis for Single Line-to-Ground Fault Location in Insulated Power Systems

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Abstract—**This paper addresses the challenge of single line-to-ground fault location in insulated electrical systems. Traditional steady-state measurement methods are often inadequate for these systems due to the minimal fault current, which is difficult to measure accurately against background noise and makes the methods sensitive to high fault resistance. Transient frequency spectrum analysis is presented as a superior alternative, utilizing the high-frequency signals generated at the moment a fault occurs, which are largely independent of fault resistance. The zero-sequence voltage and current are used to provide the transient components for this analysis. However, commonly deployed digital fault recorders in Ukrainian substations are unsuitable for fault location through spectrum analysis due to their limited frequency bandwidth, absence of a fundamental frequency filter, and high cost. To overcome these limitations, a custom digital fault recorder prototype with a 64 kHz bandwidth and an analog input filter has been designed and developed.**

Keywords—fault location; insulated systems; Transient Frequency Spectrum Analysis (TFSA); Single Line-to-Ground (SLG) fault; Digital Fault Recorder (DFR); zero-sequence components; high-frequency transients.

I. Introduction

The necessity of transient frequency spectrum analysis (TFSA) for fault location in insulated systems stems from the fundamental inadequacy of traditional, steady-state measurement methods. There is why this theme is Insulated systems are specifically designed to restrict the single line-to-ground (SLG) fault current to a minimal, primarily capacitive, magnitude. As a result, standard fundamental frequency (50 Hz) impedance calculations are unreliable because measuring the zero-sequence current accurately against background noise is extremely challenging. Furthermore, traditional impedance methods are highly sensitive to high fault resistance, leading to substantial errors in distance estimation.

TFSA overcomes these limitations by utilizing the distinct, high-frequency signals generated at the moment the fault occurs. This approach isolates the nonstationary frequency components that propagate along the line according to the Distributed Parameter Line Model (DPLM), which maps the spectral content to the distance to the fault. Critically, by focusing on these short-duration, high-frequency wave characteristics rather than the problematic steady-state current, the resulting fault location accuracy becomes largely independent of the fault resistance. Techniques like the Fast Fourier Transform (FFT) are employed to extract these high-frequency components, providing a precise measurement that locates the fault. For these reasons, TFSA-based techniques are widely investigated and applied in numerous research studies [1], [2], [3].

II. Signals Used in Transient Frequency Spectrum Analysis

For fault location in insulated systems using the TFSA, two signals are utilized in the frequency domain: the zero-sequence voltage (V0) and the zero-sequence current (I0). The use of these zero-sequence quantities is essential because an SLG fault is an inherently unbalanced condition that results exclusively in these components.

When an SLG fault occurs in an insulated system, the V0 at the bus rises substantially, and the I0 flows to the fault. While the steady-state I0 magnitude is very low and unreliable for measurement in insulated systems, the *transient* components of V0 and I0 generated immediately after the fault provide high-frequency wave characteristics that can be accurately mapped to the distance to the fault.

Modeling of the SLG fault using DPLM shows that the transient component has a frequency up to 50 kHz.

III. Commonly Used Digital Fault Recorders

Two commonly used Digital Fault Recorders (DFRs) on Ukrainian substations are the "Altra" and the "Rekon" series, both of which are deployed across various device models. Unfortunately, these devices are unsuitable for use with the proposed TFSA-based fault location method, due to the following limitations:

1) *Limited frequency bandwidth*, up to 9-12 kHz;

2) Absence of a hardware fundamental frequency filter, which significantly limits the resolution of the digitalized high-frequency component having significantly lower amplitude than the fundamental frequency component;

3) High costs make their installation unreasonable for low-power 35/10 kV substations.

IV. Prototyping of Custom Digital Fault Recorder

Reasons described above make it mandatory to develop a custom DFR to be able to satisfy the operational requirements.

The fundamental frequency component of the zero-sequence signal significantly impacts the amplitude of the measured signal. Without an analog filter, this high-amplitude fundamental component consumes the majority of the available resolution of the Analog-to-Digital Converter (ADC). This process severely limits the effective resolution available for the critical high-frequency harmonics, effectively masking the transient data required for analysis. It is essential to have a filter of fundamental frequency in the analog input of the sensor.

The prototype's Bode plot for the analog input with applied fundamental frequency filter is shown in Fig. 1. It demonstrates a significant reduction of response for 0-100 Hz frequency bandwidth.

The entire prototype of DFR is shown on Fig. 2.

V. Conclusion

Traditional steady-state methods are fundamentally inadequate for SLG fault location in insulated power systems due to minimal fault current and high sensitivity to fault resistance.

TFSA overcomes these limitations by utilizing distinct, high-frequency transients of V0 and I0. This approach ensures that the fault location accuracy is largely independent of the fault resistance.

Existing DFRs in Ukrainian substations are unsuitable for TFSA because of their limited bandwidth (up to 12 kHz), high cost, and the lack of a necessary fundamental frequency filter.

To enable the practical deployment of TFSA, a custom DFR prototype with a 64 kHz bandwidth and a dedicated analog fundamental frequency filter was successfully designed and developed. This custom hardware resolves the measurement constraints, making the precise and reliable TFSA-based fault location method viable for insulated systems.

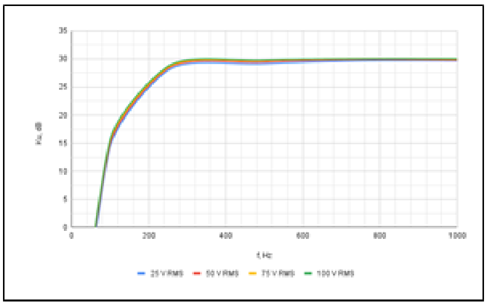

Figure 1. Bode plot of prototype's analog input

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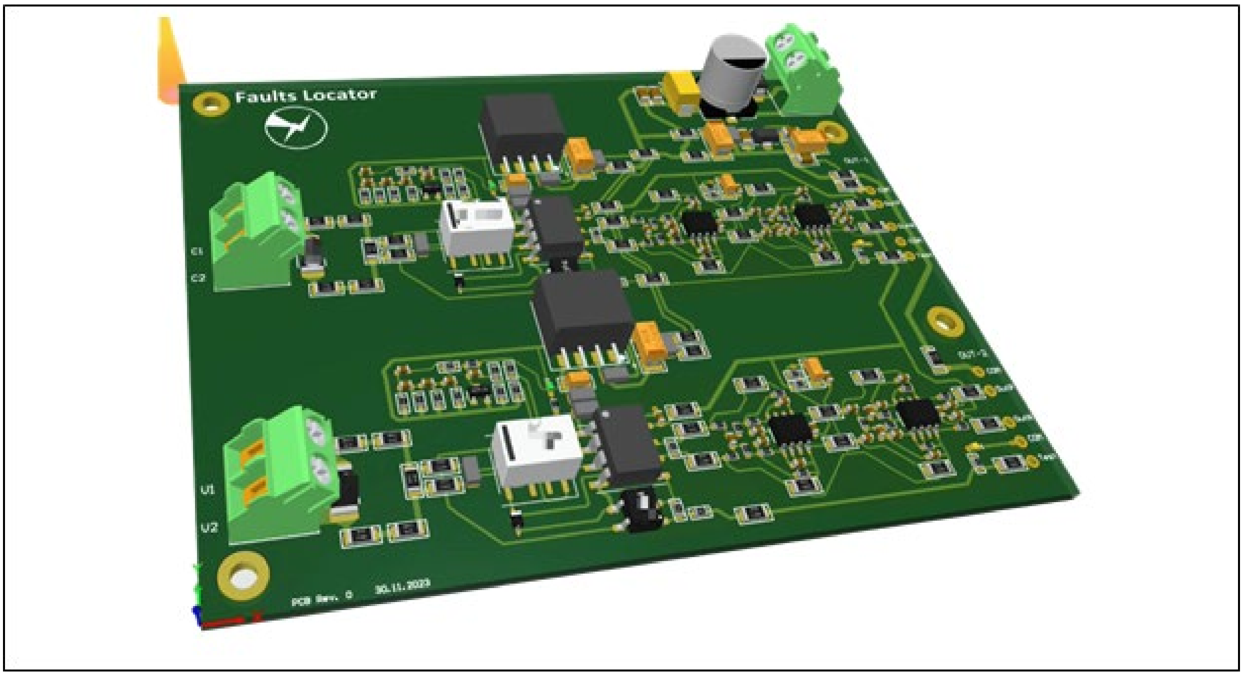

Figure 2. Prototype of DFR for SLG fault location