Effects of Frequency Deviation on the Accuracy of Harmonic Analysis and Mitigation

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Abstract- **Results of a comparison of the effects of frequency deviation on the accuracy of a number of widely used methods for signal harmonic analysis are given, together with a means of mitigation of these effects.**

1. INTRODUCTION

In modern power networks, the issue of electrical Power Quality (PQ) is becoming very important. This is because of the simultaneous influence of two trends:- Firstly; the increasing use of power electronic devices that draw current which is not sinusoidal; creating a voltage distortion which affects all loads connected to the network. Secondly; the increasing penetration of loads which are sensitive to such voltage disturbances, such as Personal Computers. As a result there is an increasing need for PQ to be monitored to establish the type, sources and locations of voltage disturbances, allowing remedial measures to be taken.

2. MAIN TECHNIQUES FOR PQ MONITORING

In the field of automatic detection and diagnosis of power quality disturbances there are two main approaches, the Fourier Transform (FFT) method, including the Short Time FT method, (STFT) [1], and the Wavelet Transform (WT) method [1]. The latter is appropriate in cases where the FT is inadequate, such as in the analysis of non stationary signals where the lack of temporal information prevents discrimination between, for instance, transients and steady-state harmonics. WT has the advantage of using a shorter window length at high frequencies and a longer one at low frequency, consequently signals may be analysed in time and frequency domains simultaneously. Two main variants of WT are in use, Continuous Wavelet Transform (CWT) [2], and the Discrete Wavelet Transform (DWT) [3], where the signal is decomposed into a number of fixed scale (frequency) levels, computational requirements being reduced compared to the basic technique of CWT. DWT is inefficient, in that it is unable to accurately measure the magnitude of the fundamental frequency, when analysing events at low frequency such as sag/swell [1]. This is due to the scale by scale recursive decomposition and reconstitution procedure. The decomposition coefficients at different scales are not directly linked to the monitored signal, hence the magnitude and frequency information cannot be explicitly obtained. A variant of DWT has been suggested, known as Wavelet Packet Transform (WPT) which is however useable for measurement of the fundamental frequency [4].

Where computational resources permit, more reliance tends to be placed on CWT, which overcomes most restrictions in the DWT approach by setting the positive scaling factor as a function of the chosen fundamental frequency e.g. 50 Hz [2].

3. PROBLEMS CAUSED BY NORMAL SYSTEM FREQUENCY DEVIATION

One problem experienced, when using any of the above techniques, is that when the signal fundamental frequency differs from the nominal value, (50Hz in the UK), the results of the analysis become erroneous. For example, Lin et al [5] describe the extraction of 3rd Harmonic with CWT, the fundamental frequency being set to 49 Hz. Error occurred in the measurement due to the deviation in the fundamental frequency; and in addition the measured amount was ill defined, being dependant upon the time of measurement..

4. PRESENTED RESEARCH

The paper presents a comparison of the effects of frequency deviation on the accuracy of extraction of signal harmonic components, for a number of widely used techniques used for

PQ analysis including the above mentioned FT, Short Time FT (STFT), CWT, and the WPT variant of the DWT techniques together with an approach using artificial neural networks [6]. A study of the literature shows that such a comparison has not been published. A test signal of 128 samples at 6400Hz comprising fundamental, 1/3 3rd harmonic, 1/5 5th harmonic and 1/7 7th harmonic was studied in the MATLAB environment under the various schemes for harmonic extraction, and the peak % error established under deviation of fundamental frequency from 48 to 52 Hz. Graphs of the results are shown in Figs 7-10.

4.1. FFT

The FFT analyzer is a batch processor; it samples the input signal for a fixed time interval, storing a predetermined number of samples, after which it performs the FFT calculation on that "batch" and displays the resulting spectrum

If the time record contains an integral number of cycles of the waveform, the resulting FFT spectrum consists of a single line with the correct amplitude and frequency. If, on the other hand, the signal level is not at zero at one or both ends of the time record, 'truncation' of the waveform will occur, resulting in a discontinuity in the sampled signal. This discontinuity is not handled well by the FFT process, and the result, 'leakage', is a smearing of the spectrum from a single line into adjacent lines.

Frequency deviation ensures that the sampled signal amplitude is never zero at both the start and finish of a rectangular window of fixed correct length for the nominal frequency. Fig 1 shows correct harmonic extraction and Fig 2 shows the error introduced by using a 20 Hz fundamental:-

4.2. STFT

One of the shortcomings of the Fourier Transform is that it gives no information on the time at which a frequency component occurs. This is not a problem for "stationary" signals but can be a problem when non stationary signals are involved.

One approach which can give information on the time resolution of the spectrum is the short time fourier transform (STFT). Here a moving window is applied to the signal and the fast fourier transform is applied to the signal within the window as the window is moved. For example, suppose that a signal consists of two frequencies, 50Hz for a period of 0.06 seconds and its seventh harmonic 350Hz for a period of 0.02 seconds within the first interval, then the STFT which would be obtained when a rectangular window of width 0.02 seconds is used is indicated in the 'specgram' shown as Fig 3:- The plot has frequency as one axis and time as the other. Colour indicates arbitrary amplitude.

Under conditions of frequency deviation, the plots for fundamental and seventh harmonic are less clearcut, as shown in Fig 4 with a fundamental frequency of 48Hz:-

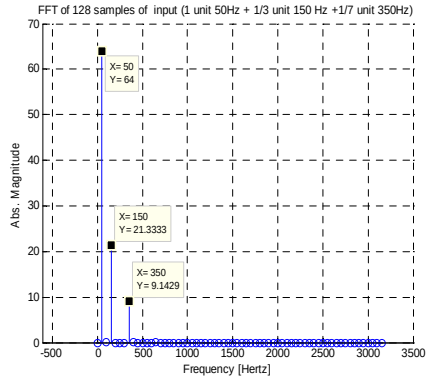

FIG 1 FFT Analysis of signal comprising 50 Hz +1/3 3rd Harmonic and 1/7 7th Harmonic

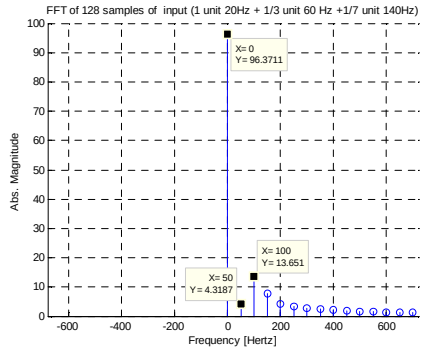

FIG 2 FFT Analysis of signal comprising 20Hz +1/3 3rd Harmonic +1/7 7th Harmonic

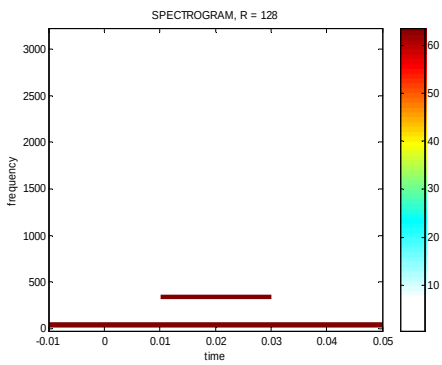

FIG 3 Specgram of signal comprising 50 Hz +350Hz

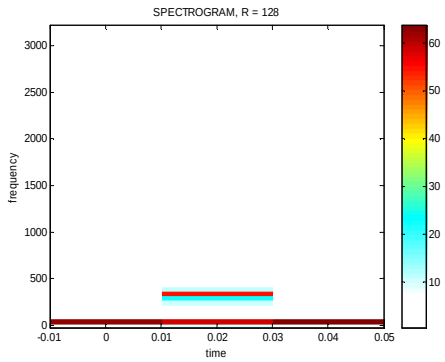

FIG 4 Specgram of Signal comprising 48Hz + 336Hz

4.3. CWT Analysis

In Continuous Wavelet Transform Analysis (CWT), the signal to be studied is compared to a variable test signal, and the congruence of the two signals is measured. To give the ability to resolve short high frequency transients, and at the same time to resolve low frequency signals such as power fundamentals, the test signal is chosen to be a 'wavelet', whose representation is short and self contained starting from zero amplitude and returning to zero amplitude within a few cycles. The wavelet may be shifted eg delaying its onset, and is also made variable in 'scale' so that whilst its amplitude remains the same the time taken for the wavelet to rise from zero to maximum amplitude and then decrease back to zero can be altered. This process, of altering the 'scale', changes the nearest equivalent continuous frequency for the wavelet, so that by progressively altering the scale and each time comparing the wavelet to an incoming signal, coefficients reflecting the degree of congruency can be recorded. The higher the coefficient value the more similar is a component of the signal being analysed to the wavelet at the particular scale being employed. Using a computerised facility such as MATLAB one can arrange for the scale being compared to be varied over a range to pick up differing components of the input signal. Given the short length of the wavelet it is possible to analyse an incoming signal, (albeit with a drop in accuracy in amplitude measurement) using less than one cycle of the latter's fundamental.

For this study, the wavelet scale, signal amplitude and sampling frequency were kept constant, and the input signal was allowed to deviate from 50Hz, for measurement of the difference in coefficient amplitude caused by the frequency deviation.

The maximum % error thus arising was measured over fundamental frequencies from 48 to 52 Hz, using the Matlab environment, for the fundamental and one at a time the 3rd, 5th and 7th Harmonics.

4.4. Wavelet Packet Transform Analysis

Discrete Wavelet Transform (DWT) is unsuitable for Harmonic measurement [1]. are not used for further decomposition.
A modification of the DWT algorithm for Harmonic analysis was proposed in [4], known as the Wavelet Packet Transform (WPT). In this scheme, both the detail and approximation coefficients are decomposed into lower levels to produce further coefficients. As a result the equivalent frequency band covered by each coefficient at a given level of decomposition is the same, allowing use of WPT analysis for the determination of Harmonic magnitudes. By combining one or more of the output coefficients at a given level, bandpass filters of a predetermined bandwidth may be obtained. In [8] using a sampling window width of 10 cycles of fundamental frequency produced 32 output bands each of 25 Hz width after 5 levels of decomposition. These are then grouped into pairs to give 15 output bands of 50Hz width, as shown in Fig 5:-

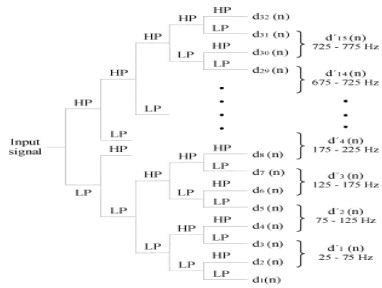

FIG 5 WPT Frequency pass bands

The overall frequency characteristics of the system from 0 to 800 Hz are shown in [3] (Fig 6) as:-

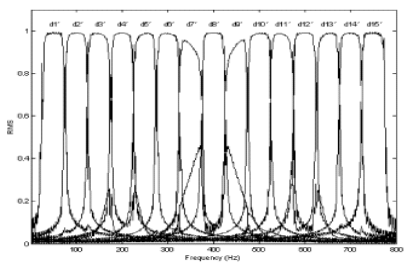

FIG 6 WPT Frequency Response

As may be seen the frequency bands have a flat topped characteristic rendering them relatively immune to the effects of frequency deviation. For many purposes it is necessary to sample a signal for a short period. In the present study 128 samples at 6400Hz were used. It was found that reduction in the sample length from 10 cycles to one removed the 'flat topped' characteristic and rendered the procedure subject to error under frequency deviation.

The results may be summarised as follows:-

WPT may be used for Harmonic Analysis but it was found that unless the number of samples used for the signal to be analysed was well in excess of that required to represent one cycle of the fundamental, then the analysis was susceptible to the effects of frequency deviation.

4.5. Harmonic Measurement using an Artificial Neural Network

For the sake of completeness, results are included, taken from a study [6] using an Artificial Neural Network for Harmonic Measurement, giving the variation in accuracy under frequency deviation:-

4.6. Relative susceptibility to the effects of Frequency Deviation

Comparisons are shown below for error arising out of Frequency Deviation under the 5 schemes, in Figures 7 - 10 :-

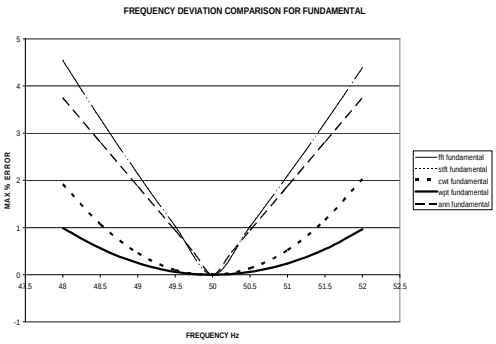

FIG 7 Frequency Deviation Comparison for Fundamental (FFT and STFT overlap)

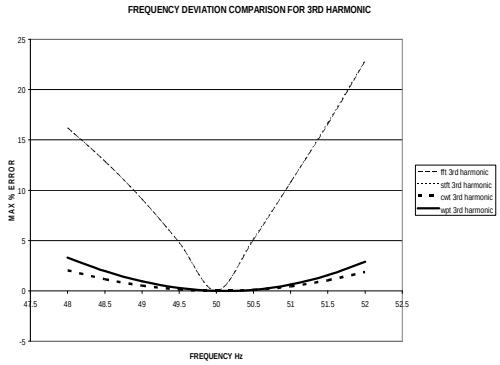

FIG 8 Frequency Deviation comparison for 3rd Harmonic (ANN Data not available from [6] for 3rd Harmonic, FFT and STFT overlap)

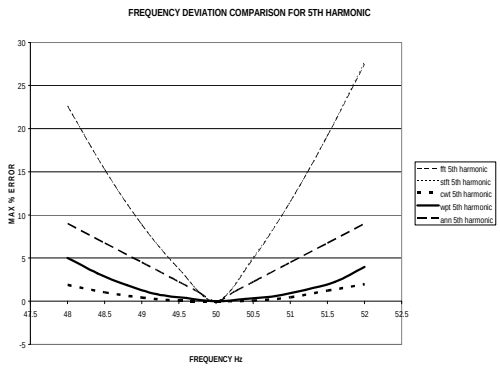

FIG 9 Frequency Deviation Comparison for 5th Harmonic (FFT and STFT overlap)

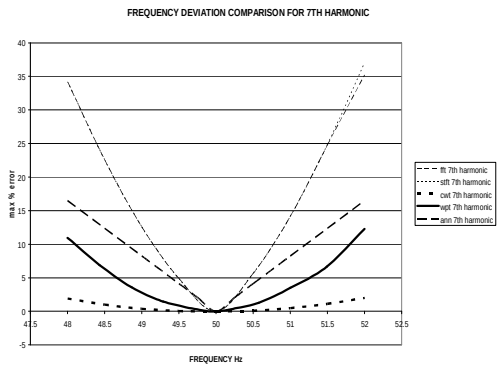

FIG 10 Frequency Deviation Comparison for 7th Harmonic

4.7. Mitigation

It proved possible to mitigate the effects of frequency deviation on any of the above schemes by altering the time between samples and number of samples in such a way as to compensate for deviation from the nominal value in the fundamental frequency. The outline of the scheme is given in Fig 11 :-

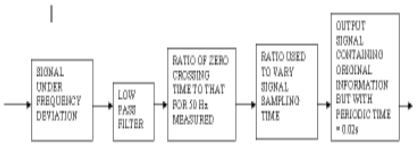

FIG 11 Correction for Frequency Deviation by Variation of Sampling time

Fig 2 demonstrates FFT leakage effects arising from frequency deviation, and Fig 12 shows their successful mitigation by this means:-

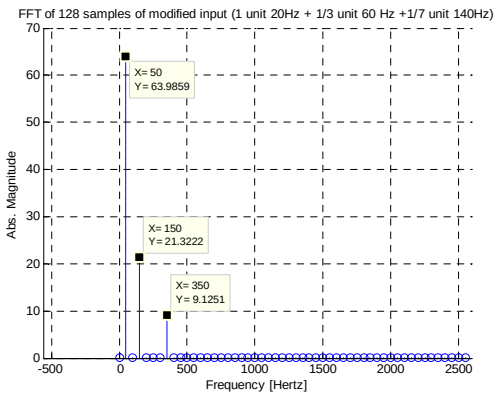

FIG 12 20Hz Fundamental Compensated to remove Leakage effects and to correct frequency to 50Hz

5. CONCLUSIONS

The study reveals that of the common methods used for Harmonic Analysis, CWT suffers least from Frequency Deviation; it is fast but makes heavy demands on computer processing power, and it's results are time dependant.

The WPT technique is very adequate if sampling is carried out for a number of cycles of the fundamental, being quite resistant to the effects of Frequency Deviation, but is prone to error from this source if sampling is carried out for 1 cycle of the fundamental only.

The FFT and STFT techniques are the most susceptible to the effects of Frequency Deviation, and require sampling for an integral number of complete cycles, of the fundamental for FFT and for the harmonic being measured for STFT, in order to produce accurate results. The FFT/STFT methods are capable of a high degree of accuracy when used within their limitations.

All of the above schemes may be rendered unsusceptible to the effects of Frequency Deviation using the compensation scheme outlined above.

6. REFERENCES

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