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Harmonic Analysis Using FFT and STFT

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Abstract

Now a day's Harmonic distortion has been a significant problem to maintain power quality. It is very essential to analyze of power signal and find different harmonics. Some harmonics in the power signals are harmful to sensitive equipments and also causes to power loss. It is therefore important to find such harmonics and use different harmonic mitigation techniques to get clean/pure signal for safe operation of the connected equipments and minimize Power loss. Harmonic distortion is the corruption of the fundamental sine wave at frequencies that are multiples of the fundamental. Aim of this paper is extraction of fundamental and harmonic components in voltage/current signal using FFT & STFT, plot the stylized spectrum of distorted signal in MATLAB with power system frequency and classify the subtypes of harmonics, study the different characteristics and calculate total harmonic distortion (THD) that will be useful for solving problems related to power quality.

Keywords: *Power Quality, FFT, STFT, Harmonic, sinusoidal source, nonlinear load, Total harmonic distortion*

1. Introduction

Power quality problems are classified in eight main categories and varies sub categories are [1]

i. Transient - Impulsive Transient/oscillatory Transient. Oscillatory Transient again subdivided in high frequency, medium frequency, low frequency, very low frequency.

ii. Short duration variation - subdivided in sag, swell

iii. Long duration variations – again this wave form subcategorize in overvoltage, under voltage, sustained/interrupted.

iv. Voltage imbalances – sub categories as magnitude/phase imbalances.

v. Wave form distortions – subcategories into DC offsets, harmonics (even & odd), inter harmonics, Notching, Noise. Voltage fluctuations.

vi. Power frequency variations

vii. Repetitive event

Harmonics are currents or voltages with frequencies that are integer multiples of the fundamental power frequency being 50 or 60Hz (50Hz for European power and 60Hz for American power). If the fundamental power frequency is 50 Hz, then the 2nd harmonic is 100 Hz, the 3rd is 150 Hz, *etc.*, Harmonic frequencies from the 3rd to the 25th are the most common range of frequencies measured in electrical distribution systems. Symptoms of harmonic problems include overheated transformers, neutral conductors, and other electrical distribution equipment, as well as the tripping of circuit breakers and loss of synchronization on timing circuits that is dependent upon a clean sine wave trigger at the zero crossover point. An overheated neutral can lead to heavy damage to attached equipment. Other loads

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contributing to this problem are variable speed motor drives, lighting ballasts and large legacy UPS systems. Methods used to mitigate this problem have included over-sizing the neutral conductors, installing K-rated transformers, and harmonic filters [2].

Harmonic distortion: Harmonics can be understood as different frequency periodic components that are superimposed on the main frequency waveform. In power systems, existing harmonics are mostly odd integer multiple of the power frequency. The 3rd, 5th, 9th, 7th, 11th and 13th orders can be identified as most the common harmonics. In addition to these common harmonics, it is possible to face signal components that are not integer multiples of the fundamental. Such components are called as "inter-harmonics" and they are usually encountered while dealing with non-periodic signals. In recent years a rapid growth in harmonic voltages and currents injected into power systems has been observed due to the increased utilization of non-linear loads. Figure 1 shows Harmonic distortion example.

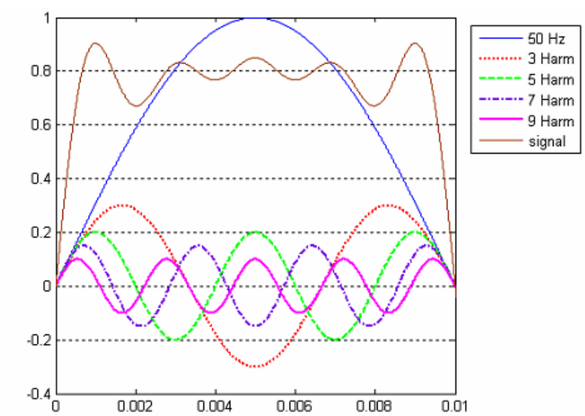


Figure 1. Harmonic Distortion

2. Types of Harmonics

1. Odd Harmonic
2. Even Harmonic

Odd harmonics distortion is typically dominant in supply voltage and load current. The effect of odd harmonics is an increase or decrease of the amplitude of the signal with 10%. The rms value increases only very little 0.5%, so that the crest factor increases or decreases by about 10%. Generally a third harmonic component leads to a change in the crest factor. The effect of the distortion is the same for the positive and for the negative half of the sine wave. The positive cycle is the same as the negative cycle of the voltage wave as long as only odd harmonics are presents in the voltage.

Even harmonics is normally small. That generates by some large converters, transformer energizing (temporary increase), but modern rule on harmonic distortion state that equipment should not generate any even harmonics. In fact, a measurement of supply voltage shows that the amount of even harmonic is indeed very small. The result of even harmonic distortion is that positive and negative half cycles of the signal are no longer symmetrical. They only occur in the presence of a D.C. component. If there are significant amount of even order harmonics then the signal is not symmetrical with respect to zero axis [3, 4]. The two most commonly used indices for measuring the harmonic content of the waveform are the total harmonic distortion (THD).

Total Harmonic Distortion (THD)

Periodic signal can be decomposed into a number of harmonics. The signal can be totally characterized by the magnitude and the phase of these harmonics. In power system applications the fundamental (50 or 60 Hz) component will normally dominate. This holds especially for the voltage. Often it is handy to characterize the deviations from the (ideal) sine wave through one quantity. This quantity should indicate how distorted the voltage or current is. The THD gives the relative amount of signal energy not in the fundamental component. The THD is typically expressed as a percentage value. In the mathematical analysis of a continuous signal, an upper limit H=∞ should be chosen. Otherwise the upper limit is determined by the sample frequency or by a standard document [3].

Total Harmonic Distortion: The total harmonic distortion is defined as the square root of the sum of the squares of the rms value of the voltages or currents from 2nd to the hth harmonic divided by the fundamental value of the voltage or current and are expressed as a percent.

$$\text{THD\% of fundamental} = \frac{(Qrms\ distorted)}{(Qfundamental)} \text{ X } 100$$
$$= \frac{\sqrt{\sum_{h=2}^{H} Q_h^2}}{Q_1} \text{ X } 100$$

where, Qrms distorted is the rms value of the distorted waveform with the fundamental left out of the summation, and Fundamental is the value of the voltage or current at the fundamental frequency. The THD is commonly used power quality index to quantify the distortion of a waveform. The THD is defined as the relative signal energy present at non fundamental frequencies, normally THD of the voltage written as

$$\text{THDv} = \frac{\sqrt{\sum_{h=2}^{H} V_h^2}}{V_1} \text{ X } 100$$

The THD of the current is defined in a similar way;

$$\text{THDi} = \frac{\sqrt{\sum_{h=2}^{H} I_h^2}}{I_1} \text{ X } 100$$

The American harmonics standard IEEE 519 also introduces the total demand distortion (TDD) for the current.

$$\text{TDD} = \frac{\sqrt{\sum_{h=2}^{H} I_h^2}}{I_d} \text{ X } 100$$

Where, Irms distorted is the rms value of the distorted waveform with the fundamental left out of the summation, and Id is the peak or maximum, demand load current at the fundamental frequency component measured at the point of common coupling. When maximum current is difficult to determine, the rated or subscribed current may be used. The advantage of using maximum or rated current is that it gives a better indication of the effect of the distorted current on the system [3].

THD is a characteristic of the waveform. It does not directly quantify the impact of the disturbance, as its value is rated to the fundamental component. For the voltage waveform the variation in fundamental component are small, so that the THD can be easily interpreted. With current distortion the situation becomes different; a low THD during high load can have bigger impact on the system than a high THD during low load. For this reason the TDD is introduced in IEEE 516. In general

- Voltage distortion level allowed 5% THD.
- Current distortion level allowed 20% THD.
- Harmonics higher than the 25th order are usually negligible.

3. Causes/Effects of Harmonics

Linear and Non - Linear Loads

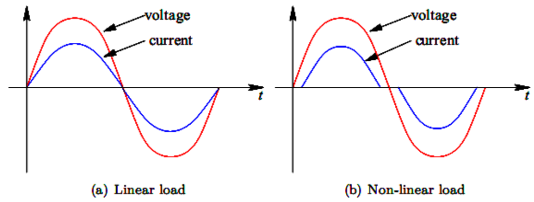


Figure 2. Voltage/Current Signals for Linear and Nonlinear Load

The main cause of harmonics in the electric power system is the presence of non linear loads. The biggest reason for poor power quality is the proliferation of the electronics devices. At the forefront is the switched mode power supply. The switched power supply is found in information technology equipment like computer, fax machines, laser printers, *etc.*, A linear electrical load draws a sinusoidal current proportional to the sinusoidal voltage as shown in Figure 2 (a). The reason for such a behavior is that the linear loads do not depend on the voltage to determine their impedance at a given frequency. These loads do not cause any problem to the network to which they are connected or other consumers of a utility. They always follow the ohm's law. Power electronics loads do not always follow the ohm's law. Unlike the linear loads they do not consume power continuously. When a sinusoidal voltage is applied to a non–linear electrical load, it does not draw a sinusoidal current. Also the current is not proportional to the applied voltage. The non-sinusoidal current is due to the device impedance changing over a complete voltage cycle. These loads have the potential of distorting the supply voltage waveform and might as well cause problems to other loads, for example, Figure 2 (b) shows a sinusoidal voltage applied to a solid state power supply. The current drawn is approximately zero until a critical firing voltage is reached on the sinusoidal wave. At this firing voltage, the transistor gates allows current to be conducted. The current increases until the peak of the sinusoidal voltage waveform is reached and then decreases until the critical firing voltage is reached on the downward side of the sine wave. The device shuts off and the current goes to zero. A second negative pulse of current is drawn in the negative half cycle of the sine wave. The current drawn is a series of positive and negative pulses and not the sine wave drawn by linear systems.

Equipment Impacts

Harmonic current injection from customer loads into the utility supply system can cause harmonic voltage distortion to appear on the utility system supply voltage. This harmonic current and voltage distortion can cause overheating of rotating equipment, increase in transformer winding temperature which reduces the efficiency and the life span. Harmonics can influence the operation of protective devices such as electromechanical relays, fuses *etc.*, they may trip too soon or too late. Harmonic voltage distortion on a utility system can cause the same problems to a customer's equipment and can cause overheating of utility transformers, power-carrying conductors, and other power equipment.

Possible solutions

Possible solutions of harmonic distortion have included over-sizing the neutral conductors, installing K-rated transformers, harmonic filters, and use of PFC power supplies *etc.*

4. Experimental Setup

To capture harmonic signals, DSO (Digital storage Oscilloscope), computer, CTs, PTs, load (Induction motor, bulb bank, computer, capacitor *etc.*,) are required. Voltage signal or current signals captured on DSO using following setup in Figure 3.

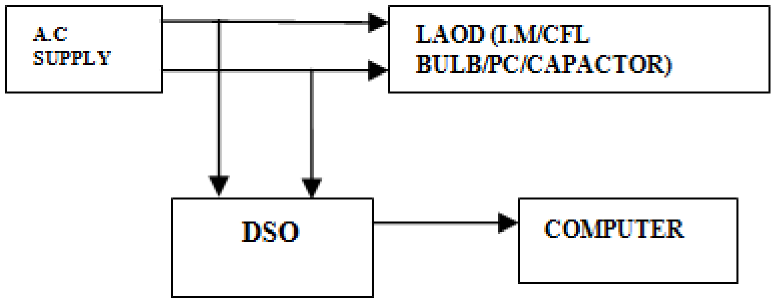


Figure 3. Block Diagram for Practical Setup to Capture Harmonic Signals

Voltage across load or current which flows in the load captured by the DSO (digital storage oscilloscope) shown in Figure 3, and from this signal get data to harmonic analysis by using signal processing technique. Figure 4 shows current signal captured on DSO, when combined load is of CFL bulb and computer. Figure 5 shows current signal when load is of computer. Figure 6 is the captured current signal when combined load of capacitor and induction motor at starting time.

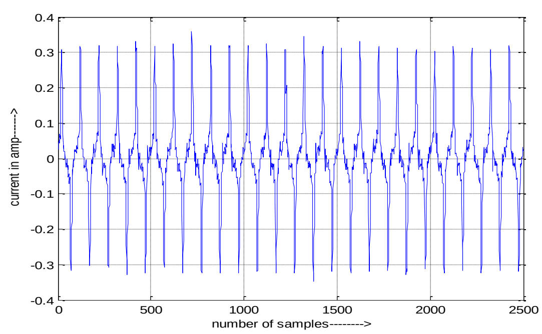


Figure 4. Captured Currents Signal used for CFL+Computer Combined Load

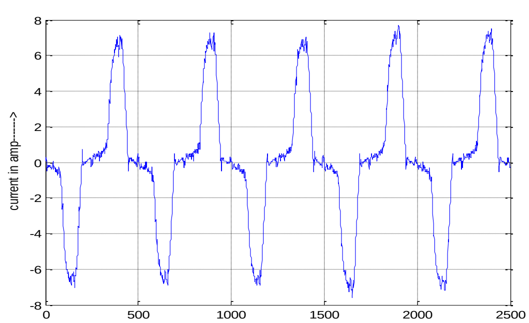


Figure 5. Captured Current Signal used for Computer Load

5. Proposed Harmonic Analysis Methods FFT and STFT

The Fast Fourier transform (FFT) can be used for harmonic analysis because of its computational efficiency. FFT can be used to calculate the harmonic distortion and to separate even/odd/inter harmonics *etc*. STFT can be used for extracting fundamental component as well as harmonic components. For analyzing harmonic related power quality disturbances STFTs are attractive.

FFT - Fast Fourier Transform

Fourier analysis is used to convert time domain waveforms into their frequency components and vice versa. When the waveform is periodical, the Fourier series can be used to calculate the magnitudes and phases of the fundamental and its harmonic components. More generally the Fourier Transform and its inverse are used to map any function in the interval –∞ to + ∞ in either the time or frequency domain into a continuous function in the inverse domain. The Fourier series therefore represents the special case of the Fourier Transform applied to a periodic signal. In practice data are always available in the form of a sampled time function, represented by a time series of amplitudes, separated by fixed time intervals of limited duration. When dealing with such data a modification of the Fourier transform, the DFT (discrete Fourier transform) is used. The implementation of the DFT by means of FFT algorithm forms the basis of the most modern spectral and harmonic analysis systems. DFT transforms a signal from the time domain to the frequency domain. This makes available the amplitude and phase of the fundamental and the harmonics present in the signal. The dc component is also available in the first bin. The Fast Fourier Transform (FFT) is the DFT's computational efficient implementation, its fast computation is considered as an advantage. With this tool it is possible to have an estimation of the fundamental amplitude and its harmonics with reasonable approximation. FFT performs well for estimation of periodic signals in stationary state; however it does not perform well for detection of sudden or fast changes in waveform e.g. transients or voltage sags. Fast Fourier transforms (FFT) is a faster version of discrete Fourier transform (DFT). The FFT utilizes some clever algorithms to do the same thing as the DFT, but in much less time [3, 5]. The finite, or discrete, Fourier transform of a complex vector y with n elements is another complex vector Y with n elements

$$\boldsymbol{Y_k} = \sum_{j=0}^{n-1} \omega^{jk}\, y_j,$$

Where ω is a complex nth root of unity:

$$\omega = e^{-2\pi i/n}.$$

STFT-Short Time Fourier Transform

The Short Time Fourier Transform (STFT) is commonly known as the sliding window version of FFT, which has shown better results in terms of frequency selectivity compared with wavelets which has center frequencies and bandwidths fixed. However STFT has fixed frequency resolution for all frequencies, and has shown to be more suitable for harmonic analysis of voltage disturbances than binary tree filters.

Low pass representation of complex band pass filter outputs

$$\mathbf{Xn}\,(\mathrm{e}^{\mathrm{j}\omega k}) = \sum_{\mathrm{m}} \mathrm{x(m)}\,\mathbf{W}\,(\mathbf{n}-\mathbf{m})\mathrm{e}^{-\mathrm{j}\omega k \mathrm{m}}$$

k = 1,……………N

Where $k = 2\pi\mathrm{k}/\mathrm{N}$: filter center frequency

ω(n) : data window size L

N : the total number of bands N ≤ L

Output of K^{th} band pass filter from STFT

$$(\mathrm{e}^{\mathrm{j}\omega k}) = (\mathrm{e}^{\mathrm{j}\omega k\mathrm{n}})\,\mathrm{Xn}(\mathrm{e}^{\mathrm{j}\omega k}) \;=\; \mathrm{hk\,(n)} \,*\, \mathrm{X(n)}$$

Where $\mathrm{hk\,(n)} \;=(\mathrm{e}^{\mathrm{j}\omega k\mathrm{n}})\,\omega(\mathrm{n})$

Instead of using an RMS sequence, fundamental magnitude extracted using STFT can be used. STFT (short time Fourier transform or sliding window FFT) can be regarded as a bank of band pass filter; hence advantage is such that voltage magnitude estimation can achieve higher time resolution than that of the RMS sequences [3, 6]. Different authors have studied the application of STFT for the detection and characterization of voltage events in power systems [5-8]. An advantage the STFT method is that it gives information on the magnitude and phase-angle of the fundamental and harmonic components of the supply [9].

6. Harmonic Reduction Methods

The limit on harmonic voltage and current based on IEEE standard 519 (1992). It should be emphasized that the philosophy behind this standard seeks to limit the harmonic injection from individual customers so that they do not create unacceptable voltage distortion under normal system characteristics and to limit overall harmonic distortion in the voltage supplied by the utility. Harmonic filters are applied at different points where power pollution due to harmonics is observed above the desirable limits as recommended by IEEE standard 519-1992 [10]. There are several methods to reduce harmonic distortion in voltage and current. Every method has its own specialization, so it is essential to select perfect method. Few methods with their advantages and disadvantages are short explained in Table 1.

Table 1. Harmonic Reduction Methods with Benefits and Concerns

Methods	Benefits	Concerns
Inductive reactance (isolation transformer)	Low cost Technically simple	Reduction only higher order harmonics, has little effect on the 5th and 7th harmonics
Passive filters	average	Filters are difficult to size
Active filters	Very effective	Costly, no reliable
12 pulse rectifier	Effective to eliminate 5th and 7th harmonics	Little to attenuate the 11th and 13thharmonics
18 pulse rectifier	Attenuates all harmonics up to 35th intensive to future system changes	Expensive at smaller HP’s

From the above Table 1 we conclude that to reduce harmonic distortion we know different methods with their advantages and disadvantages as well as the signal characteristics. For *e.g.,* If the signal contained 5Th and 7Th harmonics only then use of 12 pulse rectifier method will be beneficial to clean power signal. Signal characterization will be finding very well by using FFT and STFT.

7. Results and Discussion

FFT spectrum distinguish the harmonic components(odd and even harmonic component) and other waveform distortion components as DC offset, inter harmonic, Notching, Noise etc. from the FFT spectrum we can calculate THD (total harmonic distortion).If harmonic are “components of interest” for the analysis, STFT is more suitable [7].

7.1 Harmonic Classification Using FFT Spectrum

FFT is used to convert time domain waveform into their frequency components. When waveform is periodical, the Fourier series can be used to calculate the magnitudes and phases of the fundamental and it’s Harmonic components. Harmonic distortion is characterized by the harmonic spectrum of the voltage or current signal obtained by applying the Fourier transform. Spectrum of distorted signal obtained with power system frequency as – Even harmonic component, odd harmonic component, inter harmonic component, and sub harmonic component and noise [3]. Figure 6 and Figure 7 shows different signals and their FFT spectrum for different load conditions. Figure 6(a) shows distorted signal captured on digital storage oscilloscope when combined load of cfl and computer. Figure 6 (b) shows FFT spectrum. Figures 7 (a) shows distorted signal captured on digital storage oscilloscope when combined load of capacitor and Induction Motor at starting time. Figure 7 (b) shows FFT spectrum.

THD Calculation

From the DSO or from FFT spectrum we can calculate THD (total harmonic distortion) of the given signal.THD calculation from FFT spectrum for capacitor + induction motor starting load is as below.

$$\text{THD \% of fundamental} = \frac{\sqrt{\sum_{h=2}^{25} Q_h^2}}{Q_1} \text{X100}$$

$$= \frac{\sqrt{\begin{array}{c}0.207^2+0.08537^2+0.07088^2+0.7806^2+0.1113^2+0.7092^2+0.03582^2+0.1521^2 \\ +0.03131^2+0.0917^2+0.03594^2+0.1587^2+0.06438^2+0.1184^2+0.06251^2+0.1541^2 \\ +0.08796^2+0.2423^2+0.1194^2+0.2038^2+0.1478^2+0.3124^2+0.1512^2+0.3161^2\end{array}}}{3.206} \text{X } 100$$

$$= 40.07\ \%$$

Harmonics higher than the 25th order are usually negligible so harmonic components up to 25th are taken for the calculation. Figure 6(b) shows signal present only odd harmonics which show result of FFT spectrum. Figure 7(a) and 7(b) shows distorted waveform and spectrum for load of capacitor and induction motor at starting instant. Spectrum shows some even and odd harmonics are present, So that there is some symmetry loss at the time of starting. DC component is above zero. THD for this load is 40.07 %.

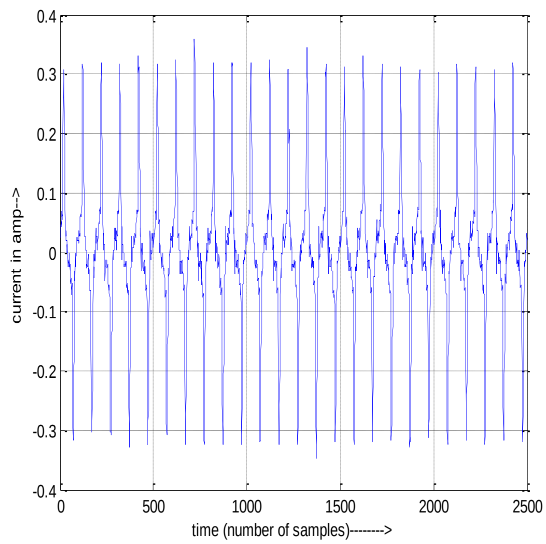
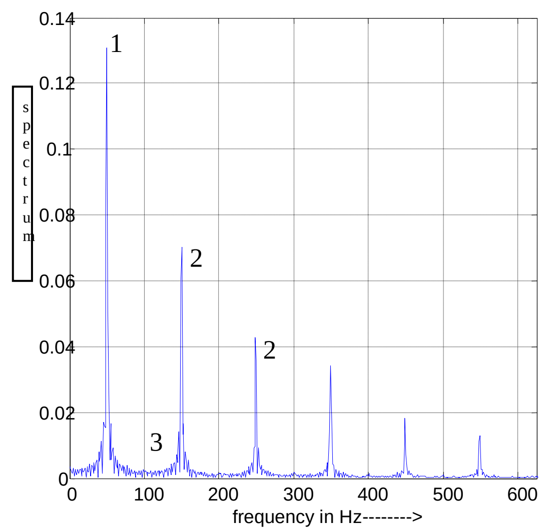


Figure 6. (a)Load Current



1-Power system frequency 2-Odd harmonic component 3-Noise

Figure 6. (b)FFT Spectrum

Figure 6. (a) Distorted Waveform Top (b) FFT bottom for Cfl+Computer Load Signal

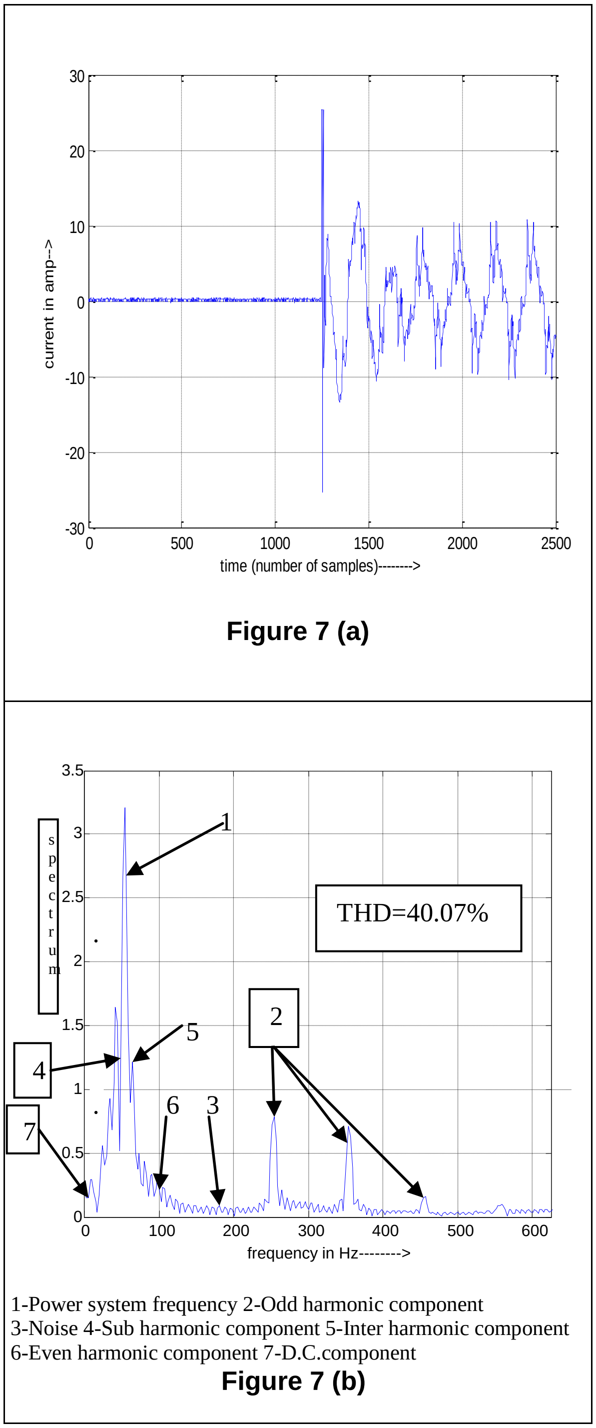


Figure 7. (a) Distorted Waveform (b) FFT for Capacitor+I.M. Starting Signal

7.2. Harmonic Analysis Using STFT

When capacitor+I.M. combined load then this current signal is applied by STFT. STFT for analyzing a current signal from top to bottom measurement containing different harmonic components output magnitudes from band pass filters 1,2,3,4,5,6,7.Analysis of measurement data voltage sampling frequency fs = 10 KHz or 200 samples per 50 Hz cycle. STFT is applied to the current signal. The center frequencies of band pass filters are set at the power system harmonics by choosing the total number of band N=200. Figure 7 (c) displays the absolute values of the filter outputs, which provide an alternative way of analysis. Figure plots the magnitudes of the harmonic signals as a function of time.

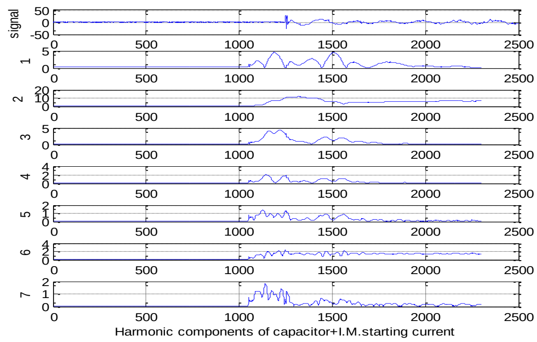


Figure 7. (c) Harmonic Components for Capacitor+I.M. Starting Signal

As STFT extract the different harmonic components, from this we got detail characteristics of each harmonic component which is very useful for finding solution of harmonic distortion. Similar to above discussion of current signal when load is capacitor+I.M. starting instant, some other signals are analyzed with their FFT spectrum and harmonic component by STFT. Current waveforms captured on DSO for different loads are shown below in Figure 8(a), 9(a), 10(a), 11(a). FFT spectrum and THD of respective load are shown in Figure 8(b), 9(b), 10(b), 11(b). Different harmonic components of respective load using STFT are also shown in Figure 8(c), 9(c), 10(c), 11(c) which is very useful to select method for minimizing harmonic distortion. THD for currents at different loading condition is noted in Table 2.

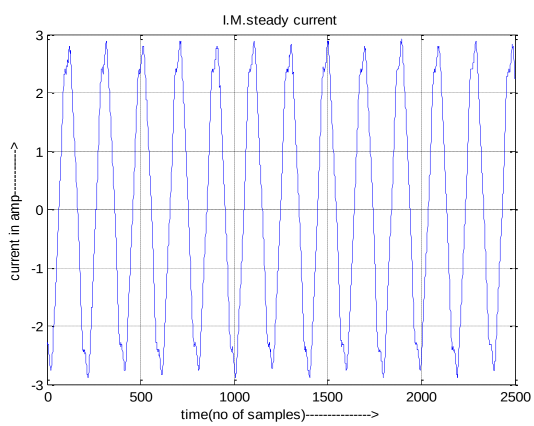


Figure 8. (a) Current Waveforms Captured on DSO for I.M. Steady Current

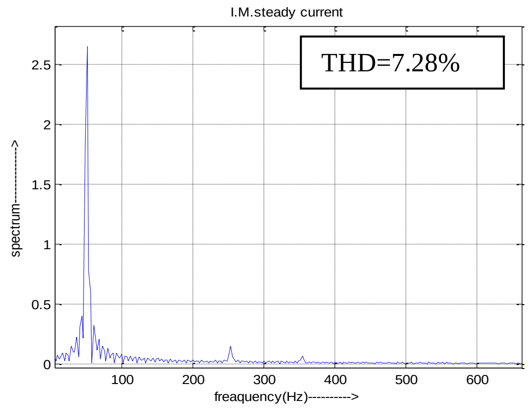


Figure 8. (b) FFT Spectrum for I.M. Steady Current

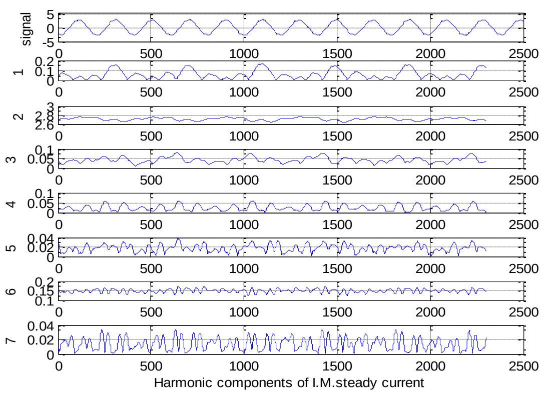


Figure 8 (c) Harmonic components for I.M. steady current

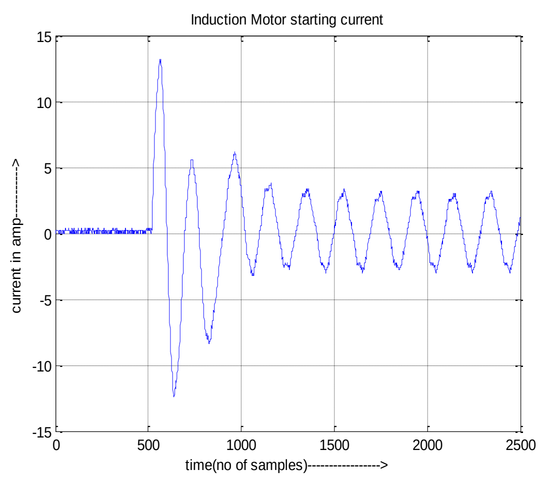


Figure 9. (a) Current Waveforms Captured on DSO for I.M. Starting Current

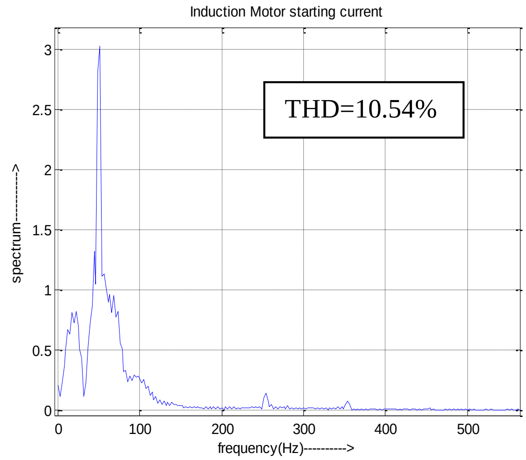


Figure 9. (b) FFT Spectrum for I.M. Starting Current

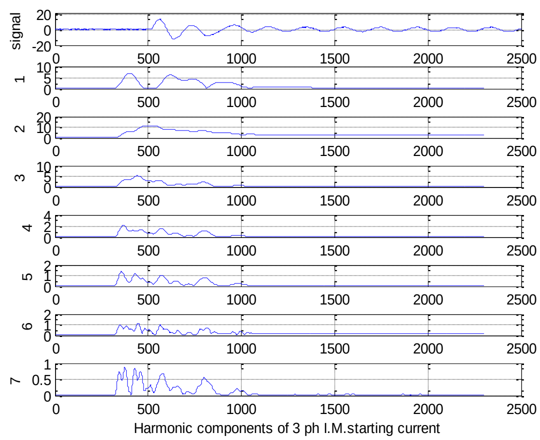


Figure 9. (c) Harmonic Components for I.M. Starting Current

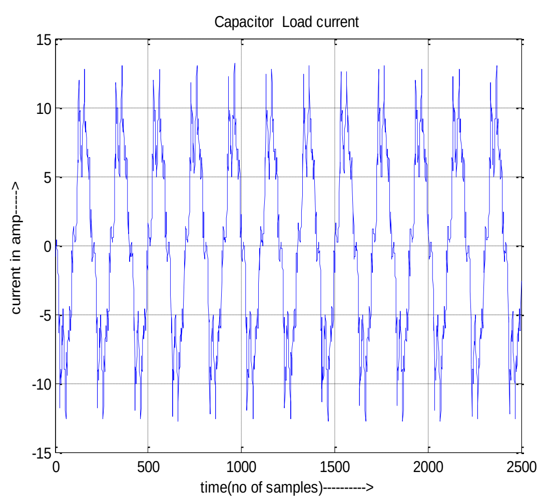


Figure 10. (a) Current Waveforms Captured on DSO for Capacitor Load Current

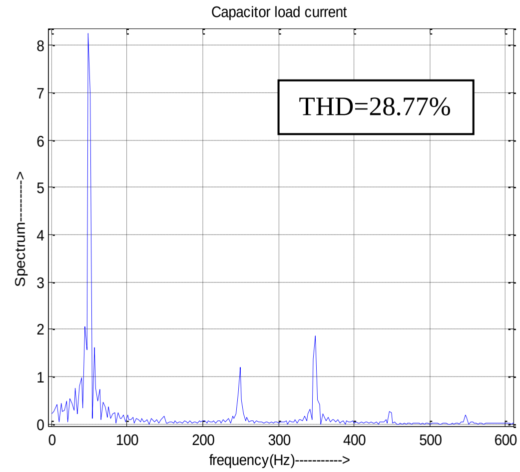


Figure 10. (b) FFT Spectrum for Capacitor Load Current

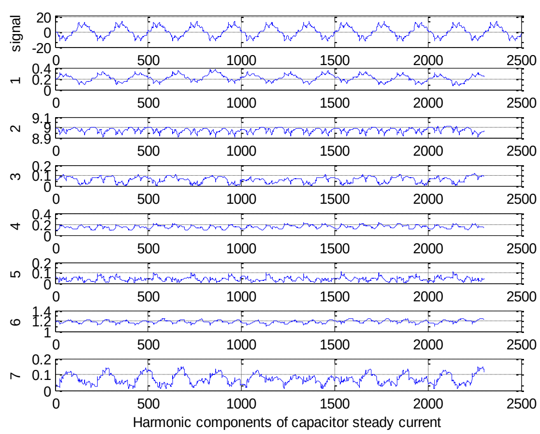


Figure 10. (c) Harmonic Components for Capacitor Load Current

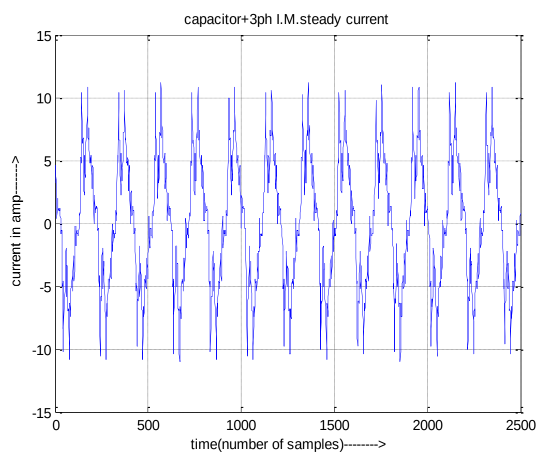


Figure 11. (a) Current Waveforms Captured on DSO for Capacito+IM Steady Load Current

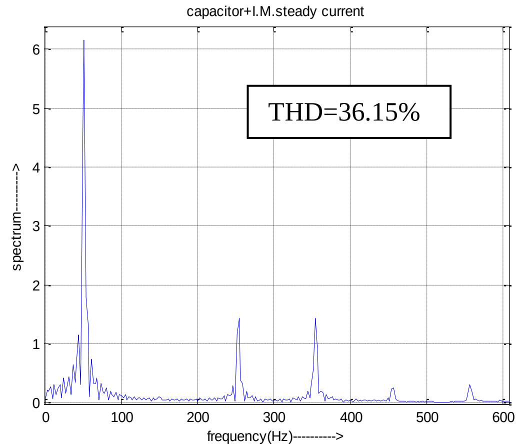


Figure 11. (b) FFT Spectrum for Capacito+IM Steady Current Load Current

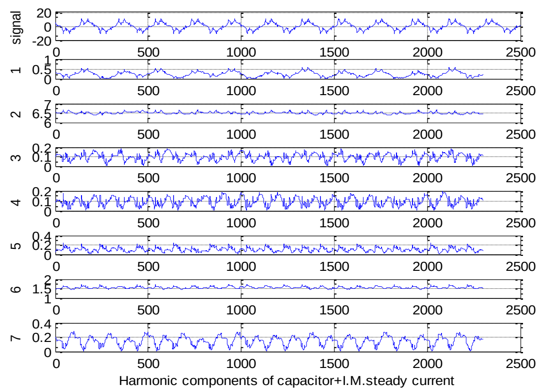


Figure 11. (c) Harmonic Components for Capacito+IM Steady Current Load Current

STFT does not give harmonics as in a Fourier's series, as those are only defined for a periodic signal. The so called "pseudo-harmonics" resulting from the STFT are the output of the signals of band pass filters centered at the harmonic frequencies (*i.e.*, integer multiples of the fundamental frequency).for the periodic signal and narrow filter bands, the output of these filters correspond to the actual harmonics. The bandwidth determines how many harmonic frequencies each band contains [7].

Table 2. THD for Different Loading Condition

Different loading condition	% THD
Capacitor+induction motor starting time	40.07%
Induction motor in running condition	7.28 %
Induction motor at starting time	10.54%
only capacitor load	28.77%
Capacitor+induction motor load	36.15%

Table 2 contains information about THD of the signal on different loading condition. It point out that THD at time of starting of Induction motor is more than normal running condition. When capacitor is on load THD is more than induction motor load.THD of capacitor+Induction motor combined load is higher than only capacitor or only induction motor is on load. Note that at the time of switching on load THD increases as 40.7% THD when capacitor+I.M. load at the starting time. STFT output shows different harmonic components from 1st harmonic component to 7th harmonic components. This data is very useful while taking action against harmonics.

8. Conclusions

Harmonic detection, classification and mitigation is today's an important task in power system. This paper presents detailed power quality problems, harmonics and their types, causes of harmonics, effects and solutions. It proposes FFT and STFT methods of harmonics analysis which is most useful to classify harmonics in odd, even, noise, inter harmonics, sub harmonics etc. Paper brief explains the THD calculation using FFT spectrum. It also shows THD varies as per connected type of load. STFT extract fundamental as well as different harmonic components in the current signal with their magnitude and characteristics. STFT determines how many harmonic frequencies each component contains. Paper also highlights on different harmonics minimization methods with their benefits and concerns. From all discussion it points out that effective methods of harmonic reduction are needed. All information generated by applying FFT and STFT gives brief idea for selection of best harmonic reduction method. This combination of methods shows promise for future improvement of power quality.

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