2010

Classification of power quality disturbances using the iterative Hilbert Huang transform

C. F. Drummond
University of Wollongong

Darmawan Sutanto
University of Wollongong, soetanto@uow.edu.au

Classification of power quality disturbances using the iterative Hilbert Huang transform

Abstract

The Hilbert Huang Transform (HHT) is a powerful tool for Power Quality (PQ) classifications. One of the main advantages of the HHT is its ability to analyse non-stationary complex waveforms with very good time resolution. However, like other waveform classification techniques, it has difficulty in resolving the instant of sudden changes in the waveform. It has also difficulty with signals that have frequency components close together. This paper summarises the fundamentals of the HHT technique and its application to power quality classifications including its advantages and disadvantages. Two novel techniques to improve the performance of the HHT technique in analysing power quality problems will be proposed. Results from simulations will be provided and discussed.

Disciplines

Physical Sciences and Mathematics

Publication Details

C. Drummond & D. Sutanto, "Classification of power quality disturbances using the iterative Hilbert Huang transform," in 14th International Conference on Harmonics and Quality of Power, ICHQP 2010, 2010, pp. 1-7.

Classification of Power Quality Disturbances using the Iterative Hilbert Huang Transform

C. F. Drummond and D. Sutanto, *Senior Member, IEEE*.

Abstract— **The Hilbert Huang Transform (HHT) is a powerful tool for Power Quality (PQ) classifications. One of the main advantages of the HHT is its ability to analyse non-stationary complex waveforms with very good time resolution. However, like other waveform classification techniques, it has difficulty in resolving the instant of sudden changes in the waveform. It has also difficulty with signals that have frequency components close together. This paper summarises the fundamentals of the HHT technique and its application to power quality classifications including its advantages and disadvantages. Two novel techniques to improve the performance of the HHT technique in analysing power quality problems will be proposed. Results from simulations will be provided and discussed.**

***Index Terms*—Hilbert Huang Transform, Power Quality, Harmonics, Empirical Mode Decomposition, Iterative Hilbert Huang Transform.**

I. Introduction

With the increased use of power electronics in residential, commercial and industrial distribution systems, combined with the proliferations of highly sensitive micro-processor controlled equipment, more and more distribution customers are sensitive to excessive harmonics in the supply system [1], some even leading to failure of equipment. Typical power quality disturbances include harmonics, voltage sags and swells, transients and flickers. End user systems can be sensitive to poor power supply quality, this may lead to malfunction and inefficiency [1]. Many industries are concerned with the operational and financial cost that disturbances in power supply quality can cause and thus there is a growing need for power quality monitoring and classification systems [2][3].

A variety of techniques can be used to identify PQ events, such as Fourier transforms [4], wavelets [5], [6], [7] and more recently empirical mode decomposition (EMD) [8] and the HHT [9]. Each of these techniques has its strengths and weaknesses. While Fast Fourier transforms (FFT) perform very well when dealing with stationary periodic signals, it cannot deal effectively with non-stationary signals that have time-dependent event. Most power quality issues are non-stationary in nature, such as sags and varying harmonics with time. Efforts to overcome this include the short-time Fourier transform (STFT) which makes use of windows to concentrate the FFT [10] on a smaller section of the overall signal but there is always a compromise between frequency and time resolution, known as the uncertainty principle or the Heisenberg inequality $\Delta t \Delta f \geq 1/4\pi$ [6].

In a similar fashion to STFTs, wavelets focus on sections or windows of the signal. The main improvement of Wavelet Transform over STFT is the choice of window function such as Coiflets, Daubechies, Dyadic, Morlet and Symlet wavelets. This, however, becomes one of the limitations of the Wavelet Transforms, because the success of identifying PQ events relies to some degree on the choice of wavelet [4]. Another disadvantage of the Wavelet Transform, is the use of ranges of frequency and hence it cannot provided an exact magnitude at a particular frequency. Morlet wavelet approach used for PQ event identification in [5] performed well when dealing with harmonics however the Morlet wavelet is Fourier based and therefore only has meaningful interpretations for linear phenomena [9].

This paper will focus on the use of recent method of the HHT technique proposed by Huang et al [9] for classification of power quality events, which uses a combination of the EMD process and the Hilbert transform (HT).

II. The Hilbert Huang Transform

A. Introduction to the Hilbert Huang Transform

The EMD process decomposes a signal into Intrinsic Mode Functions (IMFs) that have meaningful instantaneous frequency and amplitude. The EMD decomposes the signals into IMFs in such a way that the IMFs are sorted from the highest frequency to the lowest frequency, i.e., the first IMF contains the highest frequency of each event in the signal. For example a signal that contains two waveforms, one from $0 < t \leq t_1$ with 50 Hz and 150 Hz and another from $t_1 < t \leq t_2$ that contains 50 Hz and 250Hz. The first IMF will contain the 150 Hz signal from $0 < t \leq t_1$ and 250Hz from $t_1 < t \leq t_2$. The EMD process has therefore an inherently good time resolution.

Once the signal is decomposed into IMFs, the Hilbert Transform can then be applied to each IMF giving the instantaneous magnitude and instantaneous frequency vs. time. For example, when the Hilbert Transform is applied to the first IMF in the example above, it will give an instantaneous magnitude and an instantaneous frequency of the 150 Hz signal from $0 < t \leq t_1$ and an instantaneous

C. F. Drummond and D. Sutanto are with the Scholl of Electrical, Computer and Telecommunications Engineering, University of Wollongong, NSW 2522, Australia, e-mail: soetanto@uow.edu.au).

978-1-4244-7245-1/10/$26.00 ©2010 IEEE

magnitude and instantaneous frequency of 250 Hz for $t_1 < t \le t_2$. This combination of the EMD process and the Hilbert transform is known as the HHT. The HHT is well suited to non-linear and non-stationary time series data and thus is the perfect candidate for PQ event classifications. The high time resolution is the main advantage of the HHT technique over other power quality classification methods. Further, the HHT method provides intuitive visual information of the frequency and magnitudes contained in the signal, unlike the Wavelet Transform.

The HHT hinges on the ability of the EMD process to decompose a signal into separate components based on their frequencies. However, the EMD process has been found to have difficulties when an event in the signal has frequencies that are close together (less than a factor of 2) resulting in IMFs with mixed frequency and amplitude information. Such signals are often encountered in power quality waveforms, e.g. 17th and 19th harmonics. When the Hilbert transform is applied to these mixed or polluted IMFs, erroneous results can be obtained.

B. Empirical Mode Decomposition

For the HHT process to give meaningful information about a signal, the EMD process will decompose a signal S(t) into IMFs which have the following properties [10]:

(a) Each IMF must have exactly one zero between any two consecutive local extrema.

(b) Each IMF must have zero "local mean".

The following is an outline of the steps needed to complete the EMD process [9]:

1. Identify local maxima and minima of the signal S(t)
2. Create a cubic spline going through all of the maxima $C_{max}(t)$ and another going through all the minima $C_{min}(t)$.
3. Calculate the mean of the two splines.
   $C_{mean}(t) = (C_{max}(t)+ C_{min}(t))/2$. (1)
4. Calculate the first potential IMF known as a proto-mode function $P_{mf1}(t)$,
   $P_{mf1}(t) = S(t) - C_{mean}(t)$. (2)
5. If $P_{mf1}(t)$ satisfies the conditions to be an IMF then $\psi(t) = P_{mf1}(t)$. If not repeat steps 1 - 4 on P_{mf1} until it becomes an IMF.
6. Calculate the first residue $r_1(t)$,
   $r_1(t) = S(t) - \psi(t)$. (3)
7. If the maximum amplitude of the residue is below a threshold or there are three or fewer local maxima or minima, terminate the EMD process, otherwise repeat steps 1 - 6 on the residue $r_1(t)$.

Fig. 1 provides a simple illustration of the EMD process. The signal S(t) is seen to be encased by the maximum and minimum splines, the mean of these splines if then found then subtracted from the S(t) giving the first IMF.

C. The Hilbert Transform

The Hilbert Transform [11],[12] H(t) of a signal S(t) of the continuous variable t is defined as:

$$H(t) = \frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{S(\eta)}{\eta - t} d\eta \tag{4}$$

where P is the Cauchy Principal Value integral.

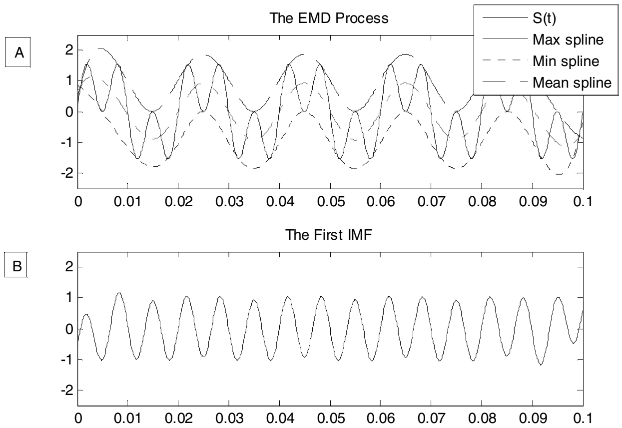

Fig. 1(A). A demonstration of the EMD process on a simple signal, showing the maxima, minima and mean of the signal. Fig. 1(B): the first IMF.

In a simple term, the Hilbert transform of a signal effectively produces an orthogonal signal that is phase shifted by 90 degrees from the original signal independent of the frequency of the signal [12].

Instantaneous frequency and amplitude of IMFs can be calculated as follows [11][12] :

Instantaneous Amplitude

$$A(t) = \sqrt{S(t)^2 + H(t)^2} \tag{5}$$

Instantaneous Phase

$$\phi(t) = \arctan\left(\frac{H(t)}{S(t)}\right) \tag{6}$$

Instantaneous frequency f(t) is found using:

$$\phi'(t) = \omega(t) = 2\pi f(t) \tag{7}$$

where:

$$\omega(t) = \frac{S(t)H'(t) - S'(t)H(t)}{S(t)^2 + H(t)^2} \tag{8}$$

Therefore, by using the HT on a signal S(t), a meaningful instantaneous magnitude, frequency and phase can be obtained as long as the signal does not have mixed frequency components. For example if we take S(t) to be a simple sinusoid sin (2π 50 t + 30^o) and apply the HT to it we obtain Fig. 2.

III. SIMULATION AND RESULTS

In this section the HHT is tested for its ability to detect and classify a number of PQ disturbances. Some common types of PQ disturbances are sags, swells, harmonics and flickers. These will be the focus of our analysis.

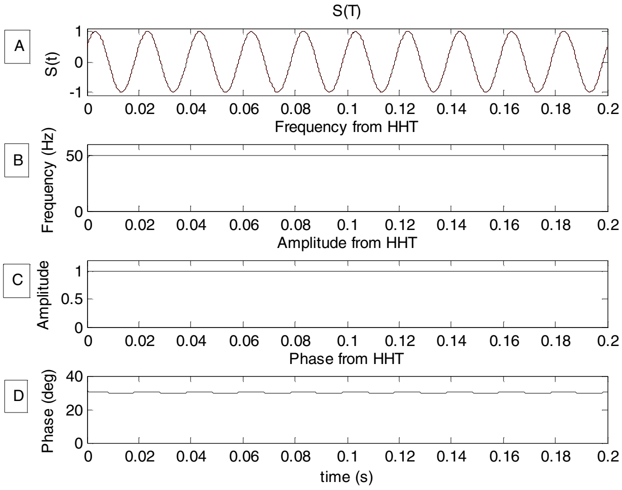

Fig. 2. The simple sinusoid S(t) = sin (2π 50 t + 30^o) shown in Fig. 2(A) has been correctly classified by the HT as having an instantaneous amplitude of 1 pu with an instantaneous frequency of 50 Hz from Fig. 2 (B) & (C) and instantaneous phase of 30^{o} from Fig. 2(D).

A. Harmonics

The simulated harmonic signal S(t) consists of a 50 Hz component with amplitude 1 per unit (pu) plus a 150 Hz component with magnitude 1/3 pu from 0 - 0.1 sec and a 50 Hz component with amplitude 1 pu plus a 250 Hz component with magnitude 1/5 pu from 0.1 - 0.2 sec. Fig. 3 shows how the signal S(t) was decomposed into its components (IMFs) using the EMD process and Fig. 4 shows the results when the Hilbert Transform is applied to the IMFs.

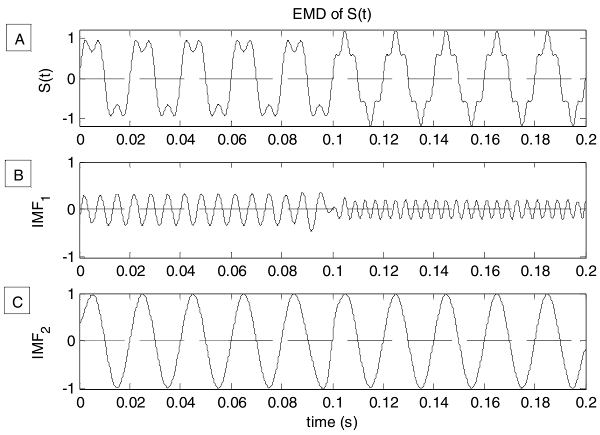

Fig. 3(A). The harmonic signal S(t).
Fig. 3(B). The first IMF containing the highest frequency data. Note that the signal was successfully separated into two different frequencies around 0.1.
Fig. 3(C). The second IMF containing the lower frequency 50 Hz signal from 0 – 0.2 sec.

B. Sags and Swells

Fig. 5(A) shows a harmonic signal (with 50 Hz and 250 Hz component and amplitude of 1 and 0.2 pu respectively), with a swell and a sag at 0.1 sec and 0.2 sec respectively. The signal S(t) was decomposed into its components using EMD and Fig. 6 displays the HT of the resulting IMFs.

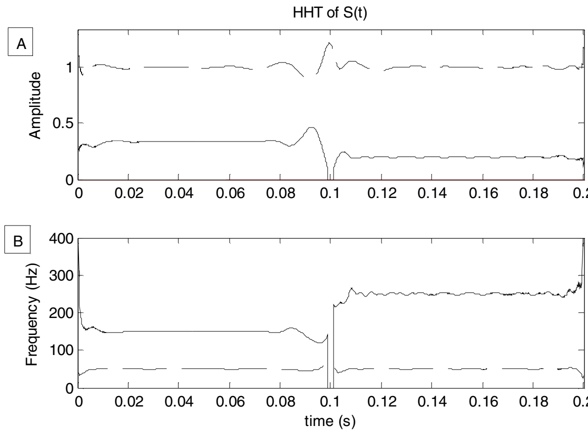

Fig. 4(A). Instantaneous Amplitude from the HT. The amplitudes for all three harmonic components are accurate with an overshoot around the transition area which can be attributed to the Gibbs phenomenon.
Fig. 4(B): Instantaneous Frequency from the HT. This figure shows how the HHT has resolved 150Hz frequency from 0 – 0.1 sec and 250Hz frequency from 0.1 – 0.2 sec with similar overshoot around the transition area.

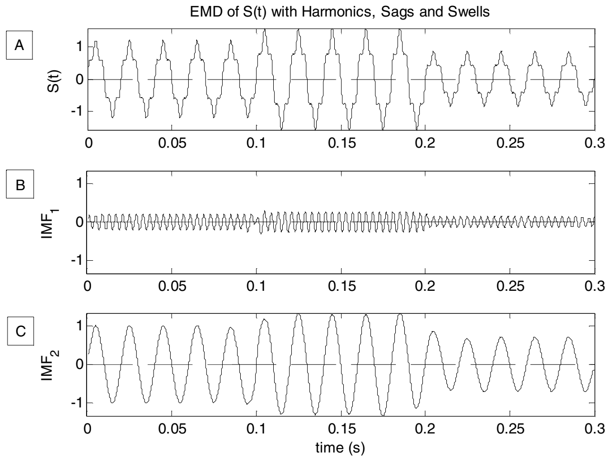

Fig. 5(A). The signal S(t) containing harmonics, sags and swells.
Fig. 5(B). The first IMF of S(t) which contains the 250 Hz component of the signal.
Fig. 5(C). The second IMF of S(t) containing the 50 Hz component.

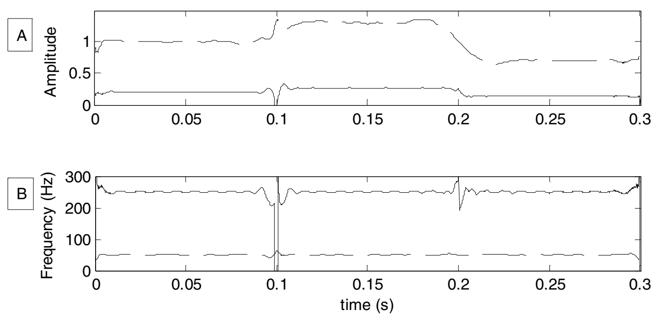

Fig. 6(A). Instantaneous Amplitude from the HT of IMFs. We observe an amplitude 1 pu between 0 – 0.1 sec, 1.3 pu between 0.1 – 0.2 sec and 0.7 pu between 0.2 - 0.3 sec for the 50 Hz component. Similarly for the 250 Hz component, an amplitude 1/5 pu between 0 – 0.1 sec, $1.3\times 1/5$ pu between 0.1 – 0.2 sec and $0.7\times 1/5$ pu between 0.2 - 0.3 sec with ambiguity around the transition areas due to Gibbs phenomenon

Fig. 6(B). Instantaneous Frequency from the HT. We observe a frequencies of 50 and 250 Hz from 0 – 0.3 with similar ambiguity around the transition areas.

C. Flicker

The flicker disturbance is of the form:

$$S(t)=\sin(2\pi f_1 t)\left(1+\frac{A_1}{2}\sin(2\pi f_2 t)\right) \tag{9}$$

Where: f_1 = fundamental frequency set at 150 Hz and amplitude of 1 pu.

f_2 = flicker frequency set at 50 Hz

A_1 = amplitude of flicker set at 0.2 pu.

Fig. 7. shows how the signal S(t) was decomposed into its components and Fig. 8 displays the HHT of the resulting IMFs.

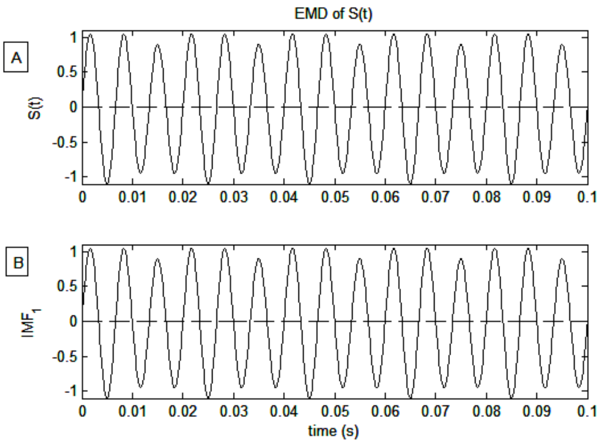

Fig. 7(A). The flicker signal S(t).

Fig. 7(B). The first and only IMF of S(t).

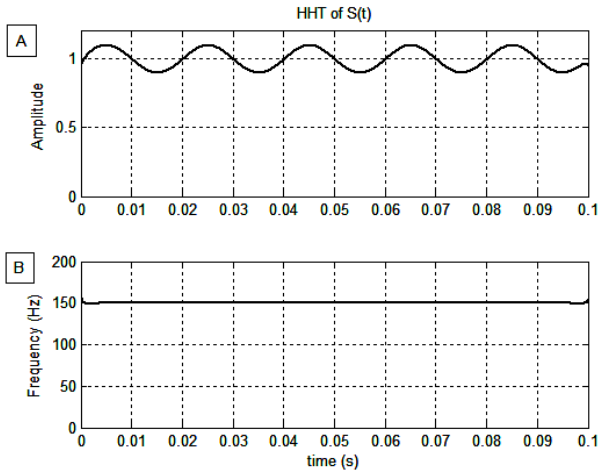

Fig. 8(A). Instantaneous Amplitude of the first IMF. The signal is detected as having amplitude of 1 pu and is changing sinusoidally with amplitude 0.2 and frequency 50 Hz which is the flicker frequency and amplitude.

Fig. 8(B). Instantaneous Frequency of the first IMF. The primary frequency of the signal is correctly identified as 150 Hz.

D. Windowed HHT applied to PQ events

It was observed in Fig. 4 and Fig. 6, that overshoot and ambiguity will occur around the transition/discontinuity area because of the Gibbs phenomenon. To overcome this, a windowing technique was developed to reduce these interferences. Another solution to the ambiguities caused by intermittency was proposed in [13], which sets limits on the frequency ranges allowed within one IMF however this is better suited to signals which change their frequency in time rather than amplitude.

A description of the windowing technique follows using S(t) as given in Fig. 5(A). Firstly a HHT is performed over a portion of the S(t), say from 0.0-0.2 sec. If a sudden change in frequency or amplitude is detected in the first IMF then the point where the change occurred is marked as a border for a window. In this example 0.1 would have been marked as such a border. The HHT is then performed again from 0-0.1 sec then the process starts again from 0.1-0.3 sec. To demonstrate the usefulness of this technique we now revisit the sag and swell disturbance encountered in Fig. 5(A) and apply the windowing technique.

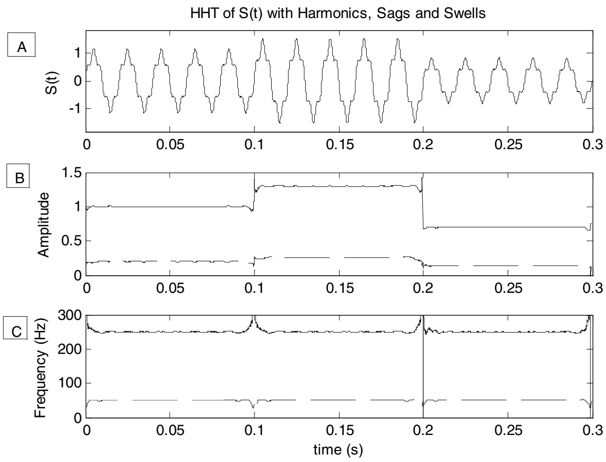

Fig. 9(A). The same harmonics, sags and swells seen in Fig. 5(A)

Fig. 9(B). HT Instantaneous Amplitude. Notice how sudden changes in amplitude are much more defined than in Fig. 5(A) allowing us to discriminate the boundaries more easily.

Fig. 9(C). HT Instantaneous Frequency. The windowing method avoids problems caused by overshoot/ambiguity due to Gibbs phenomenon.

In summary, the HHT was able to successfully classify PQ disturbances such as sags, swells, harmonics and flickers. Furthermore the HHT's ability to provide instantaneous frequency and instantaneous amplitude can, not only identify the instance of the PQ disturbances, but can accurately identify the frequency and amplitude components of each event during a PQ disturbance containing many different events in all the cases considered.

With the implementation of the windowing method the amplitude, frequency and the timing of the sinusoid for the sag, and swell disturbances can easily be determined from Fig.

9. This proved to be a worthwhile improvement over analysing the entire signal in one move.

IV. The Limitations of HHT

Once of the limitations of the HHT is the difficulty in accurately separating signals which have frequency components within a factor of two of one another. Such signals can produce IMFs containing mixed frequencies and when these are processed by the Hilbert Transform, erroneous results can be obtained. To demonstrate this, a harmonic signal with n components was studied, they were constructed as follows:

$$S(t)=A\sin(2\pi f+\phi_1)+\frac{A}{k(\beta)}\sin(2\pi k(\beta)\times f+\phi_2)+...$$
$$+\frac{A}{k(\beta+n\text{-}1)}\sin(2\pi k(\beta+n\text{-}1)\times f+\phi_{n+1}) \quad (10)$$

where: A = the magnitude of the fundamental signal
f = 50 Hz
k(m) = [3,5,7,9,…], for m=1,2,3,….
ϕ = Phase in radians
β = constant offset.

For example a signal containing 50, 350, 450, 550 Hz will have n = 3 because we only have three harmonics (7^{th}, 9^{th} and 11^{th}), β=3 because the j(3) = 7 (the first harmonic), followed by j(4) =9 and finally j(β +n-1)= j(5) =11, so the signal will be of the form:

$$S(t)=A\sin(2\pi f+\phi_1)+\frac{A}{7}\sin(2\pi\times 7f+\phi_2)$$
$$\frac{A}{9}\sin(2\pi\times 9f+\phi_3)+\frac{A}{11}\sin(2\pi\times 11f+\phi_4) \quad (11)$$

In our study, all of the harmonic signals analysed contained the fundamental frequency f at 50 Hz and one to four other harmonic components. Only the harmonics of the form given in (10) were studied because frequencies close together should be more difficult to separate than more evenly separated harmonics, i.e. a signal containing the harmonic frequency components 50, 650, 4950 should be easier to decompose than one containing 50, 4850, 4950 Hz.

The HHT was applied to the signal of the above form sampled at 10 KHz over the range 50 Hz to 4950 Hz. It was observed that when there were three or more harmonic components, the HHT's ability to separate close frequencies diminished further. The results are summarized in Table I.

TABLE I
Separation of Harmonic Signals Using the HHT

Number of harmonic components (n)	Frequencies separated correctly
1	50, 150 Hz to 50, 4950 Hz
2	50, 150, 250 Hz only
3	None
4	None

V. The Proposed Iterative HHT

A. The Iterative HHT for Harmonic Signals

To overcome the problems of separating frequencies that are close together, a novel method using an iterative HHT is proposed.

The proposed iterative HHT method uses an iterative process which differs from the usual HHT process in two important respects.

First, in the standard HHT all of the IMFs are found, then the HT is performed on these IMFs. In the proposed iterative method, the first IMF is found then the HT is performed on that IMF. This IMF is approximated by a pure sinusoid whose amplitude, frequency and phase are obtained from the mean values of the instantaneous amplitude, frequency and phase given by the HT. This pure sinusoid can then be subtracted from the signal or the residue in the succeeding steps. The process is allowed to repeat until there are fewer then three turning points in a residue or the amplitude has fallen below some threshold. Therefore at every step, only the first IMF is used. In this process, it is possible that similar frequencies are obtained in succeeding steps because the approximation of the pure sinusoidal magnitude might not be accurate enough leading to remainders in the residue. Hence in the succeeding steps the remainders of those sinusoids with similar frequencies are obtained. For example, a signal with a 50 Hz and 250Hz and magnitude of 1 pu and 0.2 pu when processed with the proposed iterative HHT method may produce initially a 250Hz signal with a magnitude of 0.15 pu, followed by another 250Hz signal with 0.03 pu followed by a 50Hz signal with 1 pu and finally a a 250Hz signal with 0.02 pu.

Second, all of the pure sinusoids of similar frequencies are combined to find the magnitudes, frequencies and phases of the original signal components.

The steps comprising the iterative HHT are as follows:

1) Find the first IMF using the standard EMD process.
2) Use the HT to approximate the frequency, amplitude and phase of the dominant part of the IMF. These approximations are of the form:
$$P(t)=\tilde{A}_k\sin(2\pi\tilde{f}_k+\tilde{\phi}_k)\,. \quad (12)$$
3) Subtract the approximation for the dominant component of the first IMF from the original signal to obtain the residue, r(t):
$$r(t) = S(t)\text{-}\tilde{A}_1\sin(2\pi\tilde{f}_1+\tilde{\phi}_1) \quad (13)$$
where: $\tilde{A}_1$ = approximate amplitude of the first IMF
$\tilde{f}_1$ = approximate frequency of the first IMF
$\tilde{\phi}_1$ = approximate phase of the first IMF (from equation 6)
4) Steps 1-3 are repeated on r(t) until the first IMF reaches a low threshold amplitude.
5) These sinusoids are then sorted by frequency and consolidated if they are of like frequency according to:

$$R_k=\tilde{A}_1\sin(2\pi\tilde{f}_k+\tilde{\phi}_1)+\tilde{A}_2\sin(2\pi\tilde{f}_k+\tilde{\phi}_2)+...$$

$$+\tilde{A}_n \sin(2\pi \tilde{f}_k + \tilde{\phi}_n) \quad (14)$$

This approach is intended for use in conjunction with the windowing technique and should be applied once the presence of harmonics has been detected by the standard HHT.

B. Results from the Iterative HHT

The proposed method of successively subtracting pure sinusoids instead of IMFs (which is used in the standard HHT) has led to greater accuracy when dealing with harmonic signals.

The standard EMD process and HHT has trouble when frequencies are within a factor of two of one another. However, the iterative HHT can separate arbitrarily close harmonic frequencies when there are up to as many as three harmonics present. For example, the iterative HHT was able to separate frequencies from a signal containing frequencies of 50, 150, 250, 350 Hz up to 50, 4750, 4850, 4950 Hz. The sampling rate has to be at least twice the highest frequency in the signal following the Nyquist criterion otherwise the signal cannot be accurately decomposed.

Test 1

For the first test of the iterative HHT a signal S(t) was created with three harmonic components. Figures 10 and 11 show how the iterative HHT differs from the standard HHT process. Table II displays the resulting frequency and amplitude approximations of the harmonic components in the signal.

The sinusoids P(t) in Fig. 10 are combined to give the amplitude and frequency estimates of test 1, shown in table II.

TABLE II
ITERATIVE HHT RESULTS

True Freq (Hz)	Freq Approx (Hz)	True Amp (pu)	Amp Approx (pu)	True Phase (Deg)	Phase Approx (Deg)
50	50.00	1	1.00	30	30.06
350	350.00	0.14	0.14	30	30.02
450	450.00	0.11	0.11	30	29.87
550	550.00	0.09	0.09	30	30.04

The Frequencies obtained via the iterative HHT are extremely close to that of the true values, the amplitude estimates are also within one percent.

Test 2

The iterative HHT was tested in the same manner as the standard HHT in IV, the results are summarized by Table III.

TABLE III
SEPARATION OF HARMONIC SIGNALS USING THE ITERATIVE HHT

Number of harmonic components (n)	Frequencies separated correctly
1	50, 150 Hz to 50, 4950 Hz
2	50, 150, 250 Hz to 50, 4850, 4950 Hz
3	50,150,250,350 Hz to 50, 4750, 4850, 4950 Hz
4	50, 150, 250, 350, 450 Hz to 50, 850, 950, 1050, 1150 Hz then intermittent success

The difficulty of separating harmonics increases as the number of harmonic components increases however the iterative HHT could still decompose a signal consisting of four harmonics up to the frequency 50, 850, 950, 1050, 1150 Hz with intermittent success beyond this point. Further work is currently being carried out to solve this problem and will be published in a future paper.

VI. CONCLUSION

The HHT's ability to deal with non-stationary signals with good time resolution makes it an invaluable tool for the classification of power quality waveforms. This paper has shown that HHT was able to successfully classify PQ waveform containing multiple events such as sags, swells, harmonics and flickers.

To avoid overshoot/ambiguity during the transition period from one event to another, we have proposed the use of windowing method to identify a segment of time when a particular event occurs. The windowing method proposed is a straightforward solution to many of the problems associated with intermittent signals. With the use of the windowing method we were able to overcome much of the interference caused by intermittency, while at the same time preserving the ability to obtain accurate instantaneous amplitude, frequency and phase from the signal, allowing for the easy detection and accurate interpretation of the sag and swell disturbances.

The Iterative HHT proposed was able to identify the amplitudes, frequencies and phases of as many as four arbitrarily close harmonic components in the PQ signal. This is a vast improvement over the regular HHT for identifying harmonics often encountered in power systems.

Overall the HHT shows a great promise as a means to classify PQ events because of its flexibility and the ease with which the instantaneous magnitude and frequency information can be interpreted.

VII. REFERENCES

[1] D. D. Sabin and A. Sundarm, “Quality enhances reliability,” IEEE Spectrum, vol 33, no. 2, pp. 34-41,1996.

[2] A. Domijan, G. T. Heydt, A. P. S. Meliopoulos, S. S. Venkata, and S. West, “Directions of research on power quality,” IEEE Transactions on Power Delivery, vol 8, no. 1, pp 429-436, January 1993.

[3] J. Douglas, “Solving power quality problems,” EPRI Journal, vol. 18, no. 8, pp. 6-15, December 1993..

[4] R. Flores, “Signal processing tools for power quality event classification,” Lic.Eng. thesis, School Elect. Eng., Chalmers Univ. Technol.,Göteborg, Sweden, 2003, Tech. Rep. 477L

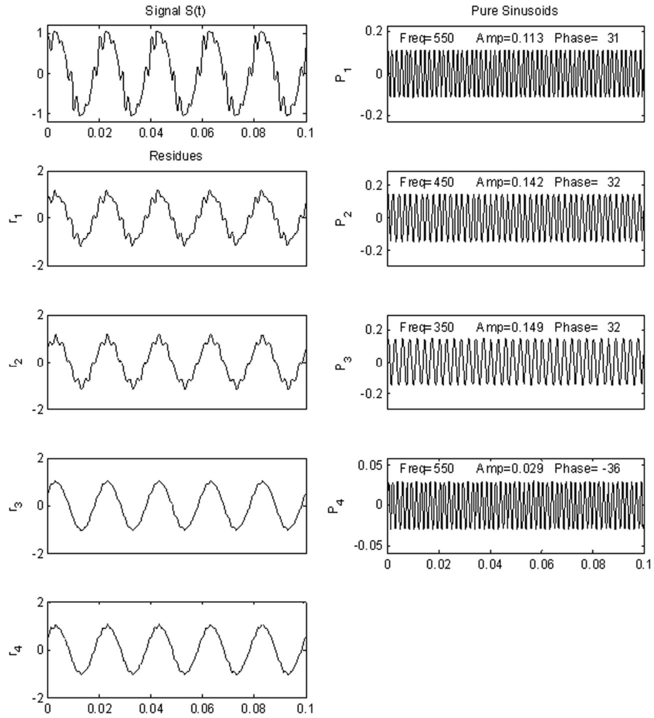

Fig. 10. This figure depicts how the iterative HHT process decomposes a signal by breaking it up into sinusoidal components. The sinusoids P(t) on the right approximate the first IMF obtained through the EMD process of S(t) or more frequently, a residue r(t). Note that the process continues until S(t) is decomposed. Also in this example the sinusoids P_1 and P_4 would be recombined since they are of similar frequencies.

[5] S. J. Huang, C.-t. Hsieh, and C.L. Huang, "Application of mortlet wavelets to supervise power system disturbances," IEEE Transactions on Power Delivery, col. 14, no. 1, pp. 235-243, January 1999.

[6] O. Rioul and M. Vetterli, Wavelets and signal processing, *IEEE Signal Process. Mag.* **8** (1991) (4), pp. 14–38.

[7] T. . B. Littler and D. J. Morrow: Wavelets for the analysis and compression of power system disturbances, IEEE Trans. Power Delivery, Vol.14, pp. 358–364, April 1999.

[8] Z. Lu, J.S. Smith, Q. H. Wu, J. Fitch, "Empirical Mode Decomposition For Power Quality Monitoring" Transmission and Distribution Conference and Exhibition: Asia and Pacific, pp. 1 – 5, 2005

[9] N. E. Huang, Z. Shen, S. R. Long, M. C. Wu, H. H. Shih, Q. Zheng, N. C. Yen, C. C. Tung, and H. H. Liu, "The empirical mode decomposition and the hilbert spectrum for nonlinear and non-stationary time series analysis," *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 454, no. 1971, pp. 903-995, March 1998.

[10] F. J. Harris, "On the use of windows for harmonic analysis with the discrete fourier transform," *Proceedings of the IEEE*, vol. 66, no. 1, pp. 51-83, 1978

[11] R. Deering, J. Kaiser, "The use of a masking signal to improve empirical mode decomposition," ICASSP, vol. 4, pp 485-488, 2005

[12] S.L. Hahn, Hilbert Transforms in Signal Processing, Artech House, Boston, London, 1996.

[13] N. E. Huang, Z Shen, and S. Long, "A new view of nonlinear, water waves: The Hilbert Spectrum," *Annu., Rev. Fluid Mech.*, vol. 31, no. 1, pp. 417–457, 1999.

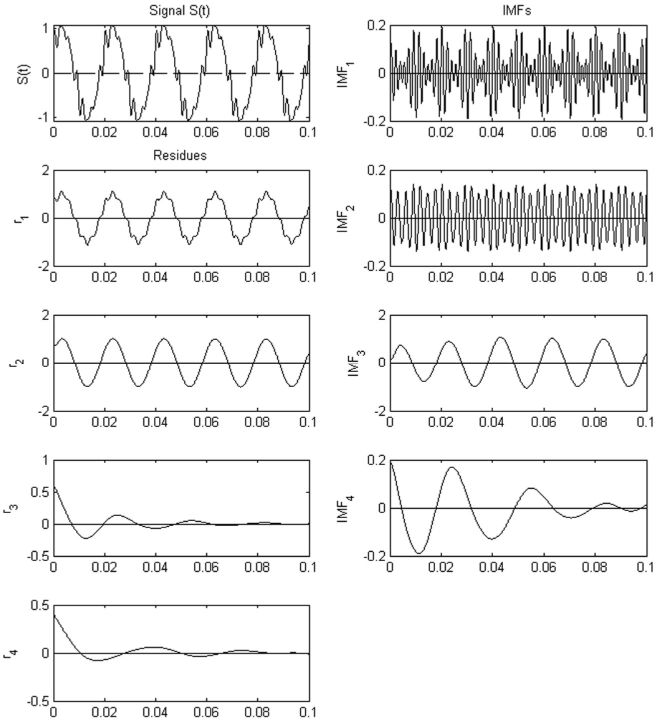

Fig. 11. This figure depicts how the standard HHT process decomposes a signal into its IMFs. Note that the two methods produce different residue and instead of having IMFs as in the standard method, the proposed method produces a series of pure sinusoids, some of which may have similar frequencies. The first IMF also appears to contain information from two frequency components and hence the HT of this IMF would give misleading results.

VII. BIOGRAPHIES

Carson F. Drummond received his BSc (Physics) and BMath in 2009 from the University of Wollongong (UOW), Australia. He is currently a Master student in Mathematics and a research assistant at UOW. His research interests include signal analysis, numerical methods for stiff ODEs and acoustic multilateration.

Danny Sutanto (SM) obtained his BEng. (Hons) and PhD from the University of Western Australia. He is presently the Professor of Power Engineering at the University of Wollongong, Australia. His research interests include power system planning, analysis and harmonics, FACTS and Battery Energy Storage systems. He was the PES Region 10 Regional Representative in 2002-2004. He is a Senior Member of IEEE.