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Harmonics Modelling and Simulation

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1. Introduction

In this modern era, it is necessary for regulated and deregulated power sectors to properly monitor power system signals in order to be able to access and maintain the quality of power according to the set standards.

Harmonics are sinusoidal voltages or currents having frequencies, that are integer multiples of the fundamental frequencies (50 or 60 HZ), at which the supply system is designed to operate.

The identification, classification, quantification and mitigation of power system harmonics signals is the burning issue for various stake holders including utilities, consumers and manufacturers world widely.

To accomplish this task mathematical and computational tools like MATLAB and Electrical Transient Analyzer Program (ETAP) have been used while conducting this research.

Experimental work and simulation, pertaining to harmonics, will really help the scientific community to understand this phenomenon comprehensively to gain in-advance information, acquired for remedial measures.

This chapter will comprise of the following:

- Harmonics background and their analysis
- Harmonics modelling and simulation at high and low distribution voltage level

2. Harmonics background

Over recent years, there has been a considerable increase in the installation and use of electronic devices in electrical power system revealing non-linear behavior. They draw current which is non-sinusoidal in nature because of the rectification/inversion phenomena of their operation. The reason of this non-sinusoidal/distorted current is the presence of harmonic contents in the current waveform drawn by these electronic equipment.

3. Harmonics Modelling & Simulation at High Voltage (HV) level

In this chapter harmonics modelling and simulation has been performed at power distribution voltage level. For this purpose the chapter is sub-divided into two main parts. The first part deals with harmonics modelling and simulation at High Voltage (HV) distribution level which is 11 kV in most of the countries including Pakistan.

A practical case of an independent 11 kV furnace has been discussed in this section. Modern induction furnace is an example of large non-linear load. Its operational and economic impacts have been analyzed comprehensively.

4. Operational and Economic Impacts of Large distorted current drawn by modern induction furnaces

Modern induction furnace draws heavy current with considerable distortion in the current waveform. This section focuses on indirect consequences caused by distorted current waveform drawn by modern induction furnaces in terms of operational and economic impacts. This heavy distorted current cause's distortion in the system voltage also. Owing to the insulation limitations at 11 kV line, it is very taxing for modern Power Quality Analyzers to capture the exact distorted voltage waveform. However the distorted waveform of current with high amplitude can be captured by these analyzers by virtue of the appropriate CT ratios of their current clamps. By using the Fast Fourier Transform (FFT) of the current waveform, a new mathematical approach using MATLAB has been developed for the exact modelling of distorted voltage waveform. This new approach has further been worked out to derive mathematical relation to compute the THDv which also shows its trend as a function of distance between the supply (utility) and Induction furnace (load). The rest of impacts are the derivation of distortion power, extra active power and reactive power in the line, percentage increase in system losses, displacement and true power factor measurement and finally the calculation of extra bill charged from the consumers. Mentioned above parameters have been derived mathematically and simulated in MATLAB, which also demonstrate their drift as a function of distance from grid to furnace at 11 kV voltage level.

4.1 Block diagram of modern induction furnace

To illustrate the basic operation of the modern induction furnace, the generalized block diagram is given in Figure 1 which is self explanatory.

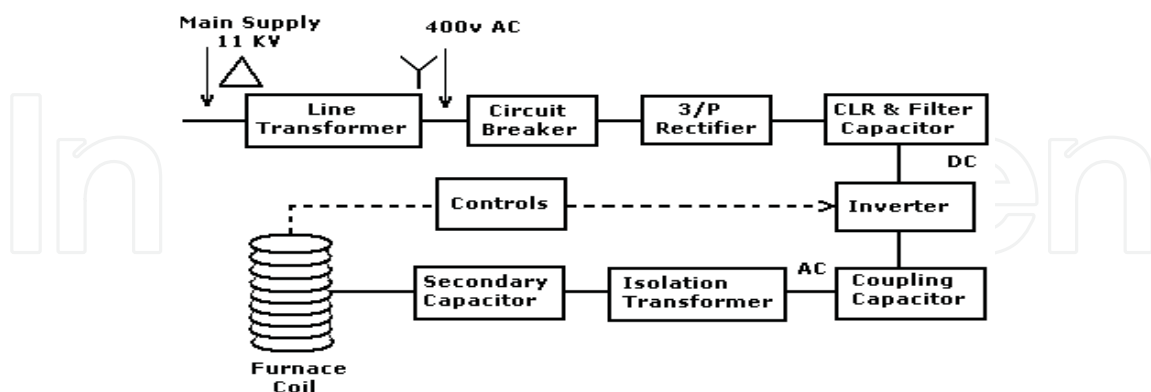


Fig. 1. Block diagram of Induction Furnace

4.2 Single line diagram of case under study

The single line diagram of 11 kV furnace feeder is given in Figure 2. The monitoring points (M1, M2, M3 and M4) have clearly been depicted in the Figure 2. At these points the

waveform, RMS value, FFT and THD (Following the IEEE standards) of distorted current have been recorded using power quality analyzer “Fluke 43B” making sure that the furnaces are running at considerable load. This type of analyzer is capable of recording the FFT of a distorted current waveform up to the 50th harmonic present in that distorted current waveform. Since all the furnaces are three phase and there is a negligible load unbalancing, therefore, only readings from red phase of 11 kV furnace feeder have been recorded for analysis. The data obtained at monitoring points shown in Figure 2, is given in Table 1.

Monitoring Point	RMS value of Current (A)	(%) THDi
M-1 (Furnace-A)	62.20 A	21.2
M-2 (Furnace-B)	160.9 A	17.8
M-3 (Furnace-C)	136.5 A	13.2
M-4 (Coupling point F)	358.1 A	14.5

Table 1. RMS Current and (%) THDi at different Monitoring Points

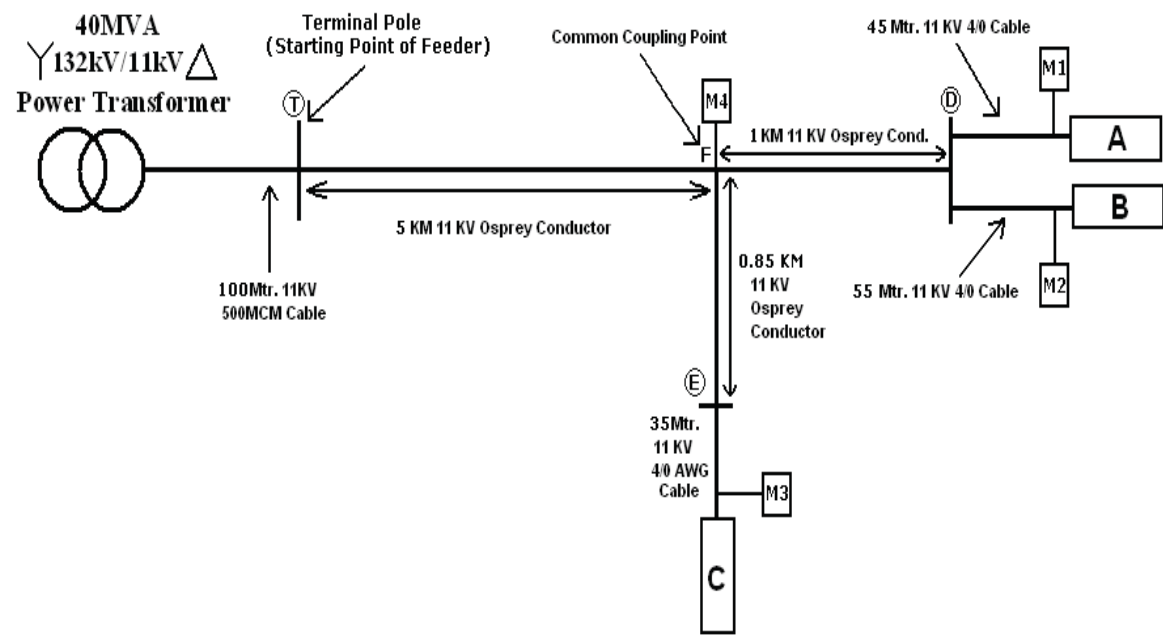


Fig. 2. Single Line diagram of 11 kV furnace feeder

4.3 Description of captured current waveforms at various monitoring points

a. Monitoring point M1 (Furnace-A)
The Current waveform captured at monitoring point M1 having RMS value of 62.2A is shown in Figure 3. It is clearly visible that this current waveform is non-sinusoidal. The FFT Spectrum of the distorted waveform of Figure 3 is given in Figure 4, which clearly indicates the significant presence of 5th, 7th, 11th and 13th harmonics. However the higher order harmonics are considerably small as compared to above mentioned harmonics.

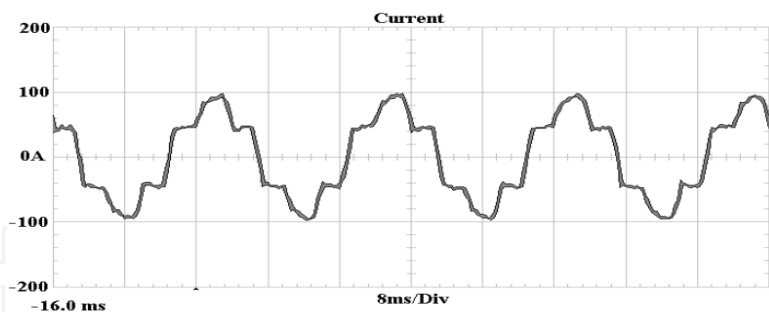


Fig. 3. Current waveform at red phase of furnace A

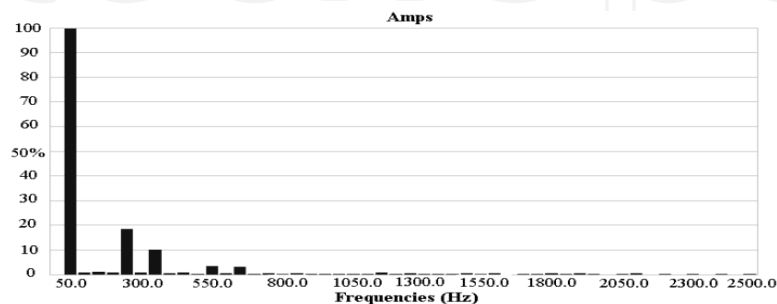


Fig. 4. Current spectrum at red phase of furnace-A

b. Monitoring point M2 (Furnace-B)
The current waveform captured at monitoring point M2 having RMS value of 160.9 A is shown in Figure 5 which is also distorted.

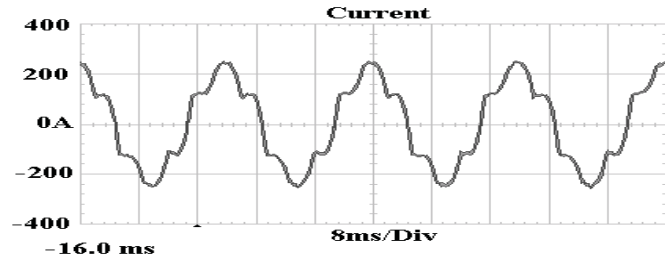


Fig. 5. Current waveform at red phase of furnace-B

The FFT Spectrum of the distorted current waveform of Figure 5 is Shown in Figure 6, which shows the considerable presence of 5th, 7th, 11th, 13th and 17th harmonics. It is obvious that harmonics higher than 17th order are significantly smaller in magnitude as compared to above mentioned harmonics.

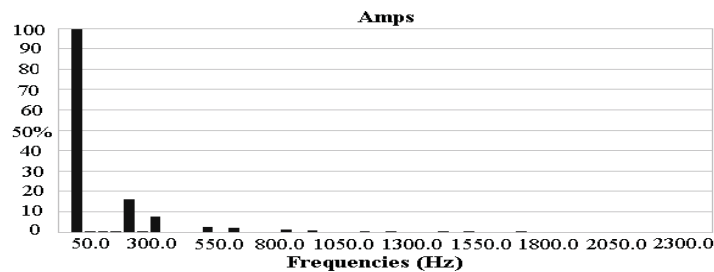


Fig. 6. Current spectrum at red phase of furnace-B

c. Monitoring point M3(Furnace-C)

The Current waveform captured at monitoring point M3 having RMS value of 136.5 A is shown in Figure 7. Again it is clearly visible that this waveform is significantly distorted.

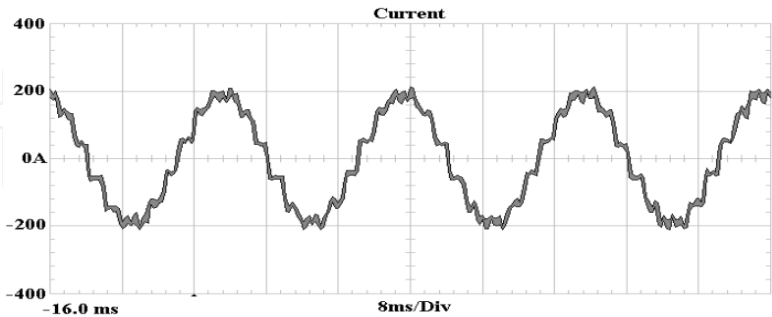


Fig. 7. Current waveform at red phase of furnace-C

The FFT Spectrum of the distorted waveform of Figure 7 is given in Figure 8, which clearly indicates the significant presence of 7th, 11th, 13th, 17th, 21th, 23rd etc harmonics. However harmonics having order higher than 23rd are visibly small as compared to above mentioned odd harmonics. The operating frequency of furnace-C is 650 Hz, while the other furnaces operate at 600 Hz. Due to this difference in frequency, current waveform drawn by furnace-C is different from rest of the two furnaces.

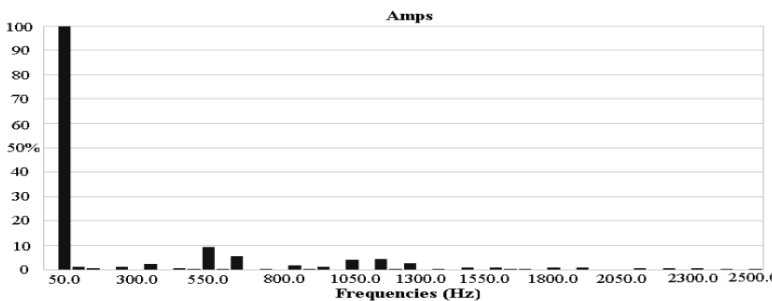


Fig. 8. Current spectrum at red phase of furnace-C

d. Monitoring point M4 (common coupling point F)

The Current waveform captured at monitoring point M4 (common coupling point F) having RMS value of 358.1 A is shown in Figure 9 and its FFT is shown in Figure 10.

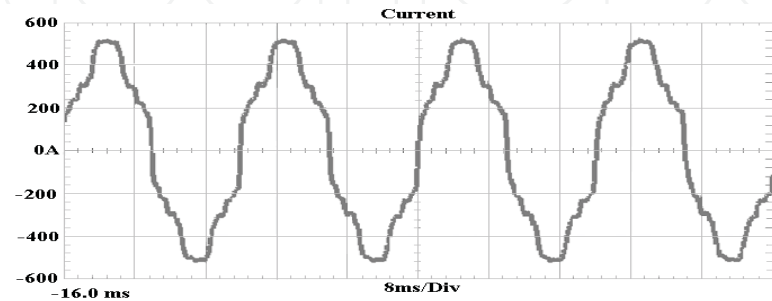


Fig. 9. Current Waveform at coupling point F

The FFT Spectrum of the distorted waveform of Figure 9 is given in Figure 10 which clearly indicates the significant presence of 5th, 7th, 11th and 13th harmonics. However, the presence of higher order harmonics seems to be insignificant as they are smaller in magnitude in comparison with previously mentioned odd harmonics. It is obvious that the reactance of the line increases directly with increase in frequency of the current passing through it. Therefore, these higher order harmonics also contribute significantly to Voltage Distortion. It is worth mentioning that triplen harmonics (3th, 9th, 15th etc) of all the waveforms shown above have been trapped by the delta-Winding of line transformers of all the Furnaces .The position of line transformer has clearly been illustrated in block diagram of furnace, which is shown in Figure 1.

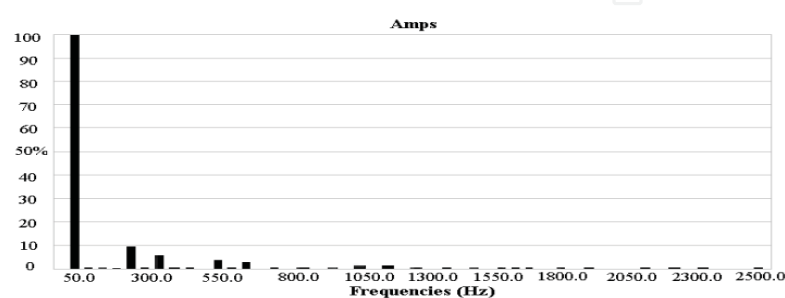


Fig. 10. Current spectrum at coupling point F

Based upon the discussion carried out in previous sections, M4 which is the reference point (Common Coupling Point F) will be focussed for modelling of distorted voltage waveform in terms of distance “d” from terminal pole T (Starting point of feeder) upto the coupling point-F. In latter sections, for mathematical analysis, the Monitoring point M4 will be denoted by F as shown in single line diagram shown in Figure 2.

4.4 Impedance diagram for the case under study

For the calculation of mathematical expressions impedance diagram corresponding to the single line diagram of Figure 2 is shown in Figure 11. Current at M4 is taken as reference current. For simplification in analysis all the three furnaces (loads) are replaced with an equivalent load F.

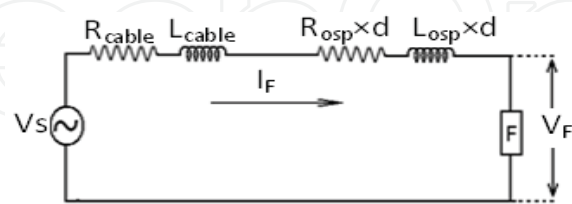


Fig. 11. Impedance diagram corresponding to single line diagram

- Where,
- V_s = Voltage at source (grid), pure sinusoid
 - V_F = Voltage at load (F) terminal, to be calculated
 - I_F = Common Coupling Point Current
 - R_{cable} = Resistance of 100meters 500 MCM cable (in Ohms)

L_{cable} = Inductance of 100meters 500 MCM cable (in Henry)
 R_{osp} = Resistance of Osprey conductor (in Ohms/Km)
 L_{osp} = Inductance of Osprey conductor (in Henry/Km)
 d = Length of Osprey conductor from terminal pole T to Common Coupling Point F

The impedance diagram will be solved using phasor algebra by converting it into two parts. First it will separately solve for fundamental frequency current (I_{F1}) and second for harmonic frequency currents (I_{Fn} , where $n = 2$ to 50). Taking I_{F1} as reference current the phasor diagram at fundamental frequency current is shown in Figure 12.

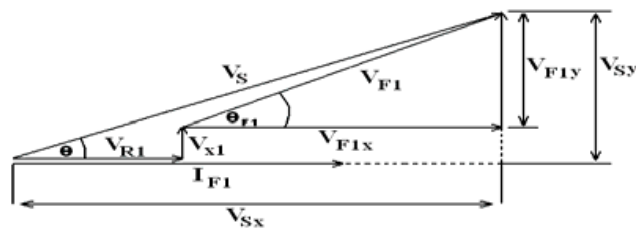


Fig. 12. Phasor diagram for fundamental frequency current

Here;

$$V_{F1x} = V_s \cos(\theta) - V_{R1}$$

$$V_{F1y} = V_s \sin(\theta) - V_{X1}, \text{ where, } \cos(\theta) \text{ is the displacement power factor at grid} = 0.95, \text{ and}$$

$$V_{R1} = I_{F1} (2R_{\text{osp}}d + 2R_{\text{cable}})$$

$$V_{X1} = I_{F1} (2\pi f(2L_{\text{osp}}d) + 2\pi f(2L_{\text{cable}})), \text{ here } f \text{ is the fundamental frequency i.e., } 50 \text{ Hz, therefore,}$$

$$V_{F1x} = V_s \cos(\theta) - I_{F1} (2R_{\text{osp}}d + 2R_{\text{cable}})$$

$$V_{F1y} = V_s \sin(\theta) - I_{F1} (4\pi fL_{\text{osp}}d + 4\pi fL_{\text{cable}})$$

Using Pythagoras theorem:

$$|V_{F1}| = \sqrt{V_{F1x}^2 + V_{F1y}^2} \quad (1)$$

$$\theta_{F1} = \tan^{-1} (V_{F1y}/V_{F1x})$$

By putting the values of V_{F1x} and V_{F1y} :

$$|V_{F1}| = \sqrt{e_1 d^2 + f_1 d + g_1} \quad (2)$$

Where:

$$e_1 = [(2I_{F1}R_{\text{osp}})^2 + (4\pi fI_{F1}L_{\text{osp}})^2] = 1.1616 \times 10^5$$

$$f_1 = [(8I_{F1}^2R_{\text{osp}}R_{\text{cable}} - I_{F1}V_s \cos(\theta)R_{\text{osp}}) + (32I_{F1}^2\pi^2f^2L_{\text{osp}}L_{\text{cable}} - 8V_s \sin(\theta)I_{F1}\pi fL_{\text{osp}})] \\ = -6.7121 \times 10^6$$

$$g_1 = [(V_s \cos(\theta) - 2I_{F1}R_{\text{cable}})^2 + (V_s \sin(\theta) - 4I_{F1}\pi fL_{\text{cable}})^2] = 2.4135 \times 10^8$$

For any n^{th} harmonic current I_{Fn} the source voltage V_s behaves as short circuit because it is pure sinusoidal in nature and load F acts as a source of harmonic current. Taking I_{Fn} as reference current, assuming V_s as zero, the required phasor diagram is shown in Figure 13.

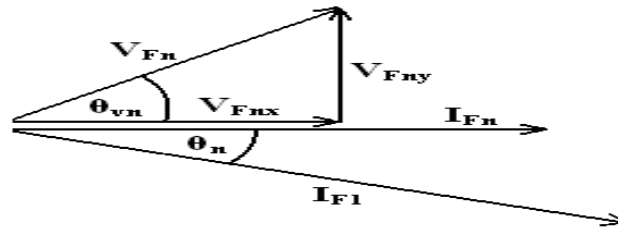


Fig. 13. Phasor diagram for harmonic currents

Here;

θ_n = Phase angle of n th harmonic current with respect to I_{F1} , and

$$V_{FnX} = I_{Fn} (2R_{osp}d + 2R_{cable})$$

$$V_{FnY} = I_{Fn} (2\pi n f (2L_{osp}d) + 2\pi n f (2L_{cable}))$$

Using Pythagoras theorem:

$$|V_{Fn}| = \sqrt{V_{FnX}^2 + V_{FnY}^2} \quad (3)$$

$$\theta_{vn} = \tan^{-1} (V_{FnY} / V_{FnX})$$

$$\theta_{Fn} = \text{Phase angle of } V_{Fn} \text{ with reference to } I_{F1} = \theta_{vn} + \theta_{Fn}$$

Putting the values of V_{FnX} and V_{FnY} in Equ. (3) and then by squaring it on both sides:

$$V_{Fn}^2 = [(I_{Fn}^2 \{ (2R_{osp})^2 + (4\pi n f L_{osp})^2 \}) d^2 + [I_{Fn}^2 \{ 8R_{osp}R_{cable} + 32\pi^2 n^2 f^2 L_{osp}L_{cable} \}] d + [I_{Fn}^2 \{ 4R_{cable}^2 + 16n^2 f^2 L_{cable}^2 \}]]$$

Taking square root on both sides:

$$|V_{Fn}| = \sqrt{a_n d^2 + b_n d + c_n} \quad (4)$$

Where,

$$a_n = I_{Fn}^2 \{ (2R_{osp})^2 + (4\pi n f L_{osp})^2 \}$$

$$b_n = I_{Fn}^2 \{ 8R_{osp}R_{cable} + 32\pi^2 n^2 f^2 L_{osp}L_{cable} \}$$

$$c_n = I_{Fn}^2 \{ 4R_{cable}^2 + 16n^2 f^2 L_{cable}^2 \}$$

Here $n = 2$ to 50 , in summation form:

$$\sum_{n=2}^{50} (V_{Fn}) = \sum_{n=2}^{50} \sqrt{a_n d^2 + b_n d + c_n} \quad (5)$$

Now the final value of voltage $V_F(t)$ in time domain is:

$$V_F(t) = |V_{F1}| \sin(2\pi f t + \theta_{F1}) + |V_{Fn}| \sin(2\pi f t + \theta_{Fn}) \quad (6)$$

4.5 Operational Impacts

a. Simulation of voltage waveforms using MATLAB

By implementing Equ. (6) using MATLAB, the distorted voltage waveform at any point along the distance d from terminal point T to common coupling point F can be generated. For instance distorted voltage waveforms and their FFT's have been generated at different points between terminal pole T and coupling point F, which are given as:

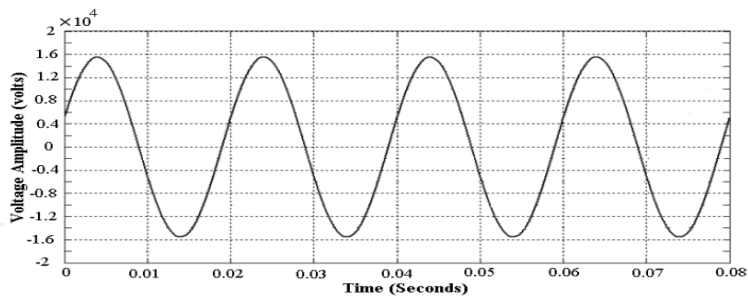


Fig. 14. Voltage wave form at terminal pole T

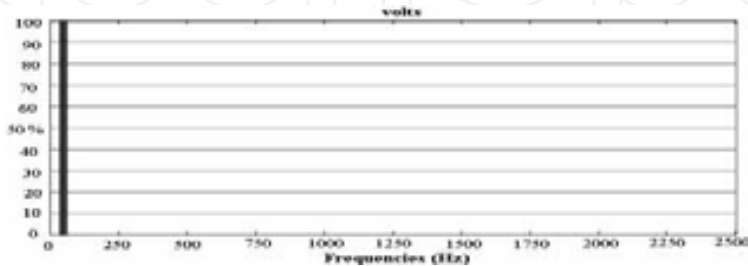


Fig. 15. FFT Spectrum of voltage waveform shown in Figure 14

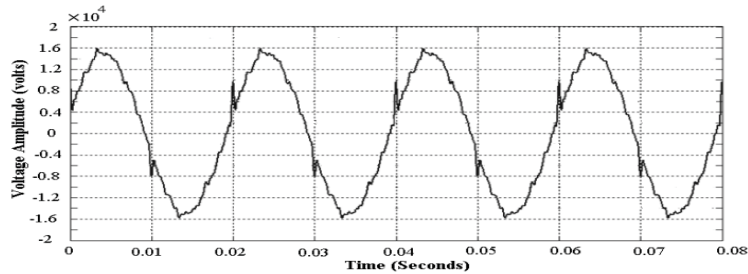


Fig. 16. Voltage waveform at 2.5 KM from Terminal pole T

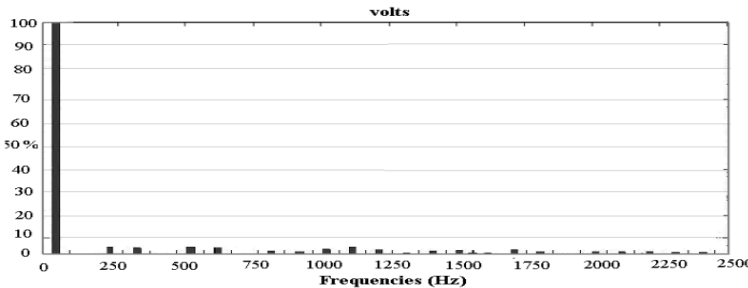


Fig. 17. FFT Spectrum of voltage waveform shown in Figure 16

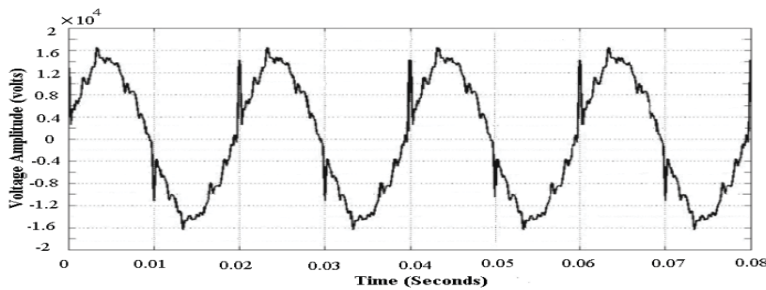


Fig. 18. Distorted Voltage waveform at common coupling point F

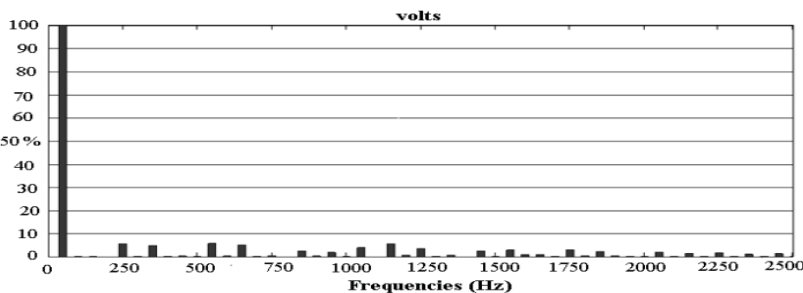


Fig. 19. FFT corresponding to waveform shown in Figure 18

The above given waveforms along with their FFT’s signify the fact that the distortion in voltage increases as it travels from terminal pole (T) to common coupling point (F).

b. Calculation of (%) THD_v in terms of distance

The expression for computation for THD_v of V_F is:

$$\text{THD}_v = \sqrt{\sum_{n=2}^{50} V_{Fn}^2} / V_{F1}$$

By putting the values of V_{F1} and $\sum_{n=2}^{50} (V_{Fn})$ from Equ.’s (2) and (5) in above expression, the following expression is obtained:

$$\text{THD}_v = \sqrt{\frac{a_n d^2 + b_n d + c_n}{e_1 d^2 + f_1 d + g_1}}, \text{ where } d \leq 5 \text{ (km's)} \tag{7}$$

Equ. (7) expresses THD_v as a function of distance d in kilo-meters from terminal pole (T) to common coupling point (F).

The values of % THD_v computed have been tabulated in Table 2.

Distance d (km's)	(%) THD _v
0.0	0.2178
0.5	1.7163
1.0	3.2357
1.5	4.7759
2.0	6.3370
2.5	7.9191
3.0	9.5222
3.5	11.146
4.0	12.792
4.5	14.458
5.0	16.145

Table 2. Variation of (%) THD_v with distance

In order to illustrate the trend of increase in THD_v from terminal pole (T) to common coupling point (F), a graph has been drawn by using the values given in the above table. This graph shows that the trend of increase in THD_v with distance is approximately linear.

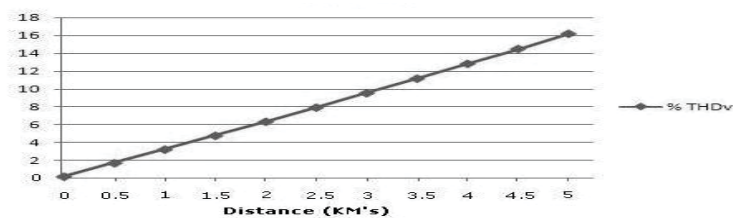


Fig. 20. Graph showing trend of (%) THDv with increasing distance d

c. Distortion Power

Following the power triangle P, Q and S are Active, Reactive and Apparent powers respectively. These are the powers present in system in case of linear load.

But in case of harmonics in the system, another power is introduced, which is called as Distortion power and represented by D. Figure 21 shows the association among the powers in case of non-linear load.

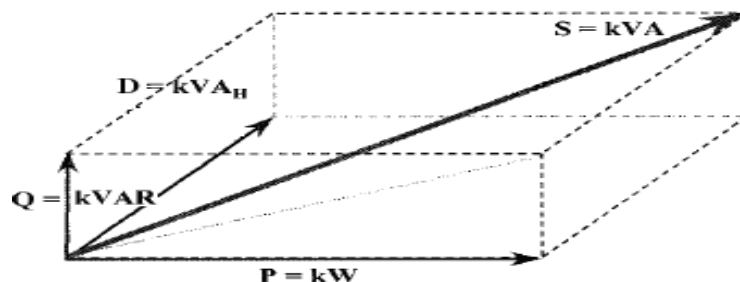


Fig. 21. Change in power triangle in case of non-linear load

Now Apparent power S can be calculated as:

$$S = V_{Frms} \times I_{Frms} \quad (8)$$

Where,

$$V_{Frms} = V_{F1rms} \sqrt{1 + THD_v^2} \text{ and } V_{F1rms} = V_{F1} / \sqrt{2}$$

$$I_{Frms} = I_{F1rms} \sqrt{1 + THD_i^2} \text{ and } I_{F1rms} = I_{F1} / \sqrt{2}$$

The total active power P and the reactive power Q are given by:

$$P = P_1 + \sum_{n=2}^{50} P_n$$

$$Q = Q_1 + \sum_{n=2}^{50} Q_n$$

After simplification the required solutions in terms of distance d from starting point (T) to common coupling point (F) are given in Equ.'s (9) and (10) respectively:

$$P = I_1 \cos(\theta) / 2 \sqrt{e_1 d^2 + f_1 d + g_1} + \sum_{n=2}^{50} [I_{Fn} \cos(\theta_{Fn}) / 2 \sqrt{a_n d^2 + b_n d + c_n}] \quad (9)$$

$$Q = I_1 \sin(\theta) / 2 \sqrt{e_1 d^2 + f_1 d + g_1} + \sum_{n=2}^{50} [I_{Fn} \sin(\theta_{Fn}) / 2 \sqrt{a_n d^2 + b_n d + c_n}] \quad (10)$$

Now, the distortion power D is given by the following formula:

$$D = \sqrt{S^2 - P^2 - Q^2}$$
 (11)

The derived expression in terms of distance d from terminal pole (T) up to common coupling point (F), is for the measurement of Distortion Power D. This expression also describes the relation between Distortion power (D) and the distance (d). In this case the value of d is fixed at 5 km's but it can be generalized by putting the value of displacement power factor along with rest of the single line diagram parameters. Simulating these Equ.'s in MATLAB, the result obtained at different values of distance d is given in Table 3.

Distance d (km's)	Distortion Power (VA)
0.0	16.86×10 ⁵
0.5	16.44×10 ⁵
1.0	16.23×10 ⁵
1.5	16.24×10 ⁵
2.0	16.46×10 ⁵
2.5	16.88×10 ⁵
3.0	17.50×10 ⁵
3.5	18.28×10 ⁵
4.0	19.22×10 ⁵
4.5	20.29×10 ⁵
5.0	21.46×10 ⁵

Table 3. Distortion Power (D) trend from Point T to F

d. Extra Active & Reactive Power

The Active and Reactive powers due to the presence of harmonics can be derived in terms of distance d from point T to F as:

$$\sum_{n=2}^{50} P_n = 3(\sum_{n=2}^{50} [I_{Fn}\cos(\theta_{Fn})/2 \sqrt{a_n d^2 + b_n d + c_n}])$$
 (12)

$$\sum_{n=2}^{50} Q_n = 3(\sum_{n=2}^{50} [I_{Fn}\sin(\theta_{Fn})/2 \sqrt{a_n d^2 + b_n d + c_n}])$$
 (13)

Implementing the Equ.'s (12) and (13) in MATLAB, the resulted values in terms of distance are given in Table 4.

Distance d (km's)	Extra Active Power (W)	Extra Reactive Power (VAR)
0.0	180.96	2536.57
0.5	975.46	19.86
1.0	1769.99	3.72×10 ³
1.5	2564.54	5.45×10 ⁴
2.0	3.36×10 ³	7.48×10 ⁴
2.5	4.16×10 ³	8.92×10 ⁴
3.0	4.95×10 ³	11.85×10 ⁴
3.5	5.75×10 ³	12.38×10 ⁴
4.0	6.54×10 ³	14.11×10 ⁴
4.5	7.33×10 ³	15.85×10 ⁴
5.0	8.13×10 ³	17.58×10 ⁴

Table 4. Extra Active & Reactive Power in terms of distance

e. Percentage Increase in Line Losses
The losses due to the ohmic resistance of the line are known as line losses or copper losses (I^2R). Here in case of harmonic currents, these losses can be calculated as:

$$W_C = 3[I_{F1}^2 (R_{cable} + R_{ospd}) + \sum_{n=2}^{50} I_{Fn}^2 (R_{cable} + R_{ospd})]$$

The percentage increased in Line Losses can be determined from the following relation:

$$\begin{aligned} \% \text{ Increased Losses} &= I_{true,rms}^2R - I_{fund,rms}^2R / I_{fund,rms}^2R \times 100 \\ I_{true,rms}^2 &= I_{fund,rms}^2(1 + THDi) \\ \% \text{ Increased Losses} &= THDi^2 \times 100 \end{aligned}$$

(14)

THDi = 0.145
% increased Losses = 2.1025 %
Following the allowable permissible limit of technical losses i.e. 5%, this considerable increase in technical losses due to the presence of harmonic currents, is really alarming for utilities and furnace owners.

f. Displacement and True Power Factors
The power factor of fundamental frequency components of the voltage and current is known as Displacement Power Factor (DPF). Where, the ratio of total active and reactive power including harmonic contents is called True Power Factor (TPF).
Mathematically expressed as:

DPF= P_1/S_1

(15)

TPF= P/S

(16)

The values of DPF and TPF obtained from MATLAB are given in Table 5.

Distance (km's)	DPF	TPF	Difference
0.0	0.9504	0.9406	0.0098
0.5	0.9530	0.9431	0.0099
1.0	0.9556	0.9454	0.0102
1.5	0.9581	0.9474	0.0107
2.0	0.9606	0.9491	0.0115
2.5	0.9631	0.9505	0.0126
3.0	0.9655	0.9517	0.0138
3.5	0.9679	0.9525	0.0154
4.0	0.9702	0.9530	0.0172
4.5	0.9725	0.9532	0.0193
5.0	0.9747	0.9530	0.0217

Table 5. Displacement and True Power Factor

The graph in Figure 22 shows the behavior of DPF and TPF in terms of distance. Here DPF follows a linear pattern, where the TPF pursues a curve pattern. The reason of this curve pattern is the quadratic behavior of Equ.'s 15 & 16.

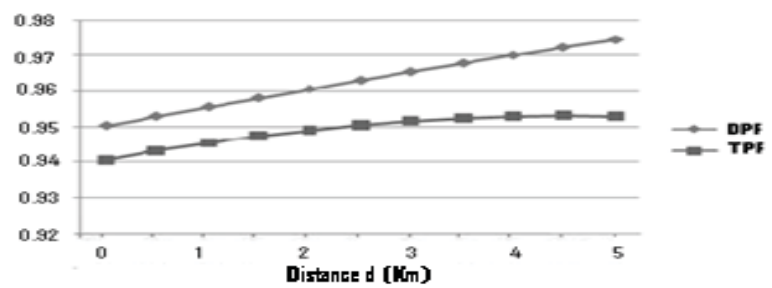


Fig. 22. Graph of DPF and TPF

4.6 Economic Impact

Table 4 shows the Extra Active Power flow in line, and its value calculated at Common Coupling Point (M4) is 8.13 KW. On the basis of this value Extra Bill of handsome amount charged from furnace owners using the tariff of the utility can be calculated. Table 6 shows the Sanctioned Load and Maximum Demand Indicator (MDI) of all the three furnaces. These MDI’s are of the same month, when readings are taken during monitoring.

Furnace	Sanctioned Load (KW)	MDI (KW)
A	1160	1008
B	3200	2442
C	2500	2083
TOTAL	6860	5533

Table 6. Sanctioned Load and MDI of all the Furnaces

The Tariff for independent industrial (furnace) consumer is given in Table 7:

Charges (Rs.)	Off Peak	Peak
Fixed (per KW per Month)	305.00	305.00
Variable (per KWh)	3.88	6.97

Table 7. Tariff for Furnace Consumers

- Extra Active Power P = 8.13 KW
Off Peak Units (per month) = 8.13*20*30= 4878 KWh
Peak Units (per month) = 8.13*4*30= 975 KWh
- Fixed Charges = 305*MDI = Rs. 1687565
 - Variable Charges:
 - Off Peak (O) = 4878*3.88 = 18927
 - Peak (P) = 975*6.97 = 6796
 - TOTAL = (O) + (P) = Rs. 25723
 - GST (15% of Variable Charges) = Rs. 3858
 - Income Tax = Rs. 2000
 - Additional Charges = Rs. 34212
 - TOTAL EXTRA BILL = Rs. 17,53,358/-

This considerable extra bill charged by utility will be divided among the furnaces according to their KWh and MDI.

4.7 Conclusion of operational and economic impacts of distorted current drawn by modern induction furnaces

The novel approach presented here will really help the power sector stake holders to measure the voltage distortion at any desired location irrespective of voltage level. Moreover, this newly developed methodology can be generalized to solve any type of electric circuits involving non-linear loads.

The above section reveals that the presences of large distorted current in a power distribution network adversely affect the performance of the system operationally and economically. Its indirect consequences result in network overloading even under normal operating conditions. The life of power system reduces and some times can cause damaging to power/distribution transformers and furnace installations etc due to excessive system losses. This novel approach will really open the pathway for researchers and scientists in mitigation of these impacts in future.

5. Harmonics Modelling & Simulation at Low Voltage (LV) level

This section deals with mathematical modelling and simulation at low voltage (LV) i.e. 400volts (secondary distribution voltage) level. Computer load, as case study has been selected for mathematical modelling and simulation.

6. Mathematical modelling of current harmonics caused by personal computers

Personal computers draw non-sinusoidal current with odd harmonics more significantly. Power quality of distribution networks is severely affected due to the flow of these generated harmonics during the operation of electronic loads. In this section, mathematical modelling of odd harmonics in current like 3rd, 5th, 7th and 9th influencing the power quality has been presented. Live signals have been captured with the help of power quality analyzer for analysis purpose. The interesting feature is that Total Harmonic Distortion (THD) in current decreases with the increase of nonlinear loads has been verified theoretically. The results obtained using mathematical expressions have been compared with the practical results.

6.1 Methodology and instrumentation

In this case study various computers were connected to the main of the power supply one by one and effect of each computer on the current waveform of the main was recorded. Figure 23 indicates the hardware arrangement and apparatus used during the experimental work. As it is evident from Figure 23, inputs for various computers under test one by one are drawn from AC mains. The waveforms of odd harmonics and THD have been observed and recorded. This data has been used to make observations about the changes and effects of electronic loads.

Following equipment have been used for the experiment work.

- i) Power quality analyzer was used to record the current waveforms and THD.
- ii) Personal Computer (PC) details are as under:
Pentium (R) 4 CPU 2.40 GHz

ATX Power supply 220 t0 230 Volts
Monitor 15 inch (100- 240V, 50/60Hz, 0.8- 1.5A)

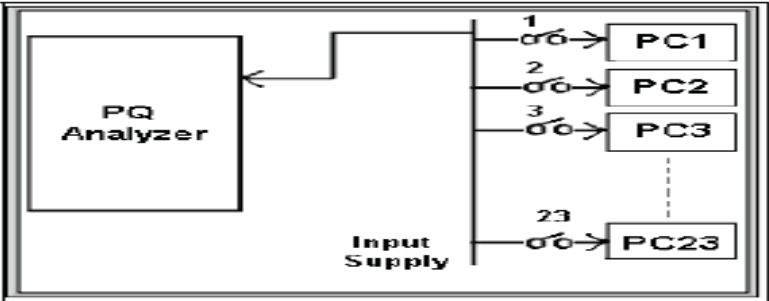


Fig. 23. Hardware arrangement

6.2 Results and discussions

PC’s numbering from PC 1 to PC 23 were connected to the AC mains gradually and then wave-forms of odd harmonics and THD in current have been captured and recorded in real time for observations. Table 8 describes the results taken for Total Harmonic Distortion (THD) in current and individual magnitudes of odd harmonics corresponding to different number of PCs connected to the main.

No. of PC’s	% Mag. of 3rd harmonic	% Mag. of 5th harmonic	% Mag. of 7th harmonic	% Mag. of 9th harmonic	% THDi
1	50	45	37	23	79.3
4	53	42	25	13	74.6
7	54	40	21	5	72.3
10	56	38	16	3	70.1
13	58	35	12	2	68.6
16	58	33	8	5	66.2
19	57	29	6	7	64.0
21	58	27	4	7	62.8
23	58	25	0	9	61.4

Table 8. Online recorded results

6.3 Graphical representation of results

a. 3rd Harmonic Only

From graph shown in Figure 24, it is clear that the magnitude of 3rd harmonic increases up- to certain level then it remains constant with further increase of the electronic load. Mathematically, using Curve Fitting technique, the relation between columns 1 and 2 of Table 8 can be written as:

$$Y = -0.0248X^2 + 0.935X + 49.228$$

In the form of current and number of PCs:

$$I_3 = - 0.0248N_{PC}^2 + 49.228 \tag{17}$$

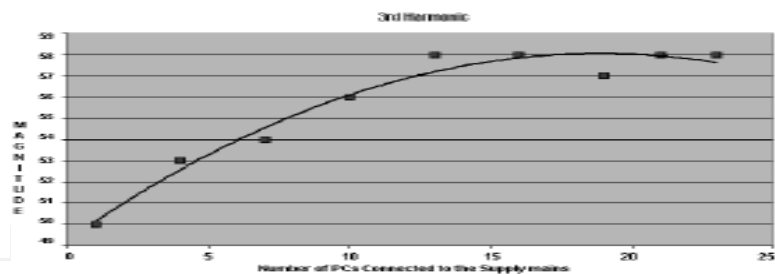


Fig. 24. Graphical representation of 3rd harmonic only

b. 5th Harmonic Only

From graph shown in Figure 25, the magnitude of 5th harmonic decreases in linear fashion, as the number of PC's connected to the supply mains increases, ultimately the magnitude of this odd harmonics approaches to zero.

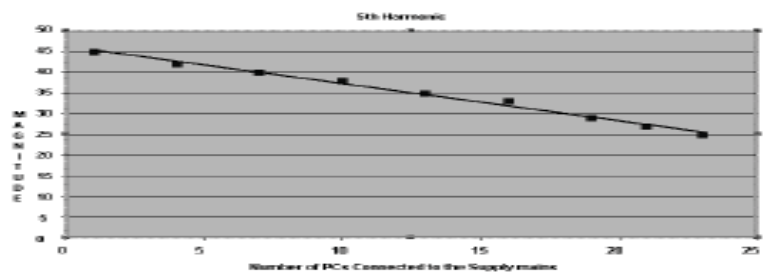


Fig. 25. Graphical representation of 5th harmonic only

Mathematically, using Curve Fitting technique relation between columns 1 and 3 of Table 8 can be written as:

$$Y = - 0.8916X + 46.239$$

In the form of magnitude of harmonic current and the no. of PCs connected to the supply mains:

$$I_5 = - 0.8961N_{PC} + 46.239 \tag{18}$$

Where, - 0.8961 is the slop of the line 46.239 is its y-intercept

c. 7th Harmonic Only

Figure 26 indicates that the magnitude of 7th harmonic decreases in a logarithmic fashion, rather than linear as in the case of 3rd and 5th harmonic, as the number of PC's increases and consequently it becomes zero.

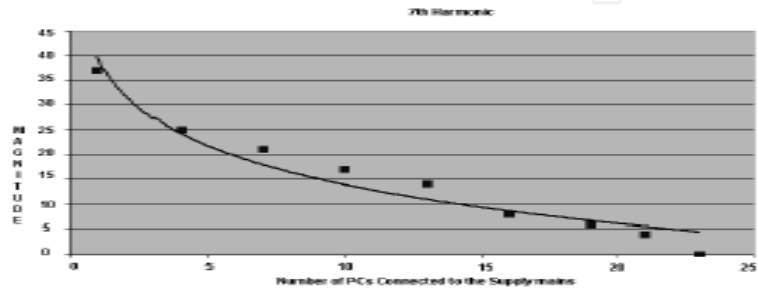


Fig. 26. Graphical representation of 7th harmonic only

Mathematically, using Curve Fitting technique relation between columns 1 and 4 of Table 8 can be written as:

$$Y = -11.278\ln(x) + 39.85$$

In the form of magnitude of harmonic current and the no. of PCs connected to the supply mains:

$$I_7 = -11.278\ln(N_{PC}) + 39.85 \quad (19)$$

Where, $\ln(x)$ is a natural logarithmic function.

d. 9th Harmonic Only

From this graph shown in Figure 27, it is observed that the magnitude of 9th harmonic is following the trend line of polynomial of order 2 as compared to other harmonics as the number of PC's is increasing the magnitude of 9th harmonic is decreasing resultantly.

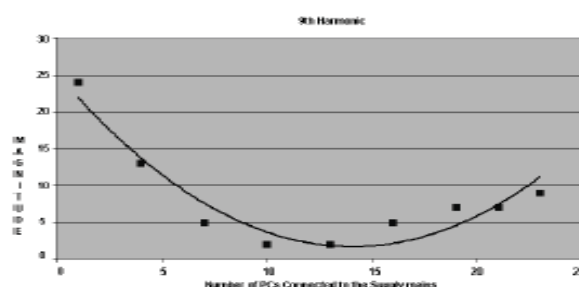


Fig. 27. Graphical representation of 9th harmonic only

Mathematically, using Curve Fitting technique relation between columns 1 and 5 of Table 8 can be written as:

$$Y = 0.1188N_{PC}^2 - 3.3403N_{PC} + 25.159$$

In the form of magnitude of harmonic current and the no. of PCs connected to the supply mains:

$$I_9 = 0.1188N_{PC}^2 - 3.3403N_{PC} + 25.159 \quad (20)$$

Where the expression on right hand side is a polynomial of 2nd order, geometrically it represents the characteristics of parabolic curve.

e. THD in Current

The percentage of Total Harmonic Distortion (%THD) can be defined in two different ways, as a percentage of the fundamental component (the IEEE definition of THD) or as a percentage of the rms (used by the Canadian Standards Association and the IEC).

$$THD = \sqrt{\sum_{n=2}^{\infty} I_{rms,n}^2} / I_1$$

Where $I_{rms,n}$ is the amplitude of the harmonic component of order n (i.e., the n th harmonic). The numerator gives the RMS current due to all harmonics and I_1 is the RMS value of fundamental component of current only. Given above is the mathematical form of the IEEE definition of THD. According to IEC standards, the mathematical form of THD is given below:

$$\text{THD} = \frac{\sqrt{\sum_{n=2}^{\infty} I_{rms,n}^2}}{I_{rms}} \text{ and}$$

$$I_{rms} = \sqrt{\sum_{n=1}^{\infty} I_{rms,n}^2}$$

Where $I_{rms,n}$ is the amplitude of the harmonic component of order n (i.e., the n th harmonic) and I_{rms} is the rms value of all the harmonics plus the fundamental component of the current. The later standard is referred in this study, because the apparatus used for analysis was based on IEC Standards. The 3rd, 5th, 7th and 9th harmonics being the most significant, the definition of THD may be modified and written as in the next page.

$$\text{THD} = \frac{\sqrt{I_{rms,3}^2 + I_{rms,5}^2 + I_{rms,7}^2 + I_{rms,9}^2}}{I_{rms}} \quad (21)$$

The value of THD may be calculated for any number of computers using the above formula. Figure 28 is showing the magnitude of individual harmonics, when 4 PCs were connected to the supply mains.

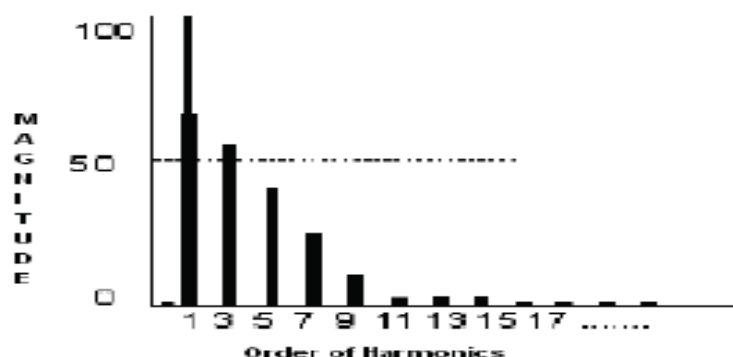


Fig. 28. FFT of current waveform

$I_{rms} = 3.28 \text{ A}$

RMS magnitude of 3rd Harmonic = 53% of 3.28 = 1.7384 A

RMS magnitude of 5th Harmonic = 42% of 3.28 = 1.3776 A

RMS magnitude of 7th Harmonic = 25% of 3.28 = 0.8200 A

RMS magnitude of 9th Harmonic = 13% of 3.28 = 0.4264 A

$$\text{THD} = \frac{\sqrt{1.7384^2 + 1.3776^2 + 0.8200^2 + 0.4264^2}}{3.28}$$

(%) THD = 73.26 %

The above Equ. can be modified as:

$$\text{THD} = \frac{\sqrt{I_3^2 + I_5^2 + I_7^2 + I_9^2}}{I_1} \quad (22)$$

Where I_3 , I_5 , I_7 and I_9 are the %age magnitudes of the 3rd, 5th, 7th and 9th harmonics respectively. In this case it can be calculated as:

$$\text{THD} = 73.26 \%$$

In the Table 8, the online value of THD is 74.6%. The difference of the calculated and experimental value is 1.34, which is only 1.8%. This negligible difference caused by other odd harmonics being neglected proves the validity of measurement and it consequently plays a pivotal role for the accurate analysis of the odd harmonics under test in this research. Figure 29 explains the overall impact of individual harmonics cumulatively. Total Harmonic Distortion (THD) in Current with increase in electronic loads is decreasing. As discussed in previous sections, among odd harmonics only third harmonic plays active role whereas the other odd harmonics impact with increase in electronic loads is negligible.

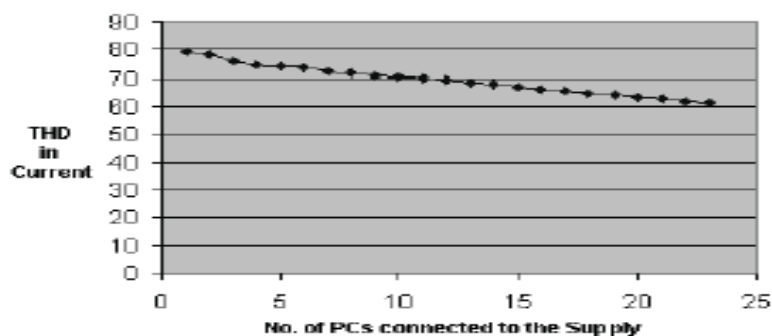


Fig. 29. Graphical representation of THD in current

The relation between THD in current and the number of PCs is given below:

$$I_t = 80.11 - 0.81 N_{PCs}$$

The relation was not justified in but the analysis of individual harmonics performed in this paper justifies this relation too, as all individual harmonic components except 3rd harmonic are decreasing with the increasing number of PCs.

6.4 Justification of mathematical models

Odd harmonic currents can be calculated for any desired number of PCs using Equ.'s (17) to (20) given in previous section. The obtained values of odd harmonics can be used to calculate THD in current using Equ. (22). For 10 PCs, the calculated values of 3rd, 5th, 7th and 9th harmonic currents are given below:

$$I_3 = 56.09 \%$$

$$I_5 = 37.28 \%$$

$$I_7 = 13.88 \%$$

$$I_9 = 3.636 \%$$

$$\text{THD} = \sqrt{56.09^2 + 37.28^2 + 13.88^2 + 3.636^2}$$

$$\text{THD} = 68.86 \%$$

Following the same pattern for any number of PCs connected to the supply mains, percentage of odd harmonics and THDi can be calculated as follows:

No. of PC's	Parameters description	Calculated values	Experimental Values	% Error
10	I3	56.09	56.00	0.16
	I5	37.28	38.00	1.89
	I7	13.88	16.00	13.25
	I9	3.636	3.000	2.12
	THDi	68.86	70.10	1.80
13	I3	57.19	58.00	1.40
	I5	34.59	35.00	1.17
	I7	10.92	12.00	9.00
	I9	1.812	2.000	9.40
	THDi	67.75	68.60	1.23

Table 9. Comparison of calculated and experimental values

Last column of Table 9 reveals the ignorable values of error; all this confirms the authenticity of the developed mathematical models.

6.5 Conclusion of mathematical modelling of current harmonics caused by PC's

During the mathematical modelling, the individual assessment of odd harmonics in current waveform which are significant in magnitudes proved theoretically that THDi decreases with the increase of electronic/nonlinear loads using IEC Standards. Keeping in view predicted magnitudes by virtue of mathematical modelling, this innovative technique will certainly draw the attention of researchers, consumers, utilities and the manufacturers to think about the remedial measures for mitigation of this undesired phenomenon for smooth operation of power distribution network.

7. Impacts of harmonics caused by personal computers on distribution transformers

As it is mentioned in previous section, Personal Computers (PC's) being electronic load draw non-sinusoidal current. When this non-sinusoidal current passes through the impedance of the line/cable, it causes considerable distortion in voltage. This distorted voltage in a parallel connection scheme appears at the LT/HT sides of distribution transformer and causes significant effects on equipment performance which are designed to operate at sinusoidal voltage and current only. The complete distribution network of Rachna College of Engineering & Technology (RCET), Pk has been simulated using Electrical Transient Analyzer Program (ETAP) software. For this purpose an experiment has been performed in which current waveform drawn by a PC along with its spectrum has been recorded using oscilloscope at RCET Research Lab as prototype. This model of a single PC is injected into the harmonic library of ETAP for simulation of RCET distribution network. The impacts of harmonics caused by PC's on distribution transformers have been completely analyzed. Moreover, the trend of Total Harmonic Distortion (THD) with variation in different types of loads using IEEE Standards has been analyzed mathematically & graphically.

7.1 Experimental work

The current waveform and its harmonic spectrum drawn by Personal Computer has been recorded using oscilloscope. The description of equipment and test unit is as under:
Digital Storage Oscilloscope: TEXIO 60 MHz, 1000 Ms/s, with voltage range 100-240 V ac.
Pentium 4.0 Computer: CPU 2.40 GHz, ATX power supply 115-230 Vac, 2/1.5 Ampere current rating. Monitor: Philips, 100-240 V ac with 1.5/0.8 Ampere current rating.
Figure 30 shows the experimental setup, in which current drawn by a single Personal Computer (Monitor & CPU) along with its FFT has been recorded using Digital Storage Oscilloscope. Resistor is a linear element in which voltage and current waveforms are in phase with each other, so voltage waveform recorded across it is also the current waveform drawn by single PC.

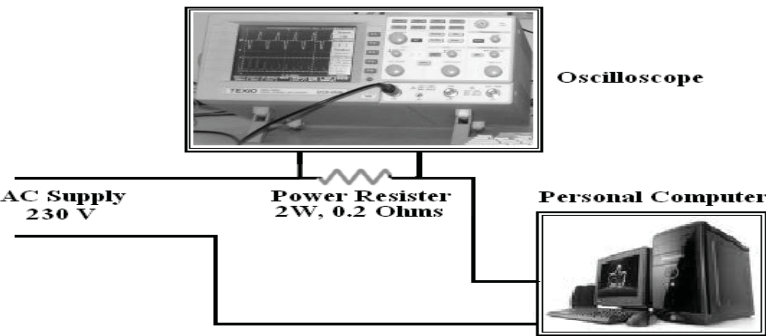


Fig. 30. Experimental setup

7.2 Software used for simulation

The software used for obtaining results is Electrical Transient Analyzer Program (ETAP), which is recognized software and currently used for power system analysis world widely. It has capacity to perform analysis including Load Flow (LF), Harmonic Load Flow (HA), Harmonic Frequency Scan, Optimal Power Flow, Short-Circuit, Motor Starting and Transient Analysis etc. In Harmonic Analysis (HA) this software has the provision to inject user defined library.
The Results obtained at RCET Research Lab of a single PC are inserted into harmonic library of ETAP for simulation.
Table 10 shows the percentage of Individual Harmonic Distortion (IHD) with reference to fundamental and Total Harmonic Distortion (THD) in current waveform drawn by single PC.

Harmonic No.	% IHD
3 rd	91.63
5 th	86.61
7 th	69.87
9 th	44.76
11 th	54.81
13 th	46.44
15 th	46.44
17 th	33.05
19 th	24.70

23 rd	11.74
25 th	7.900
29 th	5.120
% THDi	178.97

Table 10. % IHD with reference to fundamental

7.3 Single line diagram of RCET power distribution network

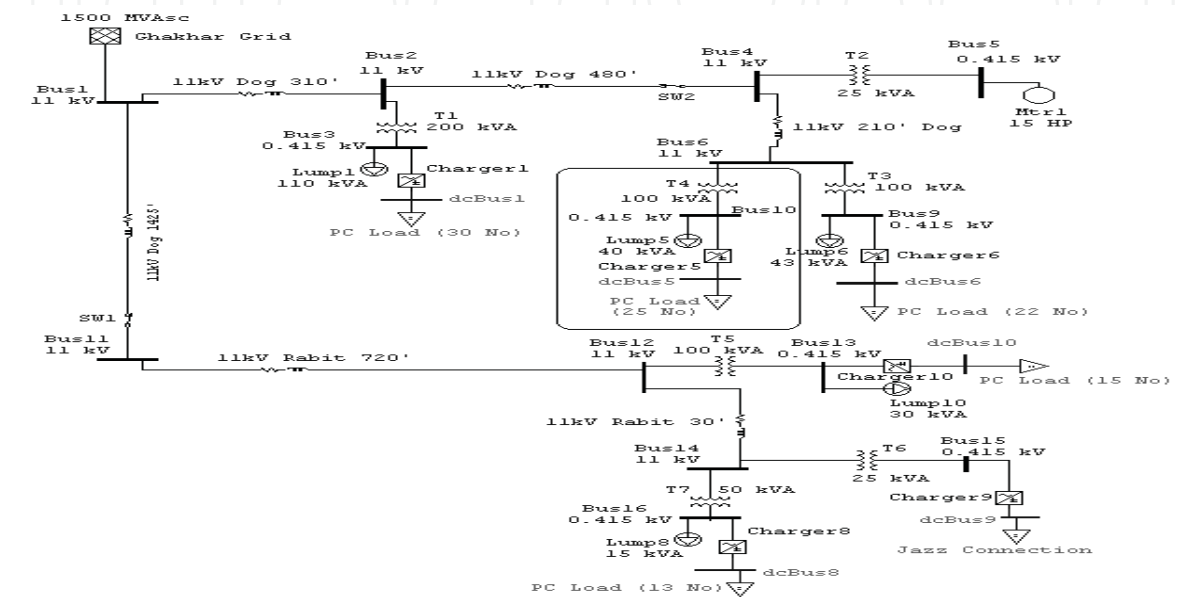


Fig. 31. Single line diagram of RCET power distribution network

Figure 31 shows the single line diagram of RCET distribution network. The 11 kV line is emanating from 20/26 MVA Power Transformer at 220 kV Grid Ghakkar, Pk. The details of distribution transformers along with their loads are shown in Table 11.

ID	Location	Ratted kVA	No. of PC's	Other Load (KW)	PC Load (KW)
T1	Old Building	200	30	93.21	22.5
T2	Independent T/F	25	-	11.18	0
T3	Hostel A,B	100	22	36.44	16.5
T4	New Building	100	25	33.89	18.75
T5	Staff Colony	100	15	25.42	11.25
T6	Mobile Tower	25	-	15.00	0
T7	Hostel E,F	50	13	12.71	9.75
TOTAL:-		600	105	212.85	78.75

Table 11. Distribution T.F's ratting and connected load

The lengths of secondary distribution line (11 kV) are clearly mentioned in single line diagram. The description for 11 kV line conductors is shown in Table 12.

Cond. Name	Resistance (Ohms/Km)	Reactance (Ohms/Km)	Max. Current (A)
Dog	0.336	0.378	307
Rabbit	0.659	0.202	202

Table 12. Conductor table

7.4 Harmonic Analysis

Current and voltage waveforms along with their harmonic spectrums at LT & HT sides of all the distribution transformers have been recorded during Harmonic Analysis. Due to lack of space available only 100 kVA New Building transformer T4 results has been discussed.

a. 100 kVA New Building Transformer T4

The waveforms recorded at LT/HT sides of distribution transformer T4 are:

i. Current waveform & its Spectrum at LT side of T4

Current waveform and its FFT recorded at LT side are given in Figures 32 & 33 respectively. The waveform is highly distorted due to the presence of 3rd, 5th, 7th, 9th, 11th etc. harmonics.

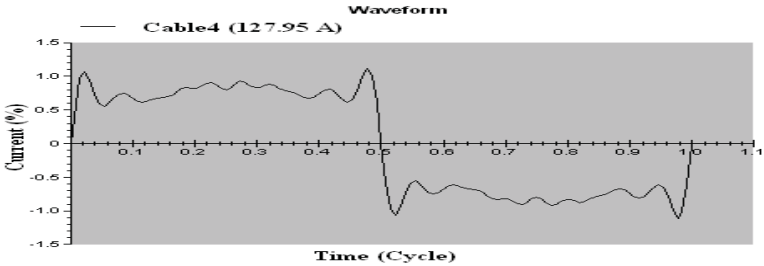


Fig. 32. Current waveform at LT side of T4

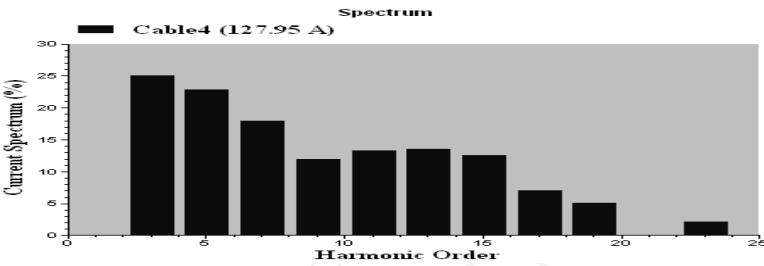


Fig. 33. FFT of current waveform of Figure 32

ii. Current waveform & its Spectrum at HT side of T4

Current waveform and its FFT recorded at HT side are given in Figures 34 & 35 respectively. This waveform is also distorted but it is noticeable that triplen harmonics (3rd, 9th, 15th etc.) have been trapped by delta winding of distribution transformer.

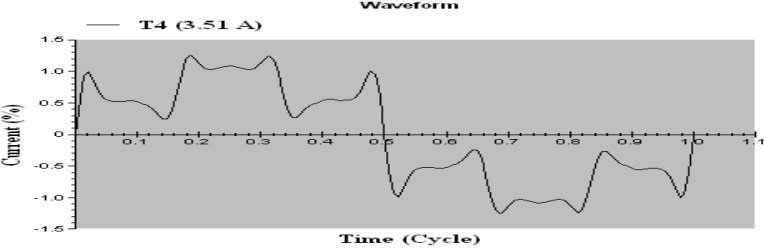


Fig. 34. Current waveform at HT of T4

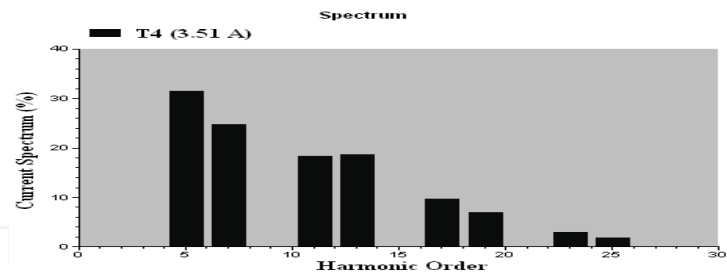


Fig. 35. FFT of current waveform of Figure 34

iii. Voltage waveform & its Spectrum at LT side of T4
Voltage waveform & its FFT at LT side of distribution transformer T4 are given in Figures 36 & 37. This distortion in voltage waveform is the result of current waveform distortion. When the distorted current passes through the series impedance of the line it causes considerable distortion in voltage waveform. The LT voltage waveform spectrum also contains the triplen harmonics which are major cause of distortion in voltage waveform.

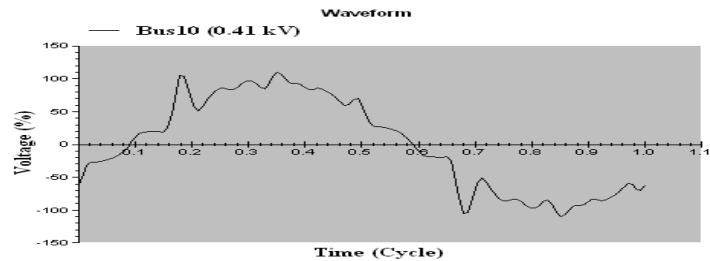


Fig. 36. Voltage waveform at LT side of T4

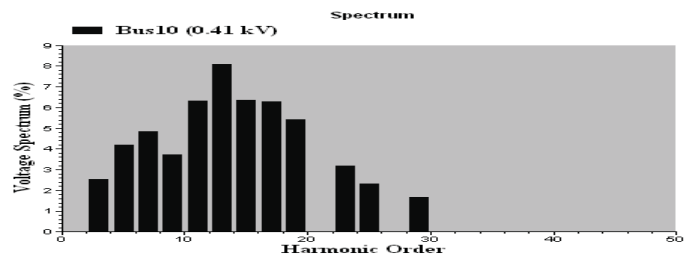


Fig. 37. FFT of voltage waveform of Figure 36

iv. Voltage waveform & its Spectrum at HT side of T4
Voltage waveform & its FFT at HT side of distribution transformer are given in Figures 38 & 39. The magnitude of harmonic contents with reference to fundamental frequency are very low and that's why the waveform is almost sinusoidal.

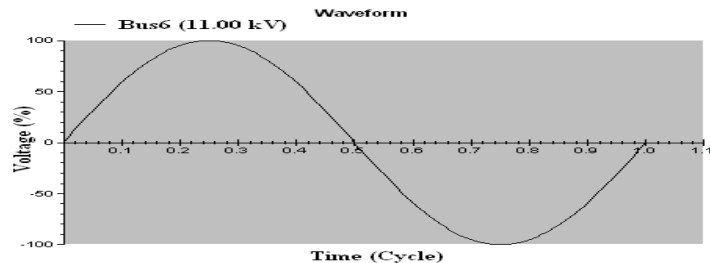


Fig. 38. Voltage waveform at HT side of T4

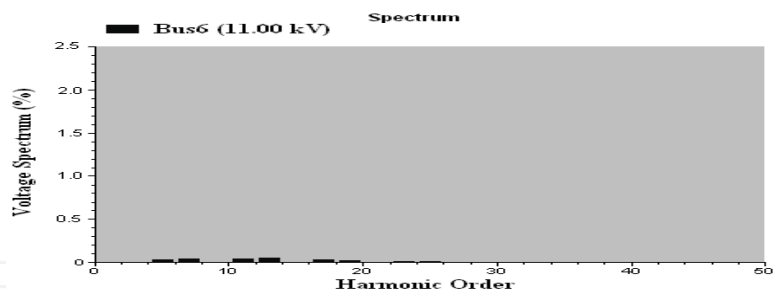


Fig. 39. FFT of voltage waveform of Figure 38

b. Summary of Over all distribution transformers THD's at LT/HT sides

It is clear from single line diagram of Figure 31 that five number transformers are general duty transformers and remaining two are independent transformers. These general duty transformers contained PC's load along with other load. The transformer T2 is running a motor load, so it has zero harmonic distortion at LT side.

The transformer T6 is also an independent transformer feeding to mobile tower having non-linear load but will not be high lighted because the focus of this research work is mainly based upon PC's.

Total Harmonic Distortion (THD) of voltage and current waveforms are summarized in Table 13 at LT and HT sides of the distribution transformers.

ID	% THDi		% THDv	
	LT	HT	LT	HT
T1	14.0	25.28	9.97	0.127
T2	0.0	0.0	0.0	0.139
T3	27.0	47.94	16.39	0.145
T4	28.0	49.41	17.26	0.149
T5	42.0	44.30	10.21	0.152
T6	30.0	27.61	34.03	0.153
T7	37.0	65.76	16.99	0.1554

Table 13. % THD at different Buses

Table 14 shows the percentage Individual Harmonic Distortion of voltage waveform (% IHDv) at LT side of those distribution transformers where its value is significant.

ID	3rd	5th	7th	9th	11th	13th	15th	17th	19th	23rd
T1	0.8	2.0	2.6	1.1	4.0	5.3	1.9	4.2	3.6	2.0
T3	2.4	4.0	4.6	3.5	6.0	7.7	6.1	5.9	5.2	3.1
T4	2.8	4.2	4.8	3.8	6.3	8.1	6.2	6.2	5.4	3.2
T5	1.5	2.4	2.9	2.1	3.7	4.8	3.6	3.8	3.4	2.1
T7	1.8	3.4	4.2	2.6	6.25	8.6	4.4	7.2	6.4	4.2

Table 14. % IHDv with ref. to fundamental at HT side of T/F's

IEEE Std. 519-1992, deals with standards and limitations of harmonics level in electrical power system in presence of non-linear loads. For voltage level up to 69 kV, the level of distortion for % THDv is 5.0% and for % IHDv is 3.0%. Table 13 and 14 give the % THD and % IHD at LT/HT sides of distribution transformers. It is clear from the Tables that voltage limit set by IEEE is violated which is a proof of poor power quality.

7.5 THD trend with variation in different types of loads

ETAP has the provision to vary the load according to requirement and then to record the harmonic distortion in voltage and current waveforms:

a. Increasing the No. of PC’s

For case study, the transformer T4 (New Building, 100 kVA) computer load has varied from 1 PC up to the 50th PC to record the values of current and voltage waveform distortion by disconnecting other linear load.

Table 15 shows that by increasing the number of PC’s, Total Harmonic Distortion in Current (THDi) remains same for 1 PC to 50th PC at LT side, by disconnecting other linear loads.

No. of PC’s	% THDi
1	159.0
5	159.0
10	159.0
15	159.0
20	159.0
30	159.0
40	159.0
50	159.0

Table 15. THD trend at LT of T4 by increasing the no. of PC’s

According to IEEE Standards, Total Harmonic Distortion is defined as “The ratio of the root-mean-square of the harmonic content to the root-mean-square value of the fundamental quantity, expressed as a percentage of the fundamental”.

Mathematically,

$$THD = \frac{\sqrt{\sum_{h>1}^{h_{max}} M_h^2}}{M_1} \tag{23}$$

If ‘n’ is the number of PC’s then the distortion for ‘n’ number of PC’s can be derived as:

$$THD = \frac{\sqrt{\sum_{h>1}^{h_{max}} n^2 M_h^2}}{nM_1} \tag{24}$$

Simplifying the above equation and final result is given in equation 25:

$$THD = \frac{\sqrt{\sum_{h>1}^{h_{max}} M_h^2}}{M_1} \tag{25}$$

The Equ. (25) proves that by increasing the number of PC’s the Total Harmonic Distortion will remain the same. It is worth mentioning here that this relation holds when the same electronic load is increased by disconnecting the other linear loads. If different types of non-

linear loads are increased their THD trend may be increasing or decreasing depending upon fundamental and individual harmonic contents magnitudes.

b. Increasing the Linear Load by fixing PC load

THD trend can also be confirmed by fixing number of PC’s and varying the linear loads (i.e. resistive & inductive). For this purpose Transformer T4 of 100 kVA has been selected. There are 25 No. of PC’s connected with this transformer and linear load comprises of 20% resistive and 80% inductive.

Table 16 indicates that by increasing the linear load by keeping PC’s load constant, THD in current and voltage will decrease accordingly at LT side of the transformer.

Linear Load (kVA)	% THDi	% THDv
1	95.0	18.08
5	82.0	17.73
10	69.0	17.31
15	60.0	16.9
20	53.0	16.52
25	47.0	16.16
30	42.0	15.82
35	38.0	15.49
40	35.0	15.18

Table 16. THD trend at LT of T4 by increasing Linear Load

The reason for this decreasing trend is given mathematically in Equ. 26. Where ‘n’ represents number of PC’s which are fixed in this case. ‘I_c’ is current drawn by PC’s where ‘I_L’ is current due to linear loads. Here, ‘m’ is the integer which shows the increase in linear load.

$$THD = \frac{\sqrt{\sum_{h>1}^{h_{max}} n^2 I_{ch}^2}}{nI_{c1} + mL_L}$$

(26)

Solving Equ. (26), the results are shown in Equ.’s (27) and (28) respectively, which verify that by increasing ‘m’ (Linear load) the THDi decreases because of the inverse relation between THD and fundamental current.

$$THD = n \frac{\sqrt{\sum_{h>1}^{h_{max}} I_{ch}^2}}{nI_{c1} + mL_L}$$

(27)

$$THD = \frac{\sqrt{\sum_{h>1}^{h_{max}} I_{ch}^2}}{I_{c1} + m/nL_L}$$

(28)

Graphical representation of decreasing trend of THDv and THDi are shown in Figure 40 and 41 respectively.

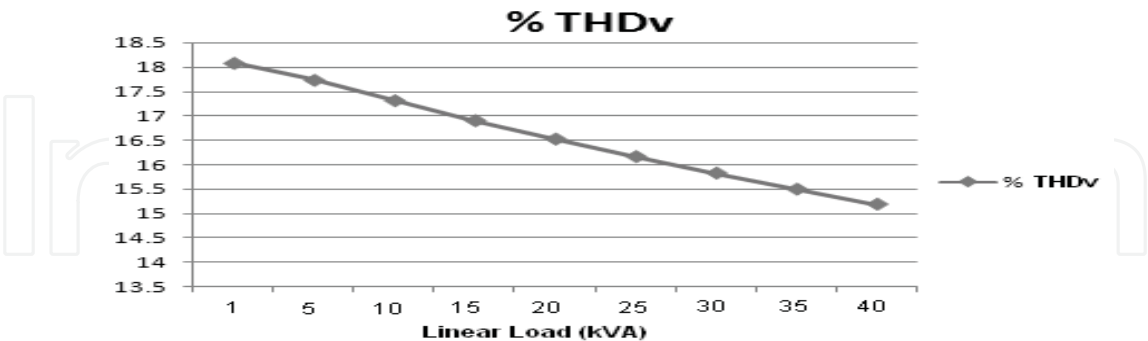


Fig. 40. Decreasing trend of THDv with increase in linear load

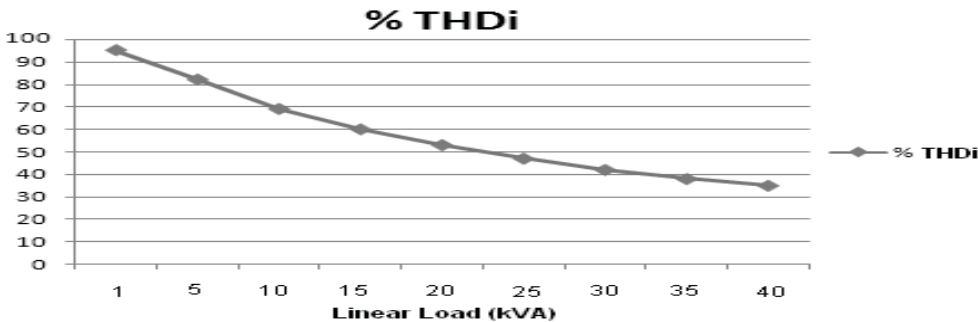


Fig. 41. Decreasing trend of THDi with increase in linear load

c. Mixing of another Non-Linear Load
For comprehensive modelling of THDi at the LT side of 100 kVA T4 transformer, another non-linear load has taken from ETAP harmonic library for further simulation. The manufacturer of this load is Toshiba and its model is PWM ASD. The Spectrum for this non-linear load is given in Figure 42.

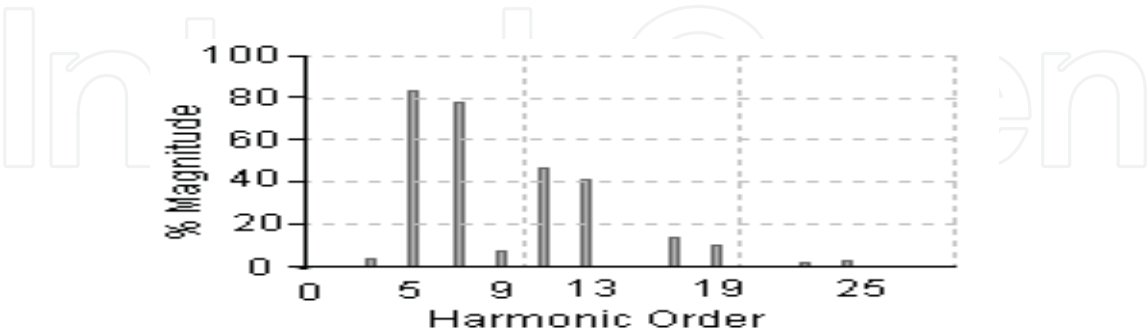


Fig. 42. Harmonic Spectrum for PWM ASD

This load is connected with PC and other linear load. The PC and linear load is kept same while this PWM ASD load has varied and results are given in Table 17:

PWM Load (KW)	% THDi
1	34.0
5	31.0
10	30.0
15	30.0
20	30.0
25	31.0
30	33.0
35	34.0
40	36.0

Table 17. THD at LT of T4 by increasing PWM

This trend can be represented graphically as shown in Figure 43.

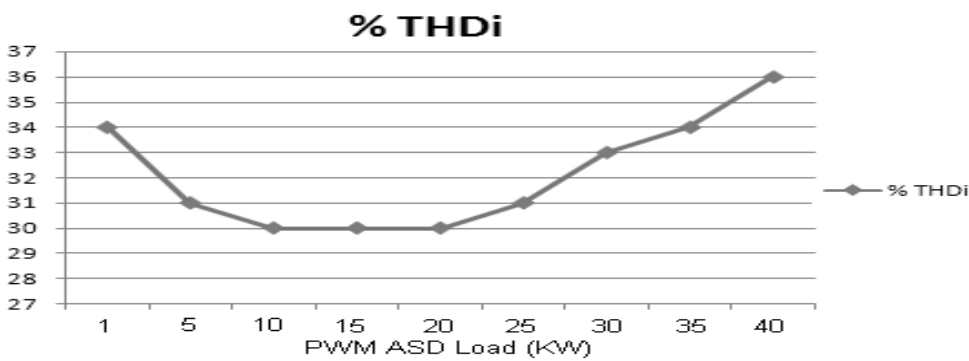


Fig. 43. THDi trend during mixing of another non-linear load

7.6 Conclusion of harmonic impacts caused by PC’s on distribution transformers

Simulation conducted in ETAP based upon the experimental work injected in its library from proto type developed at RCET Lab is really interesting and innovative. All stake holders of Power Industry, Consumers and Manufacturers can have in advance knowledge using the mathematical relations derived during this research for predictive measures. Moreover, scientific community will really be beneficiary from the mathematical models developed by varying nature of connected load, keeping in view the on ground reality.

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