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The Detection of Power System Faults Using Different Time-Frequency Domain Methods

Hamza Bin SHAFIQUE [1] **Zafer DOĞAN [2,*]**

[1] *Tokat Gaziosmanpasa University, Graduate Education Institute, Division of Electrical and Electronics Engineering, Tokat*

[2]*Tokat Gaziosmanpasa University, Engineering and Architecture Faculty, Department of Electrical and Electronics Engineering, Tokat*
**Corresponding author: zafer.dogan@gop.edu.tr*

ABSTRACT: This paper's approach evaluates the effect of faults on stability parameters, acknowledging the crucial role of power system stability. This integration aims to provide a thorough grasp of the relationship between defect detection and system stability. Phase-to-phase and phase-to-ground fault detection in power systems is the main emphasis of this research. Through the use of Wavelet Transform (WT), Hilbert-Huang Transform (HHT), and Short-Time Fourier Transform (STFT), our study offers a thorough analysis by capturing both time and frequency features. We detail the technique's WT, HHT, and STFT application principles, highlighting the significance of real-time sampling of voltage and current behaviors during faults. This improves the depth of our fault detection analysis. We use a pertinent dataset to investigate phase-to-phase and phase-to-ground faults, adopting preprocessing for strong data quality. Including faults makes it possible to sample and observe voltage and current behaviors in real time, giving information about the power system's dynamic reaction. The method's performance in fault identification is illustrated using visual aids, and the results are given and debated. The effects of dynamic variations in voltage and current behaviors on the stability of the power system are emphasized during failure situations. Our findings are more significant when seen in the larger context of creating a stable and resilient power grid, thanks to the inclusion of power system stability analysis.

Keywords *– power system, fault detection, time-frequency domain, distribution faults, power system fault diagnosis, wavelet transform, Hilbert Huang transform, Short-Time Fourier Transform*

1. Introduction

Renowned scientists' unwavering efforts have affected the development of diagnostic procedures in power systems, shaping a rich history that has contributed to an ongoing search for reliable fault detection methodologies. In the middle of the 20th century, trailblazing individuals like John J. Grainger and William D. Stevenson, Jr. established the groundwork for power system analysis (Grainger and Stevenson, 1994 ; Stevenson, 1982). Their groundbreaking study laid the groundwork for further defect identification research projects. As power systems became more complicated, early fault detection approaches mostly relied on impedance-based techniques. Although it was difficult to fully capture dynamic changes during faults and adjust to the changing power system landscape, mathematical breakthroughs pioneered by scholars like André Quadaras and Charles L. Wagner succeeded in addressing some issues (Banner and Don Russell, 1997). With the advent of wavelet transform (WT) and time-frequency analysis in the late 20th century, the field of defect detection experienced a profound transformation.

Yves Meyer's seminal work in wavelet theory during the 1980s revolutionized signal processing and introduced a powerful alternative for spotting defects in non-stationary data within power systems (Meyer and Salinger, 1993). The WT's versatility and effectiveness in managing dynamic power system data signaled the beginning of a new era in fault detection techniques. Concurrently, the Hilbert-Huang Transform (HHT), invented by Norden E. Huang, provides a breakthrough way for analyzing non-stationary and non-linear data in a power system setting (Huang, Shen, and Long, 1999 ; Li, Lin, Niu, Wu, and Wei, 2021). Because of its flexibility in obtaining intrinsic mode functions, HHT was able to overcome some of the drawbacks of previous methods and become a powerful tool for time-frequency analysis.

Over time, as power systems changed, new problems surfaced that called for an all-encompassing approach. Even though different fault detection strategies had unique benefits, it soon became clear that many approaches needed to be integrated. To utilize the synergies of WT, HHT, and Short-Time Fourier Transform (STFT) to analyze power system failures fully, this research acknowledges and improves upon the contributions of each unique approach.

In doing so, the study takes into account the dynamic character of power systems as well as the changing field of fault detection techniques. Through the integration of WT, HHT, and STFT, our goal is to create a strong and comprehensive framework that can handle the complexities of contemporary power systems and improve fault detection skills.

This integration of all the techniques combined can be useful in the following perspectives

- By promoting the integration of many fault detection techniques this study adds to the body of knowledge.
- The study provides a complete strategy for defect detection that solves the shortcomings of individual strategies by integrating the benefits of different methods.
- Power system analysis is advanced by this research by utilizing state of the art techniques like WT and HHT(Y. S. Wang, Ma, Zhu, Liu, and Zhao, 2014). The suggested approach offers insights into the dynamic behavior of contemporary power systems in addition to improving fault detection capabilities.
- By locating and addressing defects in actual power systems, the integrated fault detection framework eventually increases operational effectiveness and dependability.

This article consists of 4 parts: Part 1 is the introduction part. Fault Detection Techniques are explained in chapter 2. The 3rd section is the Results and Discussion section. The last chapter, chapter 4, is the Conclusion section.

2. Fault Detection Techniques

This section explains the methods used in this study to integrate three different time-frequency analysis techniques the WT, the HHT, and the STFT for fault identification in power systems (Huang et al., 1999 ; Prakash K. Ray, Dubey, Mohanty, Kishor, and Ganesh, 2010). Since each technique is used independently, the overall assessment of its contributions is guaranteed. We will talk about their mathematical modeling, which is useful for utilizing MATLAB to analyze signals for defects and healthy systems (Ruiz Florez, López, Jaramillo-Duque, López-Lezama, and Muñoz-Galeano, 2022).

2.1. Short Time Fourier Transform

An essential method for examining the frequency content of non-stationary signals is the STFT. It provides information on how a signal's frequency components change over time by locally computing the Fourier Transform (Basir et al., 2021).
The STFT is defined as:

$$\boldsymbol{STFT(t,f)} = \int_{-\infty}^{\infty} \boldsymbol{x(\tau)\omega(\tau - t)e^{-j2\pi f\tau}d\tau} \tag{1}$$

By this general equation (1), we can easily drive them for currents and voltages of a power system (Basir et al., 2021 ; Kehtarnavaz, 2008),

$$\boldsymbol{I(t,f)} = \int_{-\infty}^{\infty} \boldsymbol{i(\tau)\omega(\tau - t)e^{-j2\pi f\tau}d\tau} \tag{2}$$

$$\boldsymbol{V(t,f)} = \int_{-\infty}^{\infty} \boldsymbol{V(\tau)\omega(\tau - t)e^{-j2\pi f\tau}d\tau} \tag{3}$$

$\boldsymbol{I(t,f)}$ *and* $\boldsymbol{V(t,f)}$ represents the STFT of the current and voltages at time and frequency. $\boldsymbol{i(\tau)}$ *and* $\boldsymbol{V(\tau)}$ are the current and voltage signals. $\boldsymbol{\omega(\tau - t)}$ is the window function, capturing a segment of the signal at time *t*. $\boldsymbol{e^{-j2\pi f\tau}}$ is the complex exponential function determining the frequency element.
The STFT is computed for various time values, resulting in a two-dimensional representation where one axis corresponds to time (*t*), the other axis corresponds to frequency (*f*), and the intensity of the representation represents the magnitude of the frequency components (Kehtarnavaz, 2008).

2.2. Hilbert-Huang Transform

In particular, the HHT works well for non-stationary and non-linear signal analysis. It uses the Empirical Mode Decomposition (EMD) method to break down a signal into Intrinsic Mode Functions (IMFs), which are then subjected to Hilbert spectral analysis (Huang et al., 1999 ; J. Wang, Liu, Li, Liu, and Hancock, 2021).

2.2.1. Empirical Mode Decomposition

A signal is broken down into a series of intrinsic mode functions (IMFs) and a residual using the data-driven EMD technique. Each IMF represents an identifiable frequency component of the signal. Sifting is the method used to separate oscillatory modes from the original signal and produce the IMFs (Dogan and Tetik, 2021 ; J. Wang et al., 2021).

$$\boldsymbol{x(t)} = \textstyle\sum_{i=1}^{N} \boldsymbol{C_i(t) + r(t)} \tag{4}$$

$x(t)$ is the original signal.

N is the number of IMFs.

$C_i(t)$ intrinsic mode function of IMF.

$r(t)$ is the residual representing the trends or high-frequency noise.

So, the voltage and current signal equations can be written as,

$$\boldsymbol{I(t)} = \sum_{i=1}^{Ni} \boldsymbol{C_{i_i}(t)} + \boldsymbol{r_i(t)} \tag{5}$$

$$\boldsymbol{V(t)} = \sum_{i=1}^{Nv} \boldsymbol{C_{i_v}(t)} + \boldsymbol{r_v(t)} \tag{6}$$

2.2.2. Hilbert Spectral Analysis

Once the IMFs are obtained, the Hilbert Transform is applied to each IMF. The instantaneous frequency and IMF are calculated as the derivative of the phase of its analytical signal (Huang et al., 1999).

$$\boldsymbol{\omega_i(t)} = \frac{\frac{1}{2\pi}d}{dt} \arg\{\boldsymbol{Z_i(t)}\} \tag{7}$$

$$\boldsymbol{Z_i(t)} = \boldsymbol{C_i(t)} + \boldsymbol{jH}[\boldsymbol{C_i(t)}] \tag{8}$$

Equation (8) is the analytical signal, obtained by adding the IMF to its Hilbert Transform. This process allows for a detailed time-frequency analysis of voltage and current signals, capturing their intrinsic oscillatory modes and how their frequencies change over time (J. Wang et al., 2021).

2.3. Wavelet Transform

A potent mathematical tool for examining signals in the frequency and temporal domains is the WT. The WT, in contrast to the conventional Fourier Transform, can be used to analyze non-stationary signals with variable frequency content since it offers information about localized features in the signal (Daubechies, 1993 ; Vachtsevanos and Wang, 2001).

$$\boldsymbol{CWT(a,b)} = \int_{-\infty}^{\infty} \boldsymbol{x(t)u^*}\left(\frac{\boldsymbol{t-b}}{\boldsymbol{a}}\right)\boldsymbol{dt} \tag{9}$$

$\boldsymbol{x(t)}$ is the input signal.

u^* is the complex conjugate of the wavelet function.

a is the scale parameter, controlling the width of the wavelet.

b is the translation parameter, controlling the position of the wavelet along the signal axis.

Applying the Continuous WT to voltage and current signals involves expressing the signals in the wavelet domain. We will have the following equations (Daubechies, 1993):

$$\boldsymbol{W_v(a,b)} = \int_{-\infty}^{\infty} \boldsymbol{V(t)u^*}\left(\frac{\boldsymbol{t-b}}{\boldsymbol{a}}\right)\boldsymbol{dt} \tag{10}$$

$$\boldsymbol{W_i(a,b)} = \int_{-\infty}^{\infty} \boldsymbol{I(t)u^*}\left(\frac{\boldsymbol{t-b}}{\boldsymbol{a}}\right)\boldsymbol{dt} \tag{11}$$

Information regarding the frequency content of voltage and current signals at various scales and time points can be extracted using the WT. It can be applied to detect localized alterations and anomalies in the signals, offering perceptions of dynamic behaviors (P. K. Ray, Panigrahi, Rout, Mohanty, and Dubey, 2016 ; Vachtsevanos and Wang, 2001).

2.4. Fault Detection Methodology

The fault detection methodology is explained by creating a Simulink model of a 100km transmission line on MATLAB as follows (MATLAB Documentation , s.d. ; P. K. Ray et al., 2016 ; Ukil and Živanović, 2006):

I. The Power System is modeled in the Simulink with all the key components in the power transmission system.
II. Voltage and current waveforms during fault conditions are sampled from the power system. The dataset includes recordings of phase-to-phase and phase-to-ground fault scenarios. The collected data undergoes preprocessing to eliminate noise and enhance the quality of signals.
III. All Time-frequency methods (STFT, HHT, and WT) are applied to the sampled current and voltages of the power system. After this, we collectively analyze the fault parameters by plotting different time-frequency function results collectively.
IV. STFT gives us the fault patterns while HHT and WT help give instantaneous fault related features.

3. Results and Discussion

3.1. Simulation Results

The simulation approach for introducing and analyzing phase-to-phase and phase-to-ground faults in a power system is covered in this part. The objective is to assess how well time-frequency analysis techniques, such as the WT, HHT, and STFT, discover and characterize these problems.

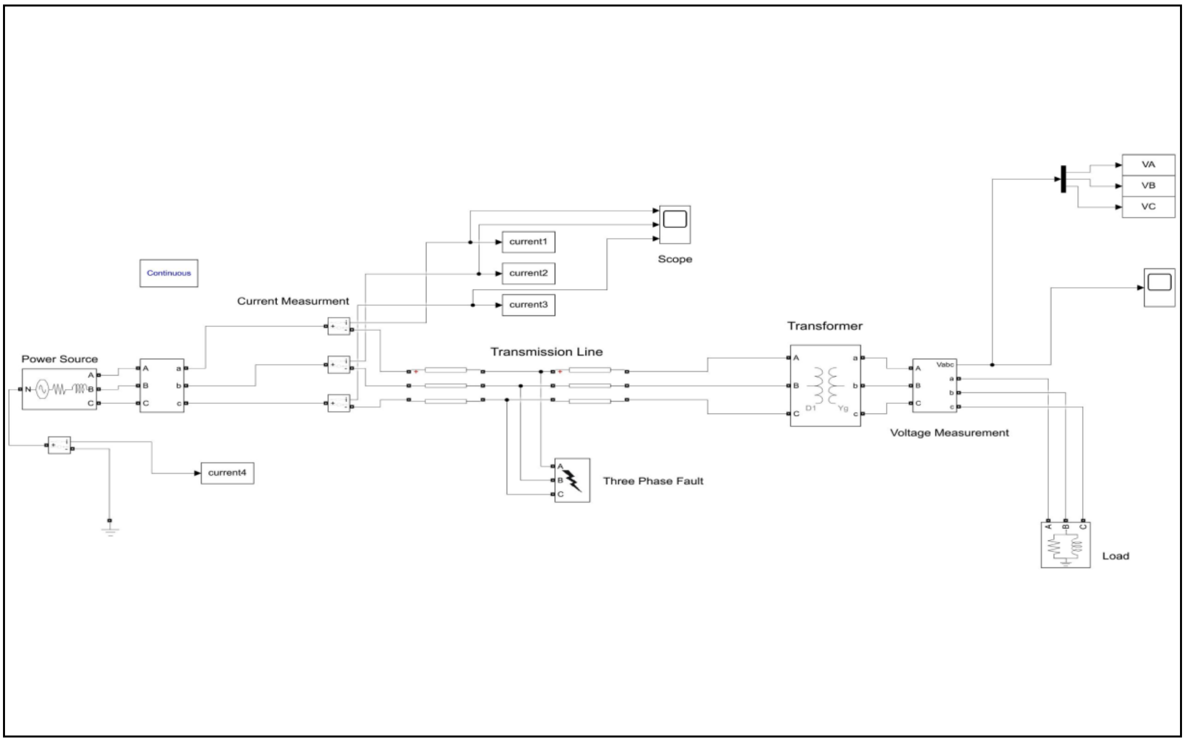

Figure 1. The power system simulation model

In this study, we created a simulation model of a power system with 110 KV voltage and 50 Hz frequency in Matlab/Simulink. We loaded the grid with a load of 110 KVA. The simulation model created can be seen in Fig.1. In the simulation model, we operated the network for 4 seconds. We created faults in the range of 1.3 -2.2 seconds of this duration. We then sampled the voltages and currents of the system. Fig. 2a and Fig. 2b show the effects of phase-to-ground fault on the voltage and current of the power system. Fig. 2c and Fig. 2d are for observing phase-to-phase fault effects. As can be seen in Fig. 2, while voltages decrease in fault situations, faulty phase currents increase.

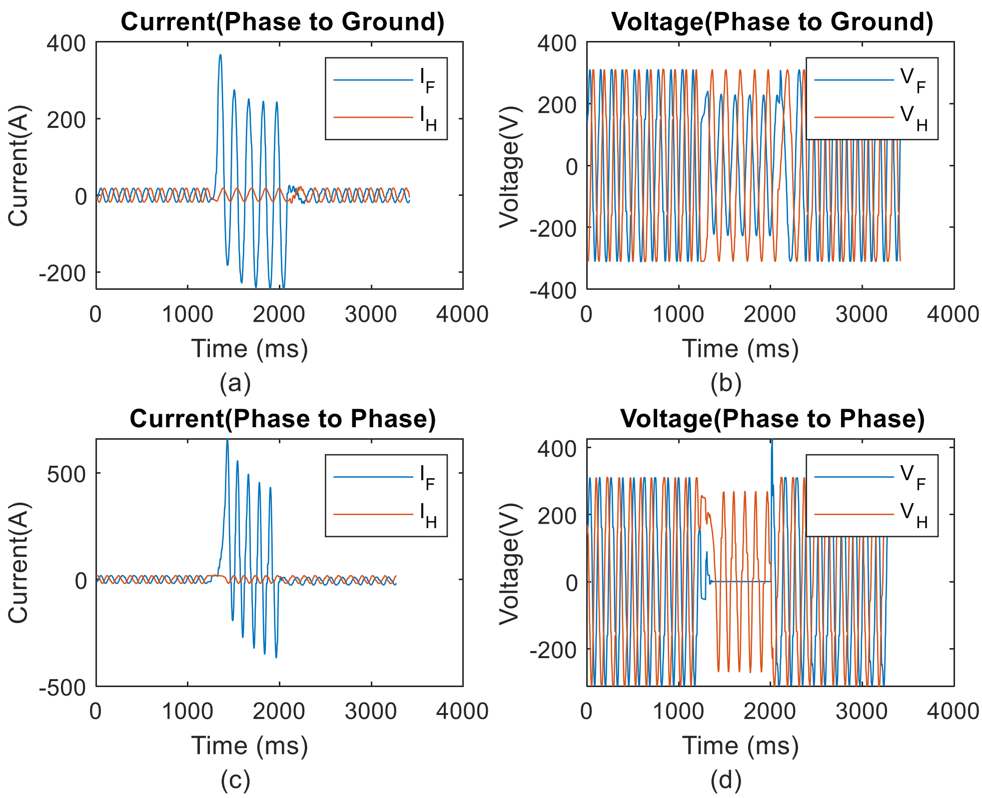

Figure 2. The voltage and current signals of the power system

3.2. Phase-to-Ground Fault

When a phase conductor in a power system comes into contact with the ground or any conducting device that is connected to the ground, an electrical defect known as a phase-to-ground fault takes place. An accidental connection between one of the energized phases and the grounding system is what distinguishes this issue. Some of the other causes include insulation breakage between the conductor and the ground if it is underground transmission. After the sample signal extraction, we applied all the Time-Frequency methods on the input signal to extract different fault features using STFT, HHT, and WT, which can be observed in Fig. 3a, Fig. 3b, and Fig.3c, respectively.

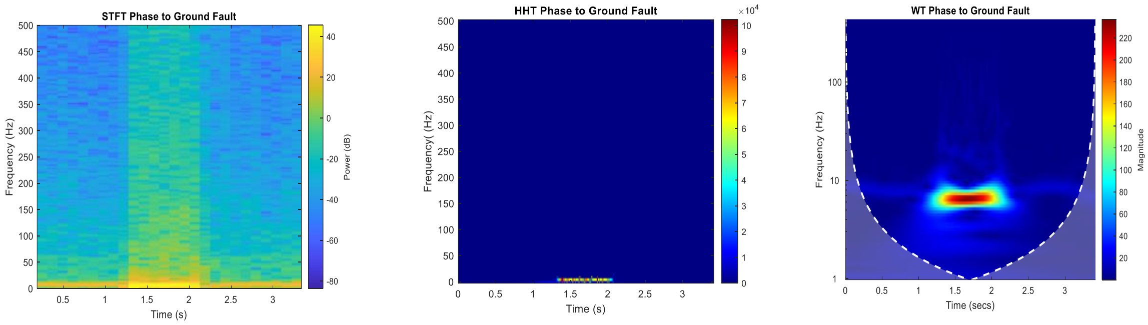

Figure 3a Figure 3b Figure 3c

Figure 3. The current signals of the phase-to-ground fault in the time-frequency domain

Fig.3a represents the energy levels of the normal as well as the faulty signals with STFT. It is observed that the change in energy levels from 20 to 40 with the introduction of fault in the system from 1.5-2 sec time in this figure. Fig.3b and Fig.3c the same phenomena are observed during fault time with abrupt rise in energy levels

3.3. Phase-to-Phase Fault

An unintentional electrical connection between two separate system phases is referred to as a phase-to-phase failure in a power system. In a three-phase power system, three conductor phases A, B, and C are used to transfer electrical power. Any direct short circuit or accidental connection between any two of these phases results in a phase-to-phase fault.
For this type of fault, we are creating phase-to-phase shortening and grounding in the Simulink and sampling the required signal. After, we analyzed the fault signal by inputting it into different time and frequency methods to extract instantaneous faults. The current signals of phase-to-phase fault in the time-frequency domain obtained by different time-frequency analysis methods can be seen in Fig. 4.

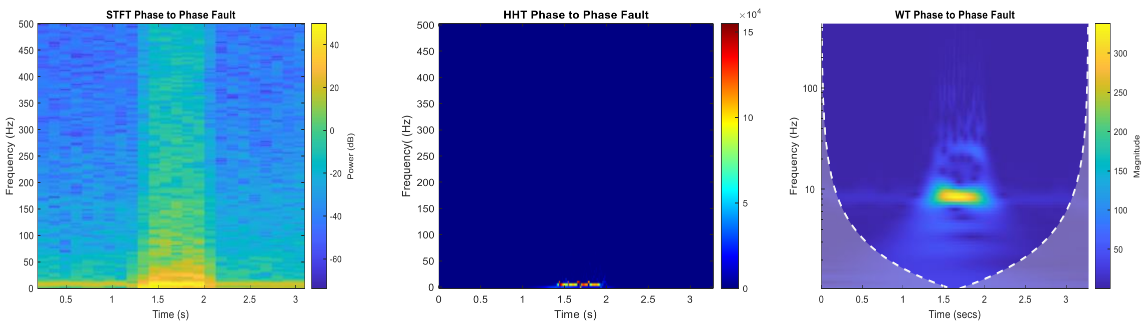

Figure 4. The current signals of the phase-to-phase fault in the time-frequency domain

In Fig.4, we can see the phenomena that were discussed in Fig. 3. Adding more to Fig.4, we can observe the energy levels are much higher than the phase-to-ground fault. So, this will differentiate between phase-to-phase and phase-to-ground faults.

The detection method employing the energy content of the processed defective signal as a performance index is seen in Table 1. The STFT, HHT, and WT are some of the signal processing transforms that are used to extract and handle the signal at the point of common coupling. After processing, the output waveform is utilized to calculate energy, which is then compared to a threshold value to determine whether the power system is malfunctioning or performing normally. It is observed that the HHT provides a larger energy value that can be a reliable method used to detect fault thresholds in the power system.

Table 1. Energy change percentages of current signals in faulty and healthy states

Fault Type	% Energy Levels		
	STFT	**WT**	**HHT**
Phase-to-Ground	51,16	84,43	86,61
Phase-to-Phase	53,19	86,98	91,6

By observing Table 1, we can see which method can be suitable to predict faults clearly. In our analysis, we can see that the HHT is giving higher changes than WT and the STFT is a fault indicator as well, but it is not a comprehensive method to diagnose faults in the power system.

4. Conclusion

This methodology uses a combination of time-frequency analysis techniques to gain a thorough understanding of power system failures. A comprehensive investigation of dynamic behaviors in phase-to-phase and phase-to-ground faults is made easier by the combination of the STFT, HHT, and WT methods. To help with fault localization, STFT detects transient occurrences, whereas HHT shows non-linear fault characteristics. Furthermore, WT improves fault signal analysis at several scales by identifying features at both low and high frequencies. Applying these techniques will increase the operational effectiveness of fault detection in power systems. Combined, these methods offer a strong fault diagnosis toolkit essential for guaranteeing the stability and dependability of electrical power networks. While our research integrates WT, HHT, and STFT to provide a comprehensive framework for fault detection, there are a few drawbacks. First off, the efficacy of the strategy could differ based on the features of the power system. Real-time implementation may be hampered by computational complexity, particularly in large-scale systems. Subsequent investigations ought to concentrate on enhancing computational effectiveness and verifying the methodology via comprehensive testing on actual systems. Examining how machine learning methods can be combined with time-frequency analysis could improve the precision of fault identification even more. By addressing these constraints and exploring these opportunities, fault detection techniques will progress, and power system reliability will increase.

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