Harmonic Analysis

Theoretical Concepts

With the growing proliferation of nonlinear loads in commercial buildings and industrial plants, which may be in the range of 30% to 50% of the total load, the effects of harmonics within the system and their impact on the utility and neighbouring loads needs to be examined before any complaints are made, equipment is damaged or production is lost.

The effects of harmonics are due to both current and voltage, although current produced effects are more likely to be seen in day-to-day performance. Voltage effects are more likely to degrade the insulation and hence shorten the life of the equipment. The following describes some of the common effects of harmonics:

- Increased losses within the equipment and associated cables, lines, etc.
- Pulsating and reduced torque in rotating equipment.
- Premature aging due to increased stress in the equipment insulation.
- Increased audible noise from rotating and static equipment.
- Erroneous operation of equipment sensitive to waveforms.
- Substantial amplification of currents and voltages due to resonances.
- Communication interference due to inductive coupling between power and communication circuits.

As per IEEE Std. 519-2014 (IEEE recommended practices and requirements for harmonic control in electrical power systems), voltage distortion and current distortion limits for different voltage levels are given below:

Table 1—Voltage distortion limits

Bus voltage V at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
$V \leq 1.0$ kV	5.0	8.0
1 kV < $V \leq 69$ kV	3.0	5.0
69 kV < $V \leq 161$ kV	1.5	2.5
161 kV < V	1.0	1.5[a]

[a]High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal whose effects will have attenuated at points in the network where future users may be connected.

Table 2—Current distortion limits for systems rated 120 V through 69 kV

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics)[a, b]						
I_{SC}/I_L	$3 \leq h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h \leq 50$	TDD
< 20[c]	4.0	2.0	1.5	0.6	0.3	5.0
20 < 50	7.0	3.5	2.5	1.0	0.5	8.0
50 < 100	10.0	4.5	4.0	1.5	0.7	12.0
100 < 1000	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

[a]Even harmonics are limited to 25% of the odd harmonic limits above.

[b]Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

[c]All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L.

where

I_{sc} = maximum short-circuit current at PCC

I_L = maximum demand load current (fundamental frequency component) at the PCC under normal load operating conditions

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Table 3—Current distortion limits for systems rated above 69 kV through 161 kV

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics) [a, b]						
I_{sc}/I_L	$3 \le h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h \le 50$	TDD
< 20[c]	2.0	1.0	0.75	0.3	0.15	2.5
$20 < 50$	3.5	1.75	1.25	0.5	0.25	4.0
$50 < 100$	5.0	2.25	2.0	0.75	0.35	6.0
$100 < 1000$	6.0	2.75	2.5	1.0	0.5	7.5
> 1000	7.5	3.5	3.0	1.25	0.7	10.0

[a]Even harmonics are limited to 25% of the odd harmonic limits above.

[b]Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

[c]All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L.
where
I_{sc} = maximum short-circuit current at PCC
I_L = maximum demand load current (fundamental frequency component) at the PCC under normal load operating conditions

Table 4—Current distortion limits for systems rated > 161 kV

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics)[a, b]						
I_{sc}/I_L	$3 \le h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h \le 50$	TDD
< 25[c]	1.0	0.5	0.38	0.15	0.1	1.5
$25 < 50$	2.0	1.0	0.75	0.3	0.15	2.5
≥ 50	3.0	1.5	1.15	0.45	0.22	3.75

[a]Even harmonics are limited to 25% of the odd harmonic limits above.

[b]Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

[c]All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L.
where
I_{sc} = maximum short-circuit current at PCC
I_L = maximum demand load current (fundamental frequency component) at the PCC under normal load operating conditions

Harmonic Index

$$\%THDv = \frac{\sqrt{v_2^2+v_3^2+v_4^2+\cdots v_n^2}}{v_1} \times 100$$

$$\text{True Vrms} = \sqrt{\sum v_n^2} \quad (h=1 \text{ to } n)$$

$$\%THDi = \frac{\sqrt{i_2^2+i_3^2+i_4^2+\cdots i_n^2}}{i_1} \times 100$$

$$\text{True Irms} = \sqrt{\sum i_n^2} \quad (h=1 \text{ to } n)$$

$$TIFv = \frac{\sqrt{\sum (v_h w_f)^2}}{v_{rms}}$$

Harmonic Analysis

$$= \frac{\sqrt{\sum(v_h w_f)^2}}{v_h^2} \qquad \text{(h=1 to n)}$$

IT product $= \sqrt{(\sum i_h^2 w_f)^2}$ (h=1 to n)

w_f = Weighing factor from the message curve corresponding to each frequency.

K-factor $= \frac{\sum_{h=1}^{n}(hI_h)^2}{\sum_{h=1}^{n} I_h^2}$

Harmonic Analysis

Input data

Network details

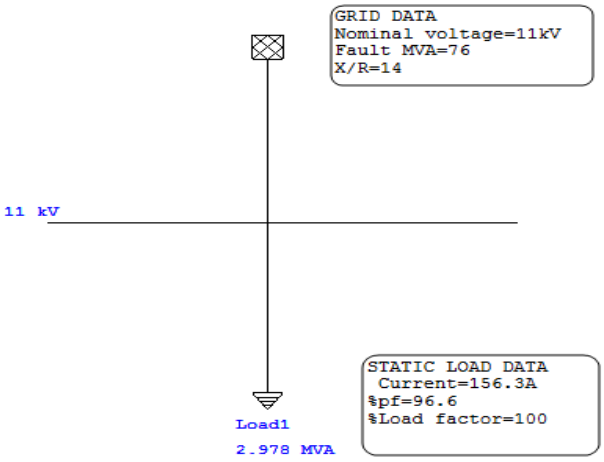
Short circuit MVA	:	76 MVA
Voltage	:	11000 V
Demand load current	:	156.3 A
Frequency	:	50 Hz

Converter transformer information

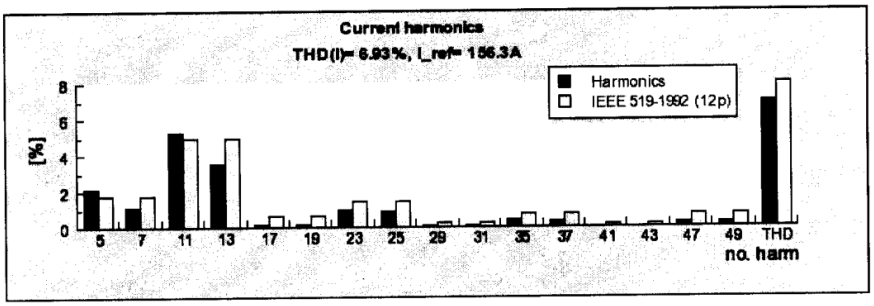
Power	:	3135 KVA
Short circuit impedance	:	6% (1567 KVA)

Converter information

No. Of pulses	:	12
Fundamental power factor	:	0.966



Current harmonic distortion



Individual current harmonics

order [#]:	5	7	11	13	17	19	23	25	29	31	35	37	41	43	47	49
currents [%]:	2.1	1.2	5.3	3.5	0.2	0.1	0.9	0.9	0.1	0.1	0.4	0.3	0	0	0.2	0.2

Results for test case

The harmonic calculation is based on an ideal network (purely inductive, no cables, no other consumer, no existing harmonic distortion, no unsymmetries in the network). In reality, a complete cancellation of the non-characteristic harmonics is not achievable and therefore they have been considered with 10% of a corresponding 6-pulse bridge.

Total harmonic voltage distortion: 3.31 %

Total harmonic current distortion: 6.93 %

Harmonic Analysis

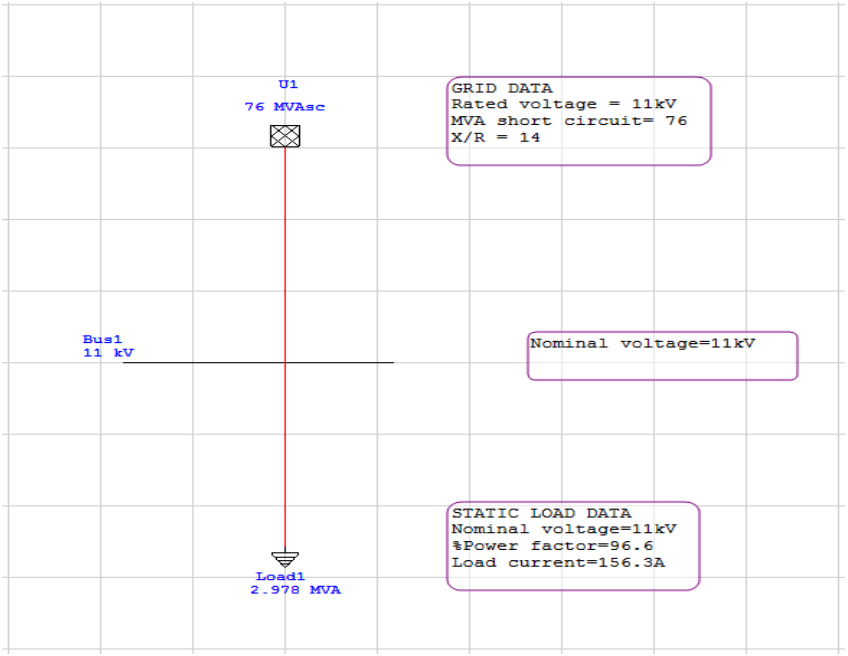
Purpose and description

The purpose of this exercise is to inject the harmonics in the system and to study harmonic impact on the system.

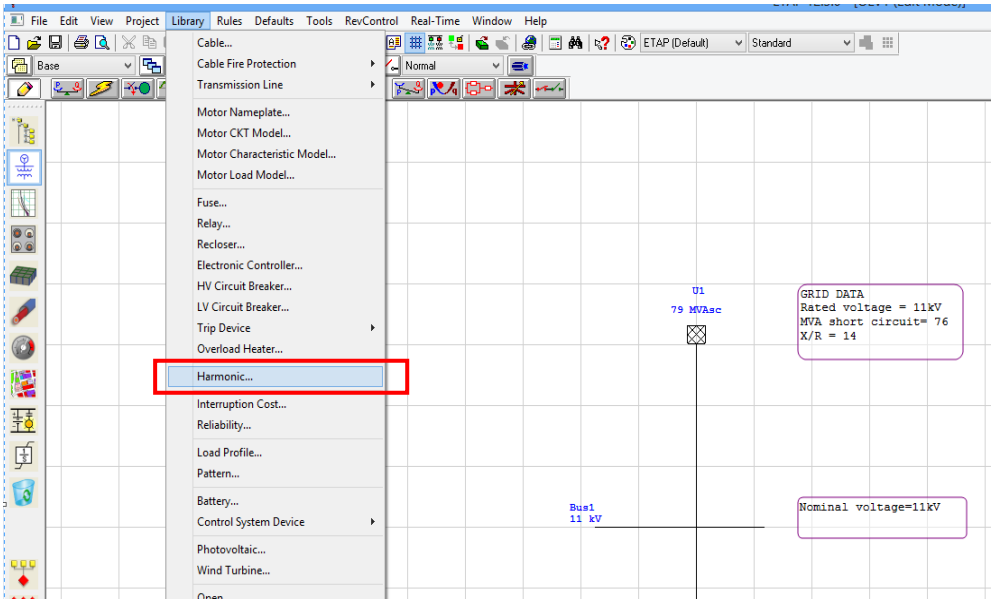
Procedure

Case-1

1. Drag and place the grid, bus & static load on the OLV and proceed to enter the input data & connect them as shown below.

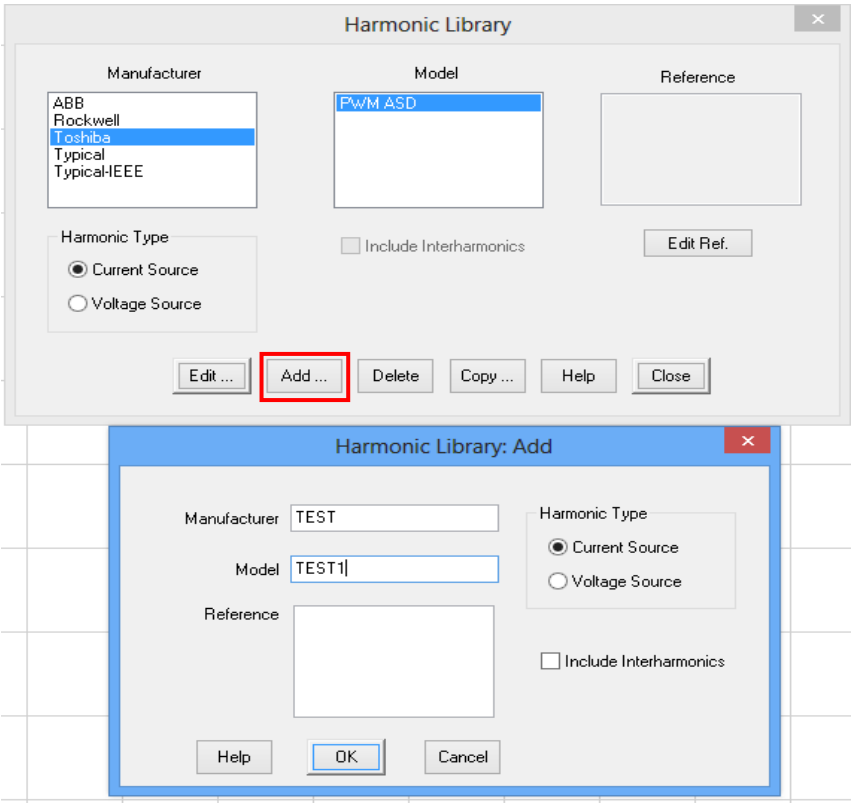


2. Click on Library and select Harmonics option from the list as shown below.

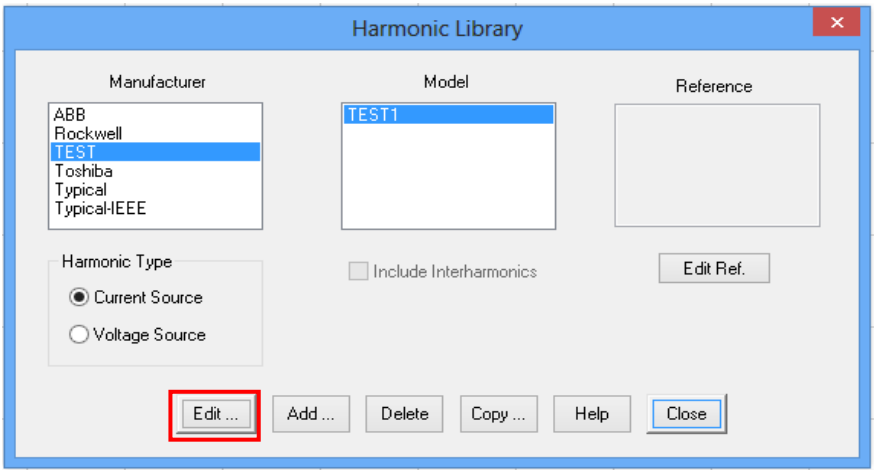


Harmonic Analysis

3. Click on Add tab and create a new model in the library as given below.
    - Manufacturer: TEST
    - Model: TEST1
    - Harmonic type: Current Source

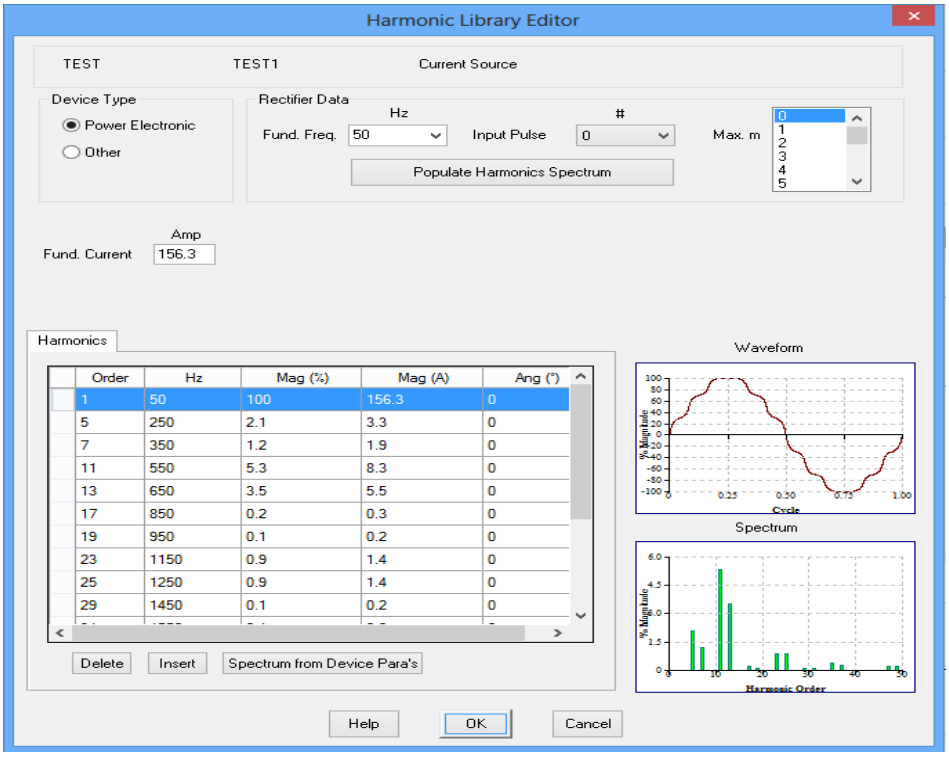


4. Pick TEST in manufacturer and TEST1 in model as shown below.

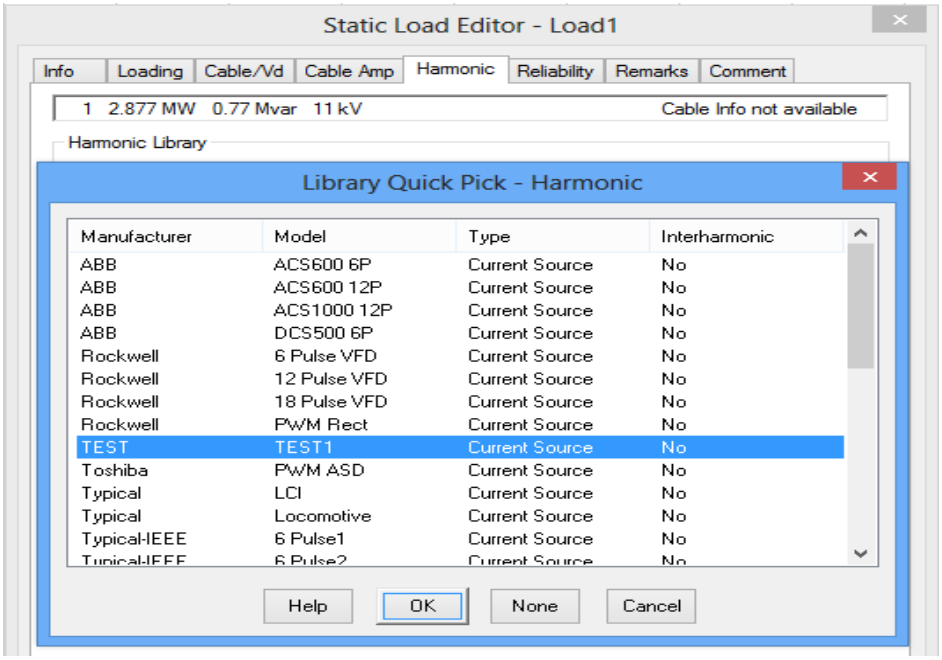


Harmonic Analysis

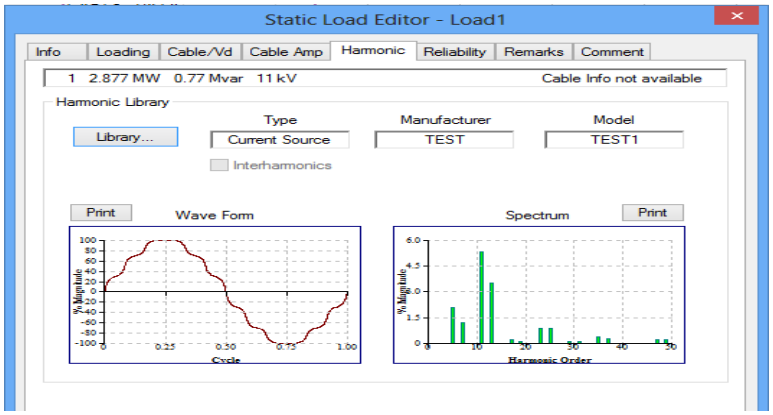
5. Click Edit and enter Fund. Freq in Hz, Fund Current in Amp & Mag (%) against appropriate harmonic order as per given input data.



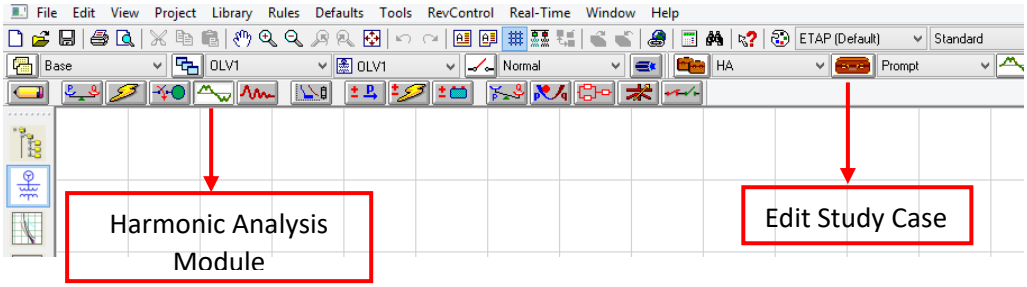
6. Go to Harmonic page in the Static Load Editor and click on Library & select the user defined harmonic library i.e. TEST.



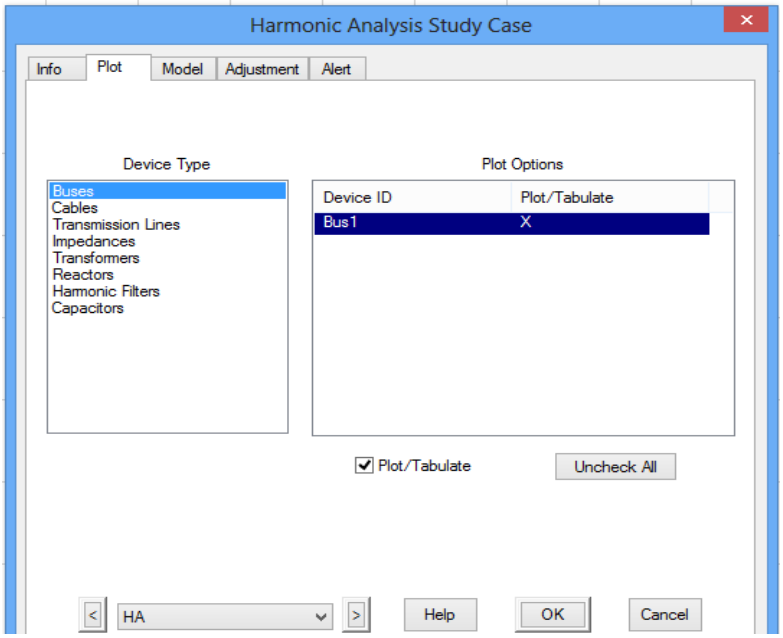
Harmonic Analysis



7. Go to Harmonic Analysis module, click Edit Study Case.

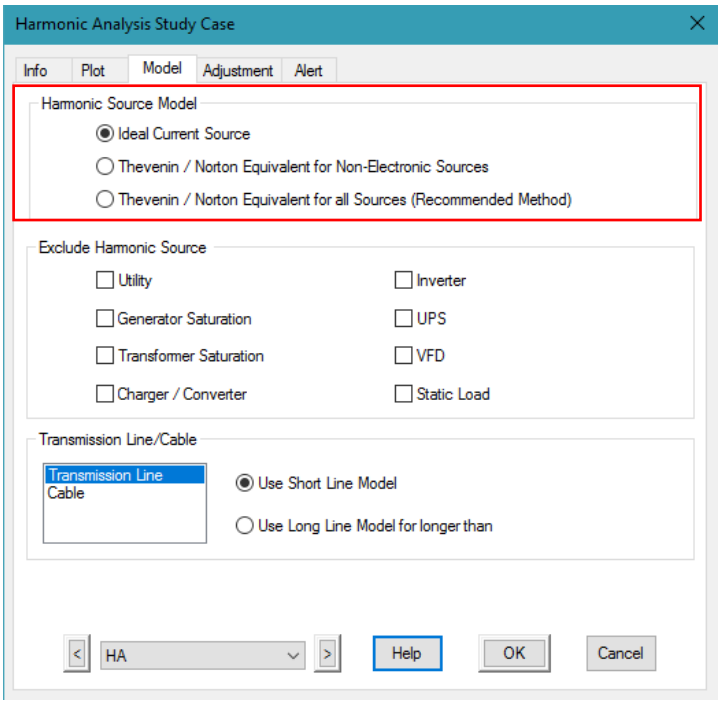


8. Go to Plot page and select the bus of interest whose %THD is to be studied.

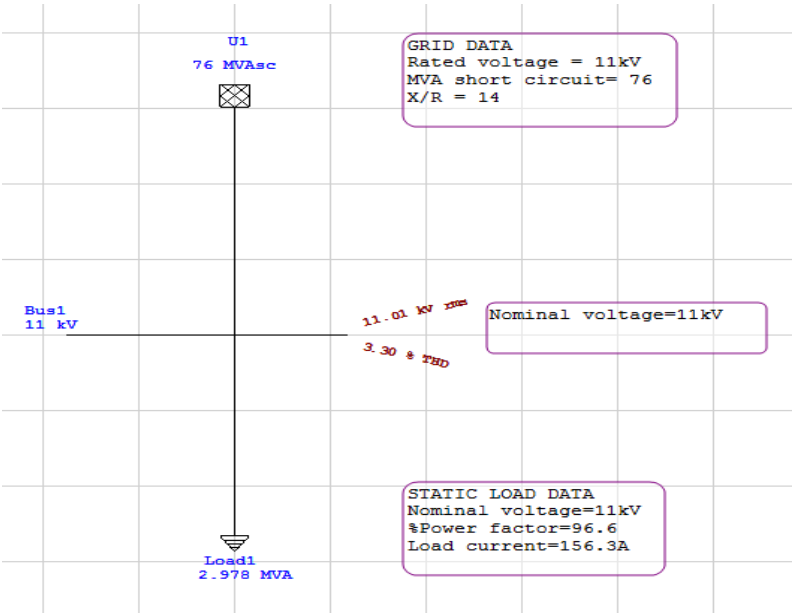


Harmonic Analysis

9. Go to model page and select Harmonic Source Model as ‘Ideal Current Source’.



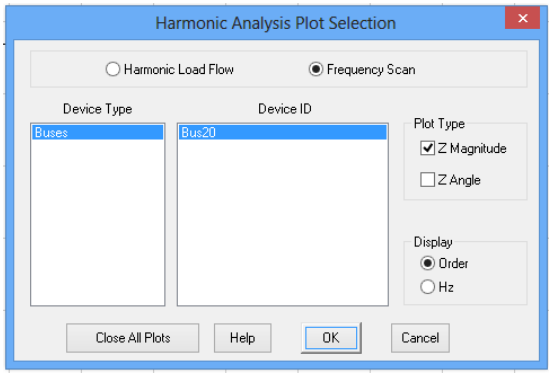
10. Run Harmonic Analysis Load Flow and check for the results.

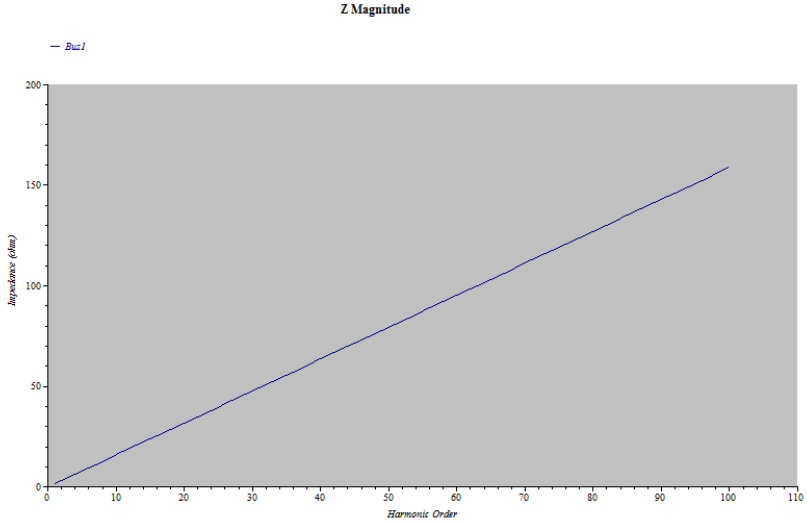


Total harmonic voltage distortion = **3.30** %

11. Run Frequency Scan, go to Harmonic Analysis Plots and check Frequency Scan option to plot Z Magnitude v/s Order as shown below.

Harmonic Analysis

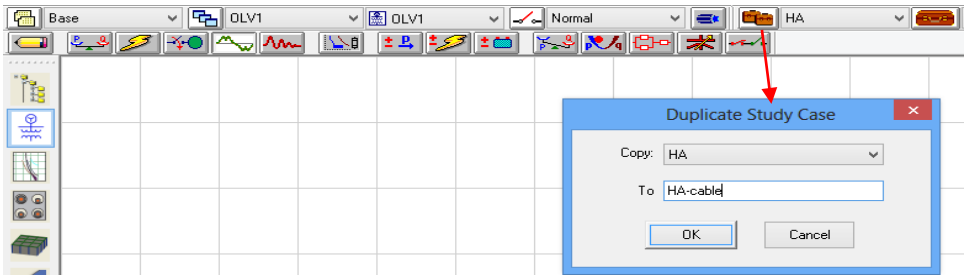




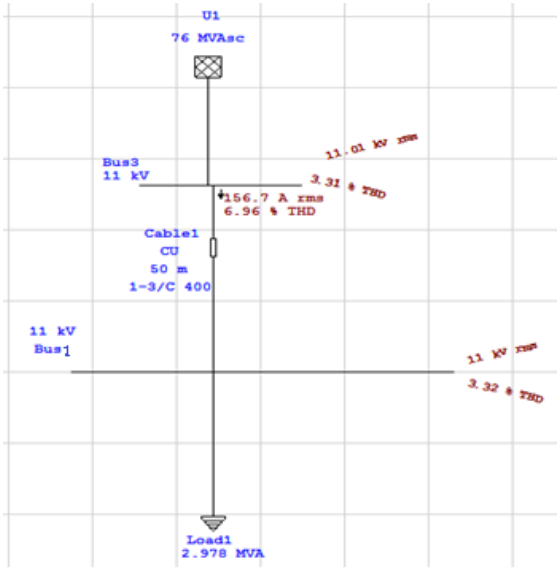
Harmonic Analysis

Case-2

1. Connect a cable (3C * 400 sq mm, 50 meter) between grid and Bus1.
2. Create a New Study Case HA-cable.



3. Go to Edit Study Case, go to Plot page and select the Cable1 & Bus1.
4. Run the Harmonic Load Flow.

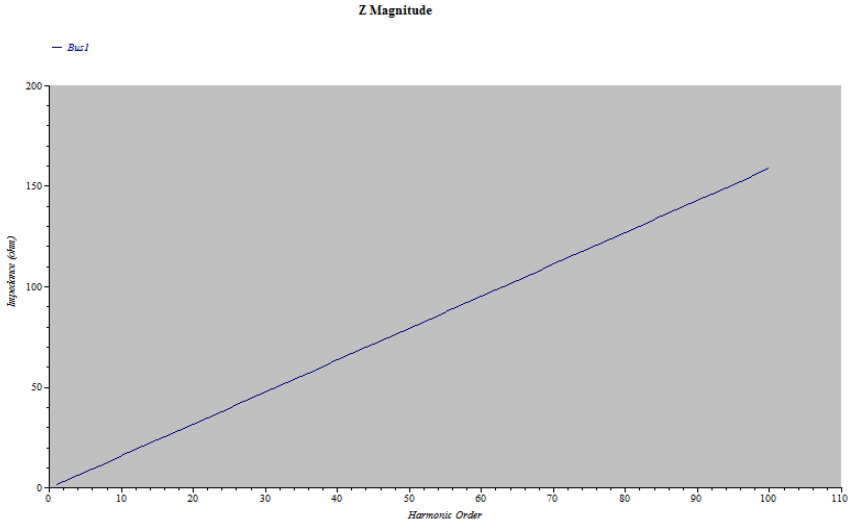


Total harmonic voltage distortion = **3.32** %

Total harmonic current distortion = **6.96**%

Harmonic Analysis

5. Run Frequency Scan and plot Z Magnitude v/s Order.



Case-3

Input data

Classic 12 pulse drive

h=np±1 p=pulse=12

h1=1*12-1=11

h2=1*12+1=13

h3=2*12-1=23

h4=2*12+1=25

h5=3*12-1=35

h6=3*12+1=37

Ih = 1/h (Ih in pu amp is inverse of 'h')

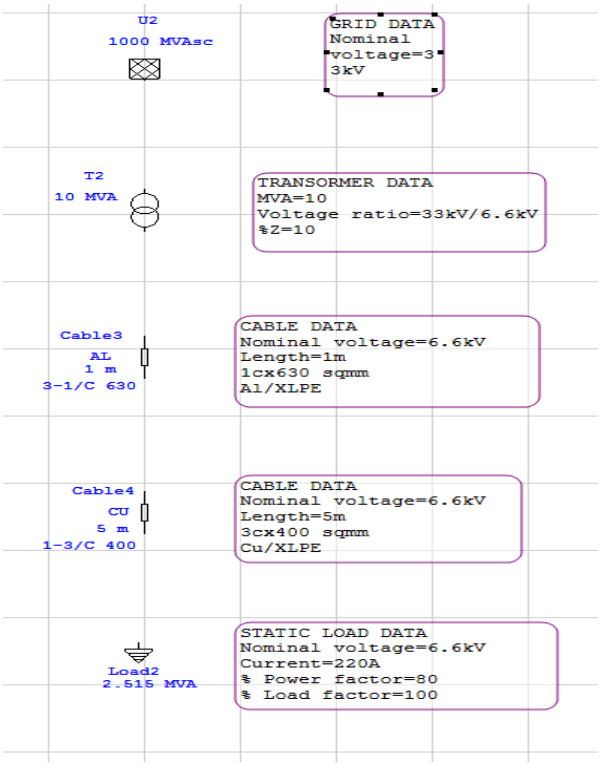
%Ir = 100/h

Use the following data to enter in ETAP harmonic library:

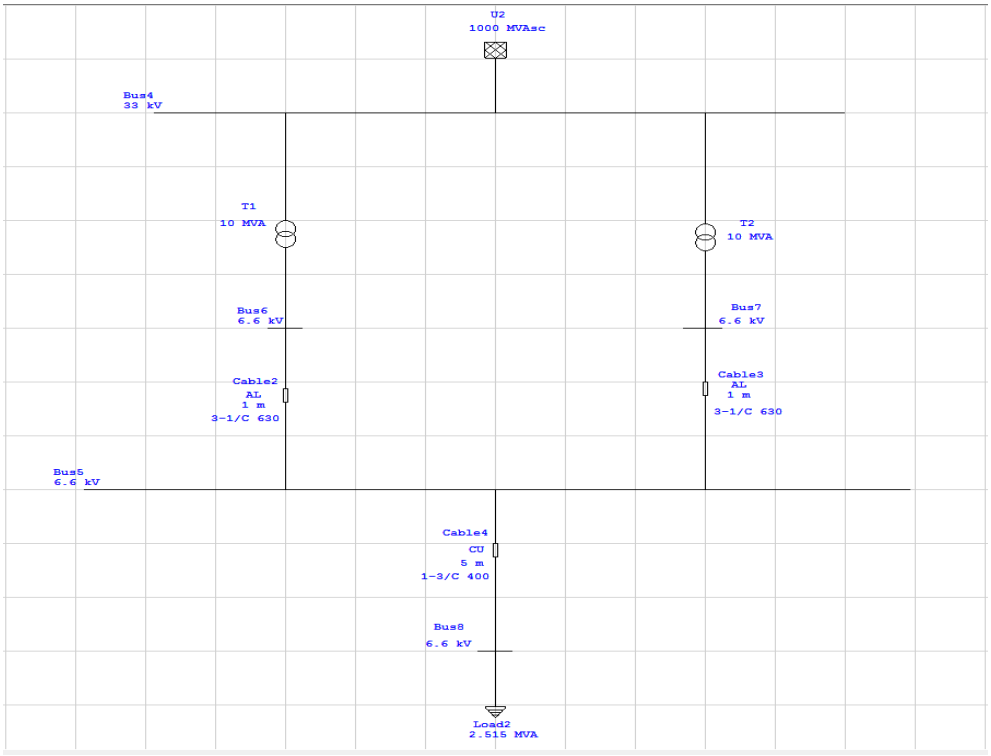
harmonic order	%Ih
11	9.09
13	7.69
23	4.35
25	4.00
35	2.86
37	2.70

Harmonic Analysis

1. Drag and place the grid, bus, transformer, cable & static load on the OLV and proceed to enter the input data as shown below.

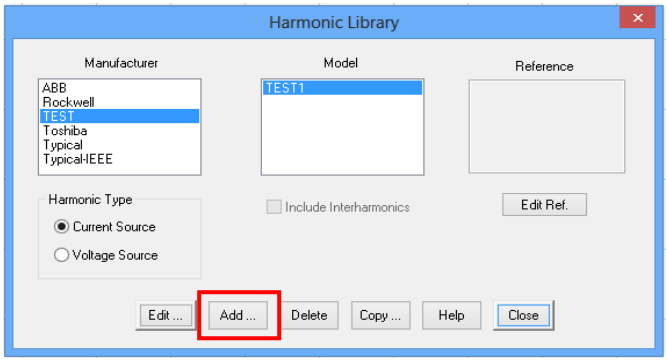


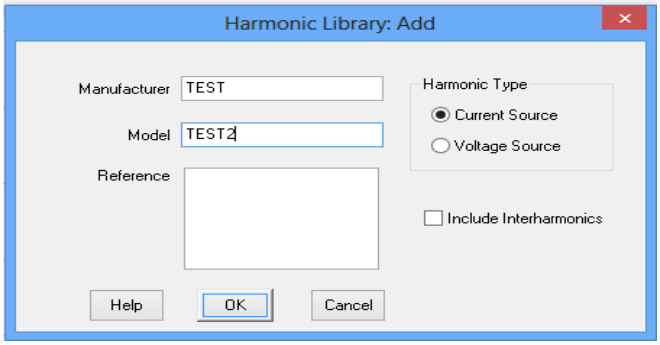
2. Construct the one line diagram as shown below.



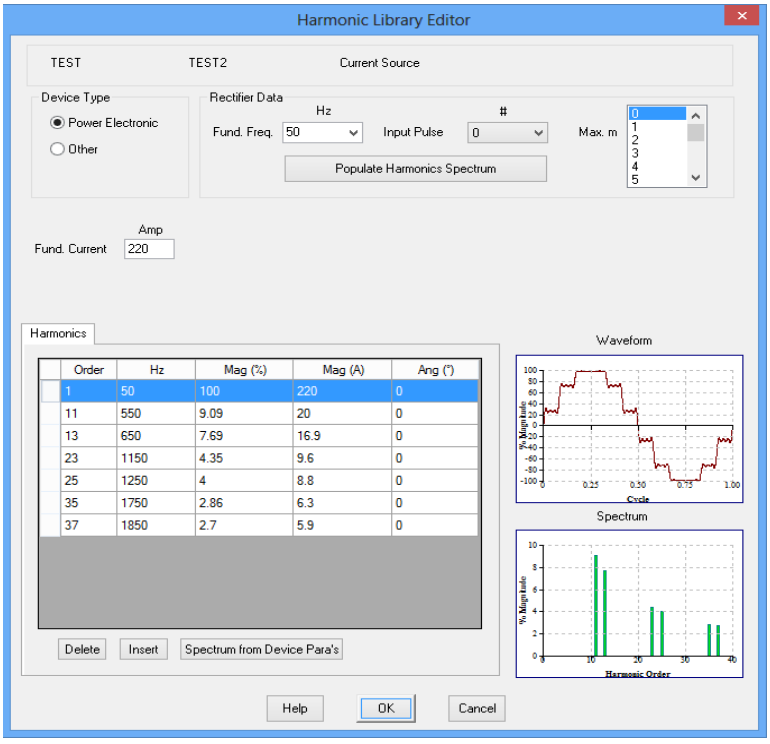
Harmonic Analysis

3. Click on Add tab and create a new model in the library.
   - Manufacturer : TEST
   - Model : TEST2
   - Harmonic type: current source



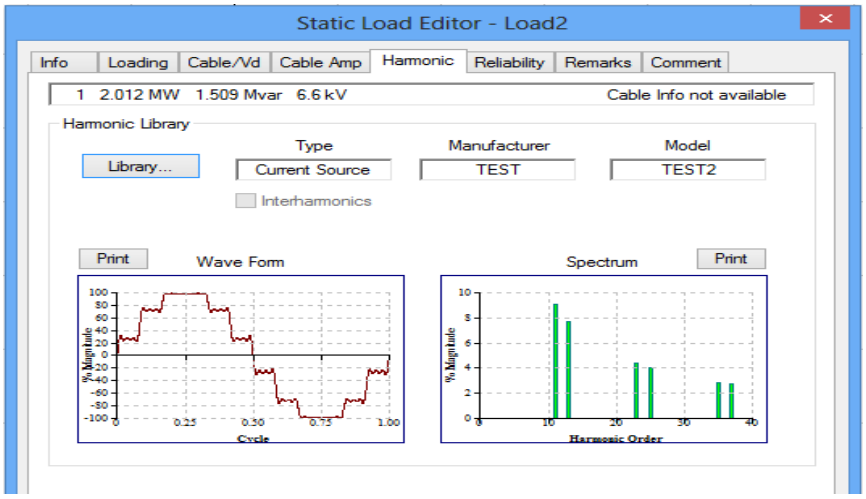


4. Click Edit and enter Fund. Freq in Hz, Fund Current in Amp & Mag (%) against appropriate harmonic order as per data shown below.

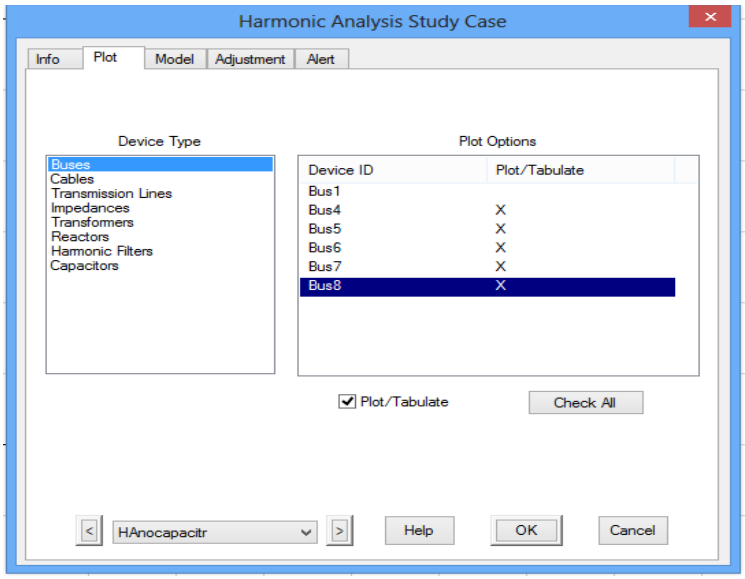


Harmonic Analysis

5. Go to Harmonic page in Static Load Editor and select the user defined harmonic library i.e. TEST.

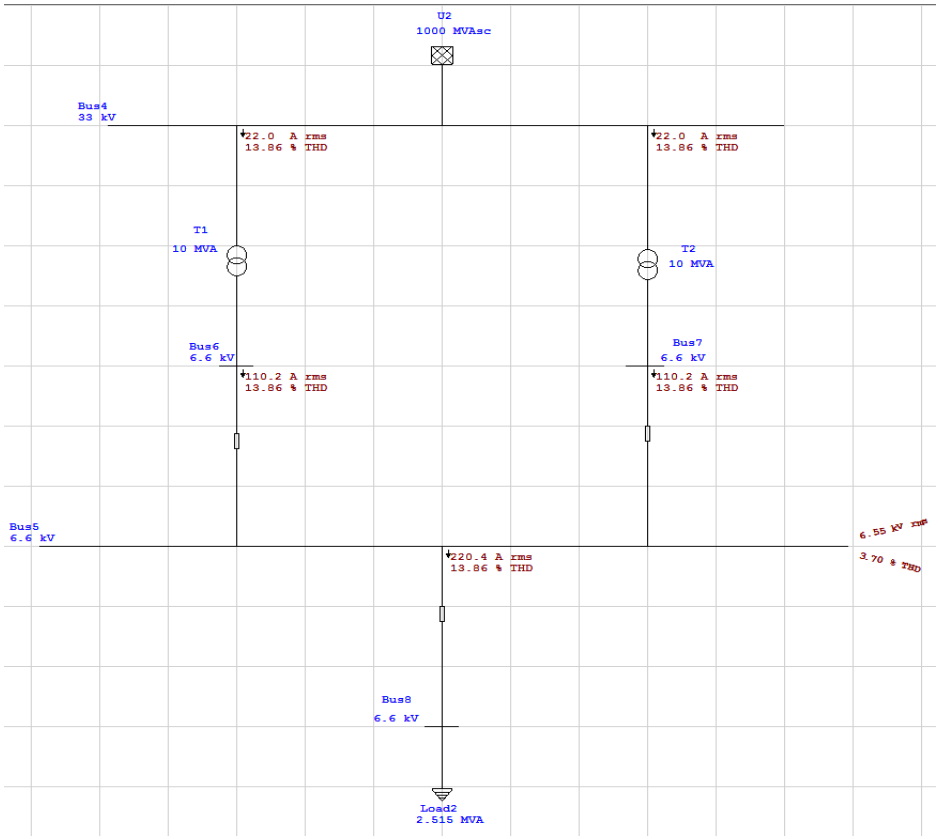


6. Go to Edit Study Case, click on Plot page and select the bus & cable of interest.



Harmonic Analysis

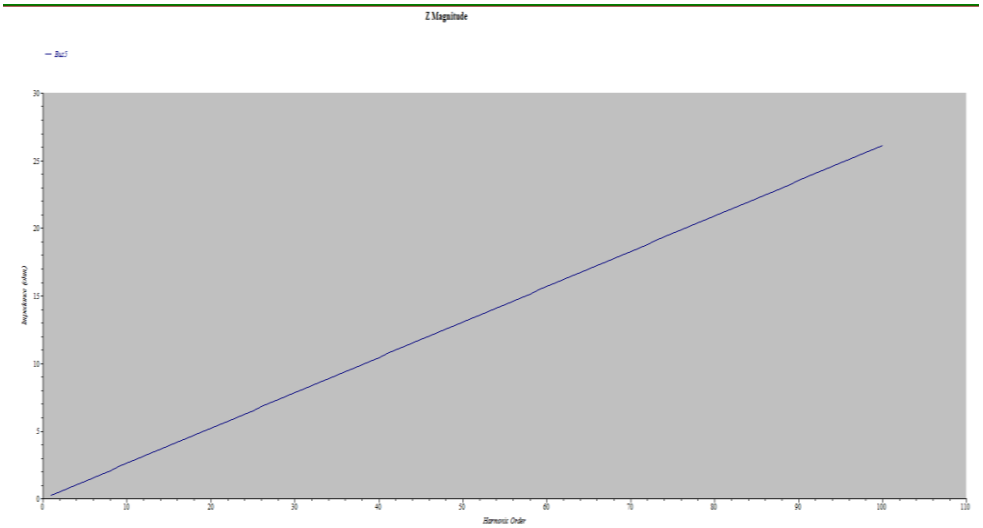
7. Run Harmonic Load Flow and check for the results.



Total harmonic voltage distortion = **3.70** %

Total harmonic current distortion = **13.86**%

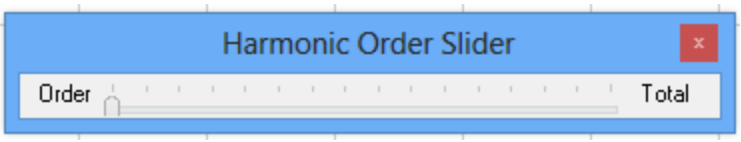
8. Run Frequency Scan and plot Z Magnitude v/s Order.

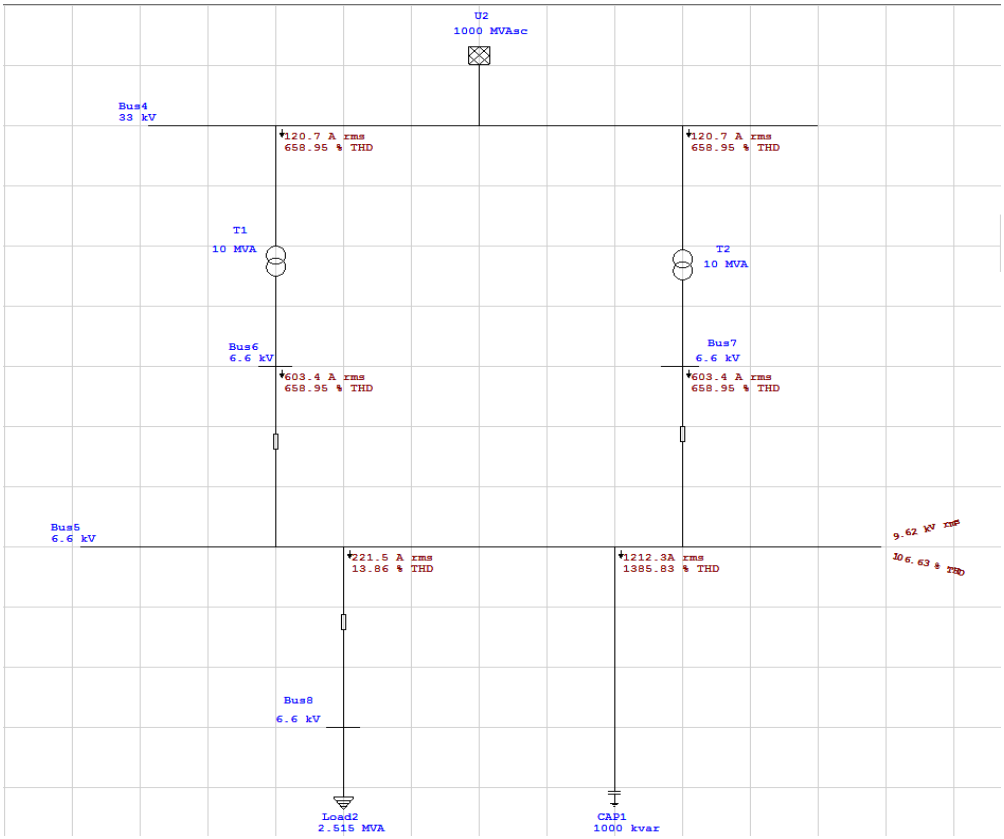


Harmonic Analysis

Case-4

1. Create a New Study Case (with capacitor).
2. Connect a capacitor of 1000 Kvar at Bus 5.
3. Run the Harmonic Load Flow and Frequency Scan.
4. Check for results with the harmonic slider set at Total.



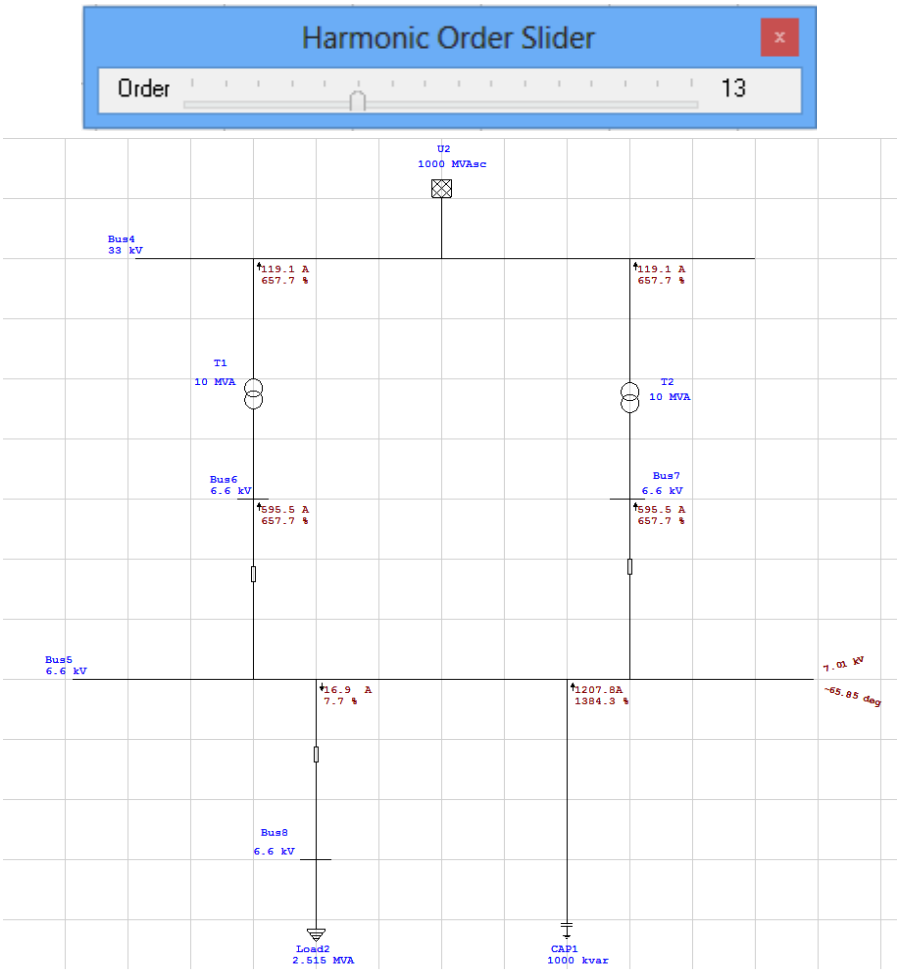


Total harmonic voltage distortion = **106.63** %

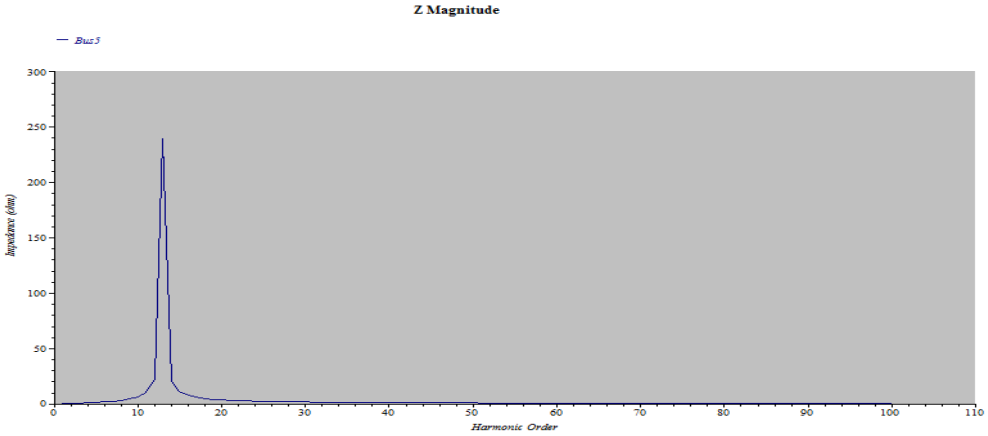
Total harmonic current distortion = **658.95**%

Harmonic Analysis

5. Check the results with harmonic slider set to 13th harmonic as shown below.



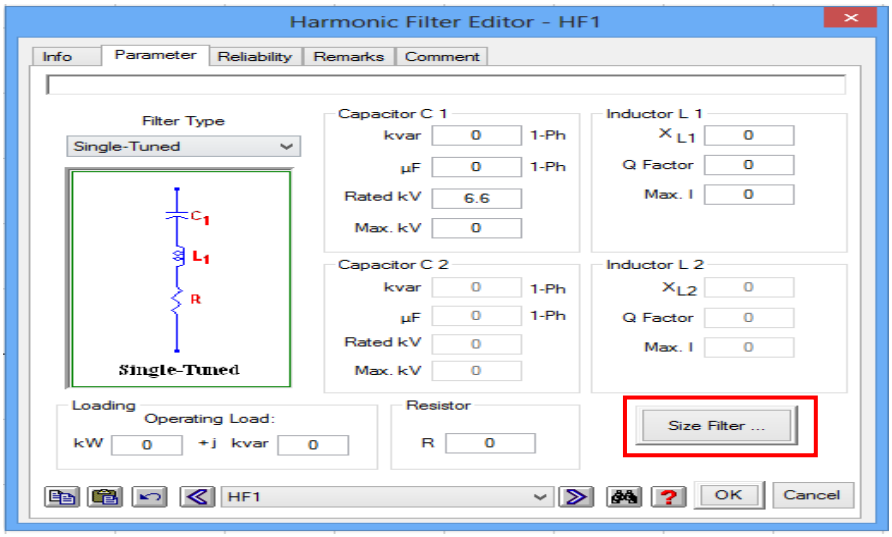
6. Run Frequency Scan and plot Z Magnitude v/s Order.



Harmonic Analysis

Case-5

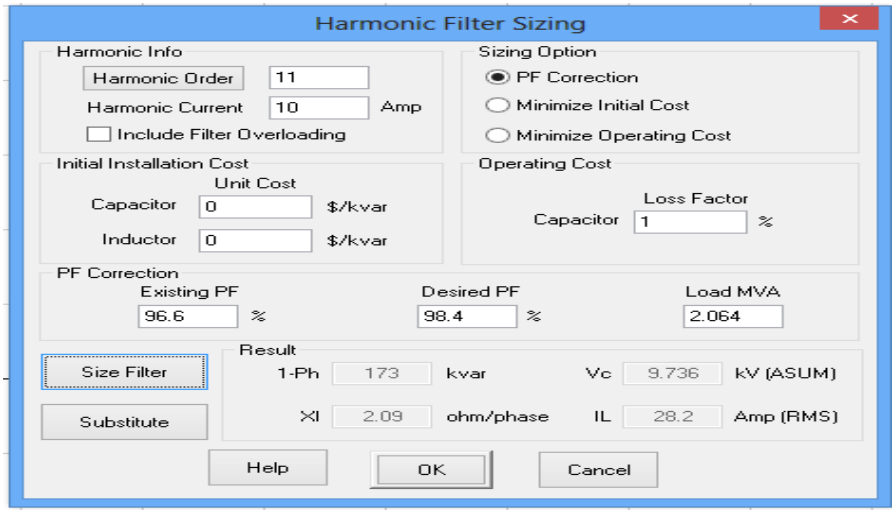
1. Create a New Study Case (Filters).
2. Connect Harmonic Filter at Bus 5 and double click on it.
3. Go to Parameter page and click on size filter.



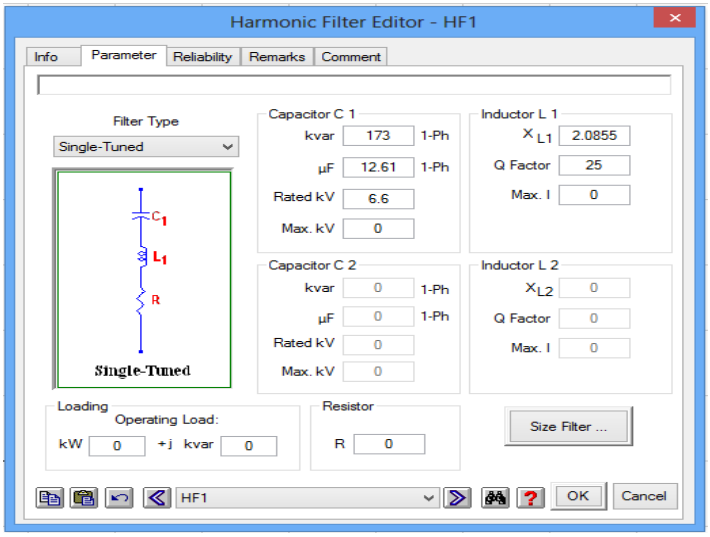
4. Enter harmonic order, harmonic current, existing & desired power factors and load MVA i.e.HF1 is tuned to 11th harmonic and to improve power factor from 96.6% to 98.4% at 2.064 MVA.

   Note: Load and power factor are noted on transformer 6.6 kV side before connecting the filters.

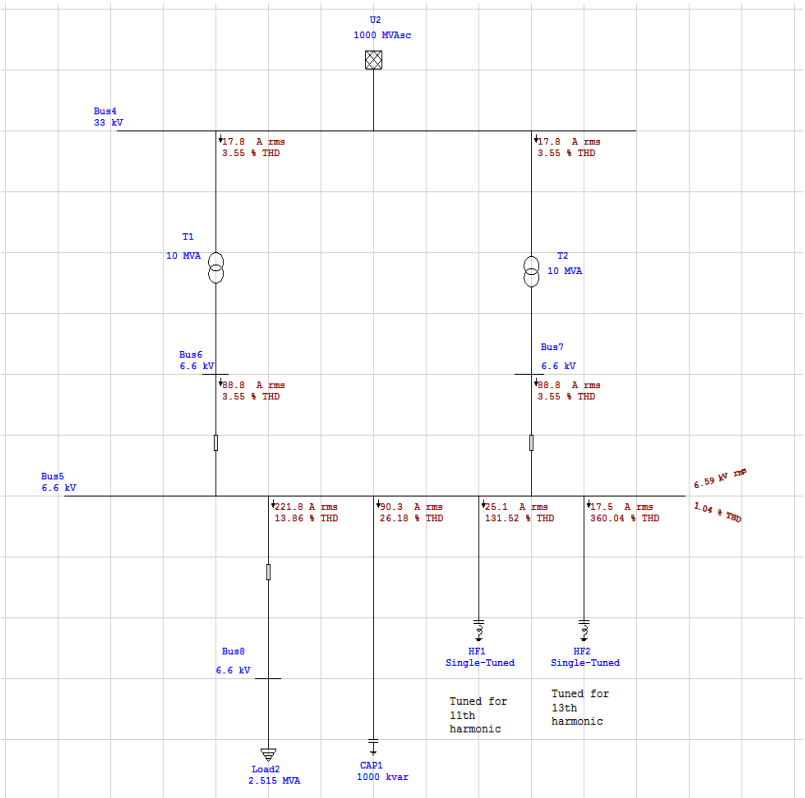
5. Click on size filter and substitute, enter the value of Q factor as 25.



Harmonic Analysis



6. Connect one more Harmonic Filter at Bus 5 and double click on it. Go to Parameter page and click on size filter.
7. Enter harmonic order, existing & desired power factors and load MVA i.e.HF2 is tuned to 13th harmonic and to improve power factor from 98.4% to 99% at 2.032 MVA.
8. Click on size filter and substitute, enter the value of Q factor as 25.
9. Run Harmonic Load Flow with both the filters ON and check the results.
10. Check for results with harmonic slider set to Total.

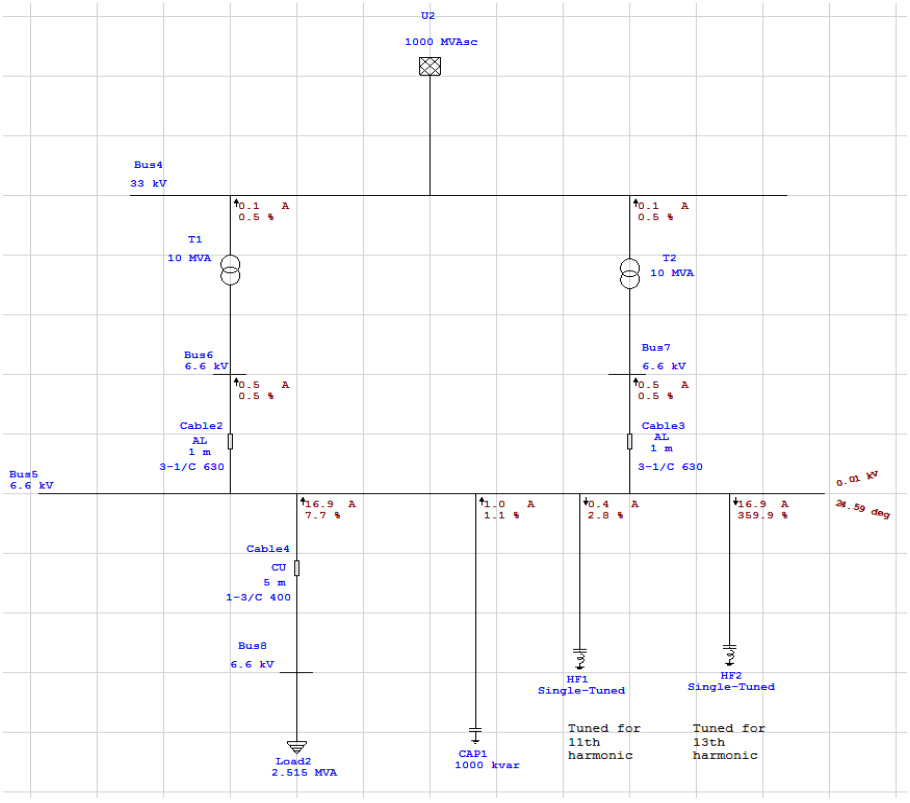


Total harmonic voltage distortion = **1.04** %

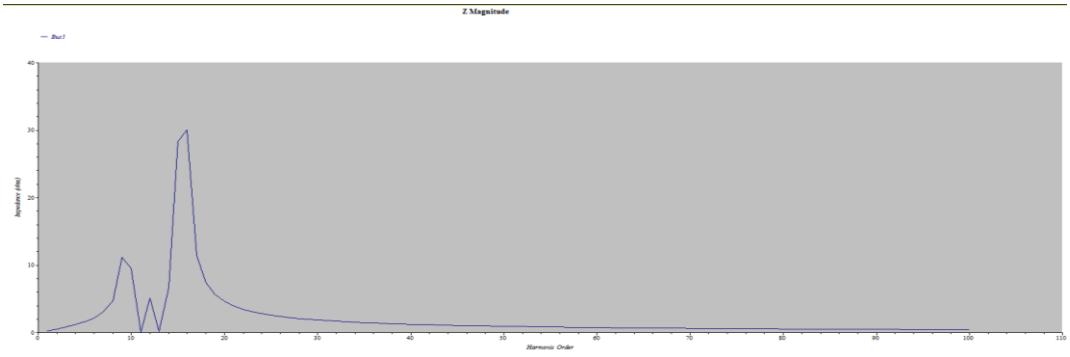
Total harmonic current distortion = **3.55**%

Harmonic Analysis

11. Check for results with harmonic slider set to 13th harmonic.



12. Check frequency scan results as shown below.



13. Comparison of results for Case-3 & Case-5 are as follows.

	System without capacitor	System with filters and capacitors
%THD-V at Bus 5	3.70	1.04
%THD-I through cable2	13.86	3.55

Observe that %THD reduces well below normally accepted values with 11th and 13th harmonic filters in the system.