Harmonics and Interharmonics Measurement using Group-harmonic Power Minimizing Algorithm

Hsiung Cheng Lin, Chao Hung Chen, Liang Yih Liu

Abstract—**The Fast Fourier Transform (FFT) is still a widely-used tool for analyzing and measuring both stationary and transient signals in power system harmonics. However, the misapplications of FFT can lead to incorrect results caused by some problems such as aliasing effect, spectral leakage and picket-fence effect. A strategy of Recursive Group-harmonic Power Minimizing (RGPM) algorithm is developed for system-wide harmonic/inter-harmonic evaluation in power systems. The proposed algorithm can restore the dispersing spectral leakage energy caused by the FFT, and regain its harmonic/inter-harmonic magnitude and respective frequency. Every iteration loop for harmonic/interharmonic evaluation can guarantee to be convergent using the proposed Group-Harmonic Bin Power (GBP) algorithm. Consequently, not only high-precision in integer harmonic measurement can be retained, but also the inter-harmonics can be identified accurately, particularly under system frequency drift. The numerical example is presented to verify the proposed algorithm in term of robust, fast and precise performance.**

Index Terms— **harmonics, inter-harmonics, group-harmonics, DFT, FFT**

I. Introduction

With increasing use of power electronic systems and time-variant non-linear loads in industry, the generated power harmonics and interharmonics have resulted in serious power line pollution. Power supply quality is therefore aggravated. Traditional harmonics may cause negative effects such as signal interference, overvoltage, data loss, equipment malfunction, equipment heating and damage, etc. The noise on data transmission line is also related with harmonics. At some special systems, harmonic current components may cause effect of carrier signals, and thus interfere other carrier signals. As a result, some facilities may be affected. Once harmonics source enter computer instruments, the data stored in the computer may be lost up to ten times. Moreover, harmonics may also cause transformer and capacitor over heating, thus reducing their working life. The resulting rotor heating and pulsating output torque will decrease the driver’s efficiency [1-8].

Manuscript received Nov. 25, 2010; revised Feb. 17, 2011. This work was supported by the National Science Council of the Republic of China, Taiwan under Grant No. NSC 99-2221-E-167 -034.

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The presence of power system interharmonics has not only brought many problems as harmonics but produced additional problems. For instance, there are thermal effects, low frequency oscillation of mechanical system, light and CRT flicker, interference of control and protection signals, high frequency overload of passive parallel filter, telecommunication interference, acoustic disturbance, saturation of current transformer, subsynchronous oscillatoions, voltage fluctuations, malfunctioning of remote control system, erroneous firing of thyristor apparatus, and the loss of useful life of induction motors, etc. These phenomenons may even happen under low amplitude [1-4].

Conventionally, Discrete Fourier transform (DFT) method is efficient for signal spectrum evaluation because of the simplicity and easy implementation. The use of the FFT can reduce the computational time required for DFT by several orders of magnitude. An improper use of DFT (or FFT) based algorithms can, however, lead to multiple interpretations of spectrum [4-6]. For example, if the periodicity of DFT data set does not match the periodicity of signal waveforms, the spectral leakage and picket-fence effect will occur. Since the power system frequency is subject to small random deviations, some degree of spectral leakage can not be avoided. A number of algorithms, e.g., short time Fourier Transform [7], least-square approach [8-10], Kalman filtering [11-12], artificial neural networks [6,13], have been proposed to extract harmonics. The approaches may either suffer from low solution accuracy or less computational efficiency. None is reported to perform well in interharmonic identification under system frequency variations though each demonstrates its specific advantages.

The presence of interharmonics strongly poses difficulties in modeling and measuring the distorted waveforms. This is mainly due to: 1) very low values of interests of interharmonics (about one order of quantity less than for harmonics), 2) the variability of their frequencies and amplitudes, 3) the variability of the waveform periodicity, and 4) the great sensitivity to the spectral leakage phenomenon. In recent years, the effect caused by interharmonics is being worsened apparently. Therefore, now the development of accurate interharmonics measurement has attracted great attention both industry and academics. This point of view is fully supported by exploring a number of publications (2007-2009) related to this field [14-31]. However, the published outcome may still suffer from low accuracy, long computational time, complexity or measurement limitation, etc. Accordingly, it is still an essential research issue to be carried on in this field.

IEC 61000-4-7 established a well disciplined measurement method for harmonics/interharmonics. This standard recently has been revised to add methodology for measuring inter-harmonics [32]. The key to the measurement of both harmonics and inter-harmonics in the standard is the utilization of a 10 or 12 cycle sample window upon which to perform the Fourier transform. However, the spectrum resolution with 5 Hz is not sufficiently precise to reflect the practical inter-harmonic locations for both 50 Hz and 60 Hz systems. This paper presents harmonic/inter-harmonic identification using FFT-based RGPM approach which retains the merits of FFT analysis and extends to inter-harmonic identification under system frequency variation environments. This paper is organized as follows. Section II gives a background of the concept of system harmonic/interharmonic measurement. Section III presents the proposed RGPM algorithm. In Section IV, the model validation with a numerical example is demonstrated. Performance results under system frequency drift is included and discussed. Conclusions are given in Section V.

II. BACKGROUND OF SYSTEM HARMONIC/INTERHARMONIC MEASUREMENT

The measurement of inter-harmonics is difficult with results depending on many factors. Based on the so-called "group" suggested by IEC 61000-4-7, the concept of group-harmonic is introduced as follows [32].

By the Parseval relation in its discrete form, the power of the waveform, *P*, can be expressed as

$$P = \frac{1}{N}\sum_{n=0}^{N/2-1} i_s[n]^2 = \sum_{k=0}^{N/2-1} I_s[k]^2 \qquad (1)$$

Both positive and negative values of spectral components are considered to transform the frequency dominant sampled signal into a periodic time dominant signal. Therefore, actual signals spectral components relevant to symmetrical frequencies are complex conjugates each other. However, most real-world frequency analysis instruments display only the positive half of the frequency spectrum because the spectrum of a real-world signal is symmetrical around DC. Thus, the negative frequency information is redundant.

For this reason, the power at the discrete frequency f_k can be expressed as

$$P[f_k] = I_s[k]^2 + I_s[N-k]^2 = 2I_s[k]^2 \qquad (2)$$

where k=0,1, 2,…,*N*/2-1.

The RMS value of the harmonic amplitude at the discrete frequency f_k is

$$I_h[f_k] = \sqrt{P[f_k]} = \sqrt{2}I_s[k] \qquad (3)$$

The power of the harmonic at f_k may disperse over a frequency band around the f_k due to the spectral leakage. Hence, the total power of harmonics within the adjacent frequencies around f_k can be restored into a "group power" [5]. Each "group power", i.e., $P^*[f_k]$, can be collected between $f_{k-\Delta k}$ and $f_{k+\Delta k}$ as follows.

$$P^*[f_k] = \sum_{\Delta k=-\tau}^{+\tau} I_h[f_{k+\Delta k}]^2 \qquad (4)$$

where τ is an integer number and denotes the group bandwidth.

Consequently, each harmonic amplitude can be estimated as

$$I_s^*[f_k] = \sqrt{P^*[f_k]} \qquad (5)$$

An interesting way to view this phenomenon is to observe the FFT implementation, shown in Fig.1. Most leakages can be collected into one group and are considered as though they were all at the dominant harmonic frequency. The amplitude of inter-harmonics (and/or sub-harmonics) can be thus identified.

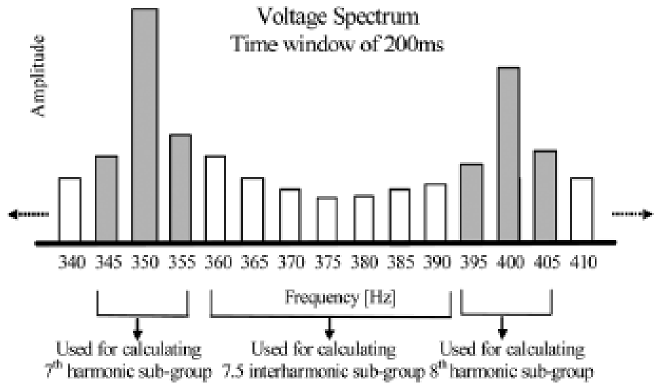

Fig. 1 IEC subgrouping of "bins" for both harmonics and interharmonics (graph reproduced from [18])

III. THE PROPOSED RECURSIVE GROUP-HARMONIC POWER MINIMIZING ALGORITHM

The power line waveform $s(t)$ (voltage/current) is sampled using the sampling rate $f_s (= 1/T_s)$, which has the fundamental frequency f_d, as follows.

$$s(n) = s(t)\big|_{t=nT_s}, \quad n = 0,1,2,....,N-1 \qquad (6)$$

where *N* is the sampled point of Fourier fundamental period T_f.

In general, the distorted signal can be composed of three parts, as follows.

$$s(n) = s_d(n) + s_h(n) + s_i(n) \qquad (7)$$

where $s_d(n)$ is the fundamental component, $s_h(n)$ is the harmonic components, and $s_i(n)$ represents the interharmonic components.

III.1 The Group-Harmonic Bin Power Algorithm

The length of the sampled window for FFT analysis plays the critical point to determinate if the spectrum can be achieved accurately. Based on the empirical observation using FFT, the second stronger amplitude is found to be located at the right side of the dominant component, i.e., $I_h[f_{k+1}] > I_h[f_{k-1}]$, in case of overlong truncated-window. On the contrary, the second stronger amplitude is located at the left side of the dominant component, i.e., $I_h[f_{k+1}] < I_h[f_{k-1}]$, the truncated-window length is insufficient for FFT analysis. Accordingly, the proposed RGPM approach is to develop the mechanism for correcting the window length according to the situation on the dispersed energy. This proposed RGPM method in deed extends the "group" concept that has been mentioned by IEC 61000-4-7 and some papers [5,18, 21,27].

ISBN: 978-988-19251-4-5
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

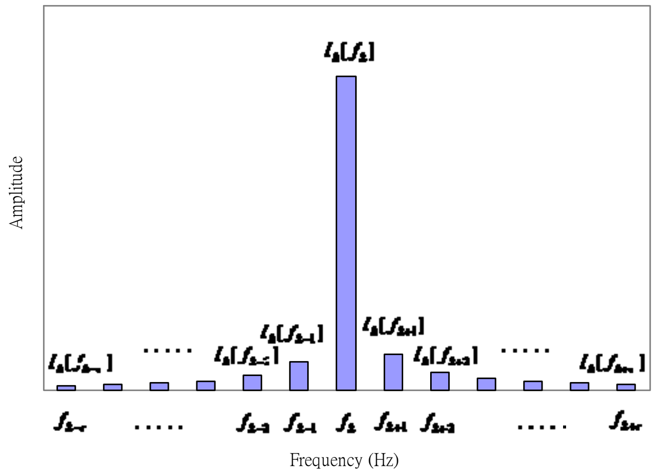

Fig. 2 Amplitude distribution around the dominant component

Based on the above concept, the Group-Harmonic Bin Power (GBP) algorithm is proposed and described as follows.

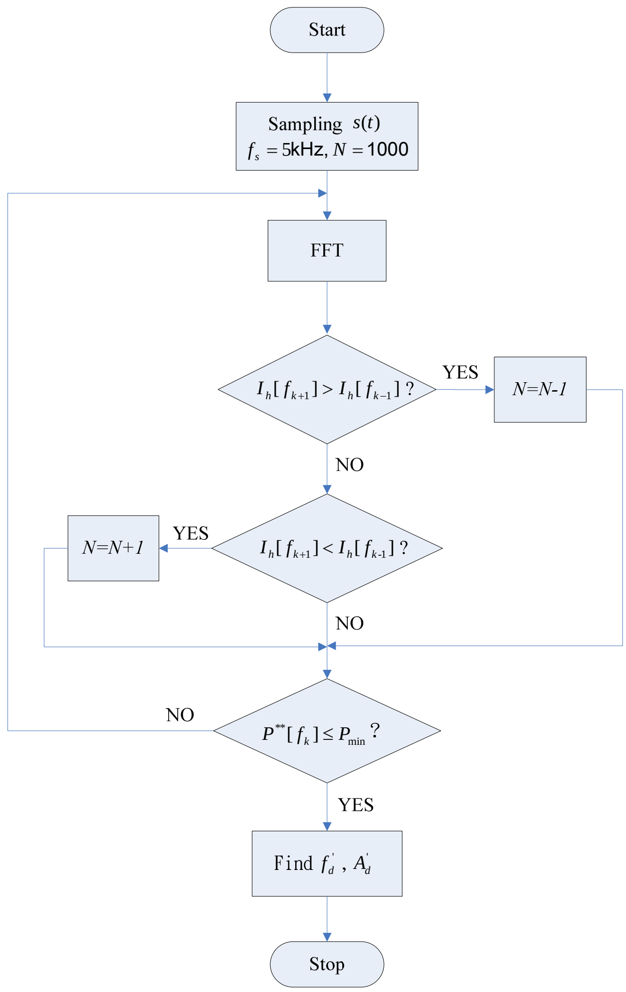

Fig. 3 The flowchart of the proposed GBP Algorithm

(1) Set $f_s = 5\text{kHz}$, N=1000 for sampling the power line signal.

(2) Implement FFT.

(3) If $I_h[f_{k+1}] > I_h[f_{k-1}]$, N=N-1. Otherwise, go to next step.

(4) If $I_h[f_{k+1}] < I_h[f_{k-1}]$, N=N+1. Otherwise, go to next step.

(5) Check if $P^{**}[f_k] \le P_{\min}$. If yes, the iteration loop stops and determine $N = N^{'}$. The fundamental frequency $f_d^{'}$ and amplitude $A_d^{'}$ can be obtained. Otherwise, go back to Step (2) to repeat the procedure until $P^{**}[f_k] \le P_{\min}$. Note that $P_{\min}$ is a predefined minima power value.

III.2 The proposed RGPM Algorithm

The proposed Recursive Group-harmonic Power Minimizing (RGPM) algorithm that integrated with the GBP algorithm is demonstrated as follows.

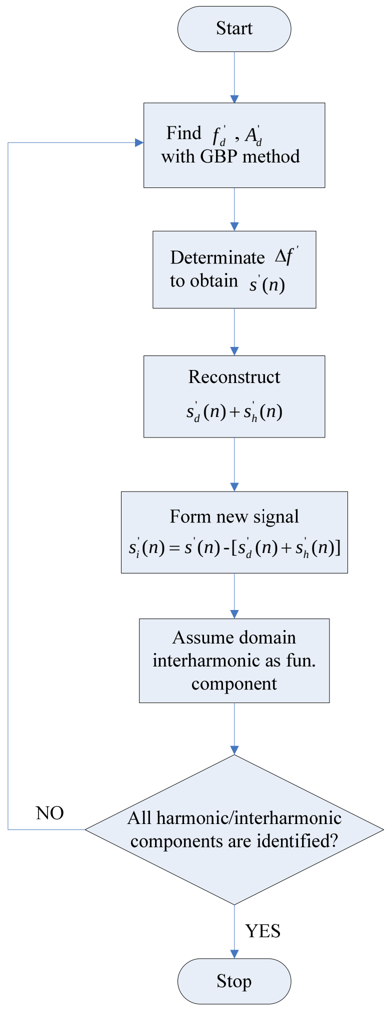

Fig. 4 Flowchart of the proposed RGPM algorithm

(1) Determine the new $\Delta f^{'} = \dfrac{f_s}{N^{'}}$ using the GBP method and find the correct fundamental frequency $f_d^{'}$ and its respective amplitude $A_d^{'}$. Accordingly, the fundamental frequency signal $s_d^{'}(n)$ and its harmonic signals $s_h^{'}(n)$ can be obtained, as follows.

$$s^{'}(n) = s(t)\Big|_{t=\frac{n}{f_s^{'}}} = s_d^{'}(n) + s_h^{'}(n) + s_i^{'}(n), \quad n = 0,1,2,3,\ldots,N^{'}-1 \tag{8}$$

(2) Reconstruct the $s_d^{'}(n)$ and $s_h^{'}(n)$ and form a composed waveform. Therefore, the new waveform that only contains interharmonic components without $s_d^{'}(n)$ and $s_h^{'}(n)$ can be obtained as follows.

ISBN: 978-988-19251-4-5
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

$$s_i^{'}(n) = s^{'}(n) - [s_d^{'}(n) + s_h^{'}(n)] \quad (9)$$

(3) Assume the major interharmonic component (biggest amplitude) as the fundamental component.

(4) Repeat steps (1) to (3) until all major interharmonics are regained.

IV. Model Validation with a Numerical Example

The proposed RGPM algorithm has been tested by the synthesized line signal (voltage/current) to verify the effectiveness of harmonic/inter-harmonic analysis. The following example is used to illustrate the harmonic analysis of a distorted waveform.

$$s(t) = \sin(2\pi f_d t + 23°) + 0.25\sin(2\pi \cdot 3 \cdot f_d \cdot t + 68°) + 0.3\sin(2\pi \cdot 5 \cdot f_d \cdot t + 16°)$$
$$+ 0.3\sin(2\pi \cdot 128 \cdot t + 78°) + 0.15\sin(2\pi \cdot 243.2 \cdot t + 94°) + 0.07\sin(2\pi \cdot 376 \cdot t) \quad (10)$$

where $f_d = 60.32$ Hz is the fundamental frequency.

Generally, the system frequency drift is a concern in power systems because it may vary slightly from time to time due to the change of system loads. This effect, in deed, influences the traditional FFT spectrum analysis. As above, the line signal has a fundamental frequency, i.e., 60.32 Hz, with 0.32 Hz drift and a scaled amplitude of 1V. The 3rd and 5th harmonic components are included in the synthesized waveform to present a possible distorted waveform situation. Non-integer components, i.e., interharmonic, such as 128 Hz, 243.2 Hz, and 376 Hz are to be considered, reflecting a possible polluted line case. Note that above harmonics/interharmonics are assigned different magnitudes and phases.

According to the equation (10), we set $f_s = 5$ kHz, $N = 1000$, i.e., $\Delta f = 5$ Hz, and the waveform is shown in Fig. 5. As can be seen in Fig. 6, a considerable spectrum leakage occurs using FFT so that the result is unable to represent its actual spectrum.

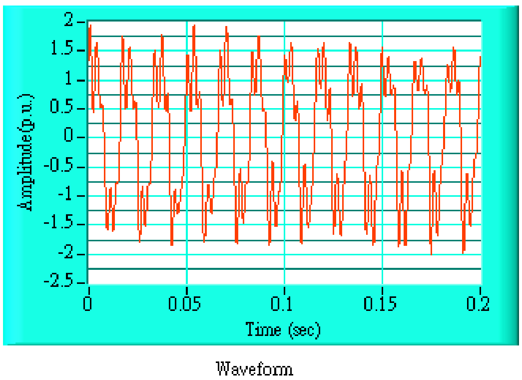

Fig. 5 The distorted waveform

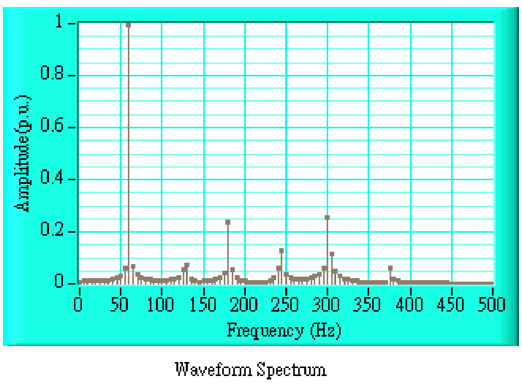

Fig. 6 Spectrum of the distorted waveform using FFT

The following steps are illustrated to find the true harmonics/interharmonics.

Step (a): Measurement of fundamental and integer harmonics with a 0.32 Hz frequency drift

In this case, the fundamental frequency component including 3^{rd} harmonic and 5^{th} harmonic is considered to have a 0.32 Hz variation. The dispersed power of the harmonics over around the frequency band is significantly reduced from 0.0364 to 0.00011 within only 6 iteration loops, shown in Fig. 7. Fig.8 indicates that each harmonic is approaching toward its true amplitude step by step. The amplitudes of fundamental, third and fifth component are thus obtained as 1.0, 0.25 and 0.3 at the sixth iteration loop from 0.99, 0.24 and 0.25 at the first iteration loop, respectively. Also, the fundamental frequency is found as 60.32 Hz, matching the true one.

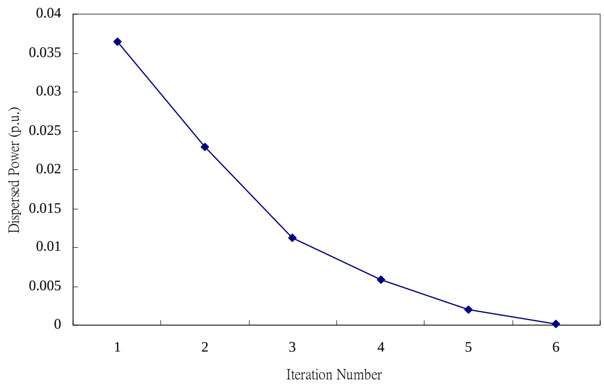

Fig. 7 Convergent curve of the dispersed power at the harmonic components

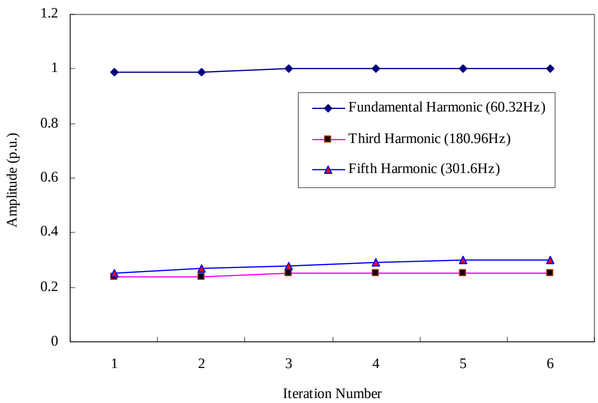

Fig. 8 Amplitude tracking curve of the harmonic components

Step (b): Measurement of the interharmonic at 243.2 Hz

In this stage, all harmonic components acquired at Step (a) are excluded in the new waveform so that the interharmonic at 243.2 Hz is assumed as the fundamental component. The dispersed power of the supposed fundamental band (interharmonic at 243.2 Hz) is considerably reduced from 0.0056 to 0.000012 within 8 iteration loops, shown in Fig. 9. Accordingly, its amplitude is obtained as 0.15 from 0.12 and the 243.2 Hz component is thus confirmed, shown in Fig. 10.

ISBN: 978-988-19251-4-5
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

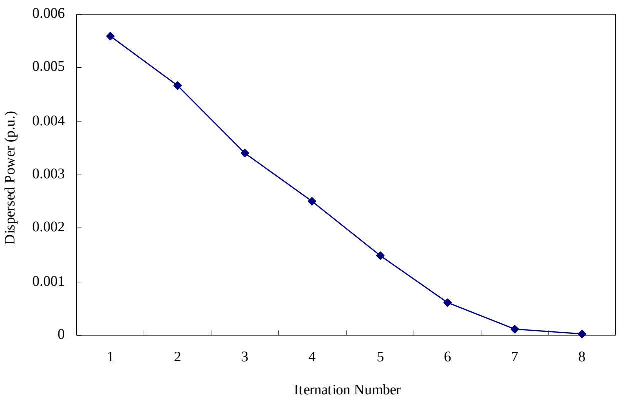

Fig. 9 Convergent curve of the dispersed power at the 243.2 Hz interharmonic

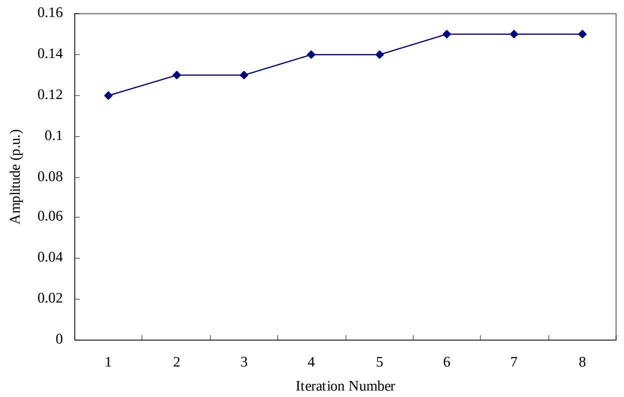

Fig. 10 Amplitude tracking curve of the 243.2 Hz interharmonic

Step (c): Measurement of the interharmonic at 128 Hz

In this stage, all harmonics and 243.2 Hz interharmonic are excluded in the new waveform. Similarly, the dispersed power of the supposed fundamental band (interharmonic at 128 Hz) is approaching toward to zero from 0.005 within 17 iteration loops, shown in Fig. 11. Accordingly, its amplitude is obtained as 0.1 from 0.076 and the 128 Hz component is therefore confirmed, shown in Fig. 12.

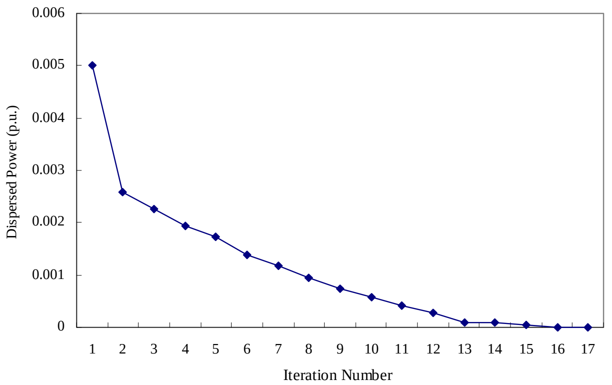

Fig. 11 Convergent curve of the dispersed power at the 128 Hz interharmonic

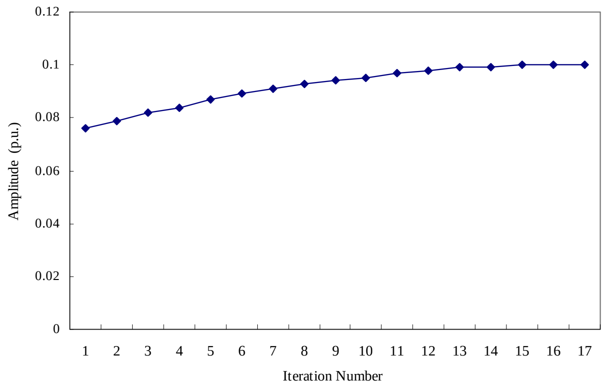

Fig. 12 Amplitude tracking curve of the 128 Hz interharmonic

Step (d): Measurement of the interharmonic at 376 Hz

In the last stage, all harmonics, 243.2 Hz and 128 interharmonic are excluded in the new waveform. Therefore, only 1 interharmonic (376 Hz) is remained. The dispersed power of the supposed fundamental band (interharmonic at 376 Hz) is going down quickly to almost zero from 0.00039 within only 4 iteration loops, shown in Fig. 13. As a result, its amplitude is obtained as 0.07 from 0.065 and the 376 Hz component is thus confirmed, shown in Fig. 14.

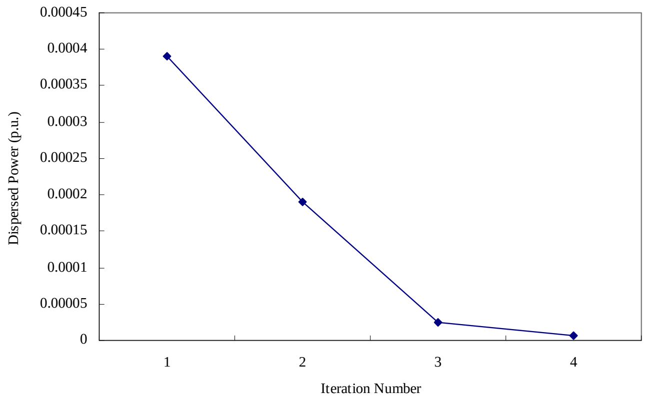

Fig. 13 Convergent curve of the dispersed power at the 376 Hz interharmonic

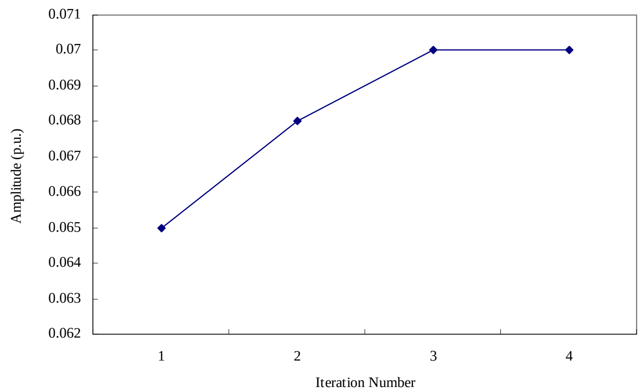

Fig. 14 Amplitude tracking curve of the 376Hz interharmonic

ISBN: 978-988-19251-4-5
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

V. Conclusions

Although the DFT (or FFT) has certain limitations in the harmonic analysis, it is still widely used in industry today. The harmonic/inter-harmonic identification using FFT-based RGPM algorithm has been developed to be extracted accurately and efficiently. The test results confirm that the proposed RGPM method can guarantee the tracking of each harmonic/interharmonic amplitude to be convergent at every iteration loop by the GBP algorithm. There is no theoretical restriction in the locations of inter-harmonic components while the group bandwidth (τ) of each harmonic/inter-harmonic should be chosen appropriately. Moreover, the RGPM methodology has been implemented successfully by a LabVIEW programming so that it can be easily extended to other software packages like microprocessor for on-line measurement. Additionally, the proposed RGPM can provide an advanced improvement for most measurement devices with some inherent errors because of the spectrum leakages caused by harmonics/inter-harmonics.

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ISBN: 978-988-19251-4-5
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