International Journal of Electrical, Electronics and Computer Engineering **1**(2): 66-70(2012)
ISSN No. (Online) : 2277-2626
Special Edition for Best Papers of Michael Faraday IET India Summit-2012, MFIIS-12

Diagnosis of Sub-Synchronous Inter-Harmonics in Arc Furnace Transformer using Multi-Resolution Analysis of Discrete Wavelet Transform

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(Received 10 October, 2012 Accepted 01 December, 2012)

ABSTRACT: Power system signals are associated with different types of abnormalities, which generate sub-synchronous inter-harmonics, thus degrading power quality and resulting in various characteristic diagnostic features, which is of utter importance now-a-days in various electrical sectors. This paper presents a novel technique for identification of those infiltrates in a real time signal obtained from industry using Multi-Resolution Analysis of Discrete Wavelet Transform. This analysis proves the presence of harmonics of the order of 0.02Hz, present in the current spectrum of an arc furnace transformer secondary.

Index Terms— Arc furnace transformer, Continuous wavelet transform, Multi-resolution analysis, Sub-synchronous inter-harmonics.

I. INTRODUCTION

Pover quality has become a major concern for utility, facility and consulting engineers in recent years. International as well as local standards have been put in place to address the power quality issues [6]. Power Quality [3] is a term that refers to maintaining the near sinusoidal waveform of power distribution bus voltages and currents at rated magnitude and frequency. Thus all distortions in the voltage and current waveform degrade the quality of power been supplied to the customers. The sources of poor power quality can be categorized in two groups: (1) actual loads, equipment and components and (2) subsystems of transmission and distribution systems. Poor quality is normally caused by power line disturbances such as impulses, notches, voltage sag and swell, voltage and current unbalances, momentary interruption and harmonic distortions. Thus right method for identification of these effects is very important. These harmonics are found to be characteristic diagnostic of specific types of abnormalities. If these harmonics can be detected abnormalities developed or to be developed can be predicted. Multi Resolution Analysis of Discrete Wavelet Transform (MRA of DWT) is mostly suitable for identification of desired small range harmonic frequencies (in the range of 1.5625-3.125 Hz and in the range of 49.2-902Hz) [4], which are responsible for specific abnormalities occurring in power system applications. Multi-Resolution analysis is also able to identify the frequency components in the range of 0.05Hz [2], [7], [8], which causes various symptoms thus concluding about the degradation of power quality. Continuous Wavelet Transform (CWT) is able to find out the sub-synchronous inter-harmonics [1] present in a signal in the range of 0.1Hz - 0.5Hz [5]. To ensure safety of a particular power system and its equipments concerned, identification and characterization of all these harmonic components are necessary, since these infiltrates cause thermal aging of conductors, generates perturbing sub-synchronous torques, increases stress on the insulation thus degrading the quality of the equipments attached therein [2]. As sub-synchronous inter-harmonics are usually generated from equipments like cyclo-converters, arc furnace transformers, wind generators and other arcing loads, so their characterization and suppression is only possible at the utility end [10]. This work deals with the identification of sub-synchronous inter-harmonic content of a current signal obtained from arc furnace transformer primary, using Multi-Resolution Analysis of Discrete Wavelet Transform, wherein each level of the Multi-resolution analysis output frame was analyzed using Continuous Wavelet Transform [9].

II. MULTI RESOLUTION ANALYSIS OF DWT

A DWT [2] gives a number of wavelet coefficients depending upon the integer number of the discretisation step in scale and translation, denoted by ‘*m*’ and ‘*n*’. So any wavelet coefficient can be described by two integers, ‘*m*’ and ‘*n*’. If ‘a_o’ and ‘b_o’ are the segmentation step sizes for the scale and translation, respectively, the scale and translation in terms of these parameters will be $a = {a_o}^m$ and $b = nb_o\ {a_o}^m$.

The power system considered in this paper is a process

In terms of the new parameters a_o, b_o , m, n becomes:

$$g'(m,n,t) = \frac{1}{\sqrt{{a_o}^m}}\, g\left(\frac{t - nb_o\, {a_o}^m}{{a_o}^m}\right) \qquad (1)$$

$$g'(m,n,t) = \frac{1}{\sqrt{{a_o}^m}}\, g(ta_o - nb_o\ ) \qquad (2)$$

and the discrete wavelet coefficients are given by:

$$DWT(m,n) = \int_{-\infty}^{m} \frac{1}{\sqrt{{a_0}^m}} f(t)\, g({a_0}^{-m} t - nb_0\,)\, d(t) \qquad (3)$$

Although the transformation is over continuous time, the wavelet representation is discrete and the discrete wavelet coefficients represent the correlation between the original signal and wavelets for different combinations of *m* and *n*. Usually DWT is implemented using multi-resolution analysis method, wherein a signal is decomposed into filter banks consisting of high- and low-frequency components. The low-frequency component usually contains most of the frequency of the signal. These are called the approximation coefficients. The high-frequency component contains the detailed coefficients of the signal. The block diagram for this decomposition is shown in Figure 1 below.

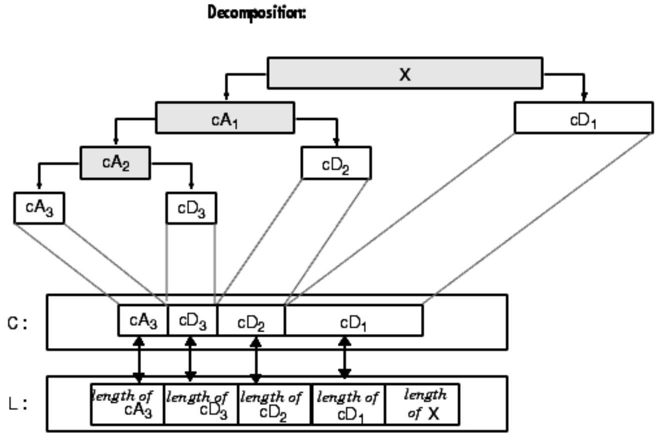

Fig.1. Block diagram for decomposition to consecutive filter banks.

After the signal has been decomposed using the MRA of DWT algorithm, the nonzero time domain components can be analyzed using CWT. The equation can be given by [9]:

$$CWT\ (a,b) = \int_{t_1}^{t_2} x(n)\,\psi^*(n)\,dt \tag{4}$$

where, x(n) and $\psi_{a,b}$ (n) are sampled versions of the continuous waveform x(t) and wavelet $\psi_{a,b}$ (t) respectively and dt is the sampling interval. The values t_1 and t_2 are the lower and upper time limits of $\psi_{a,b}$ (t) and are given by a^*t_{01} and a^*t_{02}, t_{01} and t_{02} are the lower and upper time limits of ψ(t) and have fixed values for a given ψ(t). In the above equation ψ(t) is dilated and shifted, and superimposed onto x(t). The magnitude of the CWT(a,b) is large when the frequency of $\psi_{a,b}$ (t) is the same of the harmonic frequency, otherwise it is small.

III. RESULTS AND ANALYSIS

Arc furnace [2], [5], [7], [8] is seen to be an important appliance, generating sub-synchronous inter-harmonics of very small range. To verify, whether any sub-synchronous inter-harmonic content is present in the instantaneous current spectrum of an arc furnace transformer, current spectrum of an arc furnace transformer primary has been collected from Jindal Stainless Limited, Jajpur, Odissa, which has been analyzed using Multi-resolution analysis of discrete wavelet transform and continuous wavelet transform. The single line diagram of the transformer, feeding the arc furnace is provided in Figure 2, wherein the protection schemes, provided for the transformer are also given.

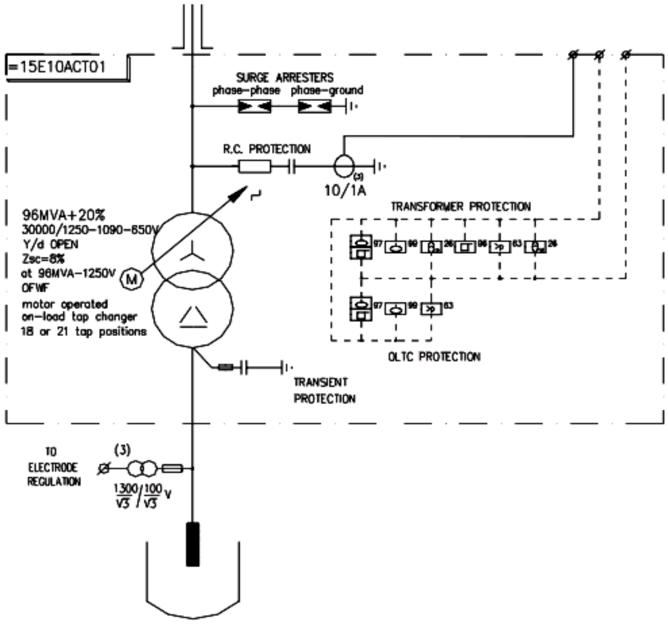

Fig. 2. Single line diagram of the Arc furnace fed from the arc furnace transformer.

Arc, in an arc furnace, forms between the charged material and the electrode. The charge is heated both by current passing through the charge and by the radiant energy evolved by the arc [7]. The electrodes are automatically raised and lowered by a positioning system and a regulating system maintains approximately constant current and power input during the melting of the charge, even though scrap move under the electrode, as it melts. Since the electrodes move up and down automatically, heavy water-cooled cables connect the bus-tubes with the transformer located at the adjacent furnaces. Generally the initial period of melting causes the most electrical disturbances. As the scrap temperature begins to raise, a liquid pool forms, and disturbances begin to diminish. This is generally about 10 minutes after power-on and can vary depending on power levels and practices. In this case, the instantaneous current spectrum of the primary side of the arc furnace transformer was collected in the industry using a Current Transformer of 10:1 ratio, provided at the 30KV side of the transformer. The signal was recorded between time intervals of 10.40am - 10.41am, after 1 minute of initial operation of the arc furnace. The ratings of the respective equipments connected therewith are provided in the key single line diagram in Figure 2. The available data has been analyzed using the developed algorithms in MATLAB (Version 7.8.0.347) (R2009a) to verify the presence of sub-synchronous inter-harmonics in the current spectrum of the Arc furnace. The Distorted waveform for each line of the available Arc furnace Transformer primary current spectrum is shown in Figures 3-5.

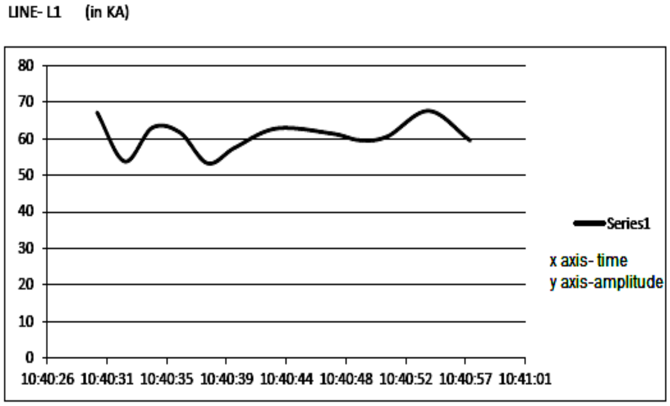

Fig. 3. Instantaneous current spectrum of line 1 of the Arc furnace Transformer primary.

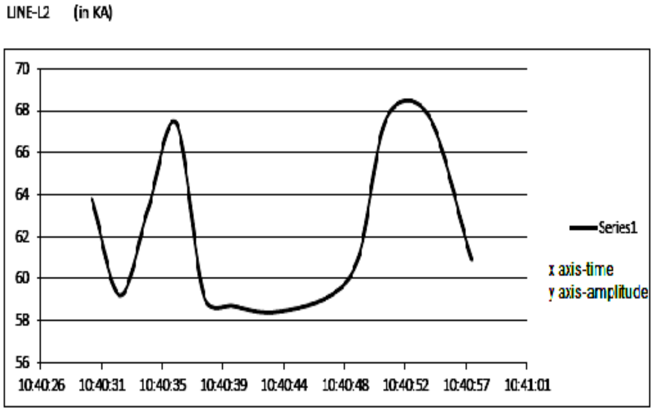

Fig. 4. Instantaneous current spectrum of line 2 of the Arc furnace Transformer primary.

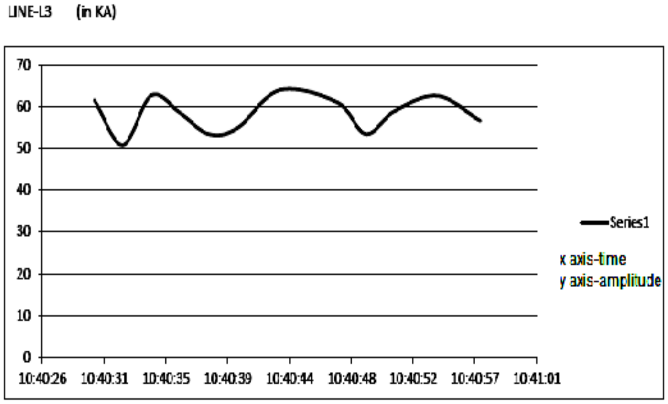

Fig. 5. Instantaneous current spectrum of line 3 of the Arc furnace Transformer primary.

The instantaneous current spectrums of the three lines have been analyzed using the developed Multi-resolution analysis of discrete wavelet transform algorithm to segregate out the lowest frequency band present in the signal. The level of filters has been chosen as 5 for the analysis purpose.

To verify the existence of sub-synchronous inter-harmonic content in the lowest band of frequency present in the signal, developed continuous wavelet transform algorithm was applied to the last level of MRA output frame, consisting of non-zero time domain components, using Daubechies 45 mother wavelet [9], [11]. The MATLAB output frames of the analysis using MRA of DWT and CWT are provided in Figures 6-15.

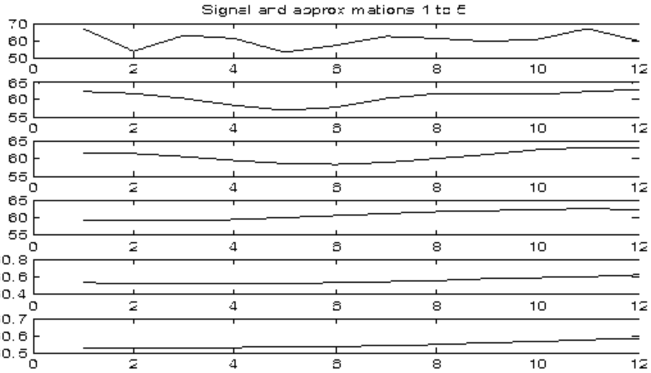

Fig. 6. MRA output frame of the signal provided in line 1 of the data obtained from industry.

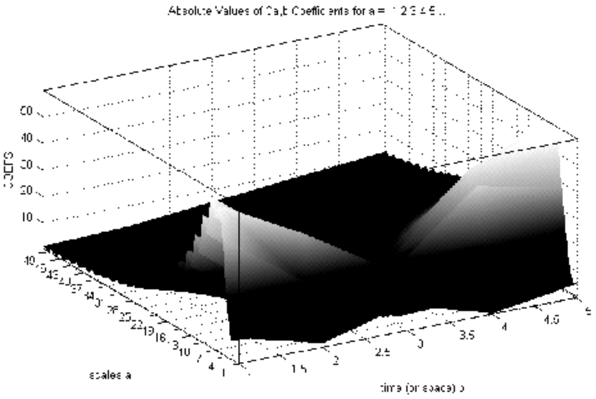

Fig. 7. CWT analysis of 1st level of MRA output frame.

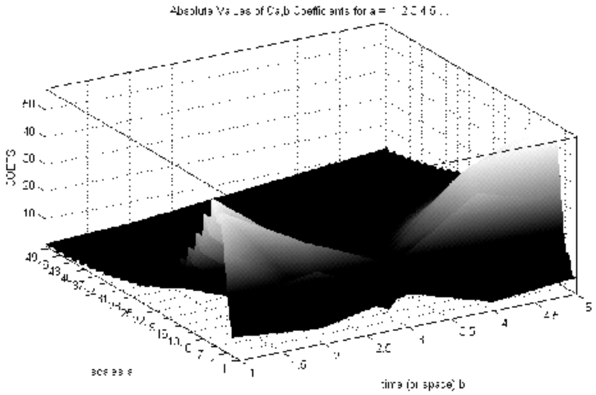

Fig. 8. CWT analysis of 2nd level of MRA output frame.

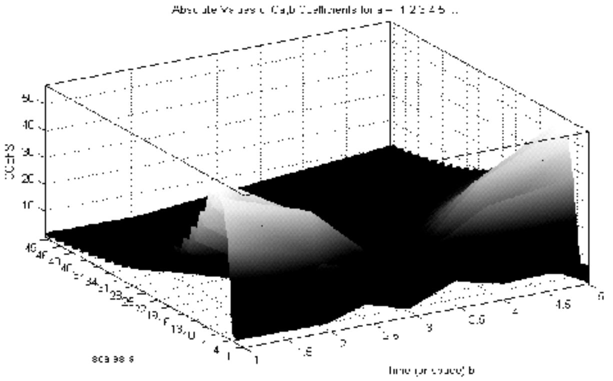

Fig. 9. CWT analysis of 3rd level of MRA output frame.

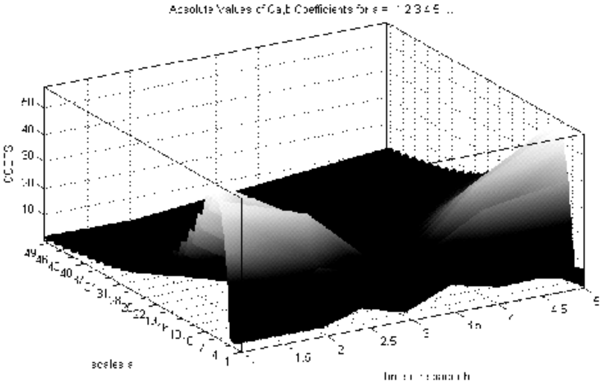

Fig. 10. CWT analysis of 4th level of MRA output frame.

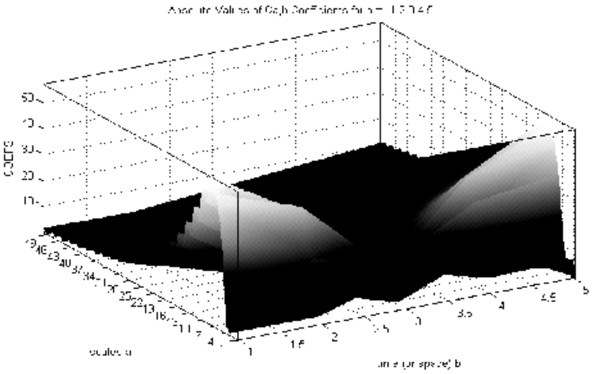

Fig. 11. CWT analysis of 5th level of MRA output frame.

Each of the 5 levels of the MRA output frame has been analyzed using developed CWT algorithm. The designed program incorporating continuous wavelet transform attenuated the frequency values above 1Hz, present in each level of the frequency bands, obtained after applying MRA of DWT, on the obtained signal. As the data, obtained from industry was for 1 minute span, it is seen that all the 5 levels showed similar responses in the CWT output frames, where the frequency band of 0.029 - 1Hz was visible in all of the cases. This analysis proves the presence of sub-synchronous inter-harmonic components in the instantaneous current spectrum of an arc furnace transformer primary, generated due to non-linearity of the load in an arc furnace. Also the coefficient values, for each level of Multi-resolution analysis algorithm were more or less similar in value, which is given in the table below.

Level 1	Level 2	Level 3	Level 4	Level 5
62.3	61.8	59.18	60.52	60.5
61.6	61.4	59.14	60.52	60.5
60.4	60.5	59.258	60.518	60.5
58.3	59.4	59.532	60.5204	60.5
56.9	58.5	59.946	60.52553	60.535
57.8	58.3	60.46	60.533	60.5
60.2	58.7	61.02	60.54435	60.54430
61.6	59.8	61.5	60.557	60.55
61.6	61.2	62.03	60.57	60.5
61.5	62.4	62.3	60.5	60.5
62.2	63.1	62.4	60.6	60.5

Therefore for the remaining two case studies, only last level spectrum of the MRA output frame has been shown to find out the lowest frequency band present in the signal clearly.

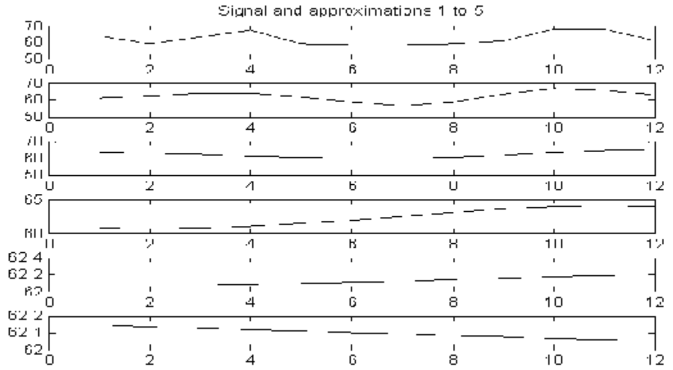

Fig. 12. MRA output frame of the signal provided in line 2 of the data obtained from industry

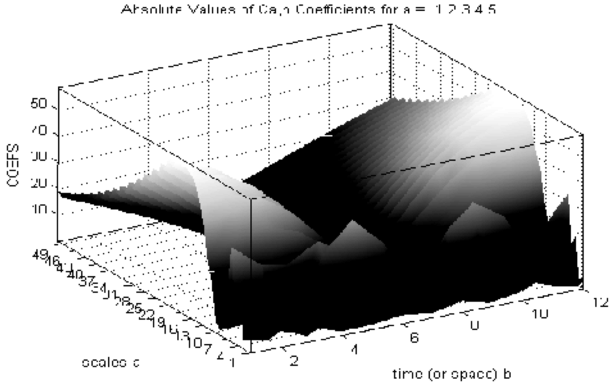

Fig. 13. CWT analysis of 5th level of above MRA output frame.

The CWT analysis of 5th level of the MRA output frame of line 2 showed the presence of harmonic frequencies in the range between 0.02 - 0.25Hz spaced throughout the time span of the signal, but with different magnitudes. In the case for line 1,frequencies in the rage between 0.029-1 Hz was obtained.Thus this analysis shows the generation of non-uniform sub-synchronous inter-harmonics from each line of the source side of the arc furnace. Also it is clear that the frequency band is much more predominant than for the case of line1.

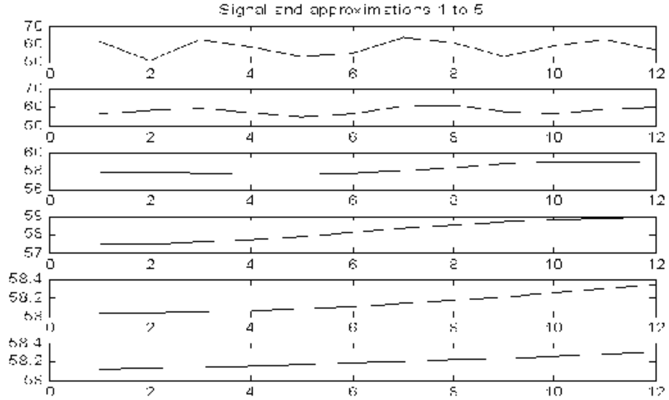

Fig. 14. MRA output frame of the signal provided in line 3 of the data obtained from industry.

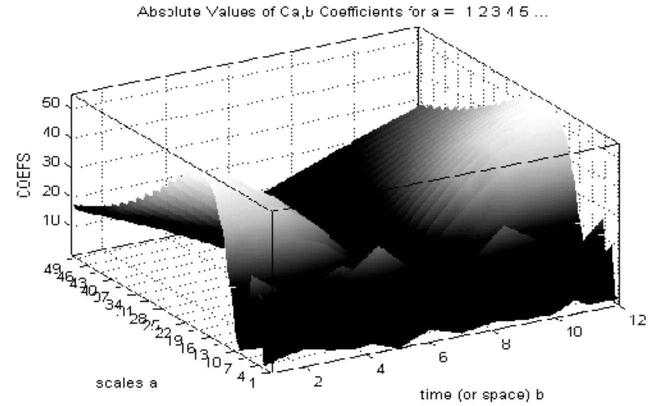

Fig. 15. CWT analysis of 5th level of above MRA output frame.

The lowest frequency band, obtained after multi-resolution analysis of discrete wavelet transform of line 3 current spectrum of the arc furnace transformer primary, when analyzed using the same CWT algorithm, to view the frequency bands, the presence of harmonic frequencies in the range between 0.02 - 0.25Hz spaced throughout the time span of the signal has been obtained.

V. CONCLUSION

This analysis shows the presence of Sub-synchronous inter-harmonics [1], [2], [5] in the range between 0.02Hz - 1Hz. As the data obtained from industry was one-twentieth of the disturbed signal been produced by the arc furnace, therefore all the CWT spectrums of each MRA Algorithm level is seemed to show more or less the same response. Any other cause for this instance is yet to be analyzed in further approaches and consequences. This analysis also shows that, the Sub-synchronous inter-harmonic frequency, generated from an Arc furnace ranges between 0.02Hz - 1Hz, which is well beneath 0.05Hz [7-8]. Thus it can be said that the frequencies generated due to arc furnace application is in the range of 0.02Hz, which is much lower as compared to the standardized frequency chosen for industrial as well as household applications.

ACKNOWLEDGMENT

We are thankful to the Jindal Stainless Limited, Jajpur, Odissa, for providing instantaneous current spectrum of an arc furnace transformer primary for the analysis purpose

REFERENCES

[1] IEEE Standard Definitions for Measurement of Electric Power Quantities under Sinusoidal, Non-Sinusoidal, Balanced or Unbalanced Conditions, *IEEE Power & Energy Society, Std.* 1459-2010 (Revision of IEEE Std 1459-2000).

[2] Kar Ray. D, Deb. S, Kumar. T, Sengupta. S, "Diagnosis of Sub-synchronous Inter-harmonics in Power System Signals using Multi-Resolution Analysis of Discrete Wavelet Transform", IEM International Journal of Management and Technology, IEMIJMT, August 2012, Vol. 2, No. 2, pp.-11-16, ISSN No. 2229-6611.

[3] Chattopadhyay. S, Mitra. M, Sengupta. S, "Electric Power Quality", ISBN 978-94-007-0634-7, e-ISBN 978-94-007-0635-4, DOI 10.1007/978-94-007-0635-4, Springer Dordrecht Heidelberg London New York, Library of Congress Control Number: 2011921328..

[4] Chen. Yu,"Research and Design of Intelligent Electric Power Quality Detection System Based on VI", *Journal of Computers,* Vol. **5**, No.I, pp.-158-165, January 2010.

[5] Kar. Ray. D, Deb. S, Kumar. T, Sengupta. S, "Diagnosis of Sub-synchronous Inter-harmonics in Power System Signals under non-sinusoidal Environment",LCIT, *National Journal of Engineering & Technology,* Vol **1**, 2012, pp.-272-276, Special issue on proceedings of "National Conference on Advances and Challenges in Engineering & Science".

[6] Tse. F. C. Norman & Lai. L. L, "Research Article-Wavelet Based Algorithm for Signal Analysis",Hindawi Publishing Corporation, *EURASIP Journal on Advances in Signal Processing,* Volume 2007, Article ID 38916, 10 pages, doi: 10.115/2007/38916.

[7] Andrei. Horia, Cepisca. Costin, Grigorescu. Sorin, "Power Quality and Electrical Arc Furnaces", study material from Valahia University of Targoviste and Politelmia University of Burcharest, Romania.

[8] User Manual of Arc furnace, Jindal Stainless Stainless Limited, Jajpur, Odissa.

[9] Pham. L. V & Wong. P. K,"Wavelet-trransform based algorithm for harmomic analysis of power system waveforms", *IEE Proceedings- Generation, Transmission, Distribution,* vol. **146**, No.3, 1999,pp.-249-254, online no.19990316, DOI:10.1049/ip-gtd:19990316

[10] Pham. Long. Van, Wong. Po. Kit, Watson. Neville& Arrillaga. Jos, "Sub-Harmonic State Estimation In Power Systems", pp.-1168-1173, 0-7803-5935-6/00/$10.00(c) 2000 IEEE.

[11] Poggi. Michael-Jean, Oppenheim. Georges, Misti. Yves and Misti. Michael, " Wavelet Toolbox™ User's Guide (R2012a)", MATLAB®, Mathwork, © COPYRIGHT 1997–2012 by The MathWorks, Inc.s.