HARMONICS ANALYSIS AND VISUALIZATION OF AN INTERRUPTED ELECTRICAL SIGNAL

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***Abstract* - In recent times there has been a wide interest in micro-grids. One area of concern in microgrids is the generation of harmonics by active devices such as converters and FACTS devices used for reactive power compensation. Accurate detection of harmonics is essential for their elimination. The currently available literature focuses on the number of operations and fundamental cycles for estimating harmonics. This usually results in a trade-off between accuracy of estimation and the choice of digital filter parameters. In this work a novel orthogonal frequency division multiplexing (OFDM) principle modified as per the power system scenario has been proposed. Odd harmonics up to 31st order are measured by demodulation as if the power signal is OFDM modulated. All these harmonics are measured using only one cycle of voltage signal and the number of operations required for the measurement is reduced by 7 times than the existing demodulated method. Instantaneous detection of harmonics is made possible using the Discrete Wavelet Transform (DWT) instead of the fast fourier transforms used in conventional OFDM. DWT is also used for noise elimination before the harmonics are analyzed and the performance of proposed method is analyzed using PSNR under different noise conditions.**

Index Terms—**Harmonics, OFDM, demodulation, FFT, DWT, power quality**

I. INTRODUCTION

For nearly one decade, attention towards construction of micro grids has been enormously increased due to the constraint of meeting the power demand. The micro grid power generation is majorly dependent on solar and wind sources. But, the power generated from these resources is variable with respect to environmental changes. This puts the system into unstable and many works are available in literature to mitigate the harmful effects using various control actions. The common issues in microgrid are the control of voltage level, real power and reactive power and when they are coupled to power grid harmonics are added into the power lines. The negative effects of harmonics, sub harmonics and inter harmonics may lead to damage of electrical loads, capacitor failure, over heating of conductors, transformers and electromagnetic radiations losses. Harmonics are also introduced in power lines while transporting the power through nonlinear devices along with the consumption through nonlinear loads [1]. Many methods are proposed to improve the power quality and stability of micro grids and hybrid grids. Among them, more methods concentrate on the control action of converters and very few methods concentrated on measurement domain. As the power quality fully depends on the control actions, it needs sufficient accuracy in measurement. The parameters such as voltage, current, real power and reactive power can be easily calculated using conventional measurements. But, the difficulty arises while measuring and tracking the fundamental frequency and its associated harmonics involving more challenges.

The effectiveness of all control systems purely based on the measurement of power quality with good accuracy and speed. Adaptive bacterial Swarm algorithm (ABSA) was used in [2] to measure the changes in fundamental frequency ad harmonics with more accuracy under dynamic conditions of system. Harmonic state estimation (HSE) using weighted least squares (WLS) was used in [3] for 3D visualizations of estimated bus voltage with respect to harmonic number and bus number. The results in this method are close to the bounds computed using monte carlo simulations. A mathematical basis for real time implementations on digital signal processors through a restructured recursive-least-squares technique is presented in [4]. The phasors and harmonics were estimated with better accuracy when compared with Adaptive linear combiner (ADALINE) and Recursive Discrete Fourier transform (RDFT). Wavelet transforms were used in [5] to decompose the input time domain signal into various sub bands using, and train the CHNN (continuous Hopfield neural network). Harmonics up to 9th order are estimated harmonics along with its phase and amplitudes. An adaptive wavelet neural network to detect the harmonics upto 6th order is estimated with its amplitude and phase in [6]. This method is proved better than FFT, WNN (wavelet neural network), RBFNN (radial basis function neural network), MLPNN (multilayer perceptron neural network). In [7], multi rate filter banks had been used, which estimate the time dependent harmonics in power converters. Harmonics produced during in rush currents and during the change of firing angle had been captured and plotted. Hilbert transform had been used to perform SSB (Single Side Band) modulation to estimate even harmonics. Odd harmonics detection up to 15th harmonic had been done. The instantaneous phase tracking using demodulation method is proposed in [8] and the performances are analysed by involving various FIR and IIR filters for testing. In this, the design of low pass filters plays a great role in estimation accuracy.

The same demodulation based scheme had been used in [9] to find the frequency of power signal under the influence of the interfering tones. In addition to this, magnitude and frequency of the interfering tones were evaluated. Interfering tones were considered up to 29Hz while the fundamental frequency was 60Hz.Frequency and amplitude of harmonics in DFIG (Doubly Fed Induction Generators) based micro grids are estimated in [10] which is generated in DFIG due to mechanical design of induction machines and Rotor side converters (RSC). Santosh Kumar Singh et al in [11] estimated harmonics up to 11th order under white Gaussian noise using signal processing algorithm called Variable Constraint based Least Mean Square (VCLMS) and showed a MSE (Mean Square of 0.0257 at no noise condition. As per the standards of signal processing the MSE should be less than 0.009 and this shows the poor performance of the measurement process flow. A recursive wavelet-based algorithm (IRWT) was introduced in [12] utilizing a new mother wavelet function and overall estimating procedure is used to find the amplitude, phase angle and frequency in power systems. The work in [13],[14] uses Recursive Least Square (RLS) harmonic estimation technique and in [15] , an Improved Recursive Newton Type (IRNTA) algorithm is implemented to estimate the fundamental frequency. The method in [16] is purely dependent on tuning the low pass filter and the amplitudes and phase angle of harmonics up to 29th order were captured. In this work, a novel orthogonal frequency division multiplexing (OFDM) principle modified as per the power system scenario has been proposed. Odd harmonics up to 31st order are measured by demodulation as if the power signal is OFDM modulated. All these harmonics are measured using only one cycle of voltage signal and the number of operations required for the measurement is reduced by 7 times than the existing demodulated method. Instantaneous detection of harmonics is made possible using the Discrete Wavelet Transform (DWT) instead of the fast fourier transforms used in conventional OFDM. DWT is also used for noise elimination before the harmonics are analyzed and the performance of proposed method is analyzed using PSNR under different noise conditions.

II. OFDM AND ITS APPLICATION TO POWER SYSTEM HARMONICS MEASUREMENT

In communication scenario, 3G systems inevitably use OFDM principle in order to get rid of signal attenuation due to deep fading. OFDM has transmitter and receiver as shown in Fig. 1 and Fig.2. It was found that multi carrier system along with proper guard band reduces the effect of multi path transmission. The major task in communication would be to transmit and receive the data bits without error and hence the best reproduction of the transmitted voice or multimedia data. The basic technique behind the OFDM is to use multiple carriers without using oscillator circuits to generate various orthogonal frequencies. This orthogonality along with guard band insertion efficiently serves to retrieve the transmitted data. But, the proposed work in this paper is meant especially for a power system application .The sub carriers dealt in OFDM are considered as harmonics in this method as both of them follow the same orthogonality principle. Another important point is the modulation stages in OFDM. There exist two modulation stages, namely, baseband modulation with various subcarriers and carrier modulation at a single frequency which is far higher than the subcarrier frequencies. In power system signals, the fundamental frequency is 50 Hz or 60 Hz and inclusion of harmonics may be viewed as baseband modulation done with various orthogonal frequency signals. So, it is very apparent that power signals are not carrier modulated, but only baseband modulated.

Few works [17-20] are present in which OFDM had been implemented with DWT (Discrete Wavelet Transforms) and IDWT (Inverse Discrete Wavelet Transforms). Noise effects under DWT-OFDM and FFT-OFDM has been discussed in [21] along with two types of noise namely Gaussian and impulse noise. In this work, firstly it is assumed that a power signal is modulated by various sub carriers i.e. harmonics. The harmonics are then estimated and measured same like the sub carriers estimation in the OFDM receiver part .The only difference is reconstruction of binary data stream is not necessary since there is no data transmission involved as in the case of typical communication systems.

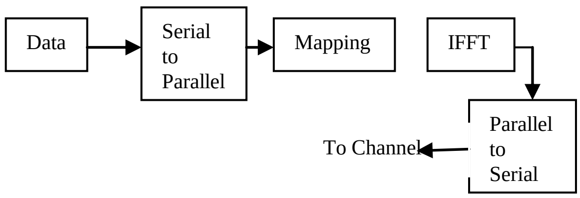

Figure 1. OFDM Transmitter

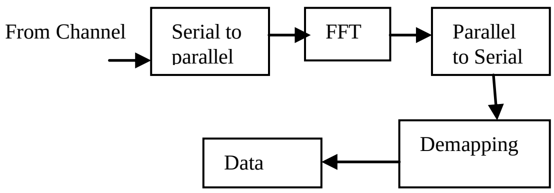

Figure 2 OFDM Receiver

Very few works are present for detecting the harmonics of a signal under noise conditions and the steps for identifying the harmonics of power signal under noise conditions using the proposed method are shown in Fig.3

1. De-noise the input power signals using certain new stage of preliminary DWT.
2. Decompose the power signal using analysis filter using wavelet based quadrature Mirror filtres.
3. Reconstruct the decomposed signals using synthesis filter banks to visualize the time varying harmonic content as per the gray code sequence in table 2.

The proposed method can also be applied for micro grid environment to visualize the time varying harmonic content . The performance of the proposed method is analysed using a metric called Peak signal to noise ratio (PSNR) for different noise conditions.

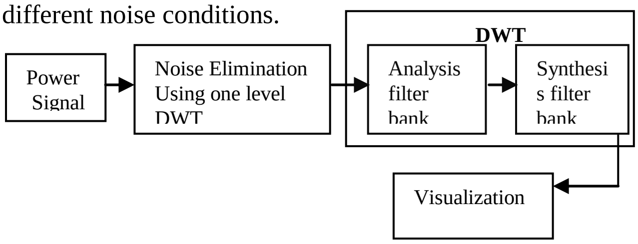

Fig. 3. OFDM based harmonic visualization

III. METHODOLOGY

Let $X(t)$ be the power signal given by (1)

$$X(t) = A_m(t)\cos(n\Omega_o(t) + \phi_m(t)) + \eta(t) \quad (1)$$

where m=1,3,5…31,

A_m is the amplitude

Ω_o is the fundamental frequency

ϕ_m is the phase of the m^{th} harmonic and

$\eta(t)$ is the noise.

Once $X(t)$ is expanded, it resembles (2) in digital form

$$X(n) = A_1(n)\cos(\omega_0(n) + \phi_1(n)) + A_3(n)\cos(3\omega_0(n) + \phi_3(n)) + \ldots\ldots A_{31}(n)\cos(31\omega_0(n) + \phi_{31}(n)) \quad (2)$$

The amplitude values $A_1, A_3, A_5 \ldots\ldots A_{31}$ considered are shown in table.1

Table 1. Amplitude values of various harmonic order

AMPLITUDE	VALUES	AMPLITUDE	VALUES
A1(n)	1	A17(n)	1/17
A3(n)	1/3	A19(n)	1/19
A5(n)	1/5	A21(n)	1/21
A7(n)	1/7	A23(n)	1/23
A9(n)	1/9	A25(n)	1/25
A11(n)	1/11	A27(n)	1/27
A13(n)	1/13	A29(n)	1/29
A15(n)	1/15	A31(n)	1/31

The noise $\eta(t)$ is normally filtered using low pass filter. But in the proposed method of wavelet based decomposition, the noise is filtered out in the preliminary stage using a one level decomposition. Then, the analysis bank and synthesis bank are applied on the signal as shown in the figure 4 and 5.The sampling frequency of the filter banks is chosen as fs=(2^{N+2} *f_o) where, f_o is the fundamental frequency (50 Hz) of the power systems and N is the number of decomposition levels.

Mother wavelets of type 'dmey' are used in analysis bank and synthesis bank and harmonics upto 31st order are measured and visualized with N=4 i.e. $(2^{N+1} - 1)f_o = (2^{4+1} - 1)*50 = 31$

Table 2.Gray code and it filter bank transfer function

GRAY CODE AND TRANSFER FUNCTION OF ANALYSIS FILTER BANK	GRAY CODE AND TRANSFER FUNCTION OF SYNTHESIS FILTER BANK	HARMONIC ORDER
0000 H0(z) H0(z) H0(z) H0(z)	0000 H0(z) H0(z) H0(z) H0(z)	1
0001 H0(z) H0(z) H0(z) H1(z)	1000 H0(z) H0(z) H0(z) H1(z)	3
0011 H0(z) H0(z) H1(z) H1(z)	1100 H1(z) H1(z)	5
0010 H0(z) H0(z)H1(z) H0(z)	0100 H0(z) H0(z) H1(z) H0(z)	7
0110 H0(z) H1(z) H1(z) H0(z)	0110 H0(z) H1(z) H1(z) H0(z)	9
0111 H0(z) H1(z) H1(z) H1(z)	1110 H0(z) H1(z) H1(z) H1(z)	11
0101 H0(z) H1(z) H0(z) H1(z)	1010 H0(z) H1(z) H0(z) H1(z)	13
0100 H0(z) H1(z) H0(z) H0(z)	0010 H0(z) H1(z) H0(z) H0(z)	15
1100 H1(z) H1(z) H0(z) H0(z)	0011 H1(z) H1(z) H0(z) H0(z)	17
1101 H1(z) H1(z) H0(z) H1(z)	1011 H1(z) H1(z) H0(z) H1(z)	19
1111 H1(z) H1(z) H1(z) H1(z)	1111 H1(z) H1(z) H1(z) H1(z)	21
1110 H1(z) H1(z) H1(z) H0(z)	0111 H1(z) H1(z) H1(z) H0(z)	23
1010 H1(z) H0(z) H1(z) H0(z)	0101 H1(z) H0(z) H1(z) H0(z)	25
1011 H1(z) H0(z) H1(z) H1(z)	1101 H1(z) H0(z) H1(z) H1(z)	27
1001 H1(z) H0(z) H0(z) H1(z)	1001 H1(z) H0(z) H0(z) H1(z)	29
1000 H1(z) H0(z) H0(z) H0(z)	0001 H1(z) H0(z) H0(z) H0(z)	31

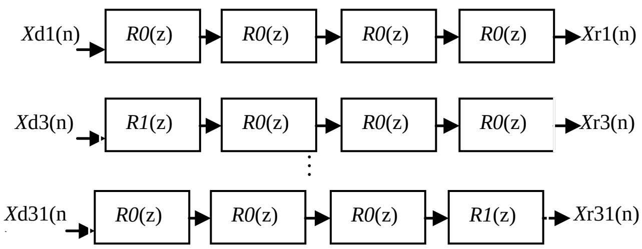

Figure 4. Synthesis bank upto 31st harmonic order

IV. RESULTS

The specialty of the QMF based separating the input power signal as sub band is that, it does not need any reference signal as generated in [5]. The decomposition and reconstruction up to 4 levels spontaneously output the harmonic order up to 31. Tuning of filter banks is not required in the proposed method as in [5] and also needs less number of operations to identify the harmonics. The harmonics obtained through the MALTAB simulations are shown in figure 6-7. Apart from the values set as per the table 1, time varying nature of harmonics have been analyzed in this work to check the visualization performance. The following changes are made for the harmonics in the input signal.

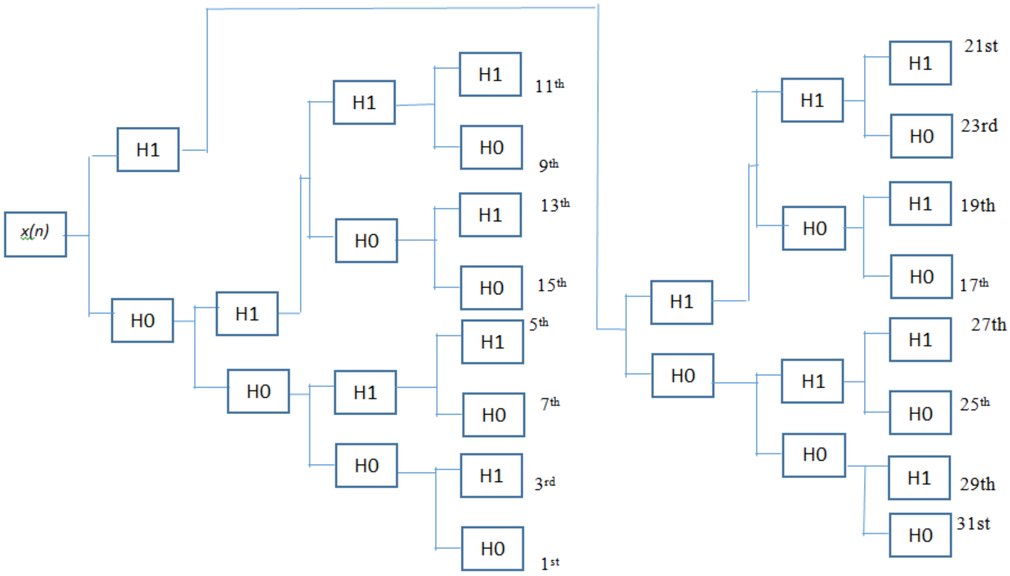

Fig. 5. Structure of Analysis bank up to 31st harmonic order

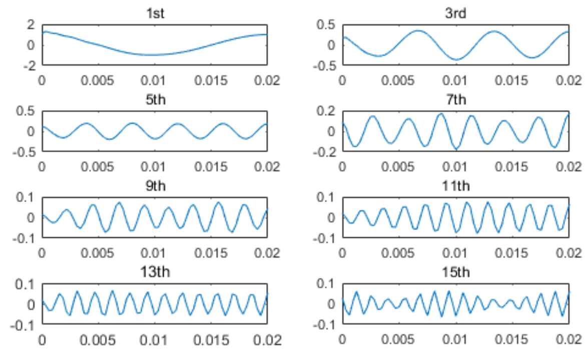

Fig. 6. Harmonics of order 1,3,5,7,9,11,13,15

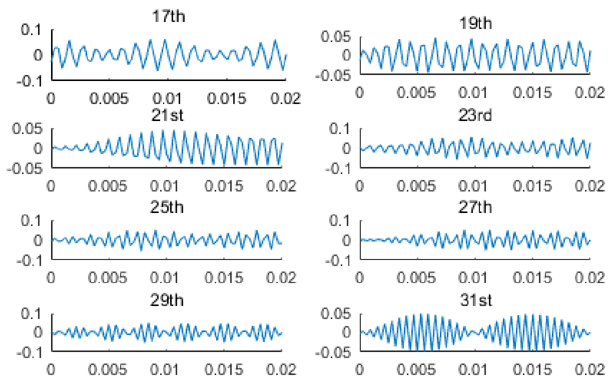

Fig. 7. Harmonics of order 15,17,19,21,23,25,27,29,31

1. Harmonics of order 1, 3 and 31 are allowed in input from the time 0.005 s to 0.003s.
2. Harmonic of order 5 is allowed in input from 0.1563s and from 0.3122s.
3. Harmonics of order 7 and 25 is allowed in input from 0.3125s and from 0.4684s

The results obtained with the modified input are shown in Fig.8. The changes made for each harmonics signal are clearly seen in the output with the proposed methods which says that the proposed method works satisfactory with tame varying harmonics.

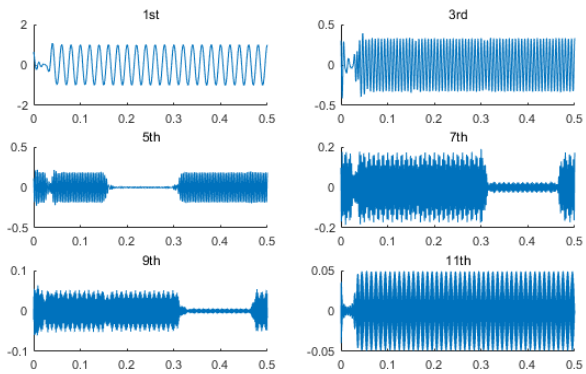

Fig. 8. Time varying harmonics of order 1,3,5,7,25 and 31

V. PERFORMANCE ANALYSIS

PSNR metric had been originally used in EEG reconstruction in [14]. Since visual based harmonic tracking is performed in this work, a new metric namely, VBAE (visual based absolute error) is used and it is defined as the difference between the peak value of the original and peak value of the reconstructed signal as shown in (3).

$$V_{BAE} = \left| X_m - X'_m \right| \qquad (3)$$

Where, X_m is the peak value of the original signal and X'_m is the peak value of the reconstructed signal. Though this metric is very sufficient for visualization based applications, this measure does not provide information regarding the amount of error in the other samples, and hence it is local in nature. It is not meaningful to compare directly V_{BAE} of power signal of different sampling resolutions. Hence it is essential to normalize the signal range leading to a distortion measure called as PSNR expressed in dB which is shown in (4). Higher the PSNR, better is the visualization.

$$PSNR = 10\log_{10}\frac{2^{Q}-1}{V_{BAE}} \quad (4)$$

Fig. 9 shows the variation of obtained PSNR for various harmonic order from 1 to 31. Red trace shows the performance of the harmonic visualization when AWGN was set at 10dB, 20dB and 30dB respectively. Black trace shows the improved PSNR using the proposed method. From Table 3, an average PSNR improvement of 3dB has been obtained when a preliminary DWT based noise filtering is employed. An average PSNR obtained at an ideal noiseless condition is 45.0840 dB and a PSNR of 44.4637 dB is obtained at a noise level of AWGN=30dB. This clearly says that the performance of filters depends the amount of noise added in the power signal.The method proposed in this work needs very less number of operations when compared to the demodulation method [5]. As per the figure 3, the number of operations for estimation of odd harmonics up to 31st order in the proposed work with M=64 and L=102 are 48,720 and is given by

Number of multiplications =ML+ (M/2) (L) + (M/4) (L) + (M/8) (L) = 12,240.

Number of additions = M(L-1)+(M/2)(L-1)+(M/4)(L-1)+(M/8)(L-1)=12,120 .

Table 3. PSNR obtained for various noise levels

Harmonic Order	PSNR **(At Awgn=10db)**		PSNR **(At Awgn=20db)**		PSNR **(At Awgn=30db)**		PSNR **Without Noise**
	With noise	**After DWT**	**With noise**	**After DWT**	**With noise**	**After DWT**	
1	31.8208	33.1315	37.3875	39.1656	42.1284	42.5685	45.4302
3	32.0308	31.9599	38.1644	37.1261	40.6032	42.4521	43.6901
5	33.1803	33.2847	37.5249	37.6330	44.2112	56.0784	44.9502
7	30.2049	31.4517	34.2795	33.7447	35.7967	37.4455	36.7766
9	31.4394	33.4551	38.5368	64.1388	50.8674	41.0891	40.9655
11	32.6885	32.4028	37.7276	41.4294	41.8145	47.1478	44.5053
13	31.4971	33.3619	36.5399	40.0741	39.8942	51.9150	44.4918
15	29.7857	31.9769	33.7618	37.4416	35.6765	45.2361	36.6186
17	31.0707	32.2256	40.9983	37.4847	43.0540	43.1676	39.4557
19	30.6411	34.5711	37.9957	40.6725	41.0086	45.4834	50.2059
21	31.8326	34.7487	37.4657	42.8831	42.5922	49.9832	56.5141
23	31.1952	34.8844	35.2829	38.8182	40.2845	41.3995	44.2699
25	30.3132	35.7315	36.1121	38.1644	40.0798	41.9564	44.8689
27	30.3793	36.0182	36.9336	40.2675	40.9514	42.3863	48.0778
29	31.8434	38.1273	37.3838	40.6997	40.5259	41.8427	49.2025
31	31.4167	39.8068	37.4658	41.1134	40.7017	41.2681	51.3208
Mean PSNR	31.3337	**34.1961**	37.0975	**40.6786**	41.2619	**44.4637**	**45.0840**

Where M is the number of samples, L is the order of the filter. Hence the number of operations needed to perform analysis filter operation for each harmonic order turns out to be 24,360. Since the next stage of synthesis filter also takes the same number operations, but in the reverse order as shown in figure 4, total number of operations required using proposed method is only 48,720. Table.4 shows the comparison of addition and multiplication operations between the proposed method and demodulation method [5].

Table 4. Comparison of number of operations

Techniques	**No. of additions**	**No. of multiplications**	**Total no. of operations**
Demodulation method[5]	21918	132691	3,09,218
Proposed method	24240	24480	48720

VI. CONCLUSION

This paper presented a novel harmonic estimation method using DWT, which mimics OFDM receiver principle mitigating the effect of noise. A preliminary

DWT based one level decomposition has been proposed in this work to improve the harmonic visualization performance and an average of 3dB improvement had been achieved. The demodulation method proposed in literature needs 3,09,218 operations whereas the proposed wavelet filter takes 48,720 operations with an additional benefit of noise removal as, OFDM receiver based operation sequence has been used without carrier demodulation stages. Moreover, the proposed work takes only one full cycle of the input power signal. Wavelet type of 'dmey' has been used in our proposal, and further research is required in optimizing the type of mother wavelets and to improve the visual performances because of sampling rate mismatches. This work is highly suitable for visualization applications and outputs are obtained at one step process irrespective of the number of harmonics to be visualized. The microgrids in real time with different energy sources make use of power converters from which the harmonics of high order are inserted into the network. These harmonics reduces the quality of power and hence has to be eliminates from network. To eliminate these harmonics, the harmonics are to be analyzed and measured accurately and for this work could be a better tool for it. Works presented in this paper suffers from the down sampling effect which spoils the visualization performance. An optimal sampling frequency of 3.2KHz considered in this paper. The further extension of this work could be using higher sampling frequency in the order of 6.4KHz, for a still better visualization, but at the cost of the number of operations.

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