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# Harmonic Study in Low Voltage Distribution Network in a Real Time Foundry Industry

**D. Ravichandran* and Er. R. Panneerselvam****

***Abstract:*** The increasing awareness about capacitor failures and concern on mitigating devices are leading to do harmonic study in every industry. As the mitigating devices are sensitive to the changes of network impedances and harmonics generations, it has become mandatory to study on harmonics impedances in the network. The current harmonics obtained from a real time measurement is considered as the model of the harmonic source. The harmonics load flow and harmonics frequency scan in critical buses are computed using simple circuit solutions. The results obtained from ETAP software tools are validated with numerical solution obtained from spread sheet. The limitation of the software is overcome in the numerical approach and accurate results are obtained. Any user in an industry can easily understand the methodology and assess their harmonics level and the point of harmonic resonance before and after the installation of filters/devices/other equipments.

***Keywords:*** Power Quality, Frequency scan, Harmonics frequency analysis, Harmonic load flow, harmonics resonance, Individual Harmonics Distortion, Total harmonics Distortion, Point of Common Coupling.

## 1. INTRODUCTION

### Overview of the Industry

A foundry industry having facility to producing 5,000 tons of casting per annum for making valves. The process requires a system having 11 kV utility distribution that provides power to one 1.2 MVA and two nos. of 500 kVA transformer, which in turn power dominantly the induction furnace and auxiliary equipments required for the processing of end product. The operation of the industry is assessed for harmonics distortion of current/voltage and harmonics impedances [1].

### Power System

One 1.2 MVA 11 kV/575 V Furnace Transformer is to feed power to an induction furnace. And two nos. of 500 kVA, 11 kV/400 V Auxiliary Transformers connected parallel to give supply to a passive load of 0.3 MVA. and 150 kVAR capacitors connected to maintain 0.95 power factor. Induction furnace load is considered as critical harmonics load in the study.[2]

### Description of Work

1. Taking field measurements for harmonics and load flow in the L.T. network of the Industry [3][4][5].
2. Developing harmonic model using harmonics impedances for the L.T. network and obtaining the result of harmonic current flow in the branches and harmonic voltage at critical buses by performing computations in spread sheet. [6]
3. Using the measured harmonic data, obtaining results from ETAP 12.6 software by performing harmonic load flow and harmonic frequency scan. [7]
4. Comparing the results of both and defining the scope of the work.

* Assistant Professor, SRM University, Kattankulathur, Tamil Nadu, India. *Email: ravichandran.d@ktr.srmuniv.ac.in*

** Former Superintending Engineer/TANGEDCO, General Manager/Projects, Indus High power Consultancy, Chennai, India. *Email: panneer.rps@gmail.com*

A Harmonics Analyser Fluke 435-II satisfying standard IEC 61000-4-5 is used for taking field measurements at the feeder to induction furnace. The measurement taken at the furnace bus is detailed below.

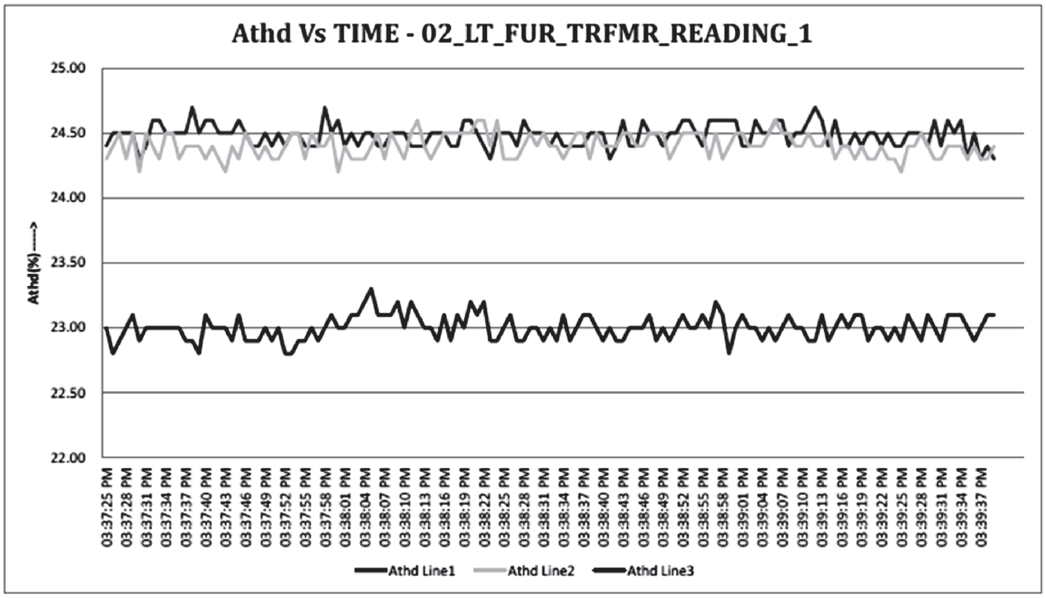



**Figure 1: Current THD trend at Furnace Bus**

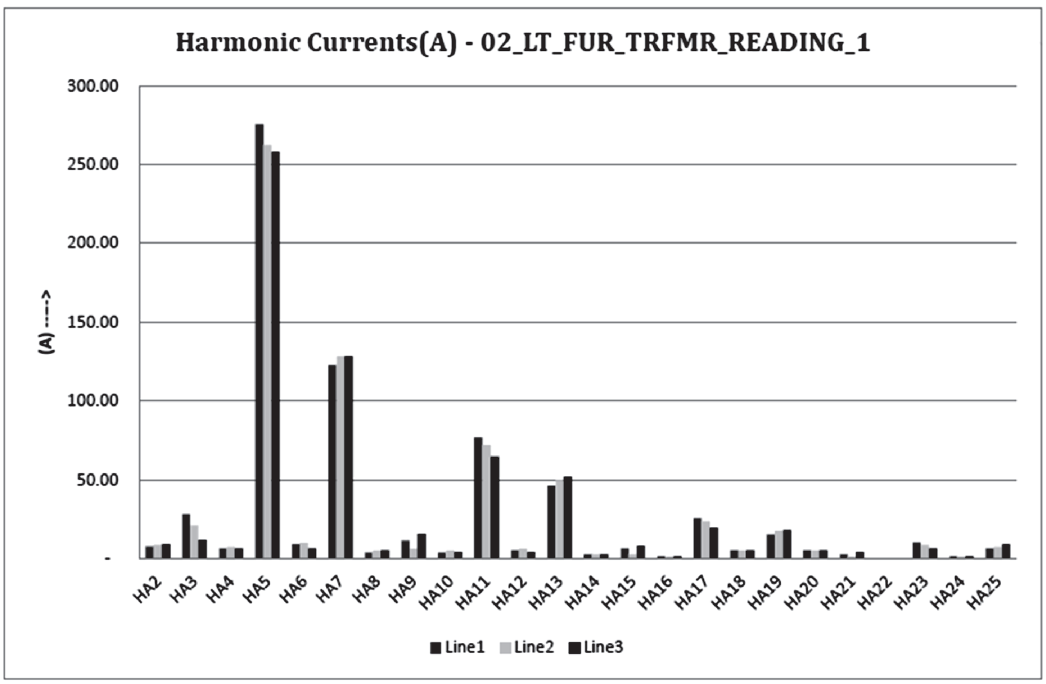



**Figure 2: Current spectrum at Furnace Bus**

The current spectrum in Figure 2 is taken for harmonics source model and same is input for harmonics study. The THD for current 24.5 % as shown in Figure 1 is verified with both ETAP 12.6 result and numerical solution. The harmonic data upto $19^{th}$ order is taken.

A real time low voltage network in a running foundry industry is taken for the harmonics study. The induction furnace is taken as harmonics source in the network. The two bus voltages 11 kV and 433 V are to be considered for harmonic calculation. The measured harmonics data is input in the induction furnace load. The system data is obtained from the supply authorities for the study. The Figure 1 showing the network as obtained from the industry. [6]

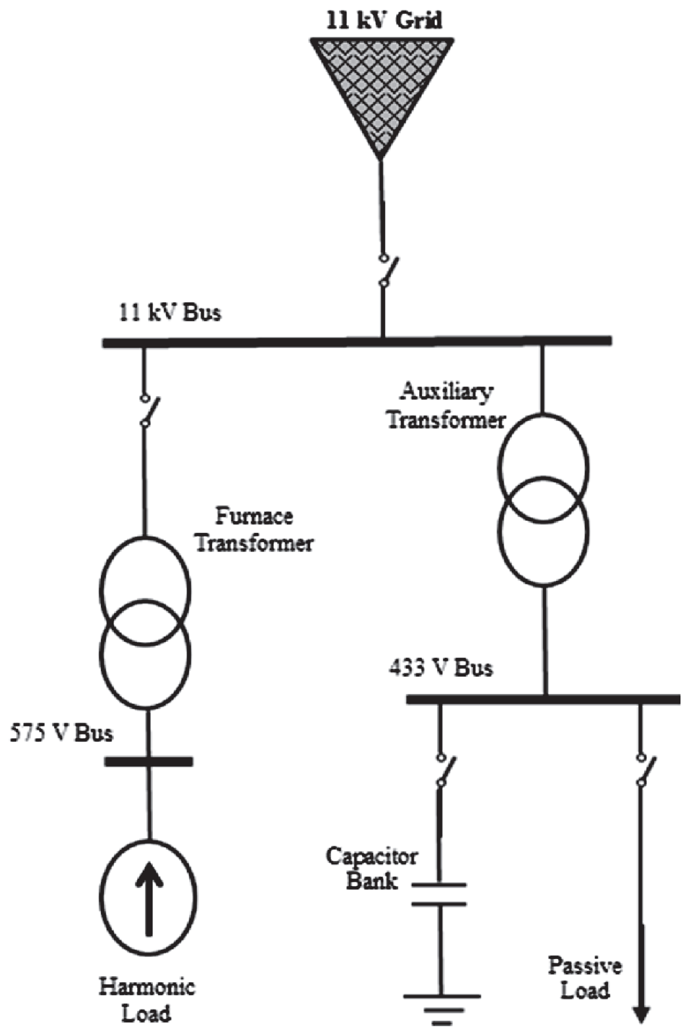


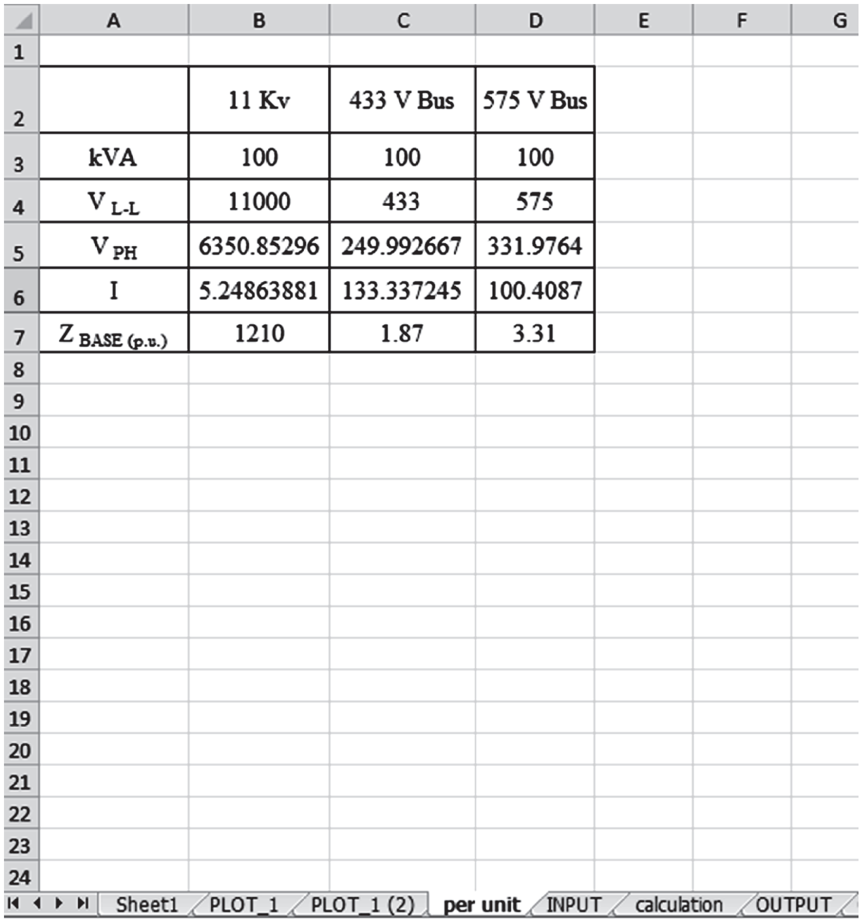

**Figure 3: Schematic Diagram of network**

The system data calculated for the base of 100 kVA is as shown in Table 1 & 2.

**Table 1**
**System data**

| | |
|---|---|
| *11 kV system* | |
| Base Voltage (kV) | 11 |
| Base Current, A | 5.25 |
| Base Impedance, Ohms | 1209.69 |
| *433 V system* | |
| Base Voltage (kV) | 0.433 |
| Base Current, A | 133.34 |
| Base Impedance, Ohms | 1.87 |
| *575 V system* | |
| Base Voltage (kV) | 0.575 |
| Base Current, A | 100.4087 |
| Base Impedance, Ohms | 3.31 |

The corresponding per unit values calculated and tabulated in Table 2.



| | 11 Kv | 433 V Bus | 575 V Bus |
|---|---|---|---|
| kVA | 100 | 100 | 100 |
| V L-L | 11000 | 433 | 575 |
| V PH | 6350.85296 | 249.992667 | 331.9764 |
| I | 5.24863881 | 133.337245 | 100.4087 |
| Z BASE (p.u.) | 1210 | 1.87 | 3.31 |



**Figure 4: Base values in spread sheet**

**Table 2**
**Base values**

| | *11 kV* | *433 V Bus* | *575 V Bus* |
|---|---|---|---|
| kVA | 100 | 100 | 100 |
| $V_{L-L}$ | 11000 | 433 | 575 |
| $V_{PH}$ | 6350.85 | 249.99 | 331.98 |
| I | 5.25 | 133.34 | 100.409 |
| $Z_{BASE\ (p.u.)}$ | 1209.69 | 1.87 | 3.31 |

The measured harmonic data is used in the induction furnace is detailed below in Table 3 with its corresponding wavefrom and spectrum as in Figure 3 & 4.

**Table 3**
**Harmonics current data**

| *h* | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* |
|---|---|---|---|---|---|---|---|---|
| $I_h$ *(%)* | 100 | 2.9 | 3.2 | 0.7 | 22.5 | 0.8 | 11.3 | 0.3 |
| *h* | *9* | *10* | *11* | *12* | *13* | *14* | *17* | *19* |
| $I_h$ *(%)* | 1.3 | 0.3 | 6.3 | 0.3 | 4.2 | 0.2 | 2.1 | 1.7 |

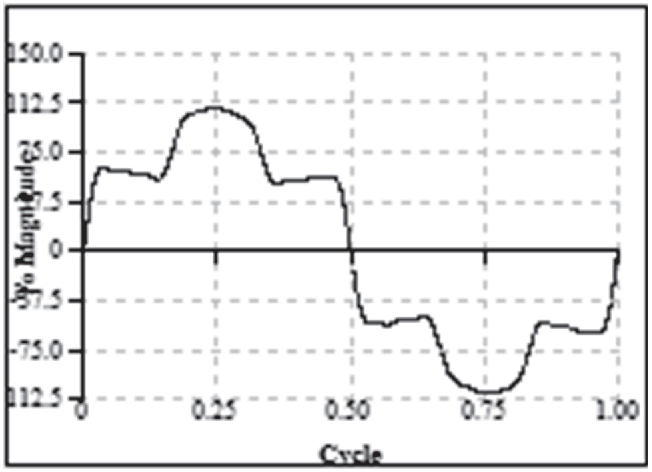



**Figure 5: Current Waveform**

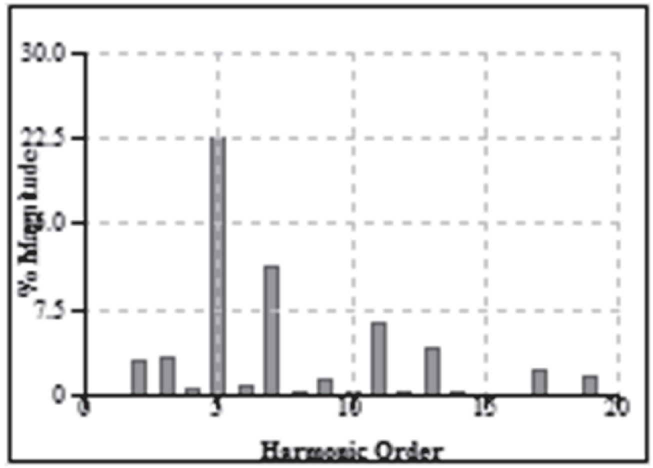



**Figure 6: Current Harmonics Spectrum**

The system impedances converted to system base values are computed and detailed in Table 4.

| | A | B | C | D | E | F | G | H | I | J | K | L | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | Base KVA | 100 | | | | | | |
| 2 | SYSTEM DATA | | | | | | | | | | | | |
| 3 | | 11 kV system | | | | 433 V system | | | | 575 V system | | | |
| 4 | | Base Voltage (kV) | | 11 | | Base Voltage (kV) | | 0.433 | | Base Voltage (kV) | | 0.575 | |
| 5 | | Base Current, A | | 5.2486 | | Base Current, A | | 133.337245 | | Base Current, A | | 100.4 | |
| 6 | | Base Impedance, Ohms | | 1210 | | Base Impedance, Ohms | | 1.87 | | Base Impedance, Ohms | | 3.31 | |
| 7 | | | | | | | | | | | | | |
| 8 | 11 kV Grid | | | | | | | | | | | | |
| 9 | | MVA | 150 | | Z (pos) | X/R | SCMVA | | | | | | |
| 10 | | kV | 11 | | 0.807 | 8 | 150 | | | | | | |
| 11 | | | | | | | | | | | | | |
| 12 | Passive Load Harmonic Loads | | | MVA | kV | pf | Mag | Ang | Real | Imag | | | |
| 13 | | Passive Load | | 0.3 | 0.433 | 0.72 | 3 | 0.76699401 | 2.16 | 2.0819 | | | |
| 14 | | Harmonics Load | | 1.2 | 11 | 0.95 | 12 | 0.31756043 | 11.4 | 3.747 | | | |
| 15 | | | | | | | | | | | | | |
| 16 | DATA CONVERTED INTO SYSTEM BASE | | | | SCMVA | \|Z\|, p.u. | R, p.u. | X, p.u. | | | | | |
| 17 | | 11 kV Grid | | (pos) | | 0.000666667 | 0.00008 | 0.00064 | | | | | |
| 18 | | | | | | | | | | | | | |
| 19 | | Auxiliary Transformer | | | MVA | R, % | X, % | Z, p.u. | R, p.u. | X, p.u. | | | |
| 20 | | | | (pos) | 0.5 | 1.061 | 5.091 | 002122+0.0101 | 0.002 | 0.0102 | | | |
| 21 | | | | | | | | | | | | | |
| 22 | | Capacitor | | | Q, MVAr | V, kV | Q, p.u. | Xc, Ohms | Xc, p.u. | | | | |
| 23 | | | | | 0.15 | 0.433 | 0.0015 | 1.24992667 | 0.668 | | | | |
| 24 | | | | | | | | | | | | | |
| 25 | | Passive Load | | | S, p.u. | Z, p.u. | R, p.u. | X, p.u. | | | | | |
| 26 | | | | (pos) | 3 | 0.24+0.2313246 | 0.24 | 0.2313 | | | | | |
| 27 | | | | | | | | | | | | | |
| 28 | | Furnace Transformer | | | MVA | R, % | X, % | Z, p.u. | R, p.u. | X, p.u. | | | |
| 29 | | | | (pos) | 1.25 | 0.819 | 4.425 | 006552+0.00 | 7E-04 | 0.0035 | | | |
| 30 | | | | | | | | | | | | | |
| 31 | | Furnace Load | | | S, p.u. | Z, p.u. | R, p.u. | X, p.u. | | | | | |
| 32 | | | | (pos) | 1.2 | 66667+0.02602 | 0.0791 | 0.026 | | | | | |
| 33 | | | | | | | | | | | | | |
| 34 | | | | | | | | | | | | | |
| 35 | | | | | | | | | | | | | |
| 36 | | | | | | | | | | | | | |
| 37 | | | | | | | | | | | | | |
| 38 | | | | | | | | | | | | | |
| 39 | | | | | | | | | | | | | |

Sheet1 / PLOT_1 / PLOT_1 (2) / per unit / INPUT / calculation / OUTPUT / OUTPUT (2) / Sheet2

**Figure 7: Impedances in p.u. in spread sheet**

**Table 4**
**System impedance input**

| | | | | |
|---|---|---|---|---|
| *11 kV Grid* | *SCMVA* | *\|Z\|, p.u.* | *R, p.u.* | *X, p.u.* |
| | 150 | 0.000666 | 0 | 0.00066 |
| *Auxiliary Transformer* | *MVA* | *Z, p.u.* | *R, p.u.* | *X, p.u.* |
| | 0.5 | 0.0021 + 0.010i | 0.002122 | 0.01018 |
| *Capacitor* | *Q, MVAr* | *Q, p.u.* | *Xc, Ohms* | *Xc, p.u.* |
| | 0.15 | 0.0015 | 1.2499 | 0.668 |
| *Passive Load* | *S, p.u.* | *Z, p.u.* | *R, p.u.* | *X, p.u.* |
| | 3 | 0.24 + 0.2313i | 0.24 | 0.2313 |
| *Furnace Transformer* | *MVA* | *Z, p.u.* | *R, p.u.* | *X, p.u.* |
| | 1.25 | 0.00065 + 0.0035i | 0.000655 | 0.00354 |
| *Furnace Load* | *S, p.u.* | *Z, p.u.* | *R, p.u.* | *X, p.u.* |
| | 1.2 | 0.079 + 0.026i | 0.0791 | 0.026 |

The impedance seen at buses are computed upstream from 433 V Bus to 11 kV with the following equations. The computations are done in spread sheet.

**From 433 V Bus**

$$\mathrm{Y_C}(h) = \frac{\mathrm{X_{C,\,p.u.}}}{h}$$

$$\mathrm{Y_L}(h) = \mathrm{Z^{-1}_{L,\,p.u.}}(h)$$

$$\mathrm{Y_{433}}(h) = \mathrm{Y_C}(h) + \mathrm{Y_L}(h)$$

**From 11 kV Bus**

$$\mathrm{Y_{Fur\ Trf}}(h) = \mathrm{Z^{-1}_{FT,\,p.u.}}(h)$$

$$\mathrm{Z_{11\ kV}}(h) = \mathrm{Z_{Aux.\ T,\ p.u.}}(h) + \mathrm{Z_{433}}(h)$$

$$\mathrm{Y_{Grid}}(h) = \mathrm{Z^{-1}_{Grid,\,p.u.}}(h)$$

$$\mathrm{Y_{eq}}(h) = \mathrm{Y_{Fur\ Trf}}(h) + \mathrm{Y_{11\ kV}}(h) + \mathrm{Y_{Grid}}(h)$$

$$\mathrm{Z_{eq.}}(h) = \frac{1}{\mathrm{Z_{Grid}}(h)} + \frac{1}{\mathrm{Z_{11\,kV}}(h)} + \frac{1}{\mathrm{Z_{F.T.\,p.u.}}(h)}$$

The harmonics current data are calculated using following equation

**Harmonics Injection**

$$\mathrm{I_{F.T.}}(h) = \frac{\%\mathrm{I}_h}{100} \times \frac{\mathrm{I_{F.T.}}}{\mathrm{I_{Base\ at\ 575\ V}}}$$

The results for the voltage harmonics distortion in buses and current harmonics distortion in the lines are computed using following equations. The results obtained in spread sheet are to check for the distortion limit as per IEEE 519 – 1992 [8] and corresponding harmonic resonance point in the network.

**Harmonics Voltage Calculations**

$$Y_{11\,kV}(h) = I_{F.T.}(h) \times Z_{eq.}(h)$$

$$Y_{433\,kV}(h) = I_{F.T.}(h) \times Z_{433\,V}(h)$$

**Computation Results**

D2 =ROUND(SQRT(SUM(AM5:AM19))/C3,5)

| | % Harmonic current | Harmonic Furnace Current Iif(h) | 11 kV BUS |
|---|---|---|---|
| % THD | | | 1.25886 |
| 1 | 100 | 382.4775869 | 11 |
| 2 | 2.9 | 1.83425 | 0.19 |
| 3 | 3.2 | 2.024 | 29 |
| 4 | 0.7 | 0.44275 | 8 |
| 5 | 22.5 | 14.23125 | 326 |
| 6 | 0.8 | 0.506 | 14 |
| 7 | 11.3 | 7.14725 | 241 |
| 8 | 0.3 | 0.18975 | 11 |
| 9 | 1.3 | 0.82225 | 26 |
| 10 | 0.3 | 0.18975 | 7 |
| 11 | 6.3 | 3.98475 | 174 |
| 12 | 0.3 | 0.18975 | 9 |
| 13 | 4.2 | 2.6565 | 140 |
| 14 | 0.2 | 0.1265 | 7 |
| 17 | 2.1 | 1.32825 | 92 |
| 19 | 1.7 | 1.07525 | 84 |

PLOT_1 (2) / per unit / INPUT / calculation / OUTPUT / OUTPUT (2) / Sheet2 / FINAL OUTPUT

**Figure 8: % Voltage THD in 11 kV Bus in spread sheet**

Total Harmonics Distortion level in the 11 kV bus is calculated and obtained as **1.26 %**

It is observed that the resonance is occurring at harmonic order 8.3 and the impedance 2.55 ohms. Since the resonance is occurring not in the characteristic harmonics in the network, it is observed the current amplification may not be appreciable.

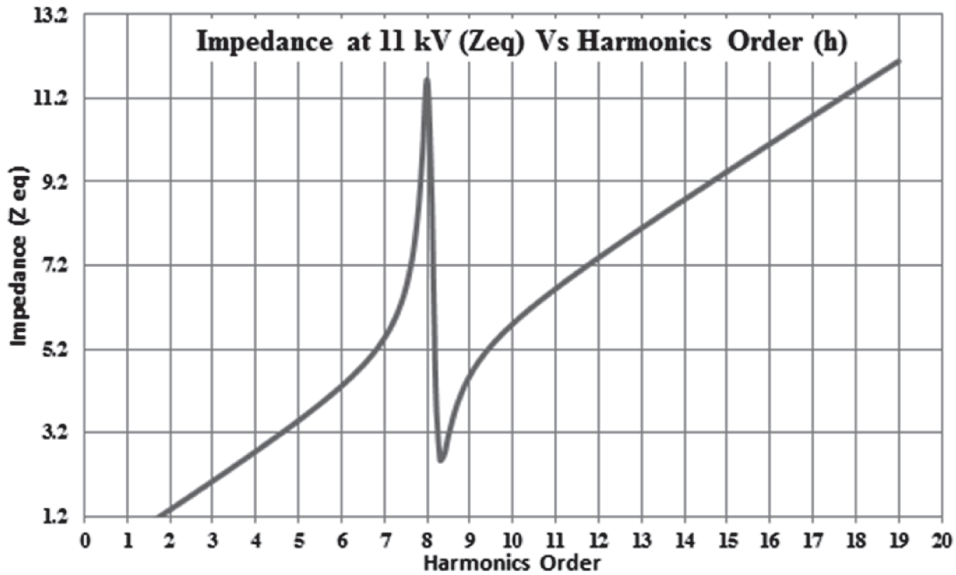



**Figure 9: Frequency scan at 11 kV Bus**

An attempt is made in this paper to validate the numerical result data in comparison with the result obtained in harmonics analysis module of the software ETAP 12.6. The network in Figure 3 is drawn as one line diagram in edit page of the software.

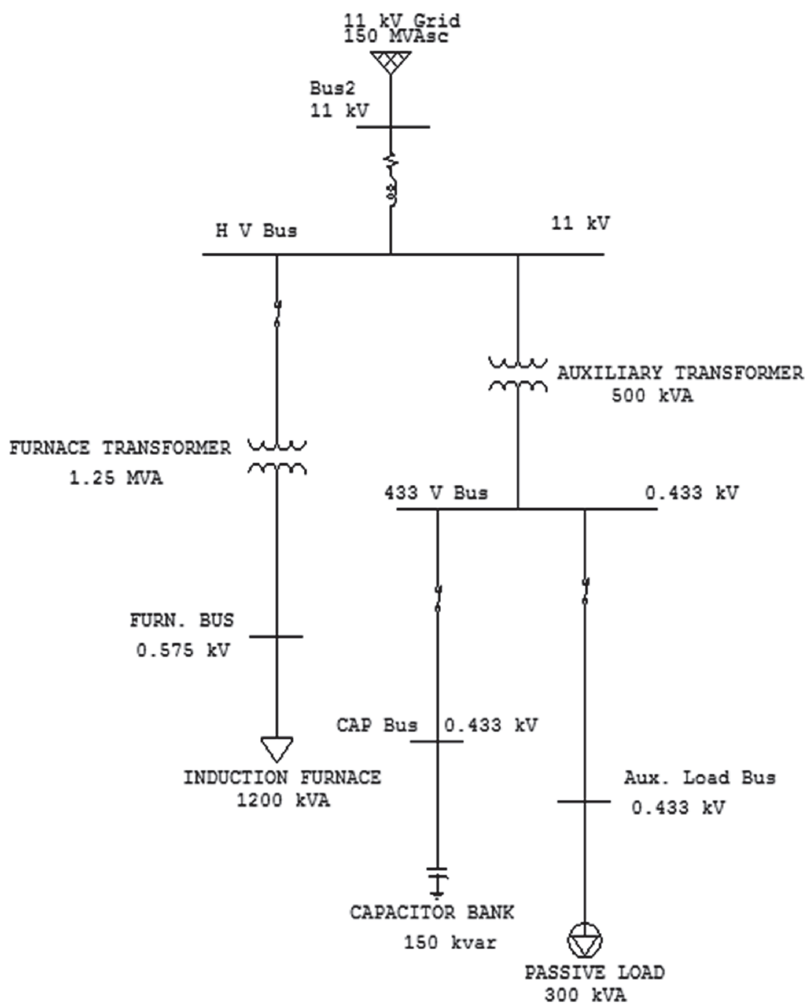



**Figure 10: One Line Diagram in ETAP**

The data are input into the software vide the editor of each component. The typical page is shown in Figure 6 for the passive load component.

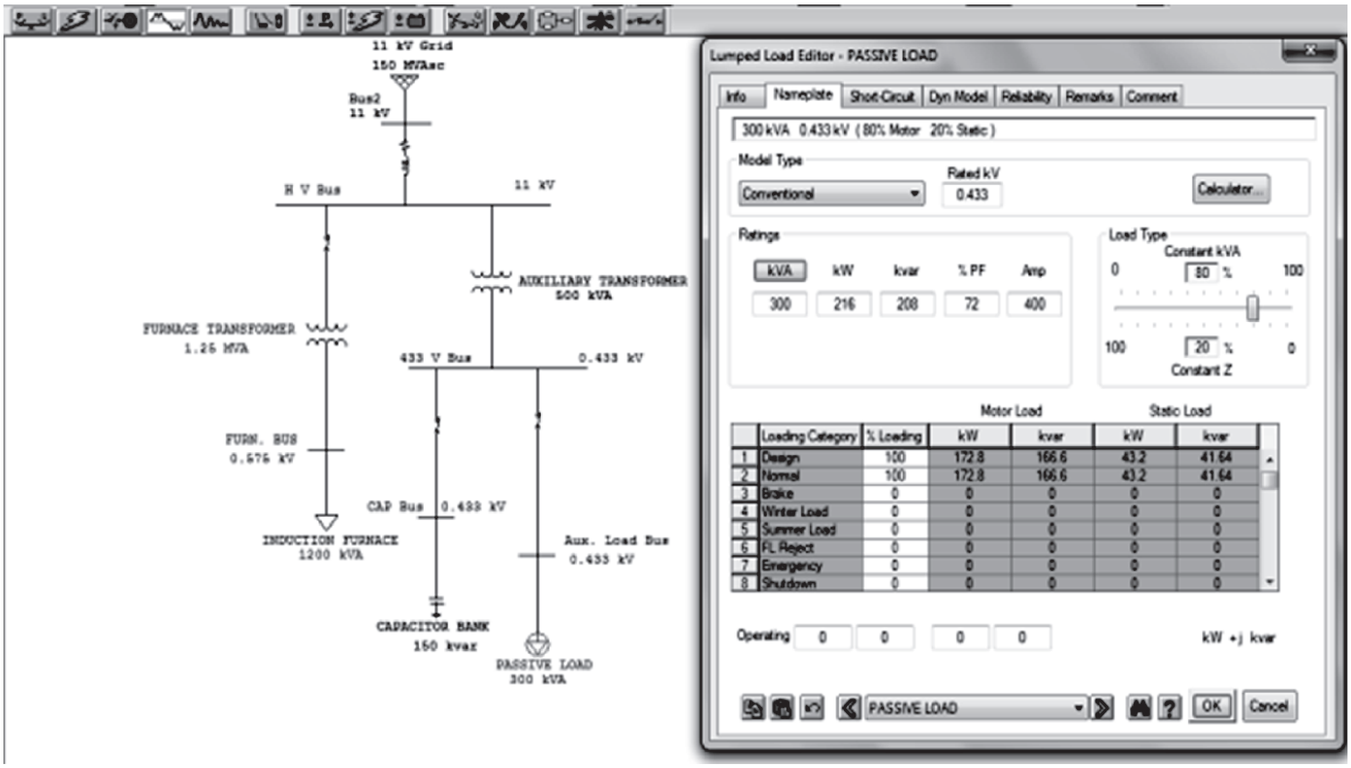



**Figure 11: Passive load data in editor**

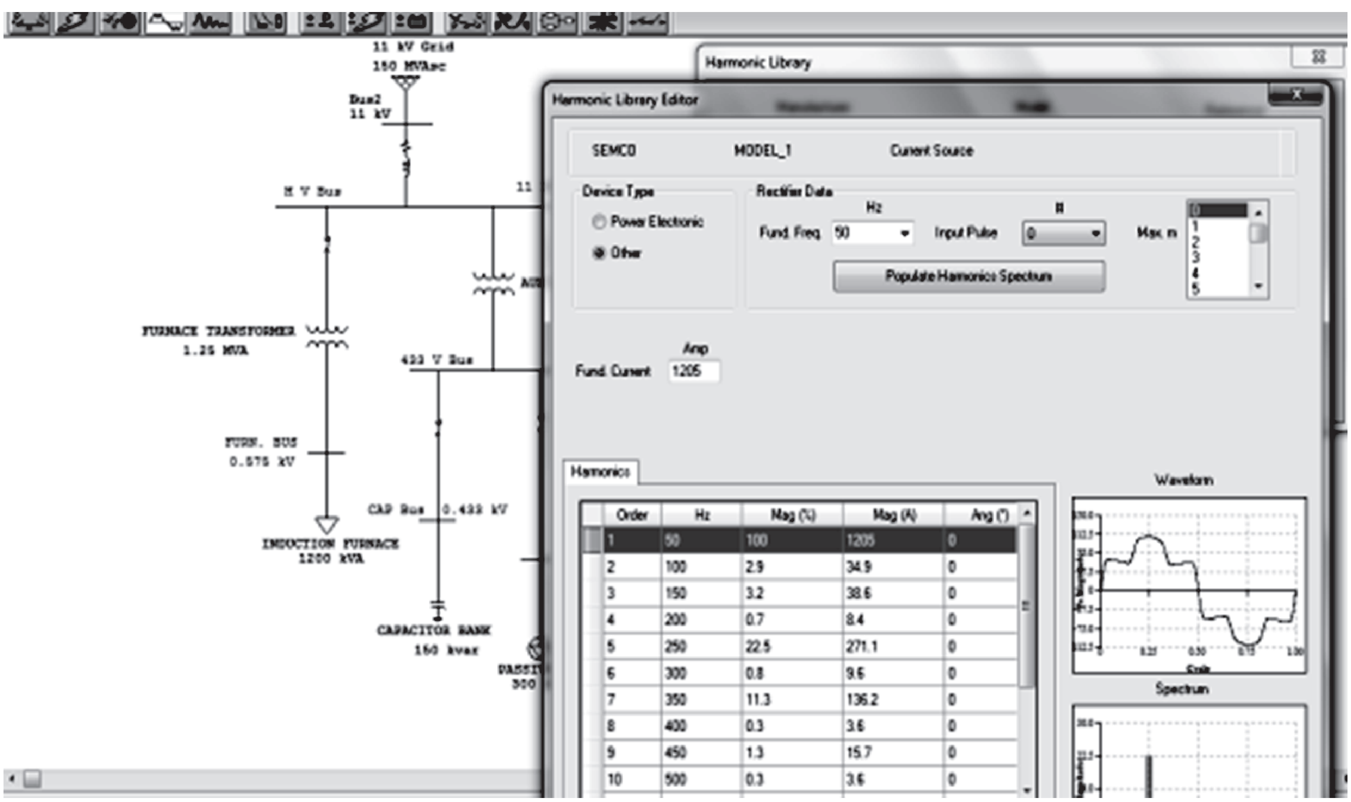



**Figure 12: Harmonics injection data in library**

The harmonics data are inserted in user defined pattern in library. The details shown in Figure 7

**ETAP Result**

The fundamental load flow is run in the software to obtain the result to check the correction of the power factor using capacitors where sufficiently maintained 0.95. The typical results in the software is shown in Figure 8.

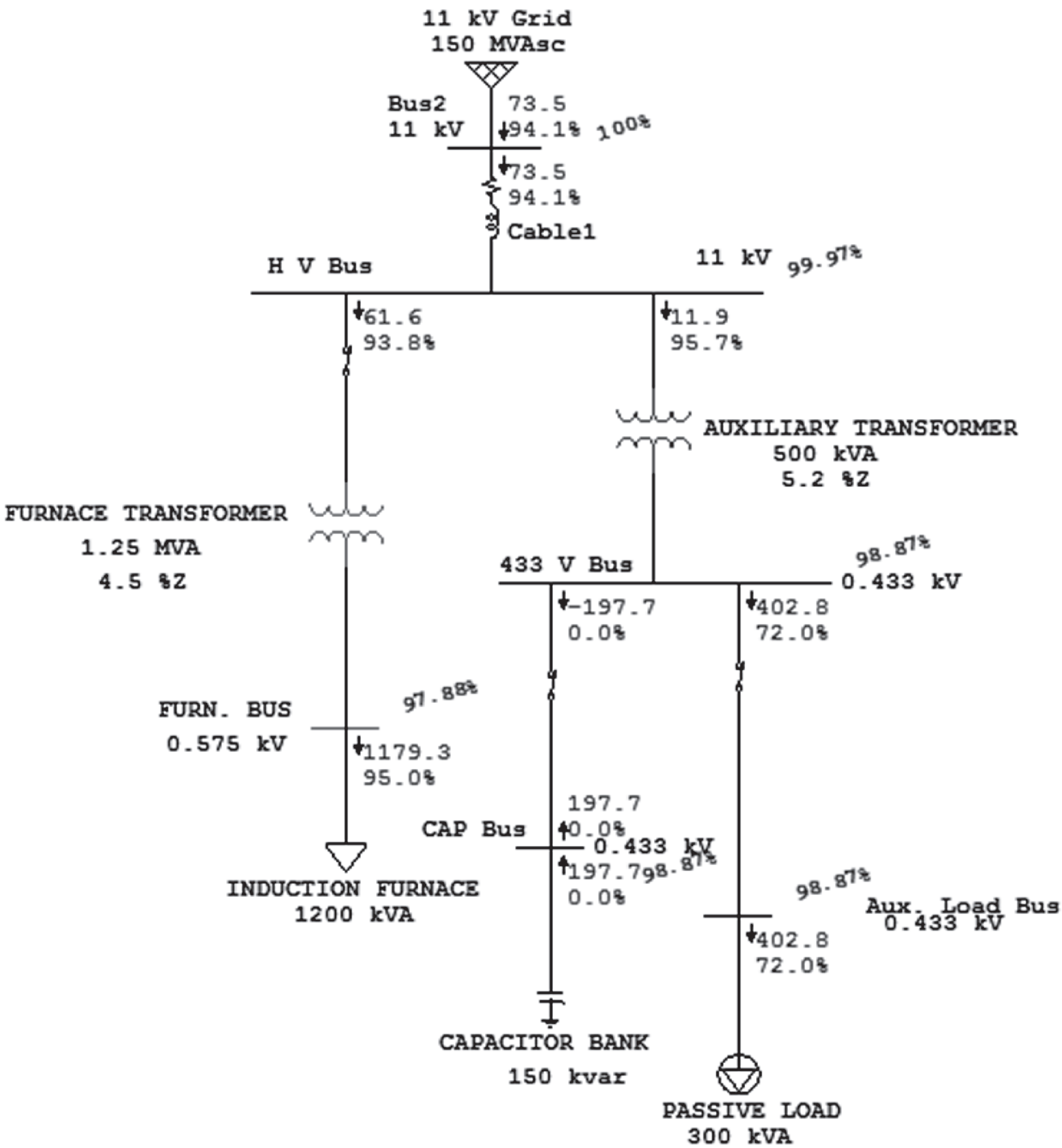



**Figure 13: Current flow result in ETAP**

**Table 5**
**Results of current flow**

| *From* | *To* | *Current (A)* | *Power factor* |
|---|---|---|---|
| Grid | 11 kV Bus | 73.5 | 0.94 |
| 11 kV Bus | 575 V Bus | 61.6 | 0.94 |
| 11 kV Bus | 433V Bus | 11.9 | 0.95 |
| 433 V Bus | Passive Load | 402.8 | 0.72 |

The harmonics load flow is done to obtain the %THD for voltage and current. The typical results in the software is shown in Figure 9.

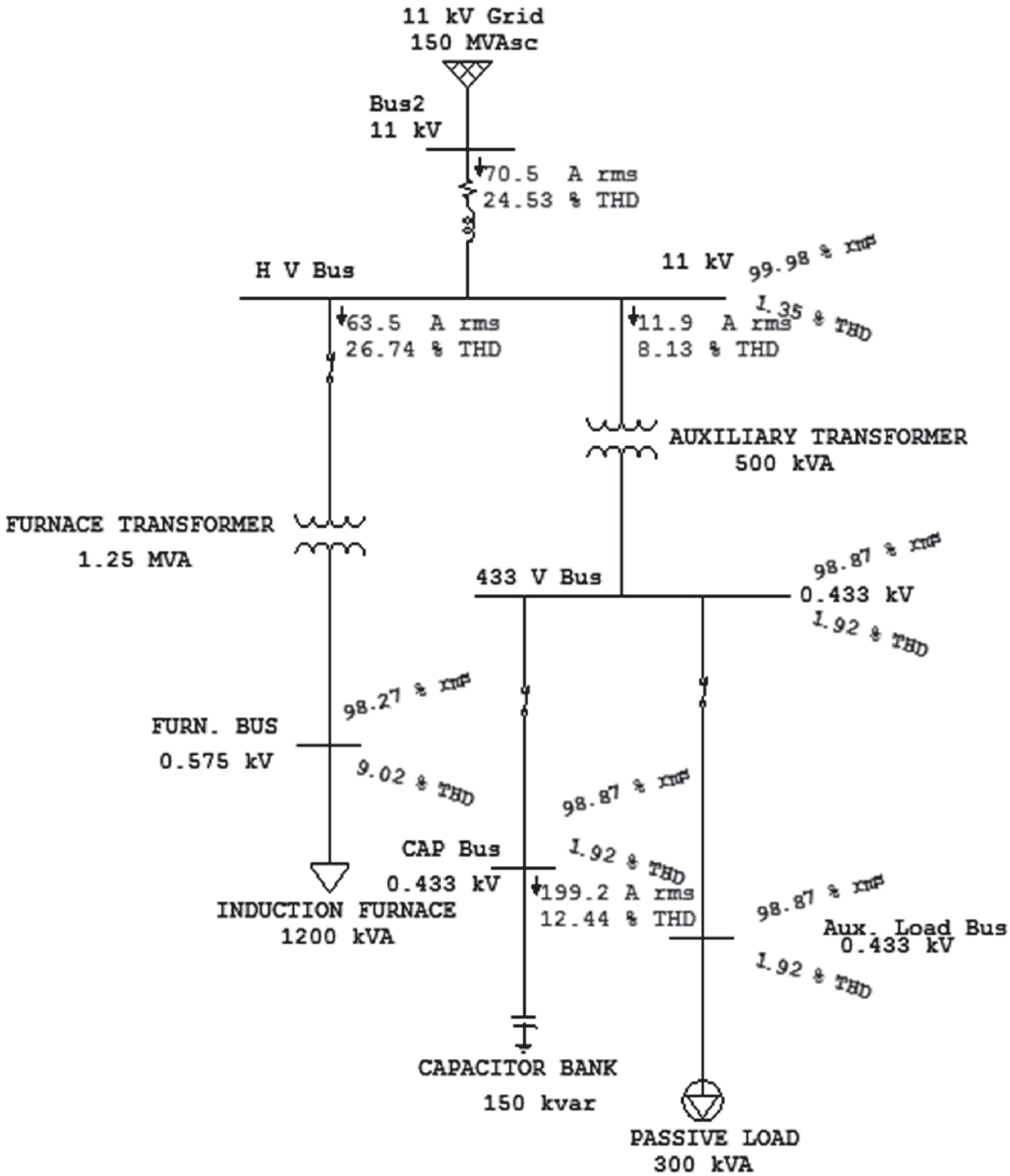



**Figure 14: Harmonics Load flow in ETAP**

**Table 6**
**Results of Harmonics**

| *From* | *To* | *Current THD (%)* | *Voltage THD (%)* |
|---|---|---|---|
| Grid | 11 kV Bus | 24.5 | 1.35 (11 kV Bus) |
| 11 kV Bus | 575 V Bus | 26.74 | 1.92 (433 V Bus) |
| 11 kV Bus | 433V Bus | 8.1 | 9.02 (Furn. Bus) |

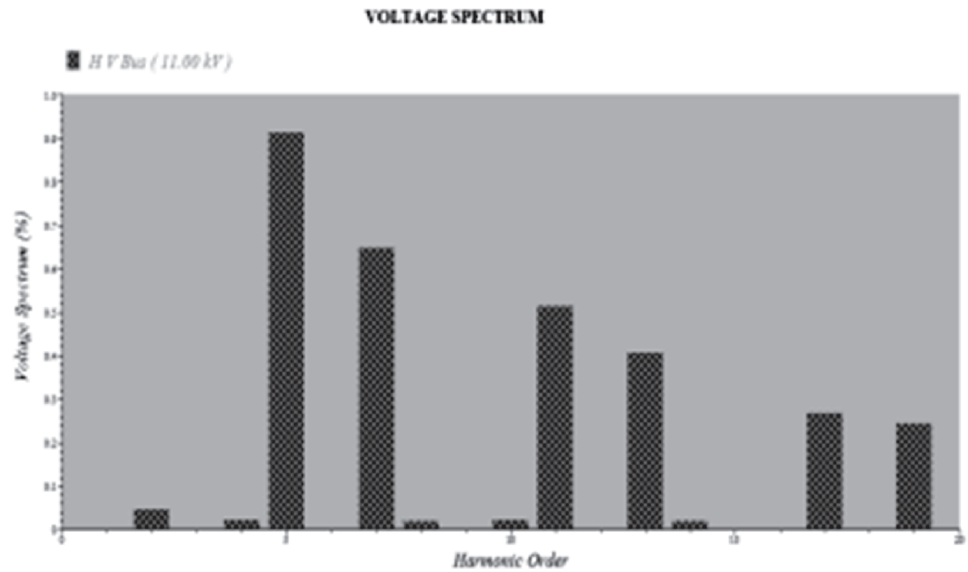



**Figure 15: Voltage Spectrum at 11 kV bus**

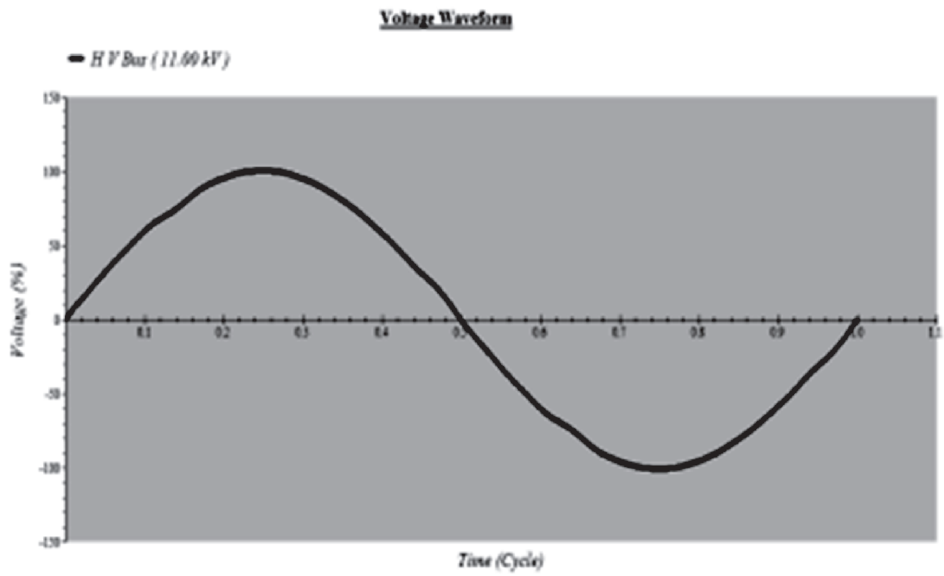



**Figure 16: Voltage Waveform at 11 kV bus**

## Comparison of Results

**Table 7**
**Harmonics Distortion result**

| *% THD* | *Numerical solution* | *ETAP result* |
|---|---|---|
| % V THD | 1.26 | 1.35 |
| % I THD | 22.53 | 24.53 |

## 2. CONCLUSION

In this paper, the harmonics measured in induction furnace at 575 V is used for the study at 11 kV bus (PCC). The power factor for the network is maintained at 0.95 and harmonic load flow in lines and percentage voltage THD in 11 kV bus are obtained. The results are verified and found close each other. Results are

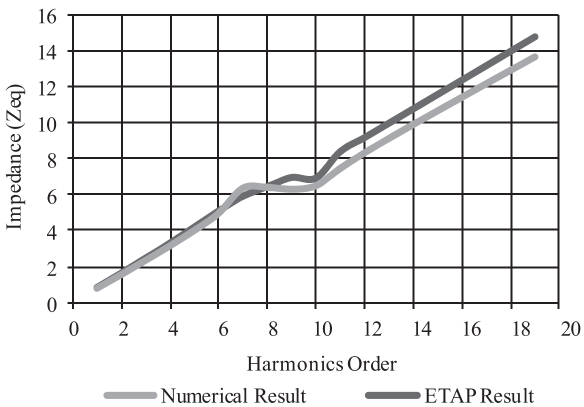



**Figure 17: Comparison of Harmonics Impedance**

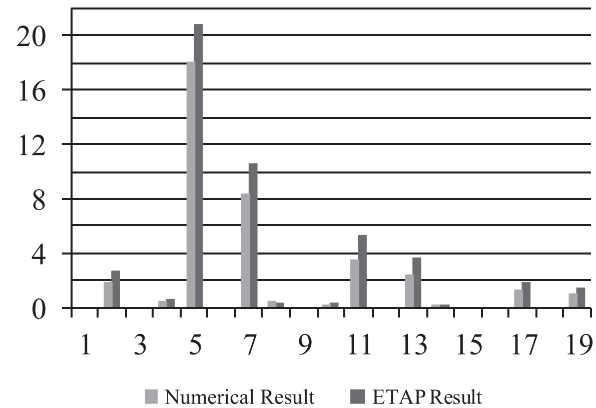



**Figure 18: Current IHD result**

evaluated with IEEE standards. The excessive THD for current is noted for adopting suitable mitigation method at appropriate bus. This study can be extended for harmonic resonance shifting with changes in grid, outage of line/transformer, increase/decrease in passive load and operation of local generators. And also with multiple harmonic patterns injection from different parts of the network can be studied.

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9. **D. Ravichandran**, received Master of Engineering from Anna University, Chennai, India in 2004. He is presently working as Assistant Professor in SRM University, Kattankulathur since 2014. He had wide experience of 18 years in various fields such construction, operation and maintenance of distribution system. He had 12 years of teaching experience in handling various core and elective subjects. He is interested in demand side management and power quality study in small and medium scale industries.
10. **Er. R. Panneer Selvam** received Bachelor of Engineering in Madras University, India in 1970. He served in state utility of Tamil Nadu state in India for 34 years in various field like meter and relay testing, grid relay testing, load dispatch centre and testing and commissioning of equipments from 11 kV to 400 kV. He also served in M/s National Switchgear, Chennai for 4 years in manufacturing equipments based on power resistors. In last 5years he served as Consulting Engineer for various industries in the fields of harmonic analysis and mitigation of power quality problems, industrial solutions, relay coordination and reactive power management.