

# 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 THD<sub>v</sub> 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.

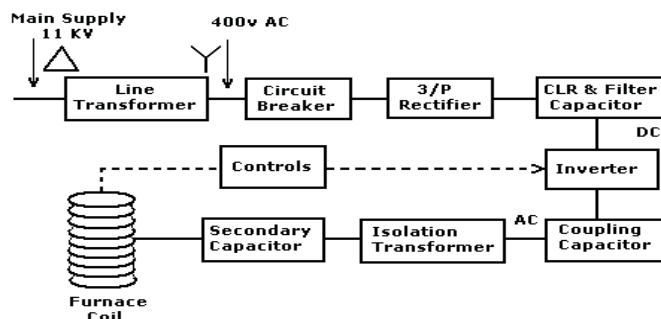


Fig. 1. Block diagram of Induction Furnace

##### 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 50<sup>th</sup> 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

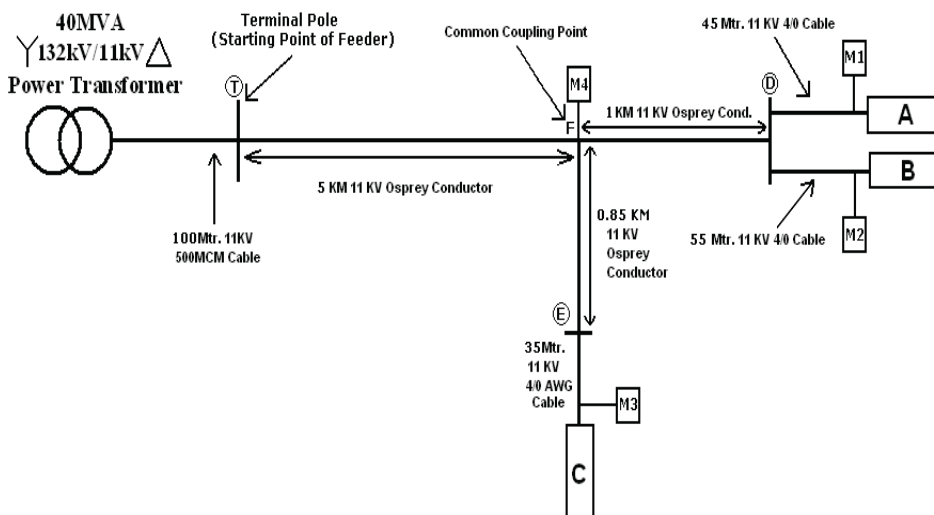


Fig. 2. Single Line diagram of 11 kV furnace feeder

### 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 5<sup>th</sup>, 7<sup>th</sup>, 11<sup>th</sup> and 13<sup>th</sup> harmonics. However the higher order harmonics are considerably small as compared to above mentioned harmonics.

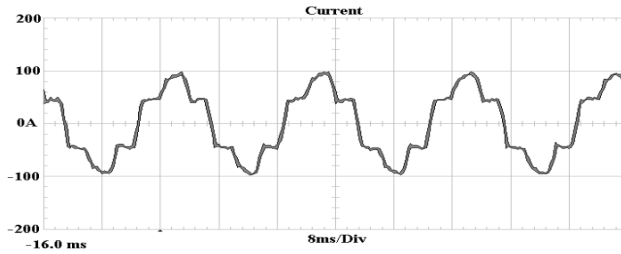


Fig. 3. Current waveform at red phase of furnace A

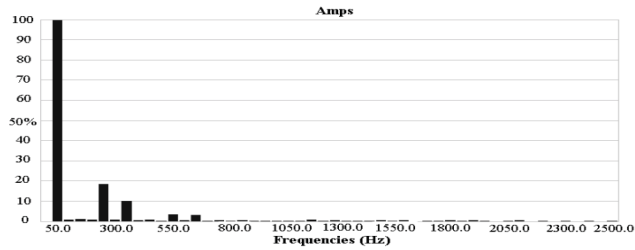


Fig. 4. Current spectrum at red phase of furnace-A

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.

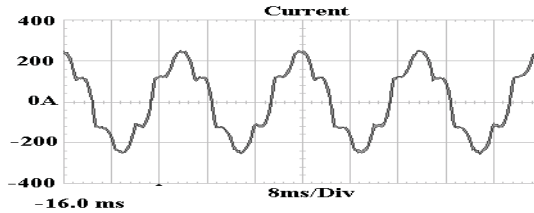


Fig. 5. Current waveform at red phase of furnace-B

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

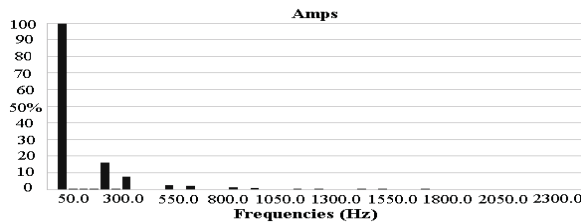


Fig. 6. Current spectrum at red phase of furnace-B

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.

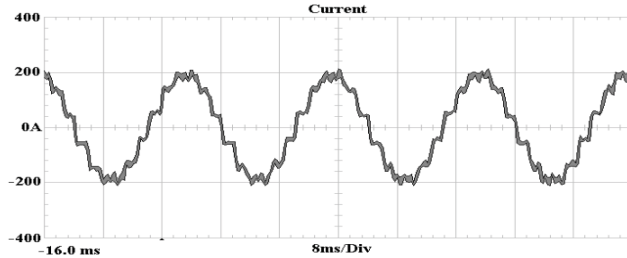


Fig. 7. Current waveform at red phase of furnace-C

The FFT Spectrum of the distorted waveform of Figure 7 is given in Figure 8, which clearly indicates the significant presence of 7<sup>th</sup>, 11<sup>th</sup>, 13<sup>th</sup>, 17<sup>th</sup>, 21<sup>th</sup>, 23<sup>rd</sup> etc harmonics. However harmonics having order higher than 23<sup>rd</sup> 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.

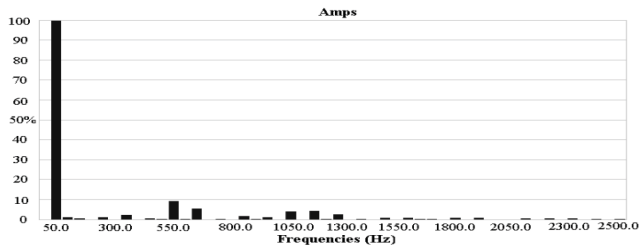


Fig. 8. Current spectrum at red phase of furnace-C

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.

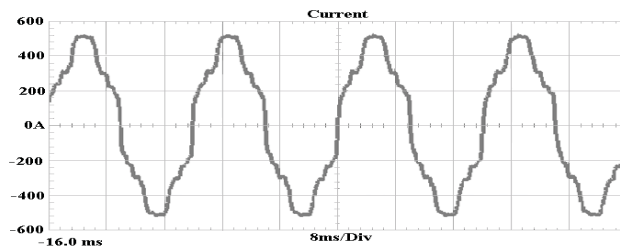


Fig. 9. Current Waveform at coupling point F

The FFT Spectrum of the distorted waveform of Figure 9 is given in Figure 10 which clearly indicates the significant presence of 5<sup>th</sup>, 7<sup>th</sup>, 11<sup>th</sup> and 13<sup>th</sup> 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 (3<sup>th</sup>, 9<sup>th</sup>, 15<sup>th</sup> 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.

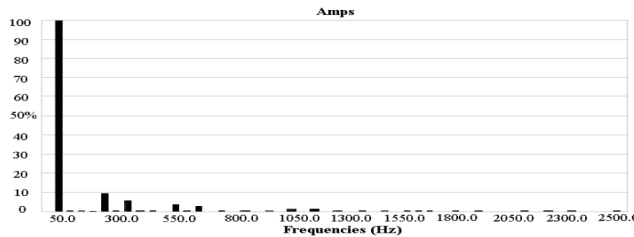


Fig. 10. Current spectrum at coupling point F

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.

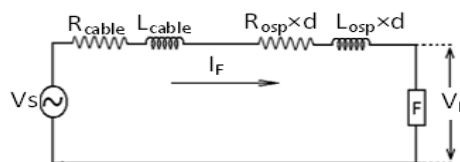


Fig. 11. Impedance diagram corresponding to single line diagram

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.

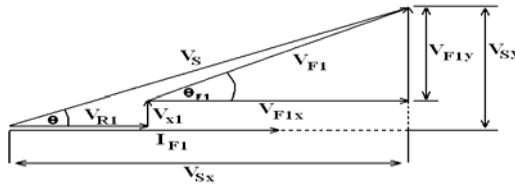


Fig. 12. Phasor diagram for fundamental frequency current

Here;

$$V_{F1X} = V_s \cos(\theta) - V_{R1}$$

$$V_{F1Y} = V_s \sin(\theta) - V_{X1}, \text{ where, } \cos(\theta) \text{ is the displacement power factor at grid} = 0.95, \text{ and}$$

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

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

$$V_{F1X} = V_s \cos(\theta) - I_{F1} (2R_{osp}d + 2R_{cable})$$

$$V_{F1Y} = V_s \sin(\theta) - I_{F1} (4\pi fL_{osp}d + 4\pi fL_{cable})$$

Using Pythagoras theorem:

$$|V_{F1}| = \sqrt{V_{F1X}^2 + V_{F1Y}^2} \tag{1}$$

$$\theta_{F1} = \tan^{-1} (V_{F1Y}/V_{F1X})$$

By putting the values of  $V_{F1X}$  and  $V_{F1Y}$ :

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

Where:

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

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

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

For any  $n^{\text{th}}$  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.

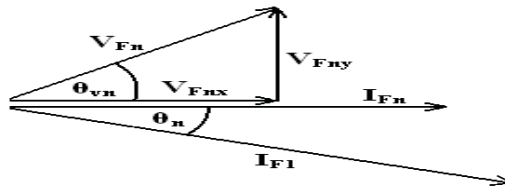


Fig. 13. Phasor diagram for harmonic currents

Here;

$\theta_n$  = Phase angle of nth 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:

$$|V_{Fn}| = \sqrt{V_{FnX}^2 + V_{FnY}^2} \tag{3}$$

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

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

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

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

Taking square root on both sides:

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

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:

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

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

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

### 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:



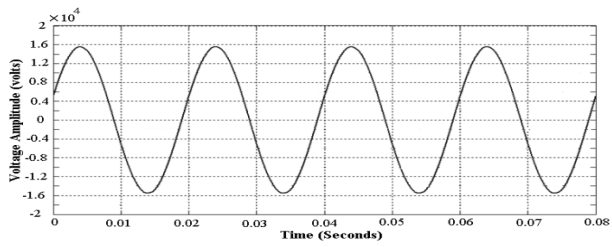


Fig. 14. Voltage wave form at terminal pole T

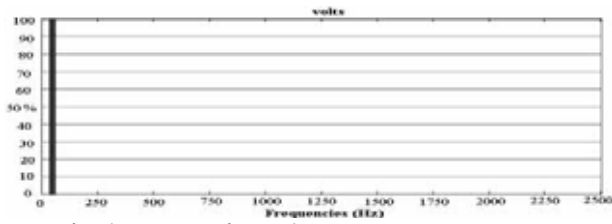


Fig. 15. FFT Spectrum of voltage waveform shown in Figure 14

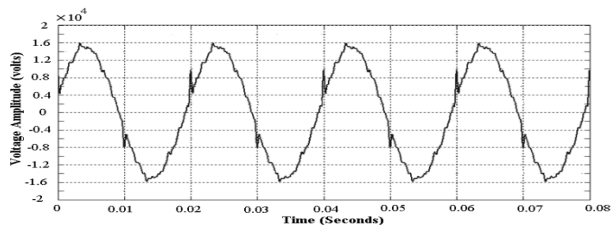


Fig. 16. Voltage waveform at 2.5 KM from Terminal pole T

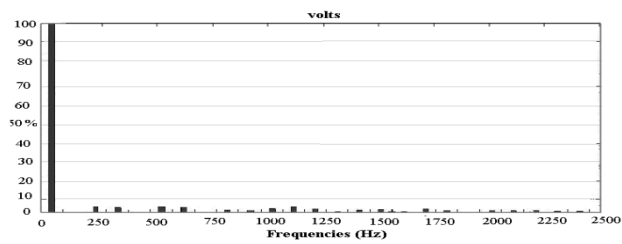


Fig. 17. FFT Spectrum of voltage waveform shown in Figure 16

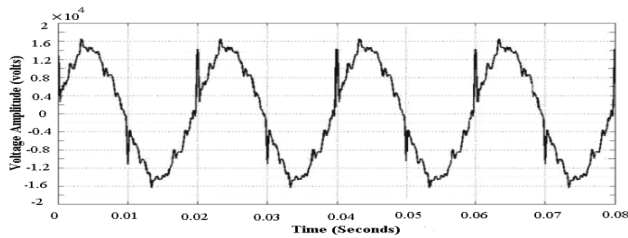


Fig. 18. Distorted Voltage waveform at common coupling point F

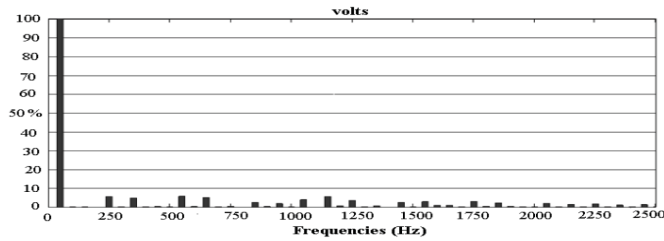


Fig. 19. FFT corresponding to waveform shown in Figure 18

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<sub>v</sub> in terms of distance  
 The expression for computation for THD<sub>v</sub> of V<sub>F</sub> is:

$$THD_v = \sqrt{\sum_{n=2}^{50} V_{Fn}^2} / V_{F1}$$

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

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

Equ. (7) expresses THD<sub>v</sub> as a function of distance d in kilo-meters from terminal pole (T) to common coupling point (F).

The values of % THD<sub>v</sub> computed have been tabulated in Table 2.

Distance d (km's)	(%) THD <sub>v</sub>
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<sub>v</sub> with distance

In order to illustrate the trend of increase in THD<sub>v</sub> 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<sub>v</sub> with distance is approximately linear.

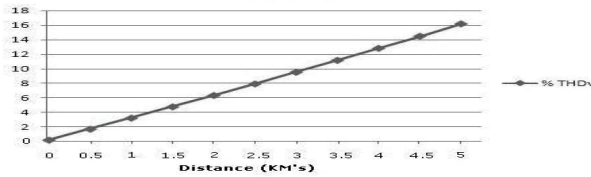


Fig. 20. Graph showing trend of (%) THDv with increasing distance d

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.

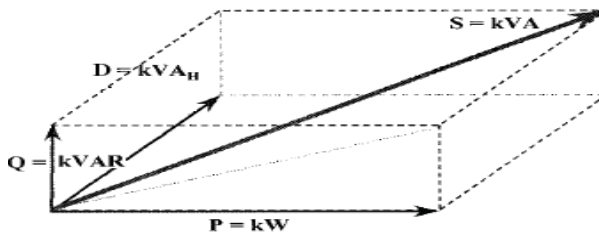


Fig. 21. Change in power triangle in case of non-linear load

Now Apparent power S can be calculated as:

$$S = V_{Frms} \times I_{Frms} \tag{8}$$

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:

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

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

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

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

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 <sup>5</sup>
0.5	16.44×10 <sup>5</sup>
1.0	16.23×10 <sup>5</sup>
1.5	16.24×10 <sup>5</sup>
2.0	16.46×10 <sup>5</sup>
2.5	16.88×10 <sup>5</sup>
3.0	17.50×10 <sup>5</sup>
3.5	18.28×10 <sup>5</sup>
4.0	19.22×10 <sup>5</sup>
4.5	20.29×10 <sup>5</sup>
5.0	21.46×10 <sup>5</sup>

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:

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

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

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 <sup>3</sup>
1.5	2564.54	5.45×10 <sup>4</sup>
2.0	3.36×10 <sup>3</sup>	7.48×10 <sup>4</sup>
2.5	4.16×10 <sup>3</sup>	8.92×10 <sup>4</sup>
3.0	4.95×10 <sup>3</sup>	11.85×10 <sup>4</sup>
3.5	5.75×10 <sup>3</sup>	12.38×10 <sup>4</sup>
4.0	6.54×10 <sup>3</sup>	14.11×10 <sup>4</sup>
4.5	7.33×10 <sup>3</sup>	15.85×10 <sup>4</sup>
5.0	8.13×10 <sup>3</sup>	17.58×10 <sup>4</sup>

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:

$$\begin{aligned} \% \text{ Increased Losses} &= I_{true,rms}^2R - I_{fund,rms}^2R / I_{fund,rms}^2R \times 100 \\ I_{true,rms}^2 &= I_{fund,rms}^2(1 + THDi) \\ \% \text{ Increased Losses} &= THDi^2 \times 100 \end{aligned} \tag{14}$$

$$THDi = 0.145$$

$$\% \text{ increased Losses} = 2.1025 \%$$

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:

$$DPF = P_1 / S_1 \tag{15}$$

$$TPF = P / S \tag{16}$$

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.

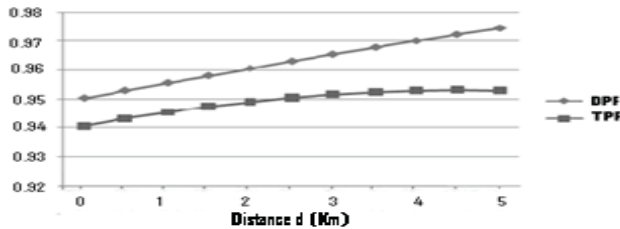


Fig. 22. Graph of DPF and TPF

### 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 3<sup>rd</sup>, 5<sup>th</sup>, 7<sup>th</sup> and 9<sup>th</sup> 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 ± 230 Volts  
 Monitor 15 inch (100- 240V, 50/60Hz, 0.8- 1.5A)

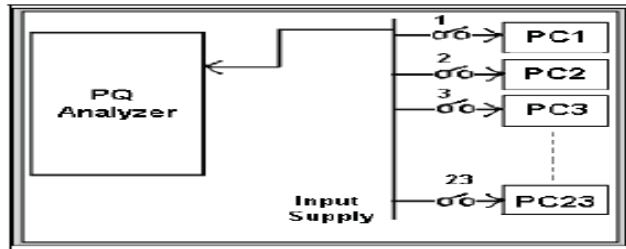


Fig. 23. Hardware arrangement

## 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. 3<sup>rd</sup> 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:

$$I_3 = -0.0248N_{PC}^2 + 49.228 \quad (17)$$



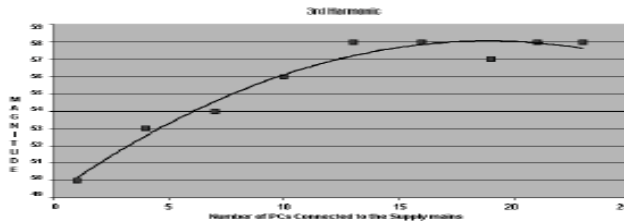


Fig. 24. Graphical representation of 3<sup>rd</sup> harmonic only

b. 5<sup>th</sup> Harmonic Only

From graph shown in Figure 25, the magnitude of 5<sup>th</sup> 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.

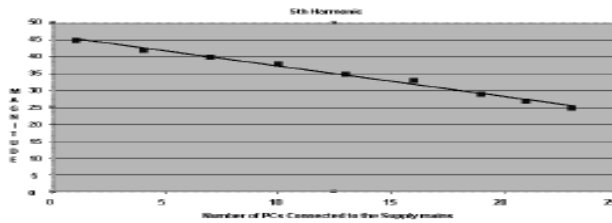


Fig. 25. Graphical representation of 5<sup>th</sup> harmonic only

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. 7<sup>th</sup> Harmonic Only

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

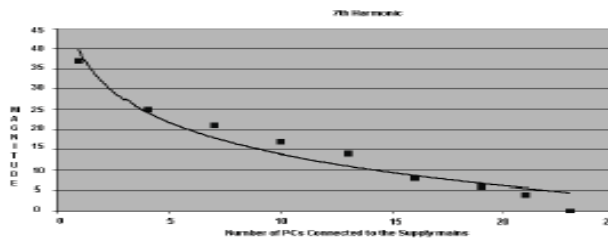


Fig. 26. Graphical representation of 7<sup>th</sup> harmonic only

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