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Border Distortion Minimization for Multiple PQ Disturbances - Stockwell Transformation Modification

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Abstract: Signal processing is a method used in electrical engineering to analyse and modify signals hence improving the quality. In power quality classification, signal processing is employed as an alternative for better detection of disturbances. This is done with the application of some extraction features to amplify the differences of each disturbance. However, due to border distortion effect, signal processing results usually encounter problem. Border distortion is the aberration in results due to tempering, appearing at the starting and the ending of the waveform when signals are processed and modified using signal processing techniques. This leads to misclassification of PQ disturbances, causing problems in determining the correct mitigation technique to be taken to reduce power quality disturbances. In this paper, minimization of border distortion of features extraction resulting from Stockwell transform will be discussed via the implementation of Hanning Taper and polynomial fitting. The discussion involves the three types of multiple power quality disturbances which are voltage sag with harmonics, voltage sag with transient, and harmonics with transient. The modification technique in Stockwell transform will be analysed to prove the accuracy and the consistency in features extraction. In this study, the border distortion effect was successfully reduced by an average of 88.704%.

Keywords: Power Quality, Multiple Power Quality Disturbance, Signal Processing, Border Distortion, Stockwell Transform.

1. Introduction

Malaysia experiences high lightning strikes due to the tropical climate. The rapid development of the country and the rapidly improving lifestyle of the people, and the increasing development and use of modern electrical equipment also contribute to the problems related to power quality [1]. Power quality (PQ) disturbance is a phenomenon in power line consisting of voltage sag, swell, harmonics, momentary interruption, flicker, notch, spike, and oscillatory transient [2]–[4]. Among the sources of the occurrence of disturbances are energization of heavy loads, starting of heavy loads such as industrial motor, lightning strikes, use of nonlinear load, and power system faults [5]. These represent single PQ Disturbances. PQ disturbances can also occur in combinations such as voltage sag with harmonics, voltage sag with transient, and harmonics with transient. These combinations are known as Multiple PQ Disturbances. The effects of these disturbances could jeopardize critical sectors such as hospitals, pharmaceutical companies, water supply, gas supply, military security system, and important government offices. The characteristics of each disturbance have been outlined in IEEE Standard 1159 [6].

Nowadays, signal processing is normally employed to detect power quality (PQ) disturbances occurring in power system. There are various types of signal processing introduced by researchers due to the growing interest to explore more on signal processing with very detailed studies in an attempt to find the best way to detect power quality disturbances.[7]–[9].

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Researchers use the existing signal processing methods and make modifications in an attempt to get the best method with improvements considering time consumption, difficulty, accuracy and consistency [7], [8]. Several extraction features were introduced and discussed to assess the differences and improvements that can be made for each of the PQ disturbances highlighted in previous studies. Among the signal processing options used by researchers are Wavelet Transform (WT), Fourier Transform (FT), Fast Fourier Transform (FFT), Hilbert Huang Transform (HHT), and Stockwell Transform (ST).

Modified WT were proposed for detection and localization of ten types of PQ events [9]. The signals were decomposed to up to four finer levels for detection stage, and seven finer levels of classification stage. The modified technique, known as Maximal Overlap Discrete Wavelet Transform (MODWT) was proposed to fix a degradation of WT where the co-efficiency of the technique was not affected by changing the starting point and limitations on the signal size can be removed. Statistically, MODWT is more stable than conventional WT, however, MODWT still has a discrete scale dimension where the numerical data has a limited number of possibilities. In some cases, mathematical functions or calculations are also not possible.

Hilbert Huang Transform (HHT) can overcome the advantages of multi resolution in WT. Instantaneous frequencies and intrinsic mode functions were analysed on eight types of single power quality disturbance [10]. The second intrinsic mode functions were employed in the study, enabling accurate signal representation and eliminating the noise produced. With the help of Multilayer Perceptron Neural Network model, the PQ classification resulted in 94.4% accuracy, with four types of PQ achieving 100% in accuracy. However, HHT suffered at mode mixing in predicting the number of Intrinsic Mode Functions (IMF). If a real signal is used, the noise problem still persists.

The Variational Mode Decomposition (VMD) proved better than HHT. VMD is more robust to noise due to the ability to isolate high frequency [11]. VMD introduces higher level modes and is able to identify the starting and the ending points of a PQ disturbance. With the appropriate threshold, the duration of PQ event can also be measured. However, VMD suffers in discriminating PQ disturbances effects due to the mode mixing features (e.g. Mode Central Frequencies (Mcfs), Relative Mode Energy Ratios (Rmers), Instantaneous Amplitude (IA), and Number of Zero Crossings (Zcs)).

Stockwell Transform (ST) is the modified version of Wavelet Transform (WT). WT suffers when at selecting an appropriate mother wavelet and is not suitable in the analysis of high-frequency signals with relatively narrow bandwidths. Due to the modification, Mode mixing problem does not happen in Stockwell Transform (ST). ST were proposed in [12] to detect five statistical features of PQ disturbances based on moving, localizing, and scalable Gaussian windows to detect five statistical features of PQ disturbances. Based on the findings, with the help of Decision Tree (DT) in the classification process, 99.78% of accuracy were achieved in classifying nine types of PQ disturbances where this includes stationary and non-stationary signal.

In signal processing, border distortion effect is an issue in power quality disturbances detection [13]–[15]. Border distortion has been discussed in various fields including mechanical engineering [14], [16] to detect crack and damage in structures. Border distortion has also been mentioned in electrical engineering [13], [17]–[20] in the discussions pertaining to power generation forecast, estimation of scalogram efficiency, correct setting for Discrete Wavelet Transform (DWT), and minimization of border distortion. Border distortion is the aberration in results due to tempering [17], appearing at the starting and the ending of the waveform when signals are processed and modified using signal processing techniques. Border distortion usually occurs due to inadequate data at the beginning and the ending of the duration of signal [20] This results in inaccuracy of data reading [19].

The unwanted results appear at the starting and the ending points of signal processing. These may disturb the detection result, resulting in misclassification of power quality disturbances recognition. This problem will be more prevalent in multiple PQ disturbances detection and classification as more and complicated characteristics are being dealt with.

Various methods have been employed to minimize border distortion in order to improve the ability of the signal processing to detect the PQ disturbances. Among these is border extension, which is normally used to reduce border distortion. This method is based on modification before the starting point and after the ending point of the signal, providing an extension window of the original waveform. Modifications can be made before the starting point and after the ending point are set to zero in zero padding method (ZPD). The next possible modification would be before the starting point and after the ending point are set to replicate the first and last point in smooth padding of order zero (SP0). Another possible modification is Smooth padding of order 1 (SP1) which is the interpolation of the first derivative border of the event. In addition, there are other methods with different technique in border extension such as periodic padding

(PPD), periodic event padding (PER), symmetric padding, and antisymmetric padding [21]. In the applications of border extension methods, there is a consideration to be taken pertaining to signal processing in which the convolution window is the sum of the sample window and the extension.

Zero Padding, Smooth Padding of Order 1, and Symmetrization Mode are 3 different extension mode schemes used to reduce border distortion effect in Discrete Wavelet Transform, discussed in [22]. The best mode to reduce border distortion effect with the presence of transient voltage in Discrete Wavelet Transform is Smooth Padding of Order 1.

Signal processing analysis without considering border distortion can produce inaccurate detection of PQ disturbance. However, the researchers focused only on single PQ disturbance [16], [18]. So, the major aim of the study is to minimize border distortion occurred in multiple PQ disturbances.

The study is focusing on Stockwell Transform. In this study, the researcher attempted to remove edges via polynomial fit. This is contrasting to what has been done before in which previous studies focused on extending the window. The performance of extraction features was evaluated via comparison with ST. The generated signal was decomposed to obtain the S-matrix with the assistance of Stockwell Transform. Different plots were obtained to visualize the patterns and characteristics of ST and modification ST output, focussing on minimization of border distortion.

2. Modification on ST

The S-transform is a temporal frequency representation created by Stockwell that incorporates the benefits of both the STFT and the wavelet transform [17] which is also known as a phase corrected Wavelet transform or a frequency dependent STFT.

S transform has a frequency dependent resolution of time-frequency domain which entirely refers to local phase information. Given a time series h (t), the local spectrum at time t= τ be determined by multiplying h (t) with a Gaussian, w (t) located at t = τ. Thus, the Stockwell Transform is given by

$$S(\tau, f) = \int_{-\infty}^{\infty} \big(h(t)\big) w(\tau - t, \sigma) e^{-i\omega t} dt$$

Border distortion minimization will be employed via polynomial which will be further continued via the implementation of Hanning Taper. The method will be used for the modification of ST. Removing edges could be done via modification on the time series;

$$S(\tau, f) = \int_{-\infty}^{\infty} \big(h(t_{new})\big) w(\tau - t, \sigma) e^{-i\omega t} dt$$

Firstly, Polynomial curve fitting is employed in time series to fit a 2nd degree polynomial to the points. The $h(t_{new})$ is the result of the Hanning Taper of polynomial curve fitting in time series, h(t).

$$p = polyfit(x, timeseries, n)$$

p returns the coefficients for a polynomial p(x) of degree n that is the best fit (in a least-squares sense) for the time series. The coefficients, x is in descending powers and n is a degree polynomial to the points. Polynomial evaluation, y is used to find out the total value of p.

$$y = polyval(p, x)$$

y returns the value of a polynomial of degree n evaluated at x. The input argument p is a vector of length n+1 whose elements are the coefficients in descending powers of the polynomial to be evaluated. Then, the time series, $h(t_m)$ is found as:

$$h(t_m) = h(t) - y$$

Hanning Taper, (HTp) on the edges of time series was done according to percentage needed. The percentage was computed via the following equation:

$$HTp = floor[length(h(t_{mid}))/R]$$

Where R is the number divided to get percentage of removing edge.

Lastly, the length of time series needed to generate Hanning Taper depends on percentage specified. Hanning window returns the length of time series (according to percentage). Then, the new time series, $h(t_{new})$ as stated in the equation below:

$$h(t_{new}) = hann(HTp)$$

The result of polynomial curve fitting with 2.5%, 5%, and 7.5% Hanning Taper will be discussed. The justification of considering the percentages is to examine the changes at different percentages. Four features will be evaluated and to see the results of border distortion minimization namely median, minimum amplitude, summation, and mean.

3. Result and Discussion

A. Raw Data Collection

Multiple PQ disturbances was generated in Matlab R2017b software based on the characteristics of each disturbance outlined in IEEE Standard 1159. The three types of multiple PQ disturbances considered in the study are voltage sag with harmonics, voltage sag with transient, and harmonics with transient. These are illustrated in Figure 1.

Voltage sag with harmonics (a type of Multiple PQ Disturbances) is a simultaneous occurrence of voltage sag and harmonics in the waveform. Voltage sag is a reduction in the AC line voltage between 10% to 90% from the nominal line-voltage at certain power frequencies in the duration of half of a cycle to 1 minute. Harmonics disturbance refers to constant changes in waveform or can be defined as the frequency of a component in the multiplier is a fundamental frequency at a given peak [6]. For the disturbances to be identified as Voltage sag with harmonics Multiple PQ Disturbances, one condition has to be met in which these two disturbances, sag and harmonics, have to occur simultaneously. Figure 1(a) shows the voltage sag with harmonics with line voltage reduction of 20% from the nominal line-voltage occurring from 0.05s to 0.15s.

Voltage sag with transient is the occurrence of voltage sag simultaneously with a sudden change in the amplitude of the voltage or the current in a power system (transient). In the same voltage sag, the generated transient was applied at 0.058s to 0.06s with amplitude of 2 as shown in Figure 1(b).

Harmonics with transient is the presence of the changing in the amplitude of the voltage or the current in a waveform of with harmonics disturbance. This is as illustrated in Figure 1(c).

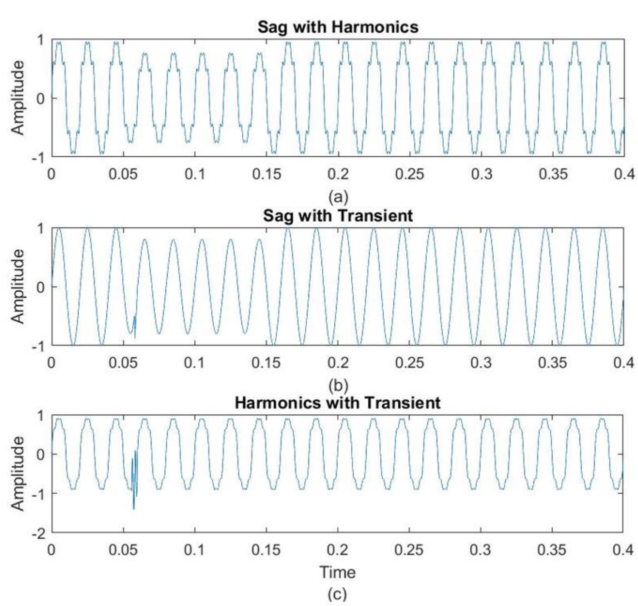

Figure 1: (a) Voltage sag with harmonics, (b) voltage sag with transient, and (c) harmonics with transient.

B. Border Distortion Detection

In this section, border distortions at the starting and the ending of the MST and ST were observed. The results with lowest border distortion depict good features extraction, as unwanted signals were minimized.

Contour of voltage sag with harmonics is illustrated in Figure 2. Figure 2(a) shows the contour of ST and Figure 2(b) shows the contour of modified ST. The plot shows the removing of polynomial curve fitting at the starting and the ending of 5% from the contour in original ST as the comparison made between ST and MST was done at 5%. A 2nd-degree polynomial to the points was used in polynomial curve fitting.

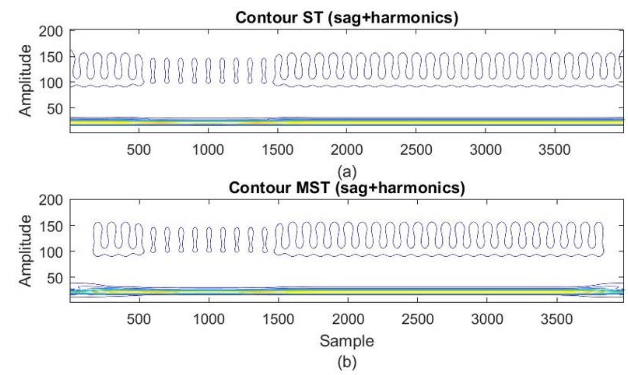

Figure 2: (a) Contour of voltage sag with harmonics in ST and (b) contour of voltage sag with harmonics in MST.

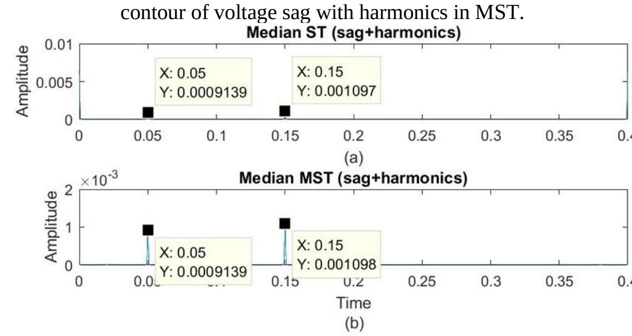

Figure 3: (a) Median of voltage sag with harmonics in ST and (b) Median of voltage sag with harmonics in MST

Figure 3 illustrates the median of voltage sag with harmonics. Two sharp break points appeared at 0.05s and 0.15s. The values of these sharp break points in ST and MST median at 0.05s are similar which is 0.0009139 while the values at 0.15s are really close to each other in which for ST, the value is 0.001097 and in MST median, the value is 0.001098. These represent voltage sag occurring in the duration.

Referring to Figure 4, in ST median, a bigger border distortion can be found. The starting point amplitude is illustrated at $6.447e^{-3}$ while the ending point amplitude is at $6.453e^{-3}$. In comparison MST median starting and ending amplitude values are at $7.52e^{-7}$ and $7.448e^{-7}$ respectively.

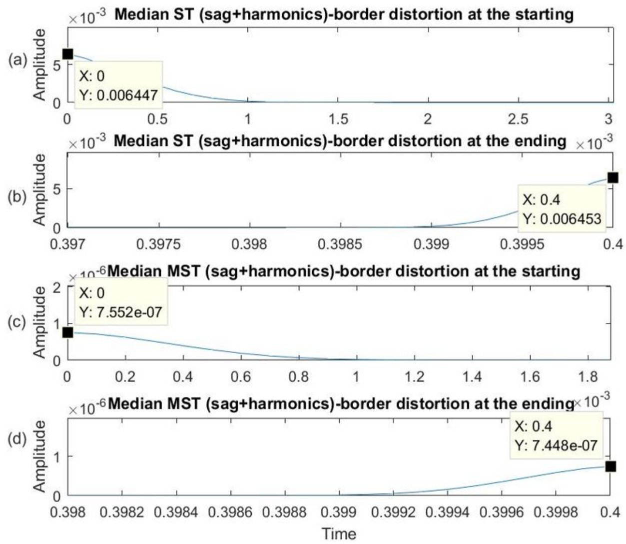

Figure 4: Border distortion at the (a) starting and (b) ending in ST, (c) starting and (d) ending in MST of the median of voltage sag with harmonics.

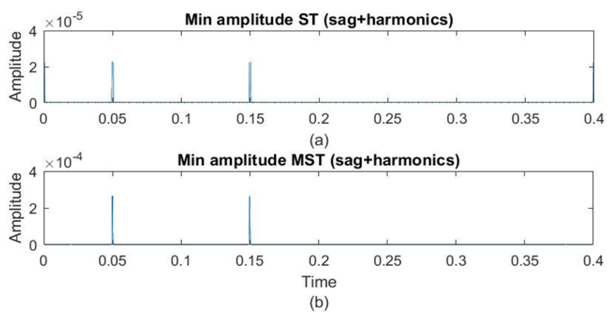

Figure 5: (a) Minimum amplitude of voltage sag with harmonics in ST and (b) Min of voltage sag with harmonics in MST.

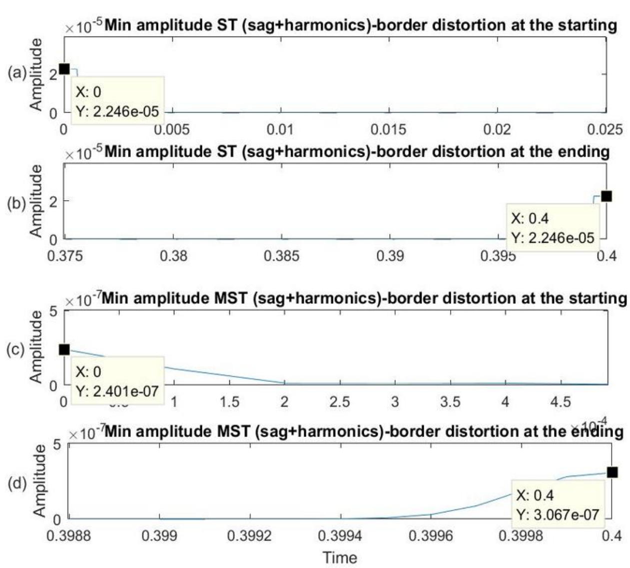

Figure 6: Border distortion at the (a) starting and (b) ending in ST, (c) starting and (d) ending in MST of the minimum amplitude of voltage sag with harmonics.

Minimum amplitude in ST and MST are shown in Figure 5 (a) and (b). Both waveforms illustrate two sharp break points occurring at the starting and the ending points of the voltage sag. These points are equal in amplitude for both ST and MST. However, the border distortion detected in ST is bigger than in MST. The border distortions of minimum amplitude of ST and MST are illustrated in Figure 6.

The summation and the mean of ST and MST are illustrated in Figure 7. These prove that the amplitude of MST technique better than ST. However, when time is considered, MST is proven to be worse than ST.

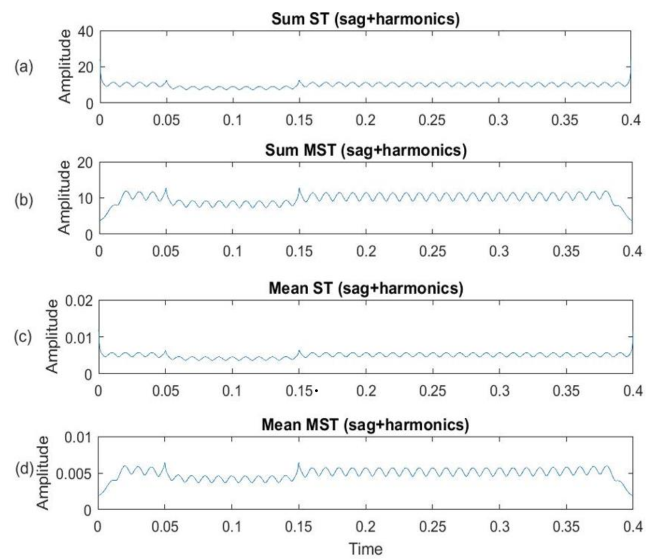

Figure 7: (a) sum and (c) mean of voltage sag with harmonics in ST and (b) sum and (d) mean of voltage sag with harmonics in MST

C. Border Distortion Analysis

Three types of multiple PQ disturbances (voltage sag with harmonics, voltage sag with transient, and harmonics with transient) were considered to discuss the performance of the proposed techniques. These three multiple PQ disturbances were processed using ST. From the ST results, the amplitude value of border distortion, a means squares error (MSE) and percentage of border distortion minimization were observed. The data were also processed via MST with 3 stages of edge removal (2.5%, 5%, 7.5%) to observe the improvements in border distortion minimization.

Table 1 depicts the amplitude during border distortion event. Y_1 is the amplitude of the starting and Y_2 is the amplitude of the ending of border distortion, as illustrated for minimum amplitude of ST (sag with harmonics) in Figure 8. The value of the data indicates that the border distortion in MST is smaller than ST. For the sake of comparison, the data also includes readings for 2.5%, 5% and 7.5% edge removal in MST.

Table 1: Border distortion at minimum amplitude, median, summation and mean of voltage sag with harmonics, voltage sag with transient and harmonics with transient of ST and MST.

FEATURES		ST IN FULL TIMESERIES	MST WITH 2.5% EDGE REMOVAL	MST WITH 5% EDGE REMOVAL	MST WITH 7.5% EDGE REMOVAL
SAG HARMONICS	Minimum amplitude	Y_1=2.246e-5	Y_1=5.416e-7	Y_1=2.4e-7	Y_1=6.018e-8
		Y_2=2.246e-5	Y_2=6.919e-7	Y_2=3.067e-7	Y_2=7.687e-8
	Median	Y_1=6.444e-3	Y_1=1.704e-6	Y_1=7.552e-7	Y_1=1.892e-7
		Y_2=6.453e-3	Y_2=1.681e-6	Y_2=7.448e-7	Y_2=1.866e-7
	Summation	Y_1=23.94	Y_1=5.073	Y_1=3.812	Y_1=1.787
		Y_2=23.95	Y_2=5.073	Y_2=3.813	Y_2=1.787
	Mean	Y_1=1.120e-2	Y_1=2.535e-3	Y_1=1.905e-3	Y_1=8.929e-4
		Y_2=1.120e-2	Y_2=2.536e-3	Y_2=1.905e-3	Y_2=8.923e-4
SAG TRANSIENT	Minimum amplitude	Y_1=7.194e-4	Y_1=1.805e-7	Y_1=8.003e-8	Y_1=2.006e-8
		Y_2=7.189e-4	Y_2=2.373e-7	Y_2=1.052e-7	Y_2=2.637e-8
	Median	Y_1=2.348e-3	Y_1=4.022e-7	Y_1=1.782e-7	Y_1=4.467e-8
		Y_2=2.348e-3	Y_2=4.116e-7	Y_2=1.824e-7	Y_2=4.572e-8
	Summation	Y_1=9.228	Y_1=4.629	Y_1=3.812	Y_1=1.709
		Y_2=9.228	Y_2=4.629	Y_2=3.813	Y_2=1.709
	Mean	Y_1=4.612e-3	Y_1=2.313e-3	Y_1=1.771e-3	Y_1=4.541e-4
		Y_2=4.612e-3	Y_2=2.313e-3	Y_2=1.770e-3	Y_2=4.540e-4
HARMONICS TRANSIENT	Minimum amplitude	Y_1=7.194e-4	Y_1=4.791e-7	Y_1=8.003e-8	Y_1=5.323e-8
		Y_2=7.189e-4	Y_2=6.005e-7	Y_2=1.052e-7	Y_2=6.672e-8
	Median	Y_1=5.678e-3	Y_1=1.415e-6	Y_1=6.269e-7	Y_1=1.571e-7
		Y_2=5.684e-3	Y_2=1.397e-6	Y_2=6.19e-7	Y_2=1.551e-7
	Summation	Y_1=21.14	Y_1=5.1	Y_1=3.842	Y_1=1.792
		Y_2=21.15	Y_2=5.103	Y_2=3.842	Y_2=1.793
	Mean	Y_1=1.056e-2	Y_1=2.549e-3	Y_1=1.92e-3	Y_1=8.958e-4
		Y_2=1.057e-2	Y_2=2.550e-3	Y_2=1.92e-3	Y_2=8.959e-4

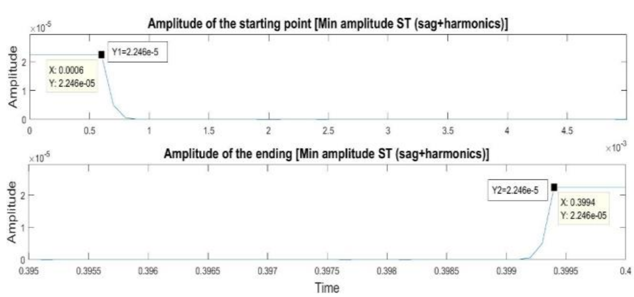

Figure 8: Border distortion (a) at the starting and (b) the ending of the minimum amplitude ST of sag with harmonics.

Table 2 illustrates the mean squares error, MSE. The MSE in this study is based on the observation on the border distortion minimization. In this case, Y_{ST} is the amplitude samples for ST and Y_{MST} is the amplitude samples for MST. Samples at the starting point are represented by n_1 and n_2 represents the samples at the ending point. These samples are respectively 20 samples at the starting point and the ending point as these are the number of samples considered for border distortion interval. The mentioned MSE can be calculated via:

$$MSE = \frac{\sum(Y_{MST} - Y_{ST})^2}{(n_1 + n_2)}$$

Table 2: MSE of Border distortion at minimum amplitude, median, summation and mean for voltage sag with harmonics, voltage sag with transient and harmonics with transient of ST and MST.

	Features	MSE 2.5% Edge Removal	MSE 5% Edge Removal	MSE 7.5% Edge Removal
Sag Harmonics	Minimum amplitude	1.702e-10	1.720e-10	1.731e-10
	Median	6.641e-06	6.643e-06	6.645e-06
	Summation	1.702e-10	1.720e-10	1.731e-10
	Mean	1.702e-10	1.720e-10	1.731e-10
Sag Transient	Minimum amplitude	9.878e-08	9.880e-08	9.881e-08
	median	9.358e-07	9.362e-07	9.365e-07
	Summation	9.878e-08	9.880e-08	9.881e-08
	Mean	9.878e-08	9.880e-08	9.881e-08
Harmonics Transient	Minimum amplitude	1.369e-09	1.374e-09	1.376e-09
	median	5.142e-06	5.144e-06	5.145e-06
	Summation	1.369e-09	1.374e-09	1.376e-09
	Mean	1.702e-10	1.720e-10	1.731e-10

Table 2 shows the MSE of border distortion at minimum amplitude and the median for three Multiple PQ Disturbances (voltage sag with harmonics, sag with transient, and harmonics with transient) in three percentages (2.5%, 5%, and 7.5%) of edge removal. Higher percentage of edge removal applied yielded a better result in border distortion minimization. However, the summation and mean features of the proposed technique illustrated bad results in time but provided good results in amplitude. Based on the result, 2.5% edge removal is the best in overall when considering the four features studied (minimum amplitude, median, summation, and mean).

Table 3: Percentage of border distortion minimization at minimum amplitude, median, summation and mean for voltage sag with harmonics, voltage sag with transient and harmonics with transient of ST and MST.

	Features	Distortion Minimization for 2.5% Edge Removal	Distortion Minimization for 5% Edge Removal	Distortion Minimization for 7.5% Edge Removal
Sag Harmonics	Minimum amplitude	97.254%	98.783%	99.695%
	Median	99.974%	99.988%	99.997%
	Summation	78.814%	84.078%	92.537%
	Mean	77.362%	82.991%	92.030%
Sag Transient	Minimum amplitude	99.971%	99.987%	99.997%
	median	99.983%	99.992%	99.998%
	Summation	49.837%	58.686%	81.480%
	Mean	49.848%	61.611%	90.155%
Harmonics Transient	Minimum amplitude	99.925%	99.987%	99.992%
	median	99.975%	99.989%	99.997%
	Summation	75.874%	81.830%	91.523%
	Mean	75.868%	81.827%	91.521%

The percentage of the border distortion is based on the equation:

$$\text{Percentage border distortion} = \frac{\left(\frac{Y_{1ST} - Y_{1MST}}{Y_{1ST}}\right) + \left(\frac{Y_{2ST} - Y_{2MST}}{Y_{2ST}}\right)}{2} x100$$

Where:
Y_{1ST} = the starting point of the border distortion in ST
Y_{1MST} = the starting point of the border distortion in MST
Y_{2ST} = the ending point of the border distortion in ST
Y_{2MST} = the ending point of the border distortion in MST

Table 3 shows the percentage of border distortion minimization for 2.5%, 5% and 7.5% edge removal. Based on the result, the reduction of border distortion for MST is around 50% to more than 99%. The average minimization for 2.5%, 5% and 7.5% edge removal are 83.724%, 87.479% and 94.910% respectively. This proves that higher percentage of edge removal yields better reduction of border distortion.

4. CONCLUSION

Multiple PQ disturbances has been occurring for a long time. The occurrence of the multiple PQ disturbances had been ignored until recently as multiple PQ disturbances has become a problem in power system, concordance to the growth of technology. Modern electrical equipment needs a good power quality to optimally function and to preserve equipment's life span.

The first step to determine the presence of PQ disturbances is via signal processing. Signal processing can extract features and recognize the behaviour of disturbances. However, the effect of border distortion in signal processing inhibits the results. Despite the small effects, border distortion still needs to be considered for more accurate results. This is even more so when multiple PQ disturbances are involved.

In this paper, polynomial proceeded by Hanning Taper were employed to minimize the border distortion in ST. Several diagrams have been presented to illustrate the presence of border distortion and to show the difference due to modification of time series at 2.5%, 5% and 7.5% via Hanning Taper.

Based on the results, ST provided good extracting features for multiple PQ disturbances contributing to good detection. 2.5% time series modification via Hanning Taper provided stable result compared to 5% and 7.5% considering all 4 features (minimum amplitude, median, summation, and mean) where 2.5% resulted in considerably good border distortion minimization (87.479% in average) and less data loss during edge removal. Contradicting to methodologies in [16], which employed the extension windows method, the current study proposes reduction windows method with modification in ST in which has proven to have reduced an average 88.704% of border distortion.

Future work needs to be carried out in classification process to determine the effectiveness of the proposed method.

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