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Performance Analysis of Wavelet Based Denoise System for Power Quality Disturbances

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***Abstract*--The performance analysis of wavelet based denoise system for power quality disturbances including sag, swell, flicker, harmonic, transient and notch is presented in this paper. The denoise algorithm uses Daubechie family wavelet and a universal soft threshold technique applied on the detailed wavelet coefficients based on its standard deviation and data length. This eliminates and reduces the noise content in the signal. Lastly, the inverse discrete wavelet transform is done to reconstruct and recover the denoised PQ disturbance signal. All the disturbance signals are contaminated with Additive White Gaussian Noise of initial noise SNR of 30dB. The wavelet based denoise system in this paper shows excellent performance for sag, swell and flicker, good performance for harmonic, moderate performance for transient and poor performance for notch. The performance analysis presented in this paper provides an understanding of how the power quality disturbance frequency contents and its magnitude effect the performance of the wavelet based denoise system.**

***Index Terms*—Power Quality, Wavelet Transform, Denoise, Daubechie wavelet**

I. Introduction

POWER quality issues have become a great concern for industry facility in recent years due to the significant economic impact to the operation of the facility [1]. Modern industry machinery control and equipments, driven by microprocessor and power electronic devices cause the equipments to become very sensitive and prone to power quality disturbance. Hence, any failure and malfunction of equipment and machinery that lead to lost of production and downtime cause by power quality disturbances can be severe for industrial [2]. Facility engineer must performance evaluation and audit on the power quality within the facility to ensure it complies with the ITIC/CBEMA or SEMI F47 standards to avoid equipment failure.

Power Quality monitoring [3] becomes the standard procedure for power quality assessment [4] and audit to determine, locate and solve the power quality problems [5]. There are many commercial power quality monitoring instruments available in the market ranging from simple handheld to high quality advance recorder [6, 7]. There are also research been carried out to develop low cost PC based power quality recorder [8]. However, power quality recorders are contaminated with noises during measurement and recording. These noises are usually due to the electronic devices within the recorder, probe cabling, thermal, electromagnetic and environmental issue.

Some noise level can be so low that it is ignored as it doesn't affect the accuracy of classification and analysis. However, some noise level are high enough to corrupt the vital information which may lead to false classification and analysis. In the event where noise level is high, a denoise or noise reduction system is required to reduce the noises from the signal prior to the next level of processing. The definition of electrical noise is defined in the IEEE 1159-1995 standard [9].

Wavelet transform are widely used for signal denoising applications in signal and image processing community [10,11]. However, the wavelet based denoise capability has not been exploited much in the area of power quality disturbance. There are some wavelet based power quality signal denoise scheme such as correlation base noise suppression algorithm [12] and statistic hypothesis thresholding [13] that have been proposed to denoise electrical or power quality signal. However, wavelet based denoising by soft threshold [14] is often overlooked in the area of power quality disturbance. This paper provide detailed performance analysis for wavelet denoising using soft threshold on power quality disturbances, covering low frequency to high frequency disturbances such as sag, swell, flicker, harmonic, transient and notch.

II. Denoise Approach

The wavelet denoise algorithm used was adopted from the algorithm proposed by Donoho [15] as shown in Fig. 1. Daubechie wavelet family was chosen as the mother wavelet for the wavelet transform. It consists of three steps: a) Discrete wavelet transform b) Soft threshold c) Inverse discrete wavelet transform.

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Fig. 1 Wavelet denoise system

The wavelet transform is used to transform the noisy signal into wavelet domain by decomposing the noisy signal into difference levels of details coefficient. The wavelet transform is represented in Eq. (1) where $s(n)$ is the signal, $C(a,b)$ are dyadic wavelet coefficients, a is dilation or scale, $a = 2^j$, b is translation, $b = k2^j$, $j \in N$, $k \in Z$ and $g_{j,k}(n)$ is the wavelet function.

$$C(a,b) = C(j,k) = \sum_{n \in Z} s(n) g_{j,k}(n) \quad (1)$$

The soft threshold technique performed on the wavelet coefficient is shown in Eq. (2) where $C(k)$ is the wavelet coefficient and TH is the threshold value.

$$C(k_{TH}) = \begin{cases} |C(k)| - TH & |C(k)| > TH \\ 0 & |C(k)| \le TH \end{cases} \quad (2)$$

The soft threshold value is computed and determined using Eq. (3) where σ is the standard deviation and n is the number of signal samples.

$$TH = \sigma \sqrt{2 \log(n)} \quad (3)$$

The inverse wavelet transform shown in Eq. (4) inverse the threshold wavelet coefficients in wavelet domain back to time domain which is the denoised signal.

$$s(t) = \sum_{j \in Z} \sum_{k \in Z} C(j, k_{TH}) \psi_{j,k}(t) \quad (4)$$

Additive White Gaussian Noise was added to artificially contaminate the clean power quality disturbance signals as shown in Eq. (5) where y is the noisy signal, $f(n)$ is the clean reference signal, σ is the standard deviation and e is the gaussian white noise $N(0,1)$. Additive White Gaussian noise was used because it highly resembles the noise that contaminates the power quality signal.

$$y(n) = f(n) + \sigma e(n)\,,\ 0 \le n \le N\text{-}1 \quad (5)$$

The additive White Gaussian Noise was carefully controlled to achieve the noise level that is expected to be present in the signal in dB. After the Gaussian white noise is generated, the noise is added to the clean signal to artificially contaminate the signal as shown in Eq. (5). Then, an initial signal-to-noise ratio shown in Eq. (6) is calculated to verify and to ensure the right noise level in dB is generated where S_i is the rms of the clean reference signal $f(n)$ and N_i is the rms of the white Gaussian noise $\sigma e(n)$.

$$SNR_i = 20 \log\left(\frac{S_i}{N_i}\right) \quad (6)$$

According to the IEEE 1159-1995 standard, noise is defined as broad band steady state disturbance with magnitude between 0 to 1% of the signal magnitude. If the noise level is within 1%, it is considered acceptable. If the noise level exceeds 1% but less then 2%, noise reduction is recommended. If the noise level exceeds 2%, reacquisition is recommended, as the noise level is considered too high and is beyond recovery via the noise reduction system.

In this paper, noise level at 2% of magnitude with its equivalent initial SNR of 30dB was generated to test the performance of the denoise system. For visual inspection purpose, the noisy signal is shown in Fig. 2.

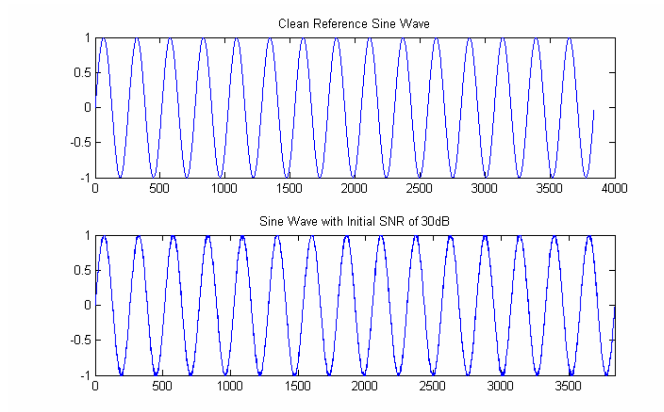

Fig. 2 Clean (top) and noisy (bottom) sine wave for visual inspection

After denoising, the output signal-to-noise ratio as shown in Eq. (7) is to be computed on the denoised power quality signal, where S_o is the rms of the clean reference signal and N_o is the rms of the residual noise.

$$SNR_o = 20 \log\left(\frac{S_o}{N_o}\right) \quad (7)$$

The evaluation was performed using Daubechie wavelets family db2, db4, db6, db8, db10 and each power quality disturbance was transformed up to 6 levels of decomposition, with initial SNR of 30dB. Noise level of 1% which is equivalent to an output SNR of 36dB is used as a reference for denoise performance evaluation.

III. Results

The power quality disturbances signals were generated at 50Hz with 12.8kHz sampling frequency and yield 256 samples per cycle.

A. Low Frequency Power Quality Disturbance

Low frequency power quality disturbances refer to voltage sag, voltage swell and flicker. Both sag and swell have a three cycles 560ms magnitude variation of 0.3pu and flicker has a magnitude of 0.1pu at 10Hz. Since these disturbances only have variation on its magnitude, the denoised performance for sag, swell and flicker are very similar. The denoise results for sag, swell and flicker is shown in Fig. 3.

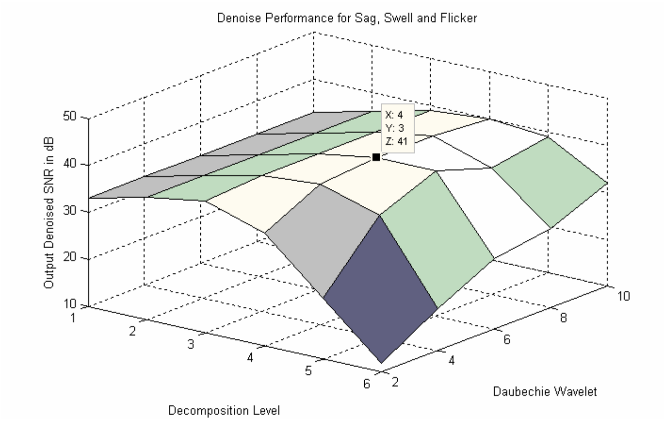

Fig. 3 Denoise performance for sag, swell and flicker

Fig. 3 shows that Daubechie 6 wavelet at decomposition level 4 have the highest output denoised SNR of 41dB, which is greater then the reference which is 36dB. This means that the noise level has been reduced to less than 1% of the signal magnitude within the acceptable range. It has 11dB improvement. Fig.4 shows the denoised results of sag, swell and flicker in waveforms before and after denoise for visual inspection. It can be clearly seen that noise has been removed from the power quality signals.

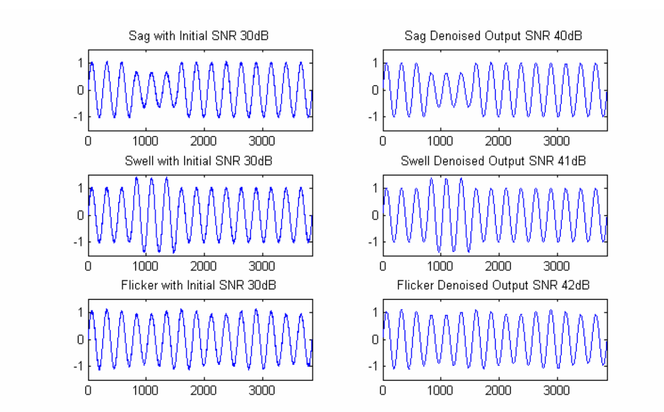

Fig. 4 Denoise results for sag, swell and flicker for visual inspection

B. Harmonic Disturbance

The harmonic disturbance consists of 3rd, 5th and 7th order with 0.15pu, 0.12pu and 0.1pu magnitude respectively. The denoise results for harmonic is shown in Fig. 5.

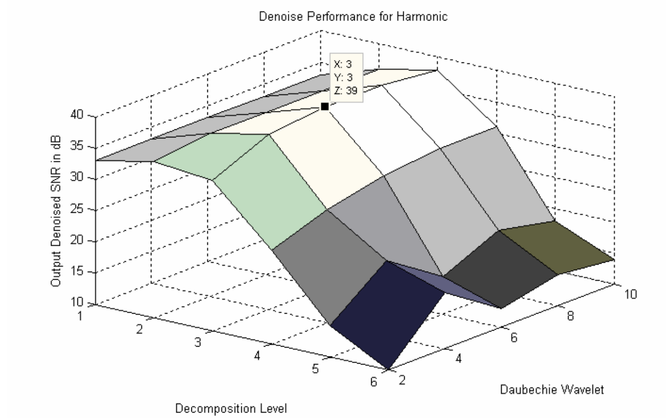

Fig. 5 Denoise performance for harmonic

Fig. 5 shows that Daubechie 6 wavelet at decomposition level 3 have the highest output denoised SNR of 39dB, which is greater then the reference 36dB. This indicates that the noise level has been reduced to less than 1% of the signal magnitude within the acceptable range. It has a 9dB improvement.

C. Transient Disturbance

The transient disturbance consist 422Hz oscillatory frequency and 1.5pu of magnitude which resembling capacitor bank switching oscillatory transient. The denoise results for transient is shown in Fig. 6.

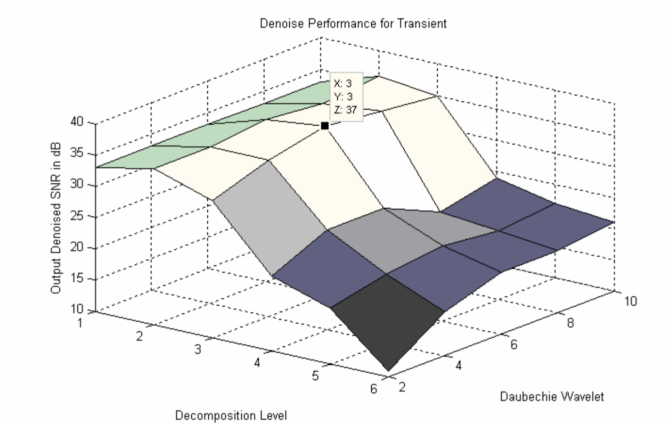

Fig. 6 Denoise performance for transient

Fig. 6 shows that the Daubechie 6 wavelet at decomposition level 3 have the highest output denoised SNR of 37dB, which is again greater then the reference 36dB. Hence, the noise level have been reduced to less than 1% of the signal magnitude within the acceptable range. However, the improvement for transient is only 7dB.

D. Voltage Notch Disturbance

The notch disturbance consist of 12 notches per cycle with notch depth of 0.2pu which resembles three phase rectifier switching. The denoised result for voltage notch is shown in Fig. 7.

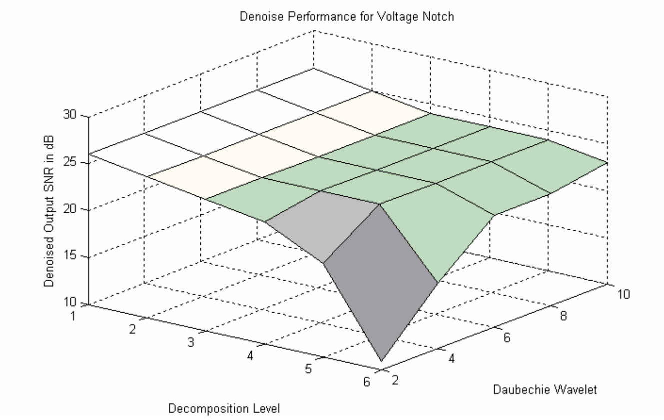

Fig. 7 Denoise performance for voltage notch

For voltage notch, the wavelet denoise approach doesn't seem to effectively remove the noise. Instead, it results in higher denoised SNR of 26dB which is -4dB below the initial SNR of 30dB before denoise. The denoise quality is worse and therefore denoise is not recommended for voltage notch.

Fig. 8 shows the denoised results of harmonic, transient and voltage notch in waveforms before and after denoise for visual inspection. It can be clearly seen that noise has been removed from harmonic and transient, except for voltage notch.

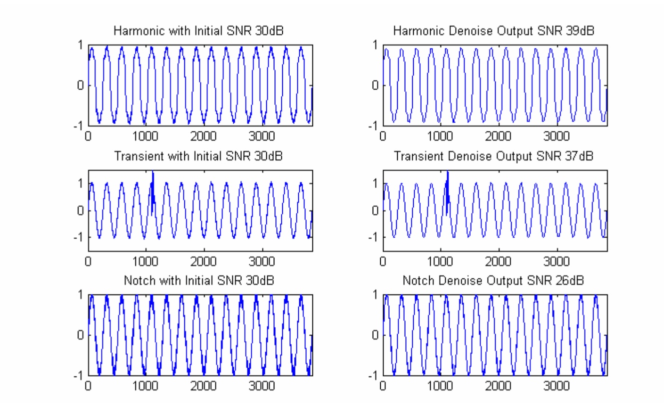

Fig. 8 Denoise results for harmonic, transient and voltage notch for visual inspection

IV. Discussion

From the evaluation results shown in Section III, Daubechie 6 wavelet yield the best denoised and positive performance for all power quality disturbances except voltage notch. In terms of wavelet transform decomposition level selection, for sag, swell and flicker, decomposition level 4 yields the best denoise results. Since low frequency disturbances do not contain high frequency information, the high frequency bands can be discarded without losing vital information of the low frequency disturbance. Hence, better signal recovery, up to 11dB can be achieved.

For harmonic and transient, the disturbances consist of higher frequency components as compared to sag, swell and flicker. The wavelet transform decomposition level cannot be performed up to level 4 as it will discard the harmonic and transient frequency. Due to this reason, the decomposition level have to reduced to level 3 in order to achieve the best denoise result instead of level 4. The selection of wavelet transform decomposition level is also subject to the sampling frequency of the power quality signal.

Since the denoise performance for harmonic and transient are very dependent on the frequencies content and its magnitude, a further elaboration is carried out for harmonic and transient. Fig. 9 shows the detailed denoise results for harmonic with initial noise SNR of 30dB ranging from 3rd, 5th, 7th,9th and 11th order harmonics, each having a magnitude ranging from 0.05 to 0.15 pu. Fig. 9 clearly shows that the higher the harmonic order and its magnitude, the lower the denoise SNR. The wavelet based denoise approach is only effective for harmonic up to 7th order. Harmonics above 7th order will be discarded by the denoise system.

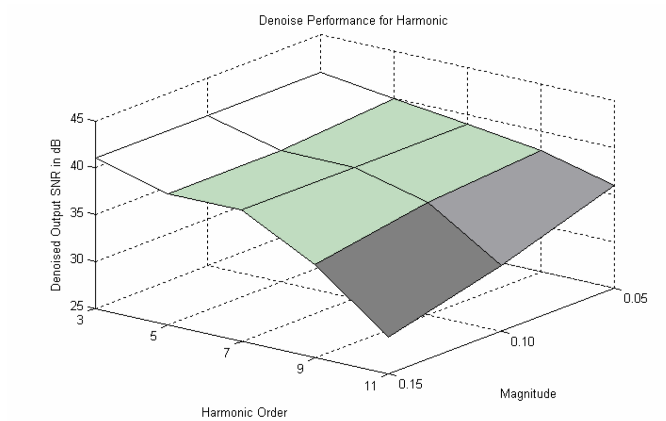

Fig. 9 Denoise results for harmonic

Fig. 10 shows the denoise results for transient with initial noise SNR of 30dB and transient frequency ranging from 400Hz to 1000Hz, each having magnitude from 0.5 to 1.5 pu. Fig. 10 clearly shows that the higher the transient frequency and its magnitude, the lower the denoise SNR. The wavelet based denoise approach is only effective for transient disturbance that is less than 400Hz. Transient above 400Hz will be discarded by the denoise system.

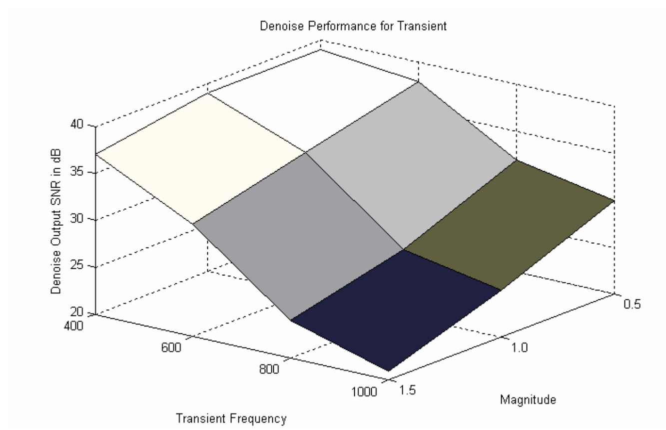

Fig. 10 Detail denoise results for transient

Voltage notch have high spectral content which is very similar to noise. Therefore, denoise is not suitable for voltage notch.

V. Conclusion

The wavelet denoise approach using Daubechie 6 wavelet shows excellent performance up to 11dB improvement for sag, swell and flicker, good performance up to 9dB improvement for harmonic, moderate performance up to 7dB improvement for transient and poor performance of -4dB for voltage notch. In short, wavelet based denoise system is well suited for sag, swell and flicker. Harmonic frequency contents not higher than 7^{th} order and transient frequencies not higher than 400Hz can also be recovered from noise contamination. Lastly, denoise is ineffective for voltage notch due to its high spectral content which is very similar to the noise. The denoise system may eliminate the noise together with the notches, therefore denoise is not recommended for voltage notch.

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VII. Biographies

Rodney H.G. Tan received his BSc degree in Electronic and Electrical Engineering from Robert Gordon University, UK in 1994 and MSc degree in Microelectronic and Information System from Liverpool John Moores University, UK in 1996.

He is currently working as a Senior Lecturer in the Department of Electrical & Electronics Engineering and is the leader of the Embedded System Design Research Group at UCSI University, Malaysia. He is currently pursuing his PhD in Electrical Engineering at Universiti Tenaga Nasional, Malaysia. His research interest includes Power Quality, Signal Processing and Embedded System Design.

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