Power Quality Analysis Using Spectrogram and Gabor Transformation

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***Abstract* -** This paper discusses the implementation of time-frequency analysis techniques to analyze power quality disturbances. The approached methods are spectrogram and Gabor transform algorithms. Signal parameters such as time marginal and frequency marginal are extracted from the time-frequency distributions. The parameters are analyzed in terms of correctness measurement of root mean square (RMS), total harmonic distortion (THD), total waveform distortion (TWD) and total interharmonic distortion (TnHD) values. Power quality events that are analyzed are swell, sag, interruption, harmonic, interharmonic, transient, notching and normal voltage. The results show that Gabor transform provides better performance in terms of correctness of parameters measurement, window length, frequency resolution and memory size.

Keywords: Power Quality Disturbances; Spectrogram; Gabor; Time-Frequency Analysis

1. Introduction

Power Quality is the availability of pure sinusoidal voltage and current waveforms at 50 Hz (frequency power-line in Malaysia) without any disturbances at the incoming point of the supply system. Power quality problem is any problem manifested in voltage, current or frequency deviations with results in the failure or disoperation of end-use equipment [1], [2]. With the rapid advance in industrial applications that rely on sophisticated electronic devices, a demand for power quality and reliability has become a great concern. Power quality problems can cost business billions of dollars each year in lost revenue, process improvement and scrapped product. Major causes of power quality related revenue losses are interrupted manufacturing processes and computer network downtime [3].

Conventional techniques that are currently used for power quality monitoring are based on visual inspection of voltage and current waveforms [4]. The available equipment in the market for the inspection can capture and print the power quality data only at the current time. Therefore, a computerized and automated technique for monitoring and analysis of power quality waveforms are very important to provide improvement in power system's infrastructure.

Many techniques were presented by various researchers for analyzing or classifying power quality problems [5]-[7]. However, this paper looks at the use of time-frequency analysis techniques to analyze power quality problems. Spectrogram and Gabor transform algorithms are proposed and signal parameters are extracted based on their time-frequency characteristics. The performance of both algorithms are analyzed and compared to perform power quality classifications.

2. Power Quality Events

Power quality events refer to a wide variety of electromagnetic phenomena that characterize the voltage and current at a given time and at a given location on the power system. According to the International Electrotechnical Commission (IEC), electromagnetic phenomena are classified into several groups as shown in Table 1 [10], [11]. This paper focused on seven types of power quality problems: voltage swell, voltage sag, interruption, harmonic, interharmonic, transient and notching.

Table 1: Categories and typical characteristics of power system electromagnetic phenomena.

Categories	Typical spectral content	Typical duration	Typical voltage magnitude
1.0 Transients			
1.1 Impulsive	5 ns rise	< 50 ns	
1.2 Nanosecond	1 ms rise	50 ns-1 ms	
1.3 Millsecond	0.1 ms rise	> 1 ms	
1.2 Oscillatory			
1.2.1 Low frequency	< 5 kHz	0.3-50 ms	0-4 pu
1.2.2 Medium frequency	5-500 kHz	20 ms	0-8 pu
1.2.3 High frequency	0.5-5 MHz	5 ms	0-4 pu
2.0 Short duration variations			
2.1 Instantaneous			
2.1.1 Sag		0.5-30 cycles	0.1-0.9 pu
2.1.2 Swell		0.5-30 cycles	1.1-1.8 pu
2.2 Momentary			
2.2.1 Interruption		0.5 cycles-3s	< 0.1 pu
2.2.2 Sag		30 cycles-3 s	0.1-0.9 pu
2.2.3 Swell		30 cycles-3 s	1.1-1.4 pu
2.3 Temporary			
2.3.1 Interruption		3 s-1 min	< 0.1 pu
2.3.2 Sag		3 s-1 min	0.1-0.9 pu
2.3.3 Swell		3 s-1 min	1.1-1.2 pu

3.0 Long duration variations			
3.1 Interruption, sustained		> 1 min	0.0 pu
3.2 Undervoltages		> 1 min	0.8-0.9 pu
3.3 Overvoltages		> 1 min	1.1-1.2 pu
4.0 Voltage imbalance		steady state	0.5-2%
5.0 Waveform distortion			
5.1 DC offset		steady state	0-0.1%
5.2 Harmonics	0-100th H	steady state	0-20%
5.3 Interharmonics	0-6 kHz	steady state	0-2%
5.4 Notching		steady state	
5.5 Noise	broad-band	steady state	0-1%
6.0 Voltage fluctuations	< 25 Hz	Intermittent	0.1-7%
7.0 Power frequency variations		< 10 s	

3. Time-Frequency Analysis Techniques

Time-frequency analysis techniques present a three-dimensional plot of a signal in terms of the signal energy or magnitude with respect to time and frequency [8]. This study focused on spectrogram and Gabor transform to perform time-frequency of power quality events.

3.1 Spectrogram

The spectrogram is the result of calculating the frequency spectrum of windowed frames of a compound signal [9], [10]. The spectrogram time-frequency representation is calculated as follows:

$$P_x[n,k] = \frac{1}{M}\left|\sum_{m=0}^{M-1} x[m]\, w[m-n]\, e^{-j\frac{2\pi km}{M}}\right|^2 \qquad (1)$$

$$0 \le n \le N-1 \text{ and } 0 \le k \le M-1$$

$x(n)$ is the input signal, $w(n)$ is the window function, N is the number of samples and M is the window length.

3.2 Gabor Transform

Let a signal $s[k]$ and an analysis window function $\gamma[k]$ is all periodic with same period L [8]. Then,

$$C_{m,n} = \sum_{k=0}^{L-1} s[k]\gamma^{*}_{m,n}[k] \qquad (2)$$

$$\gamma_{m,n}[k] = \gamma[k - m\Delta M]e^{j\frac{2\pi n\Delta Nk}{L}} \qquad (3)$$

Where ΔM and ΔN are the time and the frequency sampling interval lengths while M and N are the numbers of sampling points in the time and frequency domains, respectively, $M \cdot \Delta M = N \cdot \Delta N = L$, $MN \ge L$ (or $\Delta M \Delta N \le L$). The coefficients $C_{m,n}$ are called the discrete Gabor transform (DGT) of the signal $s[k]$.

4. Parameter Estimation

4.1 Time and Frequency Marginal

Integration of the time frequency distribution over frequency gives the instantaneous power and power spectrum. The instantaneous power known as time marginal and the power spectrum known as frequency marginal are calculated in (4) and (5) respectively:

$$Z[n] = \sum_{k=0}^{M-1} TF[n,k] \qquad (4)$$

$$Z[k] = \sum_{n=0}^{N-1} TF[n,k] \qquad (5)$$

4.3 Root Mean Square (RMS)

From the time marginal in (4), RMS value in time can be defined as below:

$$X(n)_{rms} = \sqrt{Z[n]} \qquad (6)$$

N is the number of samples and M is the window length.

4.4 Total Harmonic Distortion (THD)

THD is a commonly used power quality index to quantify the distortion of a waveform. The THD is defined as the relative signal energy present at nonfundamental frequencies, written as:

$$\text{THD} = \frac{\sqrt{\sum_{h=2}^{H} V_h^2}}{V_1} \qquad (7)$$

4.5 Total Waveform Distortion (TWD)

Waveform distortion includes all deviations of the voltage waveform from the ideal sine wave. The distortion consists of harmonic and interharmonic distortion. The TWD is calculated as:

$$\text{TWD} = \frac{\sqrt{V_{rms}^2 - V_1^2}}{V_1} \qquad (8)$$

4.6 Total nonharmonic Distortion (TnHD)

TnHD is also referred to as total interharmonic distortion due to difficulty in distinguishing between interharmonic and noise. Interharmonics are signal components frequencies that are not integer multiples of the power system frequency. The TnHD can be defined as:

$$\text{TnHD} = \frac{\sqrt{V_{rms}^2 - \sum_{h=0}^{H} V_h^2}}{V_1} \qquad (10)$$

5. Results

Analysis results were obtained from the time-frequency distributions of power quality signals using both spectrogram and Gabor transform algorithms. Time marginal and frequency marginal are extracted from the time-frequency distributions. The parameters that are analyzed are RMS, THD, TWD and TnHD values.

5.1 Spectrogram Results

Figure 1a-d illustrates the results for voltage swell using spectrogram technique. Voltage swell can be characterized by the increase of amplitude level in voltage per unit (Vpu). Figure 1a shows the momentary increase of magnitude in the voltage signal. The spectrogram representation of the voltage swell is shown in Figure 1b. The highest power is represented in red colour, while the lowest is represented by blue colour. The figure shows that the voltage swell occurs in the time-frequency distribution during 40 to 120 milliseconds.

Figure 1c shows the time marginal of voltage swell, extracted from the spectrogram. It shows that the voltage magnitude increases up to 1.45 Vpu from 0.01 to 0.15 milliseconds. Figure 1d observes that the frequency marginal of the voltage swell lies at 50 Hz, while Figure 1e detects that the RMS magnitude from the spectrogram increases up to 1.2 V_{rms}pu compared to unit value .

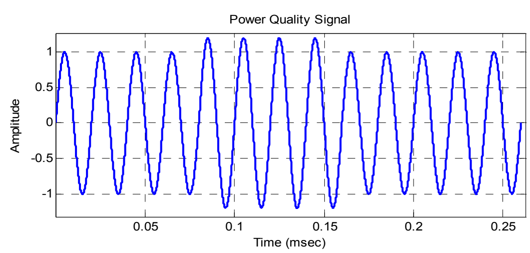

Figure 1a: Voltage swell.

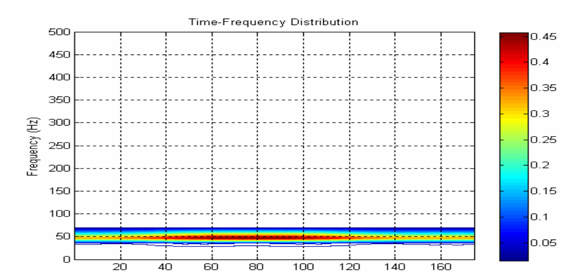

Figure 1b: Time-frequency representation using Spectrogram.

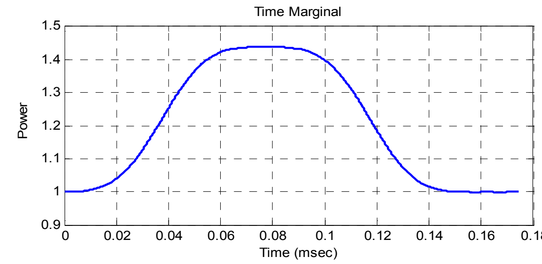

Figure 1c: Time Marginal from Spectrogram.

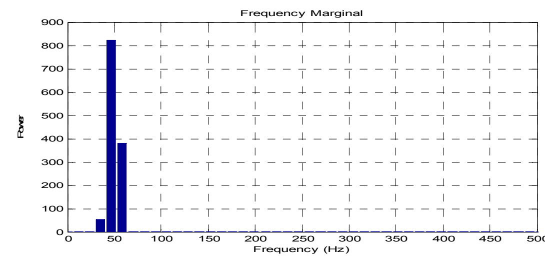

Figure 1d: Frequency Marginal from Spectrogram.

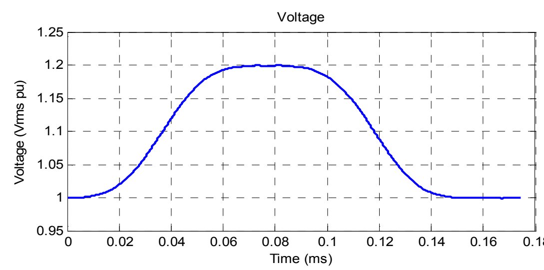

Figure 1e: Voltage ($V_{rms\ pu}$) from Spectrogram.

5.2 Gabor Transform Results

The power quality disturbances were also tested using Gabor transform. The example of harmonic event and its results can be seen in Figure 2a-d. Harmonic signal is defined by sinusoidal voltages or currents having frequencies that are multiples of its fundamental frequency.

Figure 2a shows that the voltage signal is having some waveform distortions. Figure 2b detects a nonfundamental frequency at 300 Hz in the time-frequency axis by using Gabor transform.

Figure 2c shows the time marginal, which points out that the magnitude of powers per unit signal is higher than unit value. The frequency marginal in Figure 2d points out the sixth harmonic event occurred at 300 Hz. Figure 2e shows that the magnitude of V_{rms}pu is higher than unit value on the time observed.

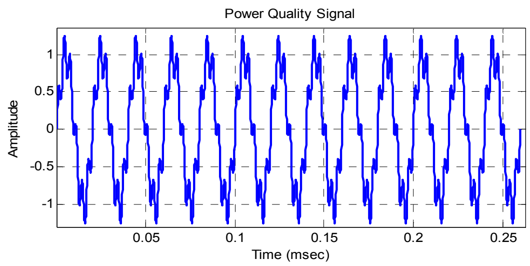

Figure 2a: Harmonic signal.

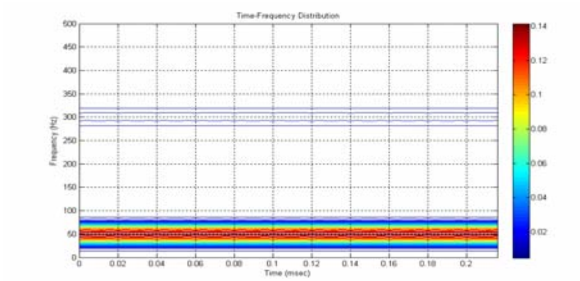

Figure 2b: Time-frequency representation using Gabor.

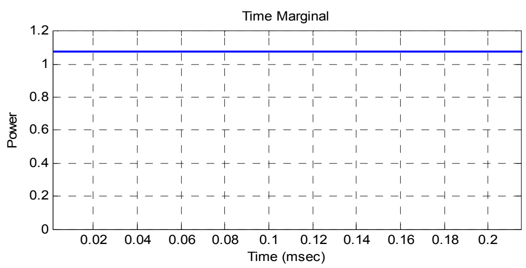

Figure 2c: Time Marginal from Gabor.

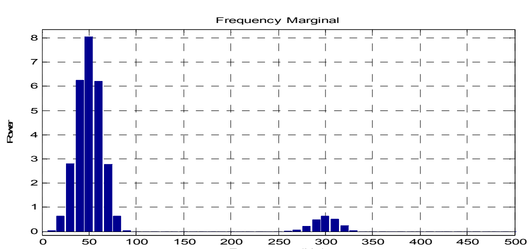

Figure 2d: Frequency Marginal from Gabor.

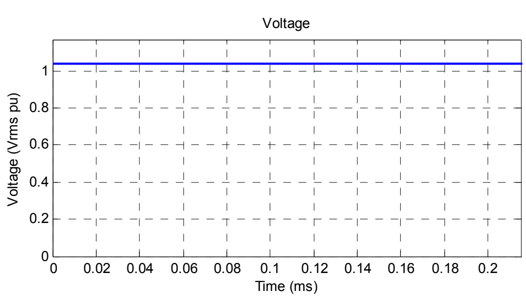

Figure 2e: Voltage ($V_{rms\ pu}$) from Gabor.

5.3 Comparison between Spectrogram and Gabor transform analysis

Comparison between spectrogram and Gabor transform analysis has been made to measure their correctness. Each technique was compared with an actual or theoretical value as a guideline to verify their accuracy.

Figure 3-5 demonstrate the correctness of duration measurements between spectrogram, Gabor and the actual values for voltage swell, voltage sag and interruption. The results clearly show that Gabor transform provides more accurate measurement compared to the spectrogram.

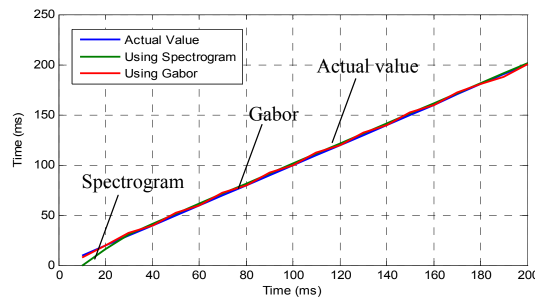

Figure 3: Duration measurements of voltage swell.

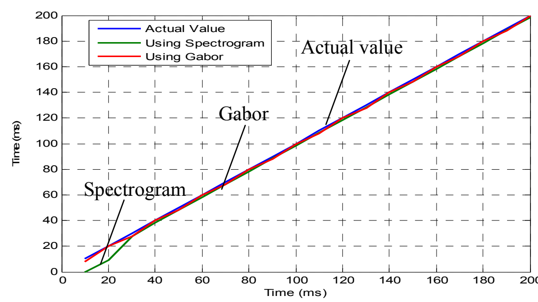

Figure 4: Duration measurements of voltage sag.

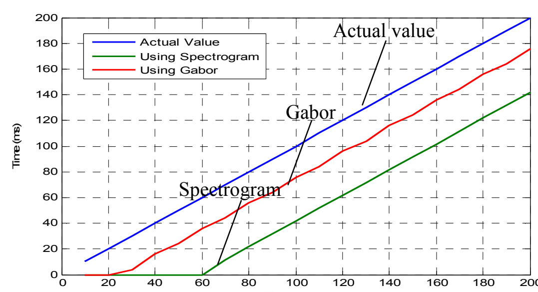

Figure 5: Duration measurements of interruption.

Comparison of total THD, TWD and TnHD were also performed to measure the accuracy of both techniques. Figure 6-8 concludes that both techniques can achieve almost accurate measurements to their actual values for all measurements.

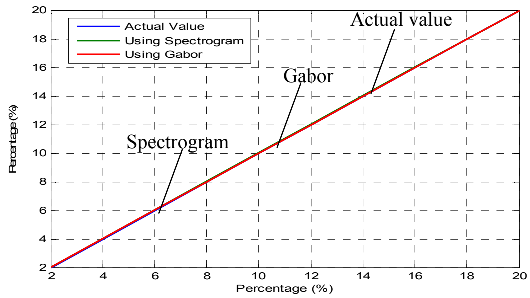

Figure 6: Total harmonic distortion (THD) measurements.

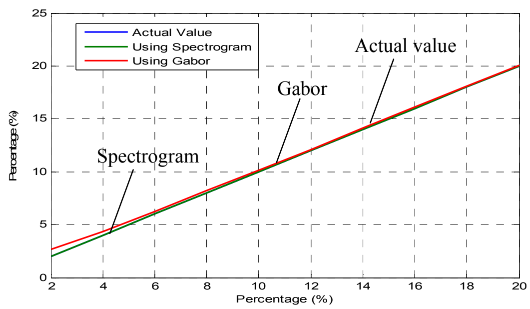

Figure 6: Total waveform distortion (TWD) measurements.

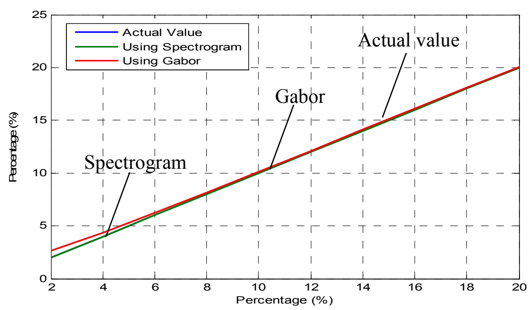

Figure 6: Total nonharmonic distortion (TnHD) measurements.

Table 2: Parameters of Spectrogram and Gabor.

Time-frequency technique	**Spectrogram**	**Gabor**
Number of samples (signal)	3120	3120
Window length	1024	480
Frequency Resolution (Hz)	11.7188	10
Memory Size (data)	3194880	39000

Table 2 presents evaluation of parameter values between spectrogram and Gabor transform used to perform this research. For equal number of sample sizes, spectrogram uses higher number of window length compared to Gabor transform to get similar frequency resolution. Spectrogram needs bigger bigger memory size compared to Gabor transform. All in all, it can be considered that Gabor transform provides the best technique to perform the power quality classifications.

6. Conclusion

The analysis of power quality disturbances have been performed using both spectrogram and Gabor transformation time-frequency analysis techniques. The signal parameters are extracted from time-frequency distribution in terms of the root mean square (RMS), total harmonic distortion (THD),total waveform distortion (TWD) and total nonharmonic distortion (TnHD). The correctness of signal parameters measurements for both techniques are demonstrated and compared. The results show that Gabor transform is the best technique in terms of correctness of parameters measurements, window length, frequency resolution and memory size for power quality analysis and classification. The analysis provides a powerful means of studying power quality disturbances especially to construct an automated expert system that can overcome the power quality problems.

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