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# Identification of Power Quality Disturbances in Electrical Systems - A Signal Processing Approach

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***Abstract: The Detection and Classification of Power Quality Disturbances (PQD) is important for quick diagnosis and mitigation disturbances. Poor power quality could have serious effects on sensitive electric devices. Consumers face difficulty to quantify the cost of failure equipment. There is a need to recognize and mitigate PQD to supply clean power to the consumer. In this Project PQDs simulated with MATLAB R2022b to be validated experimentally on a test bench using stepdown transformer***
***Keywords: Fast Fourier transform (FFT), Continuous Wavelet transform (CWT), Power Quality (PQ), Power Quality Disturbances (PQD).***

## I. INTRODUCTION

Nowadays, the emphasis is on improving the quality of electrical power and delivering it to the distribution end without Power Quality Disturbances (PQD), which have developed into a significant worry in an electric system. Recent technological advancements in solid-state devices, the spread of renewable energy sources, and non-linear loads have all increased the significance of PQ, “the concept of powering and grounding sensitive electronic equipment in a manner suitable for the equipment” [1].

PQD issues disrupt electrical and electronic equipment, which is often discovered using instrumentation methods. These PQD have a significant negative impact on expensive equipment like computers, production line control systems, etc. PQD issues include voltage sag and swells, different interruptions, noise, harmonics, transients, voltage fluctuation, and flickering. In general, the methods for identifying PQDs rely on the graphical analysis of voltage and current waveforms in the time and frequency domain [2].

Fault Detection is essential to describe for accuracy operation of fault mitigation devices. There are various methods to identifying power quality problems. The method to detect power quality discuss in this paper is Fast Fourier Transform. The FFT plays important roles in analysis, design and implementation of discrete signal processing. FFT algorithms are based on fundamental of discrete fourier computation. An FFT computes the DFT and produces exactly the same result as evaluating the DFT definition directly; the most important difference is that an FFT is much faster [3]. Likewise refined frequency techniques have been created. For instance, Wavelet transform (WT), stockwell transform (S-transform), and Hilbert Huang transform (HHT). S-transform is a variable window hybrid of STFT and WT. When the PQ disturbance occurs, WT can precisely identify a single event under non-stationary conditions. WT is capable of handling some acceptable levels of noise and has an appropriate frequency, focusing characteristics, and resolution. Different methods should be taken into consideration when setting up the WT. The Continuous Wavelet Transform (CWT) examines how a signal changes over time as various scaling factors are applied [4]. In this paper the real time and simulated PQ signal have been generate and the signal processing techniques like Fast Fourier Transform (FFT) and Continuous Wavelet Transform (CWT) have been applied for the identification of the power quality disturbances.

## II. THEORETICAL BACKGROUND

### *A. Fast Fourier Transform (FFT)*

The Fast Fourier Transform (FFT) is a mathematical algorithm used to convert a signal from the time domain to the frequency domain. It is a widely used tool for analysing signals and is used in a wide range of fields, including audio processing, telecommunications, and image processing.

The basic idea behind the FFT is to break down a signal into its component frequencies. This is done by analysing the signal over a specific time interval and looking at how its amplitude changes over time. The signal is then divided into a number of smaller sections, each of which is analysed separately. These sections are called "frames" or "windows."

X(k) = Σ_{n=0}^{N-1} x(n) * e^(-i * 2π * k * n / N) (1) Where:

X(k) represents the frequency component at index k in the frequency spectrum.

Σ_{n=0}^{N-1} represents the sum of values from 0 to N-1, where N is the length of the input signal.
x(n) represents the amplitude of the input signal at index n.
e^(-i * 2π * k * n / N) represents a complex exponential function with a frequency of k/N. This function is used to weight each input value based on its position in the signal.
The FFT algorithm performs this calculation for each frequency component in the spectrum, from 0 to N-1. The resulting frequency spectrum shows the strength of each frequency component in the input signal.
Once the signal is divided into windows, the FFT is applied to each window individually. The FFT algorithm computes the frequency spectrum of the window, which gives a measure of the strength of each frequency component present in the window. This is done by performing a series of mathematical operations on the data in the window.
The output of the FFT is a graph of frequency versus magnitude, which is called a frequency spectrum or power spectrum. The x-axis represents frequency, and the y-axis represents the magnitude of each frequency component. The FFT can provide important information about the frequency content of a signal, such as which frequencies are present and how strong they are. Thus, the FFT is used to analyse a wide range of signals, including audio signals, images, and biomedical signals. For example, the FFT can be used to analyse the frequency content of an audio signal to determine which notes are being played or to identify noise in the signal. It can also be used to analyse the frequency content of an image to identify specific features or patterns. In biomedical research, the FFT can be used to analyse the frequency content of physiological signals such as electroencephalogram (EEG) and electrocardiogram (ECG) signals to detect abnormalities or identify specific features.

### *B. Continuous Wavelet Transform (CWT*

Continuous Wavelet Transform (CWT) is a mathematical tool used for signal analysis that provides time-frequency representation of signals. It is particularly useful for analysing non-stationary signals, such as transients. The CWT is computed by changing the scale of the analysis window and shifting the window in time, multiplying the signal with the mother wavelet, and integrating over all times.
The CWT uses a wavelet function, called the mother wavelet, which is dilated and shifted to analyse the signal at different scales and times. The CWT provides a continuous time-frequency analysis, which means that it provides a high-resolution representation of the signal in both time and frequency domains. The CWT is more computationally expensive than the Discrete Wavelet Transform (DWT), but it provides a higher resolution time-frequency analysis. The formula for Continuous Wavelet Transform:

$$CWT(a,b) = (1/\sqrt{|a|}) \int h(t)\, \Psi^* [(t-b)/a]\, dt \qquad (2)$$

Where h(t) is the input signal, Ψ(t) is the mother wavelet, a and b are dilation and translation parameters, respectively, and * denotes the complex conjugate.
The CWT is a mathematical tool used to analyse various types of signals, including audio, images, and biomedical signals. It provides a time-frequency representation of the signal that shows the strength of the signal at different scales and shifts. The CWT is particularly useful for analysing non-stationary signals, such as transient signals, and provides a high-resolution representation of the signal in both time and frequency domains.
By selecting an appropriate mother wavelet and adjusting the dilation and translation parameters, the CWT can be used to analyse signals with different characteristics and properties. For example, the CWT can be used to detect and analyse transient events in audio signals, identify features in biomedical signals, and extract texture and edge information from images. In summary, the FFT and CWT are two powerful mathematical tools used for signal analysis that provide important information about the frequency content and time-frequency representation of a signal, respectively. While the FFT is more commonly used for stationary signals, the CWT is particularly useful for analysing non-stationary signals and providing a high-resolution timefrequency analysis.

## III. SIMULATION RESULTS DISCUSSION

In this study, five Power Quality Disturbance (PQD) signals have been simulated using MATLAB. PQD signals are sag, swell, interruption, transient, fluctuation. Detailed simulation results along with discussion are provided in the following subsections.

### *A. Pure Voltage Signal*

Fig. 1(a) displays the normal sinusoidal voltage signal generated for 0.5 sec. Figure 1(a) Pure voltage signal. The proposed FFT and CWT is obtained by the complex-valued analytic signal output of the input signal.

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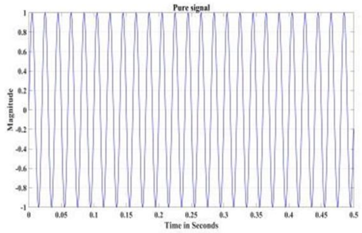
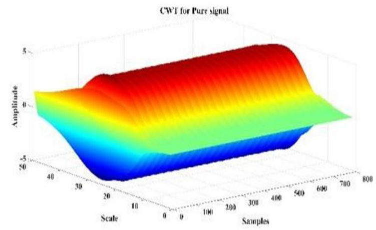


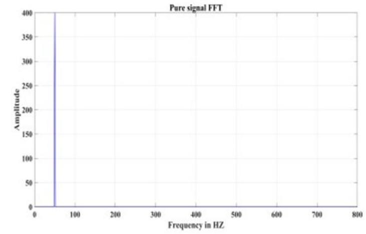




Figure 1(a Pure voltage signal      Figure 1(b) & 1(c) CWT of pure voltage signal-3D view & FFT of pure signal

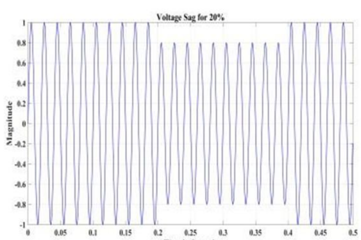
The FFT and CWT for the pure voltage signal are delineated in Fig. 1(b) and Fig. 4.1(c). It is seen from the Figures that, absence of PQD in the signal results in no disturbances observed from the above figures.

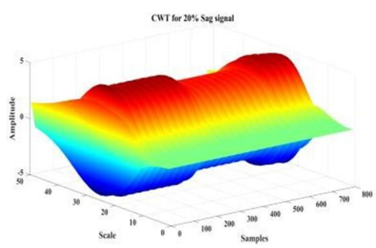
### *B. Voltage Sag*

A sag is demarcated as, “a short duration (half a cycle to 1 min) decrease in the supply voltage between 0.1 p.u. and 0.9 p.u. at rated frequency” . The main reasons for sags are a huge increase in currents owing to faults or high starting inrush currents and sudden change in system impedance.

Fig. 2(a) shows voltage signal generated for 0.5 sec with 20% sag is simulated from 0.2 sec to 0.4 sec.

| Sag disturbance equation and its Parameter | |
|---|---|
| Equation | $A\,(1 - \alpha\,(\mu\,(t - t1) - \mu\,(t - t2)))\,\sin(\omega t)$ |
| Parameter | $0.1 < \alpha < 0.9,\ T \le t2 - t1 \le 9T$ |



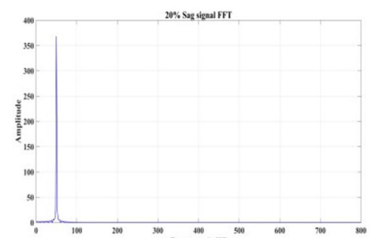




Figure 2(a) Voltage signal with sag      Figure 2(b) & 2(c) CWT of voltage signal with sag-3D view & FFT of sag signal

The FFT and CWT for the sag voltage signal are delineated in Fig. 2(b) and Fig. 2(c). It is seen from the Figures that, the sag disturbance is clearly observed from above techniques. In FFT the magnitude of the spike at 50Hz frequency have been decreased as compared to pure signal and we can observe a dip in the CWT which represents sag.

### *C. Voltage Swell*

A swell is well-defined as, “a short duration (few cycles to one min) increase in the voltage between 1.1 p.u. and 1.8 p.u. at rated frequency”. The reasons for voltage swell are abrupt dismissal of load and slackening of neutral association. Fig. 3(a) represents the voltage signal generated for 0.5 sec and a 25% swell is simulated from 0.2 sec to 0.4 sec.

| Swell disturbance equation and its Parameter | |
|---|---|
| Equation | $A(1 + \alpha(\mu(t - t1) - \mu(t - t2)))\sin(\omega t)$ |
| Parameter | $0.1 < \alpha < 0.9,\ T \le t2 - t1 \le 9T$ |

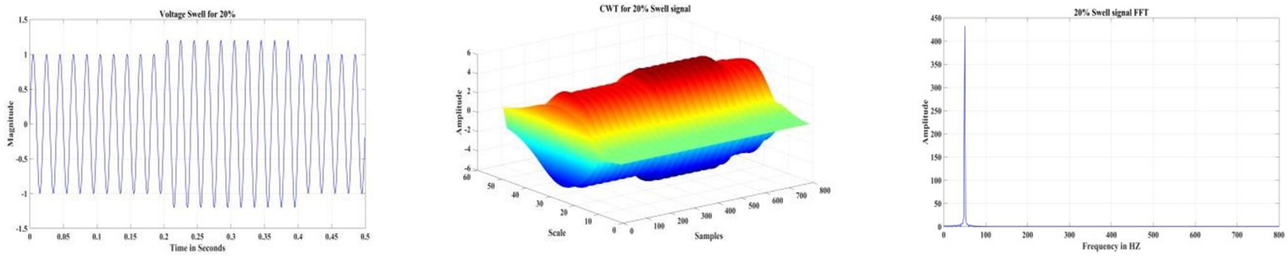



Figure 4(a) Voltage signal with swell Figure 4(b) & 4(c) CWT of voltage signal with Swell-3D view & FFT of Swell signal

The FFT and CWT for the swell voltage signal are delineated in Fig. 3(b) and Fig. 3(c). It is seen from the Figures that, the swell disturbance is clearly observed from above techniques. In FFT the magnitude of the spike at 50Hz frequency have been increased as compared to pure signal and we can observe the uphill in the CWT which represents swell**.**

### *D. Voltage Interruption*

Interruption is demarcated as, "the decrease in voltage less than 0.1 p.u. or a total loss of voltage. They are sorted as instantaneous (1/2 cycle to 3 sec), temporary (3 sec to 1 minute) or sustained (more than 1 minute)". Fig. 4(a) depicts the voltage signal generated for 0.5 sec and a voltage interrupt (instantaneous type) is simulated from 0.2 to 0.4 sec.

| Interruption disturbance equation and its Parameter | |
|---|---|
| Equation | $A(1 - \alpha(\mu(t - t1) - \mu(t - t2))) \sin(\omega t)$ |
| Parameter | $0.1 < \alpha < 0.9$, $T \leq t2 - t1 \leq 9T$ |

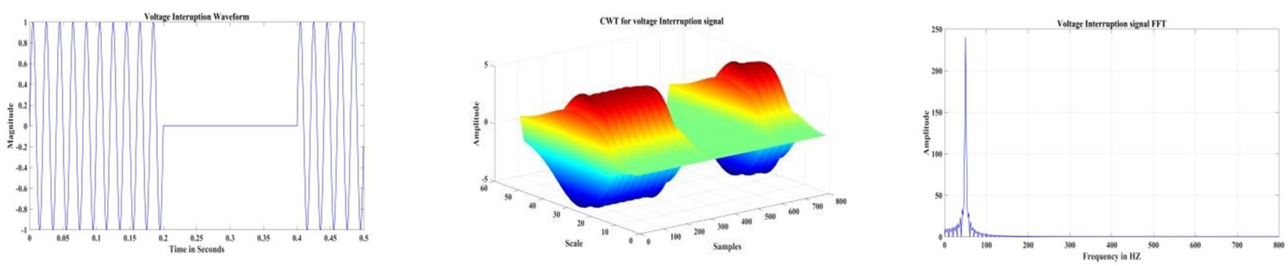



Figure 4(a) Voltage signal with Interruption

Figure 4(b) & 4(c) CWT of voltage signal with Interruption-3D view & FFT of interruption signal

The FFT and CWT for the voltage signal with interruption are delineated in Fig. 4(b) and Fig. 4(c). It is seen from the Figures that, the interruption disturbance is clearly observed from above techniques. In FFT the magnitude of the spike at 50Hz frequency have been decreased as compared to pure signal as well as sag signal and we can observe the flat in middle of the signal in CWT which represents interruption.

### *E. Transient*

A transient voltage is defined as, "a transient can be a unidirectional impulse of either polarity or a damped oscillatory wave with the first peak occurring in either polarity". Repeatable transients are caused by operation of motors, switching reactive power devices, etc. Fig. 5(a) depicts the signal generated for 0.5 sec and a transient is simulated twice.

| Interruption disturbance equation and its Parameter | |
|---|---|
| Equation | $y(t) = \sin(\omega t) + \alpha^{-(t-t1)/T} \sin \omega n(t - t_1)$ |
| Parameter | $0.1 < \alpha < 0.8$, $0.5T \leq t2 - t1 \leq 3T, 8ms \leq T \leq 40ms$ |

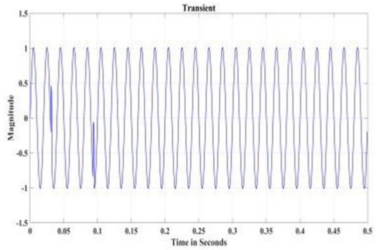
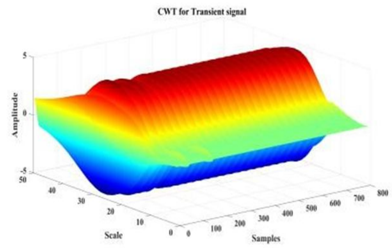



Figure 5(a) Voltage signal with Transient



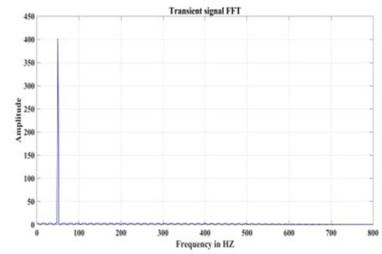




Figure 5(b) & 5(c) CWT of voltage signal with Transient-3D view & FFT of Transient Signal

The FFT and CWT for the Transient are delineated in Fig. 5(b) and Fig. 5(c). It is seen from the Figures that, the Transient disturbance is clearly observed from above techniques. In FFT the very small spikes along the signal is observed and we can observe the two uneven spikes in the signal in CWT which represents transient.

## IV. HARDWARE RESULTS

A test bed was created to experimentally validate the role of power signal identification in detecting power quality disturbances (PQD). The experiment was conducted on a 230V, 50 Hz, single-phase step-down transformer with outputs tapped at 3V, 6V, 12V, 15V, and 18V, with a current rating of 3A. The acquired signals were captured using a 10:1 voltage probe, which was connected to Edux1002A. The signals were acquired at a sampling frequency of 2kHz and visualized in real-time on a laptop screen using Keysight Technologies Software tool.

To analyze the PQD, the procured signals were processed using two techniques: Fast Fourier Transform and Continuous Wavelet Transform based Signal Processing. These techniques were implemented using MATLAB R2023b and adhered to the IEEE Std. 1159-1995 standard for power quality analysis.

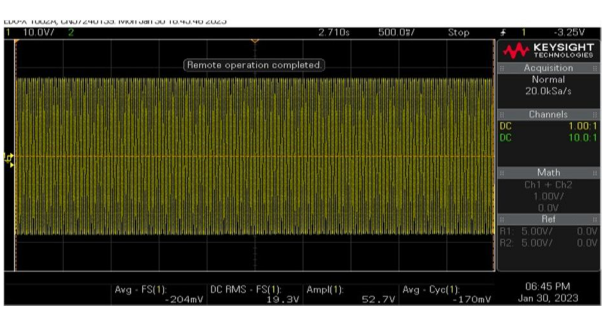
The Fast Fourier Transform was used to convert the time-domain signals into the frequency-domain, allowing for the identification of the frequency components present in the signal. The output of the FFT was a graph of frequency versus magnitude, which is called a frequency spectrum or power spectrum. By analyzing the power spectrum, it was possible to identify the presence of PQD and determine their frequency and magnitude.

The Continuous Wavelet Transform was used to analyse the PQD events in the time-frequency domain. This technique allowed for the identification of the exact time and frequency location of the PQD events, providing more detailed information about their characteristics.

Overall, the experimental setup and data processing techniques used in this study provided an effective means of detecting and analysing PQD in power systems. The results obtained from this study can be used to improve power quality monitoring and maintenance in the future, ultimately leading to more reliable and efficient power systems.

### *A. Normal Voltage Signal*

Fig. 6(a) and Fig. 6(b) show snapshot and power signal output from the secondary of a transformer for the duration of 5sec with an rms of 18 volts. The proposed FFT and CWT is obtained by the complex-valued analytic signal output of the input signal.



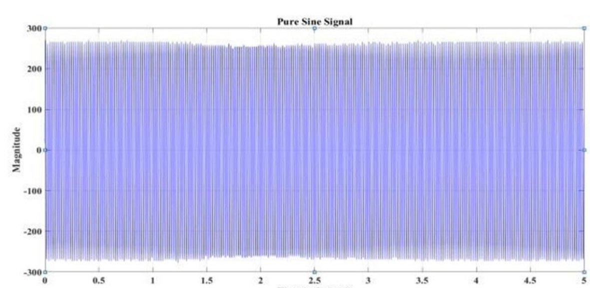




Figure 6(a) & 6(b) Normal voltage snapshot and signal

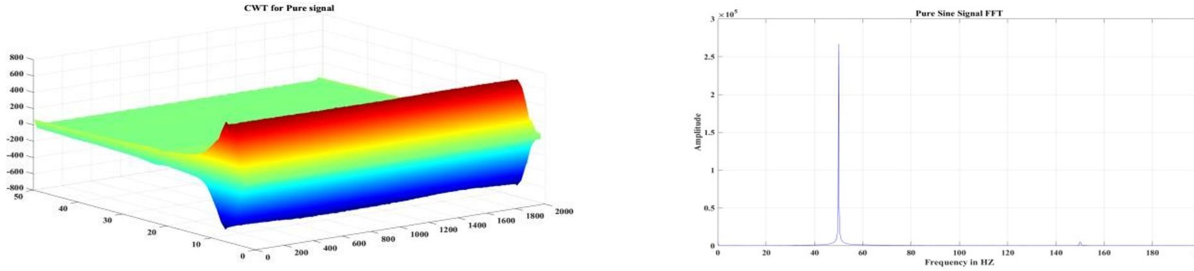



Figure 6(c) & 6(d) CWT of Normal voltage signal – 3D view & FFT of Normal voltage signal

The FFT and CWT for the pure voltage signal are delineated in Fig. 6(c) and Fig.6 (d). It is seen from the Figures that, absence of PQD in the signal results in no disturbances observed from the above figures. The real-time pure voltage signal analysed through FFT and CWT provides valuable insights into the frequency and time-frequency characteristics of the signal, aiding in the identification of any potential power quality disturbances

## *B. Voltage Sag*

Fig. 7(a) and Fig. 7(b) show snapshot and voltage signal output from the secondary of a transformer for a duration of 5 seconds, with a root-mean-square (rms) value of 18 volts, and 20% sag is observed during 1.9 to 3.3 sec. The complex-valued analytic signal output of the input signal is used to obtain the proposed FFT and CWT, as shown in Fig. 6(c) and Fig. 6(d), respectively.

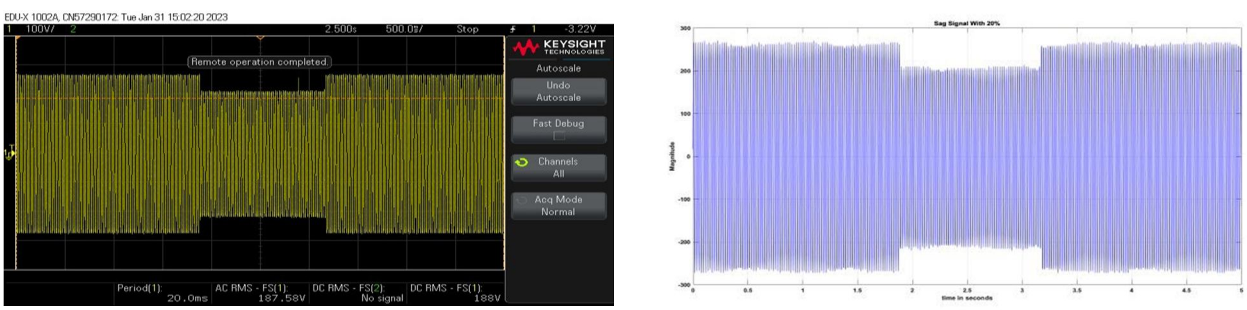



Figure 7(a) & 7(b) Voltage with sag – Snapshot & Signal

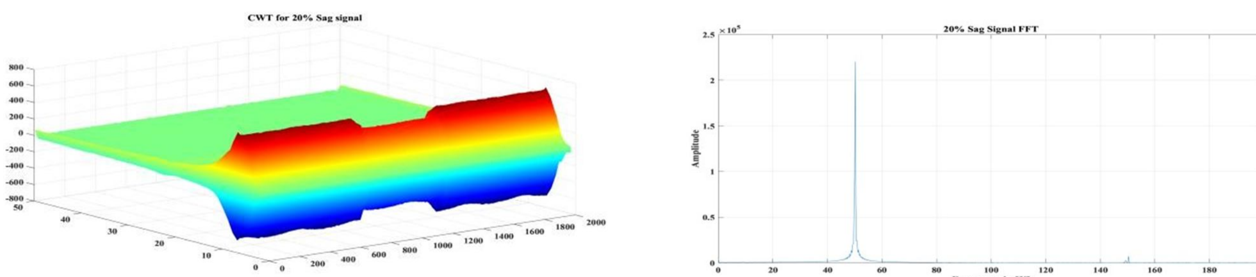



Figure 7(c) & 7(d) CWT of voltage with sag signal – 3D view & FFT of voltage with sag signal

The voltage sag disturbance is clearly visible in the FFT, where the magnitude of the spike at the fundamental frequency (50 Hz) is reduced as compared to the pure signal, indicating a reduction in the signal strength. Additionally, a dip in the CWT is observed at the time when the voltage sag occurs, highlighting the time-frequency characteristics of the signal.

Real-time analysis of voltage signals using FFT and CWT can provide valuable insights into power quality disturbances, aiding in the early detection and diagnosis of potential issues.

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### *C. Voltage Swell*

Fig. 8(a) and Fig. 8(b) display the snapshot and voltage signal output from the secondary of a transformer for a duration of 5 seconds, with a root-mean-square (rms) value of 14 volts and a voltage swell of 20% at 2.1 seconds. The complex-valued analytic signal output of the input signal is utilized to obtain the proposed FFT and CWT, as shown in Fig. 8(c) and Fig. 8(d), respectively.

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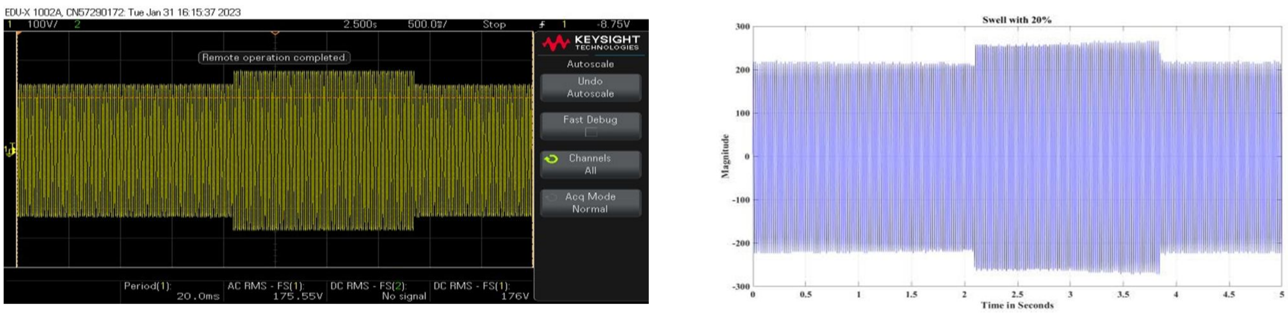


Figure 8(a) & 8(b) Voltage with swell – Snapshot & Signal

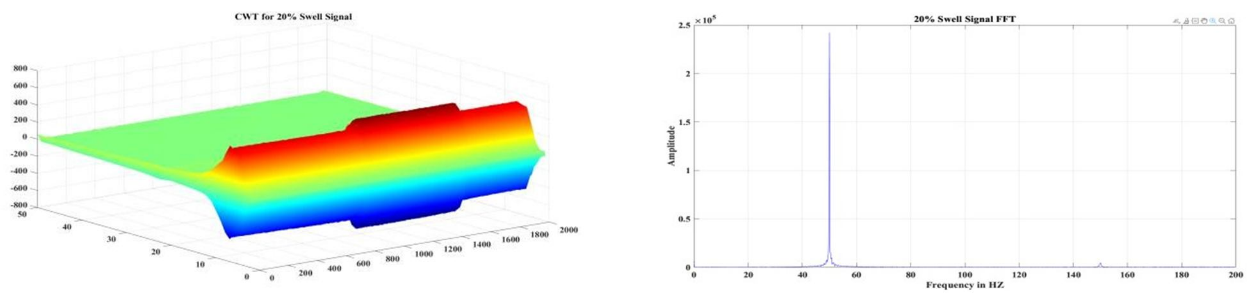


Figure 8(c) & 8(d) CWT of voltage with swell signal – 3D view & FFT of voltage with swell signal

The voltage swell disturbance is evident in the FFT, where the magnitude of the spike at the fundamental frequency (50 Hz) is increased compared to the pure signal, indicating an increase in signal strength. A uphill in the CWT is observed at the time when the voltage swell occurs, highlighting the time-frequency characteristics of the signal.

Real-time analysis of voltage signals using FFT and CWT can provide valuable insights into power quality disturbances, aiding in the early detection and diagnosis of potential issues.

### *D. Voltage Interruption*

Fig. 9(a) and Fig. 9(b) show a snapshot and voltage signal output from the secondary of a transformer for a duration of 1 second, with a root-mean-square (rms) value of 18 volts. An interruption was created in the signal, causing a drop in voltage from 18 volts to 0 volts during the period of 2 to 3 seconds. The complex-valued analytic signal output of the input signal is used to obtain the proposed FFT and CWT, as shown in Fig. 9(c) and Fig. 9(d), respectively.

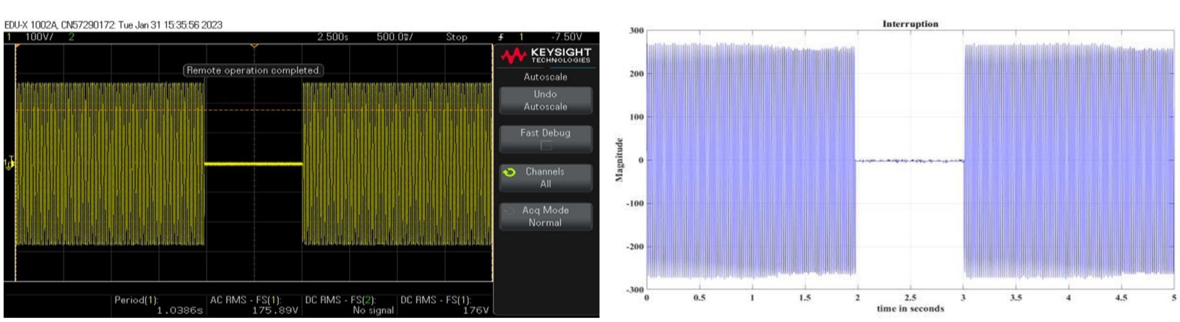


Figure 9(a) & 9(b) Voltage with Interruption – Snapshot & Signal

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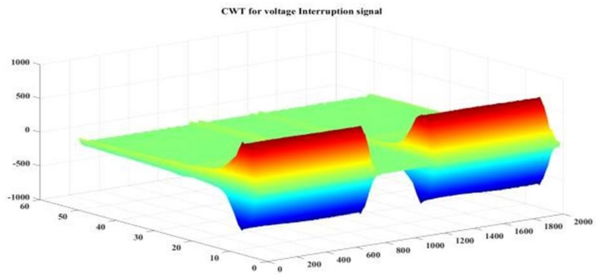


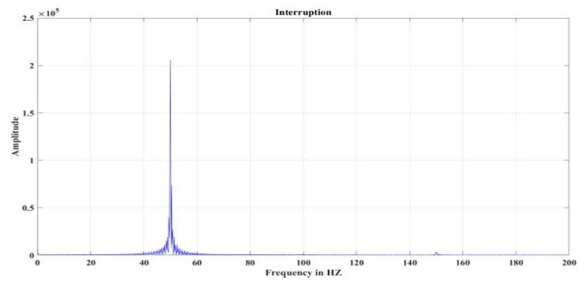



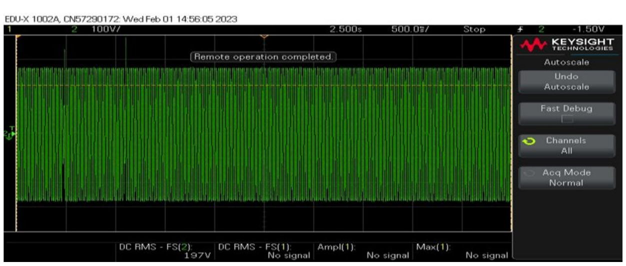

Figure 9(c) & 9(d) CWT of voltage with Interruption signal – 3D view & FFT of voltage with Interruption signal

The interruption disturbance is clearly visible in both the FFT and CWT. In the FFT, the magnitude of the spike at the fundamental frequency (50 Hz) is completely diminished during the period of the interruption, indicating a complete loss of signal strength. Additionally, in the CWT, a complete absence of signal power is observed during the period of the interruption. Real-time analysis of voltage signals using FFT and CWT can provide valuable insights into power quality disturbances, aiding in the early detection and diagnosis of potential issues. Interruptions in voltage signals can lead to significant problems in power systems, and the ability to detect and diagnose them early can help prevent or mitigate their effects.

## V. VOLTAGE TRANSIENT

Fig. 10(a) and Fig. 10(b) illustrate a snapshot and voltage signal captured in the presence of sampling noise for a duration of 5 seconds, with a root-mean-square (rms) value of 18 volts. In this case, a transient occurs at 0.8 seconds by deliberately shorting a few turns of the secondary of a transformer. The complex-valued analytic signal output of the input signal is used to obtain the proposed FFT and CWT, as shown in Fig. 10(c) and Fig. 10(d), respectively.

Sampling noise can introduce unwanted artifacts into voltage signals, making it challenging to detect and diagnose power quality disturbances. However, real-time analysis of voltage signals using FFT and CWT can provide valuable insights into the frequency and time-frequency characteristics of the signal, even in the presence of noise.



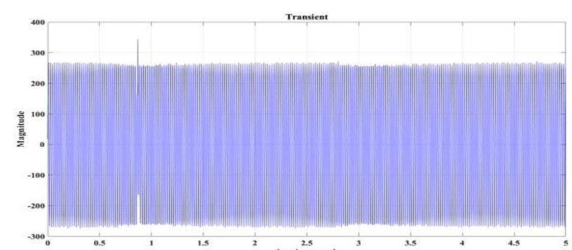
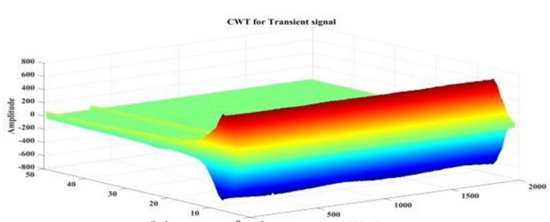




Figure 10(a) & 10(b) Voltage with Transient – Snapshot & Signal



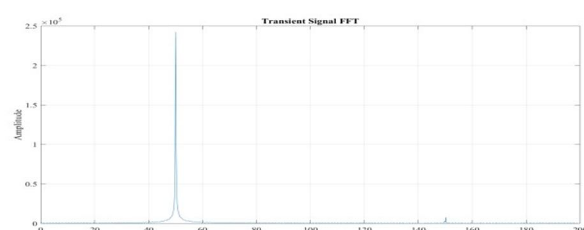




Figure 10(c) & 10(d) CWT of voltage with Transient signal – 3D view & FFT of voltage with Transient signal

The transient disturbance caused by the short circuit is visible in both the FFT and CWT. In the FFT, the magnitude of the spike at the fundamental frequency (50 Hz) is reduced, indicating a reduction in the signal strength during the transient. Additionally, a sharp peak is observed at the time of the transient in the CWT, highlighting the time-frequency characteristics of the signal. It is essential to consider the impact of sampling noise on voltage signals when studying power quality disturbances. The use of advanced signal processing techniques, such as FFT and CWT, can provide valuable insights into the behaviour of voltage signals, aiding in the early detection and diagnosis of potential issues.

## VI. TEST BENCH SETUP

Fig. 16 Picture of Test Bench Setup for Real Time Signal Acquisition

## VII. CONCLUSION

This research paper demonstrated the role of power signal identification in detecting and analysing power quality disturbances (PQD) in a step-down transformer. An experimental test bed was created to simulate PQD events, and the acquired signals were processed using Fast Fourier Transform and Continuous Wavelet Transform based Signal Processing techniques. The results obtained from this study showed that these techniques were effective in identifying the frequency and magnitude of PQD events and providing more detailed information about their characteristics in the time-frequency domain. The study highlights the importance of power quality monitoring and maintenance in power systems. By using the techniques presented in this study, power system engineers can identify and analyse PQD events, ultimately leading to more reliable and efficient power systems. Future research can build upon these findings to develop more sophisticated techniques for power quality analysis, leading to even better power system performance.

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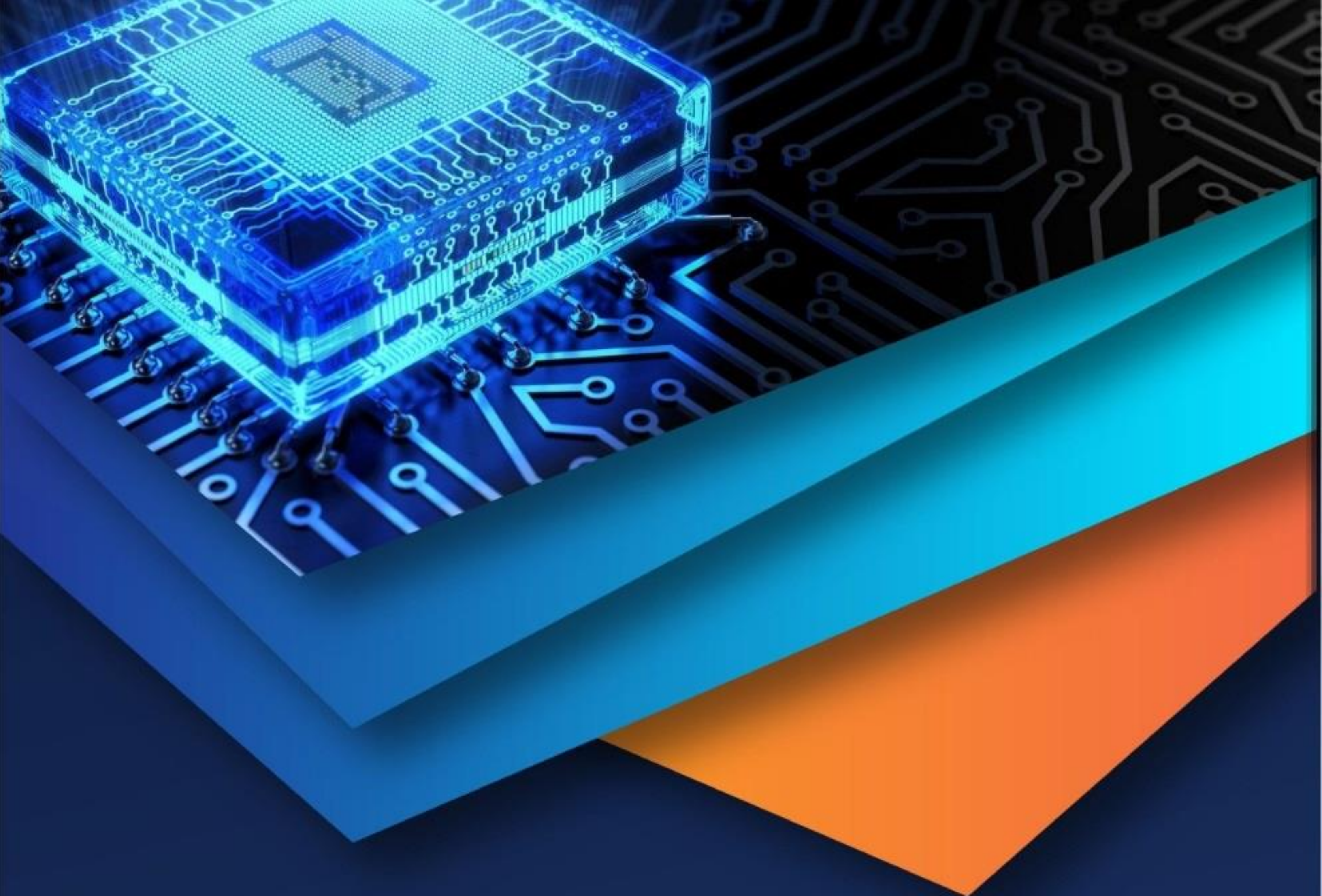

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