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# Harmonics and Their Impact in Determining the Method of Reactive Power Compensation in Electrical Grids

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***Abstract*—The paper presents the modeling of different ways to compensate for the reactive power of an electrical grid using Matlab, where the parameters of transformers and filters used in this exam are calculated. The network is modeled, the calculated parameters of transformers and filters are entered. The paper discusses different cases to compensate the reactive power and presents the process of selecting a way providing low-value harmonics. Note that the grid is three-phase and balanced and filters are installed on 5.5 KV grid. The results prove that the best way to compensate the reactive power is to install the resonant shunt filter tuned on (5th) harmonic and the (2nd) damped filter tuned on the (7th) harmonic.**

***Keywords*—harmonic, spectrum, total harmonic distortion (THD), disturbing equipment, parallel resonant (anti-resonant)**

## NOMENCLATURE

THD: Total harmonic distortion (in per unit).

$f_1$ Fundamental frequency (Hz).

$f_1$ Anti-resonance frequency (Hz).

$f_r$ Resonance frequency (Hz).

$n_{ar}$ The order of anti-resonance (in per unit).

$n_r$ The order of resonance (in per unit).

$q$ Quality factor of a reactor.

$Q$ Quality factor of a filter (in per unit).

$Q$ Reactive power (var).

$P_0$ Loss of active power (W).

$i_0$ Transformer current without load (A).

## I. INTRODUCTION

Electricity is generally distributed as three voltage waves forming a 3-phase sinusoidal system. One of the characteristics of such a system is its waveform, which must always remain as close as possible to that of a pure sine wave[1],[2],[3]. If distorted beyond certain limits, as is often the case on networks comprising sources of harmonic currents and voltages such as arc furnaces, static power converters [4],[5] lighting systems, etc., the waveform must be corrected [6].Demonstration of the effect of harmonics generated in electrical networks on the method of compensation reactive power.

## II. CALCULATE THE PARAMETERS OF THE TRANSFORMER FILTERS USED IN THE ELECTRICAL GRID

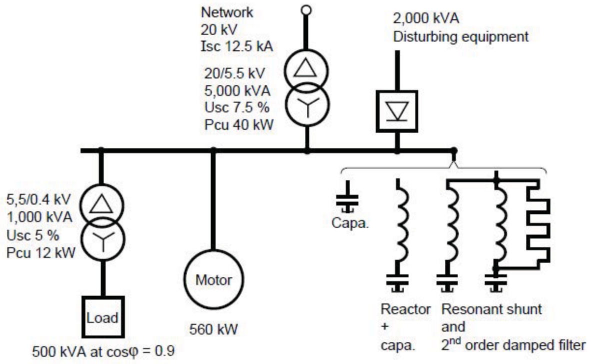

Fig. 1. .Electric power grid [5].

Calculate the first transformer parameters:

From fig.1, the first transformer constants can be observed:

$U_n$=20[KV] , Sn=5000 [KVA] , Usc= 7.5% ,

Pcu = 40 [Kw]

To calculate the magnetic resistance(Rm) and the inductance(Lm) should be know (Po)and (io%)[7],[8]:

$$S = 5[\mathrm{MVA}], \mathrm{H_V} = 20[\mathrm{KV}], \mathrm{L_V} = 5.5[\mathrm{KV}],$$
$$U_{sc}\% = 7.5, \mathrm{P}_{sc} = 40[\mathrm{Kw}], \mathrm{P}_0 = 7.88[\mathrm{Kw}], i_0\% = 0.95$$

Now we can calculate the first transformer parameters:

Primary coil:

$$\left.\begin{aligned} R_{T\text{-}1} &= \frac{Psc \times U_1^{\,2}}{S_n^{\,2}} \times 10^3 = 0.64[\Omega] \\ X_1 &= \frac{U_{sc} \times U_1^{\,2}}{S_n} \times 10 = 6[\Omega] \\ L_1 &= \frac{X}{2 \times \pi \times f} = .019[H] \end{aligned}\right\} \tag{1}$$

Secondary coil:

$$\left.\begin{aligned} R_{T\text{-}2} &= \frac{Psc \times U_2^{\,2}}{(S_n^{\,2})} \times 10^3 = 0.0484[\Omega] \\ X_2 &= \frac{U_{sc} \times U_2^{\,2}}{S_n} \times 10 = 0.453[\Omega] \\ L_2 &= \frac{X}{2 \times \pi \times f} = 1.441 \times 10^{-3}[H] \end{aligned}\right\} \tag{2}$$

For transformer:

$$\left.\begin{aligned} G_m &= \frac{Po}{Un^2 \times 10^3} = 1.97 \times 10^{-5}[Sm] \\ B_m &= \frac{io \times Sn}{Un^2 \times 10^5} = 1.1875 \times 10^{-4}[Sm] \\ Y &= G_m - jB_m = 1.97 \times 10^{-5} - j1.1875 \times 10^{-4} \;\; [Sm] \\ Z_m &= R_m + jX_m = 1359.59 + j8195.5 \;\; [\Omega] \\ L &= \frac{X_m}{2\pi \times f} = 26.087 \;\; [H] \end{aligned}\right\} \tag{3}$$

Calculate the second transformer parameters:

From fig.1, the second transformer constants can be observed:

Un=5.5[KV] , Sn=1000 [KVA] , Usc= 5% , Pcu = 12 [Kw]

To calculate the magnetic resistance(Rm) and the inductance(Lm) should be know (Po)and (io%):

$$S = 1[\mathrm{MVA}], H_V = 5.5[\mathrm{KV}], L_V = 0.4[\mathrm{KV}], U_{sc}\% = 5,$$
$$P_{sc} = 12[\mathrm{Kw}], P_0 = 2.1[\mathrm{Kw}], i_0\% = 1.4$$

Now we can calculate the second transformer parameters:

Primary coil:

$$\left.\begin{aligned} R &= \frac{Psc \times U_1^{\,2}}{S_n^{\,2}} \times 10^3 = 0.363[\Omega] \\ X_1 &= \frac{U_{sc} \times U_1^{\,2}}{S_n} \times 10 = 1.512[\Omega] \\ L_1 &= \frac{X}{2 \times \pi \times f} = 4.812 \times 10^{-3}[H] \end{aligned}\right\} \tag{4}$$

Secondary coil:

$$\left.\begin{aligned} R_{T\text{-}2} &= \frac{Psc \times U_2^{\,2}}{(S_n^{\,2})} \times 10^3 = 1.92 \times 10^{-3}[\Omega] \\ X_2 &= \frac{U_{sc} \times U_2^{\,2}}{S_n} \times 10 = 8 \times 10^{-3}[\Omega] \\ L_2 &= \frac{X}{2 \times \pi \times f} = 2.545 \times 10^{-5}[H] \end{aligned}\right\} \tag{5}$$

For transformer:

$$\left.\begin{aligned} G_m &= \frac{Po}{Un^2 \times 10^3} = 3.942 \times 10^{-5}[Sm] \\ B_m &= \frac{io \times Sn}{Un^2 \times 10^5} = 4.628 \times 10^{-4}[Sm] \\ Y &= G_m - jB_m = 3.942 \times 10^{-5} - j4.628 \times 10^{-4} \;\; [Sm] \\ Z_m &= R_m + jX_m = 316.98 + j2113.21 \,[\Omega] \\ L &= \frac{X_m}{2\pi \times f} = 6.7265 \,[H] \end{aligned}\right\} \tag{6}$$

Calculate short-circuit (Ssc)[9], short-circuit resistance (rsc) and short-circuit inductance( Lsc)

From Fig.1: Un=20[KV] , Isc = 12.5 [KA]

$$\left.\begin{aligned} S_{sc} &= U_n \times I_{sc} = 20 \times 12.5 = 250[MVA] \\ Z_{sc} &= \frac{U_n^{\,2}}{\sqrt{3} \times S_{sc}} = 0.923[\Omega] \\ X_{sc} &= 0.98 \times Z_{sc} = 0.904[\Omega] \\ L_{sc} &= \frac{X_{sc}}{2\pi \times f} = 2.879 \times 10^{-3}[H] \\ r_{sc} &= 0.2 \times Z_{sc} = 0.1846[\Omega] \end{aligned}\right\} \tag{7}$$

The calculation of the reactive power to be compensated in this network:

From Fig.1: Load:

$$\left.\begin{aligned} P_L &= S_L \times \cos\phi_1 = 450[KW] \\ Q_L &= S_L \times \sin\phi_1 = 217.5[KVAR] \end{aligned}\right\} \tag{8}$$

Motor : Pn=560[KW] $\cos\phi_2$=0.92, PF=0.8

$$\left.\begin{aligned} P_m &= \frac{P_n}{\eta} = 608.69[KW] \\ S_m &= \frac{P_{in}}{\cos\phi_2} = 760.8[KVA] \\ Q_m &= S_m \times \sin\phi_2 = 456.48[KVAR] \end{aligned}\right\} \tag{9}$$

Disturbing Equipment: S=2000[KVA], PF=0.98

$$\left.\begin{array}{l} P_D = S_D \times \cos\phi_3 = 1960[KW] \\ Q_D = S_D \times \sin\phi_3 = 397.99[KVAR] \end{array}\right\} \tag{10}$$

$$\left.\begin{array}{l} \sum Q = Q_L + Q_m + Q_D = \\ \sum Q = 1071.97[KVAR] \end{array}\right\} \tag{11}$$

Reactive power to be compensated:

$$Q_c = 1000\left[KVAR\right] \tag{12}$$

The power scheme for the electric grid:

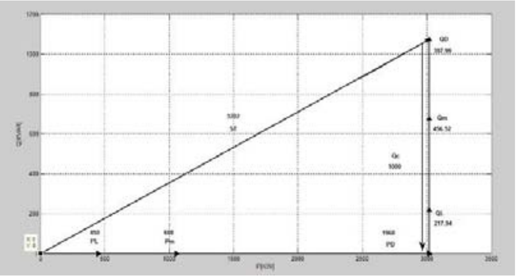

Fig. 2. The power scheme for the electric grid.

## III. METHODS OF COMPENSATING REACTIVE POWER:

Capacitor bank alone to compensate reactive power:

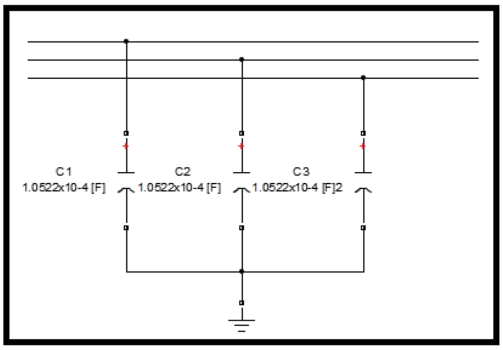

Fig. 3. Bank of capacitors compensates connected as $(\lambda)$

The reactive power required to be compensated from bank of capacitors is $Q_c = 1000\ [KVAR]$

Since the load is three phases and balanced, the capacitors will be connected to the rod in which the harmonic disturbance device is connected 5.5[KV].

We should be calculated [10],[11],[12],[13]:

The capacitance of the reactive power compensation [14] of one phase:

$$C = \frac{Q_{\text{var},ph}}{U_{ph}{}^2 \times 2 \times \pi \times f_1} = 1.0522 \times 10^{-4}[F] \tag{13}$$

Short-circuit inductance of the secondary coil:

$$L_{sc,2} = K^2 \times L_{sc,1} = 2.178 \times 10^{-4}[\mathrm{H}] \tag{14}$$

Anti-resonance frequency:

$$f_{ar} = \frac{1}{2\pi\sqrt{(\mathrm{L}_{\mathrm{SC}} + \mathrm{L}_{\mathrm{T}}).\mathrm{C}}} = 381.56[\mathrm{H}z] \tag{15}$$

The order of anti-resonance:

$$n_{ar} = \frac{f_{ar}}{f_1} = 7.63 \tag{16}$$

Reactor-connected capacitor bank to compensate reactive power:

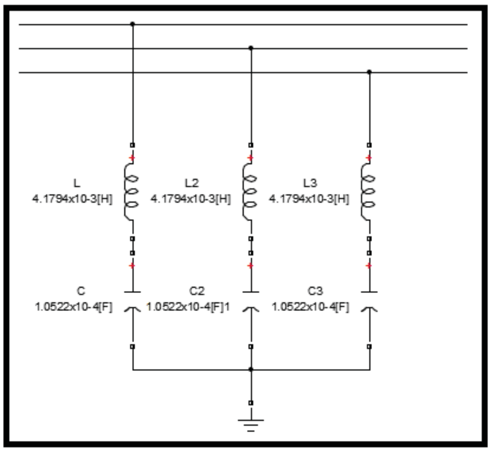

Fig. 4. .Bank of capacitors compensates with inductances connected as $(\lambda)$

This equipment is arbitrarily tuned to

$$f_r = 4.8 \times f_1 = 240[\mathrm{H}z] \tag{17}$$

Inductance connected to capacitor compensation:

$$L = \frac{1}{(2\pi)^2 \times f_r{}^2 \times C} = 4.1794 \times 10^{-3}[\mathrm{H}] \tag{18}$$

Resonant shunt filter tuned to the 5th harmonic and a damped filter tuned to the 7th harmonic:

In this case, the distribution of the reactive power between the two filters is such that the filtered 5th and 7th voltage harmonics have roughly the same value:

$$Q_{\text{var},rf} = Q_{\text{var},df} = 500[KVAR] \tag{19}$$

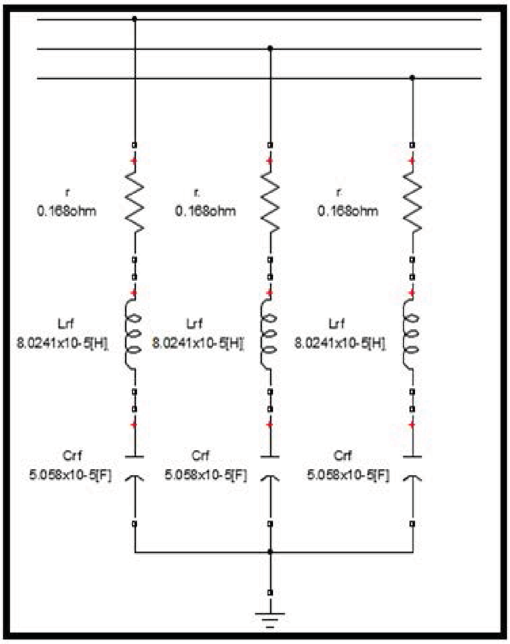

Fig. 5. Resonant shunt filter tuned to the 5th harmonic.

$Q_{\text{var}} = 500[KVAR]$

$n_r = 5$ The order of resonance:

The quality factor of a filter: $Q = 75$

$$\left.\begin{aligned}
&C = \frac{Q_{\text{var}}}{\frac{n_r^2}{n_r^2-1} \times U^2 \times 2 \times \pi \times f_1} = 5.0508 \times 10^{-5}[F] \quad f_r = n_r \times f_1 = 250[\text{Hz}] \\
&L = \frac{1}{(2\pi)^2 \times f_r^2 \times C} = 8.0241 \times 10^{-3}[\text{H}] \quad \text{X}_0 = \sqrt{\frac{L}{C}} = 12.604[\Omega] \\
&r = \frac{\text{X}_0}{Q} = 0.168[\Omega]
\end{aligned}\right\} \tag{20}$$

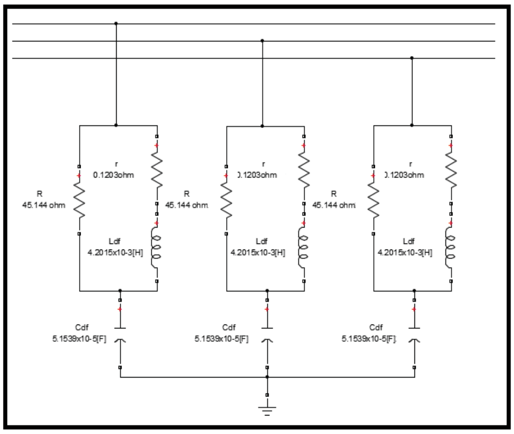

Fig. 6. Damped filter tuned to the 7th harmonic.

$Q_{\text{var}} = 500[KVAR]$

$$\left.\begin{aligned}
&C = \frac{Q_{\text{var}}}{\frac{n_r^2}{n_r^2-1} \times U^2 \times 2 \times \pi \times f_1} = 5.1539 \times 10^{-5}[F] \quad f_r = n_r \times f_1 = 350[\text{Hz}] \\
&L = \frac{(1+Q \times q)^2}{(2\pi \times q)^2 \times (Q^2-1)^2 \times f_r^2 \times C} = 4.2075 \times 10^{-3}[\text{H}] \\
&\text{X}_0 = \sqrt{\frac{L}{C}} = 9.028[\Omega] \Rightarrow r = \frac{\text{X}_0}{q} = \frac{9.028}{75} = 0.12[\Omega] \\
&R = \text{X}_0 \times Q = 45.144[\Omega]
\end{aligned}\right\} \tag{21}$$

## IV. MODELING THE ELECTRICAL GRID USING MATLAB [15],[16] AND DISCUSSING THE DIFFERENT COMPENSATION CASES FOR REACTIVE POWER

Modelling the electrical grid:

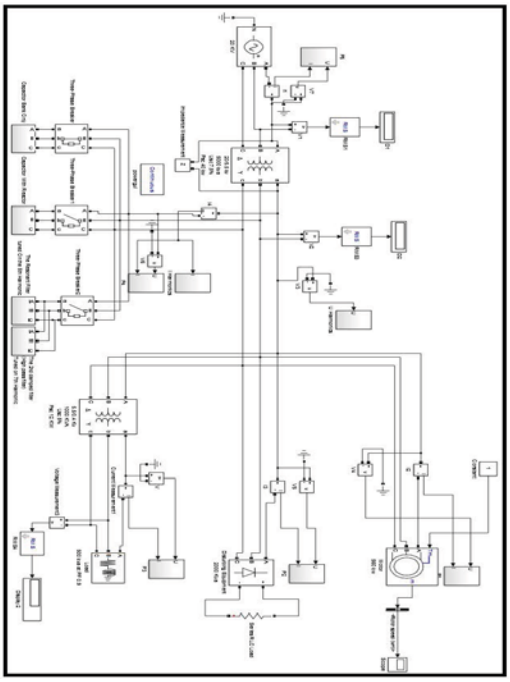

Fig. 7. Modeling the electrical grid.

Fig.7 Illustrates Modeling the electrical grid using Matlab where we entered: Parameters of the(First transformer- Second transformer-Motor Disturbing equipment-Load).

Discussing the different compensation cases:

Capacitor bank alone to compensate reactive power:

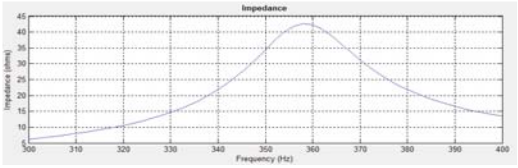

Fig. 8. The network harmonic impedance curve.

Fig.8 shows the curve of the resistance of the grid to the harmonic angle seen from the node where the harmonic currents are injected, exhibits a maximum(anti-resonance) in the vicinity of the 7th current.

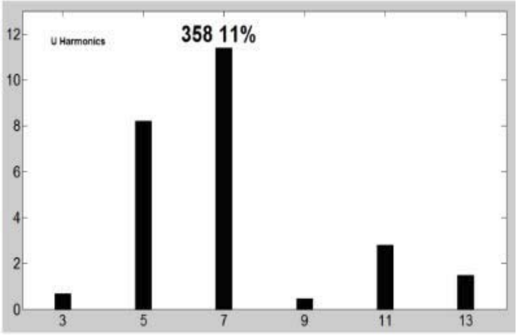

Fig. 9. Harmonic voltage spectrum of a 5.5[KV] network.

TABLE I. HARMONIC VOLTAGE

| **Harmonic Voltage** | 3 | 5 | 7 | 9 | 11 | 13 |
|---|---|---|---|---|---|---|
| % | 0.02% | 8.21% | 11% | 0.22% | 2.8% | 1.4% |

This results in an unacceptable individual harmonic voltage[17] distortion of 11% for the 7th harmonic.

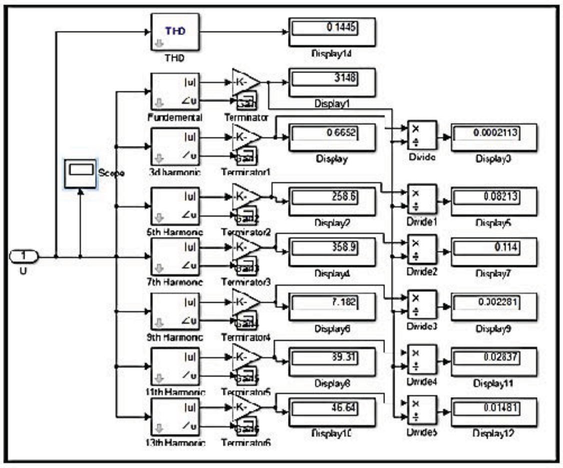

Fig. 10. Value of total harmonic distortion (THDV).

The following characteristics are also unacceptable: From fig.10, total harmonic voltage distortion of 14.25% for 5.5[KV] the network. Compared to the maximum permissible value of 5%.This percentage is unacceptable[18].The solution with capacitors alone is therefore unacceptable. Reactor-connected capacitor bank to compensate reactive power: This equipment is arbitrarily tuned to:

$$f_r = 4.8 \times f_1 = 4.8 \times 50 = 240[\mathrm{H}z] \tag{22}$$

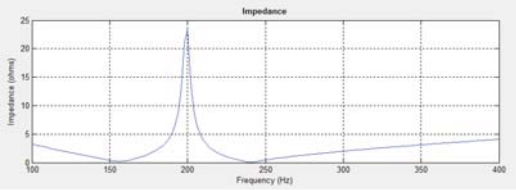

Fig. 11. The network harmonic impedance curve.

Fig.11 shows the network harmonic impedance curve seen from the node where the harmonic currents are injected, exhibits a maximum of 23 ohms (anti-resonance) in the vicinity of the 4th current.

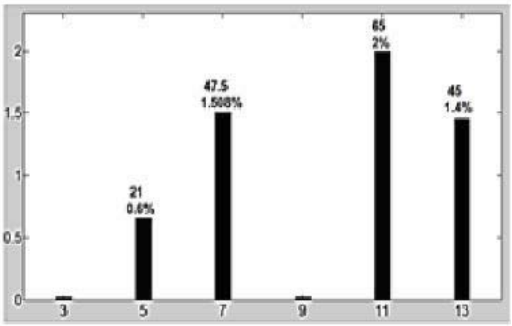

Fig. 12. .Harmonic voltage spectrum of a 5.5[KV] network.

TABLE II. HARMONIC VOLTAGE

| **Harmonic Voltage** | 3 | 5 | 7 | 9 | 11 | | 13 |
|---|---|---|---|---|---|---|---|
| % | 0.012 % | 0.60 % | 1.508% | 0.031% | 2% | | 1.4% |

For the 5.5[KV] network, the individual harmonic voltage ratios of 1.508%(7th harmonic),2% (11th harmonic) and 1.4%(13th harmonic) may be too high for certain sensitive loads.

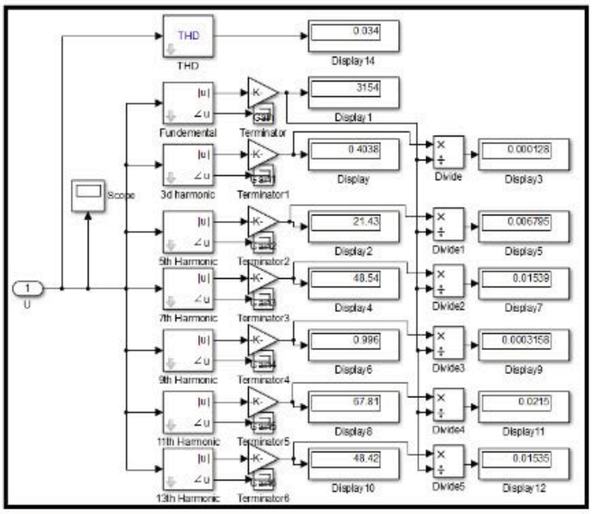

Fig. 13. Value of total harmonic distortion(THDV).

From fig.13 the total harmonic voltage distortion of 3.4% is acceptable. Resonant shunt filter[19] tuned to the 5th harmonic and a damped filter tuned to the 7th harmonic:

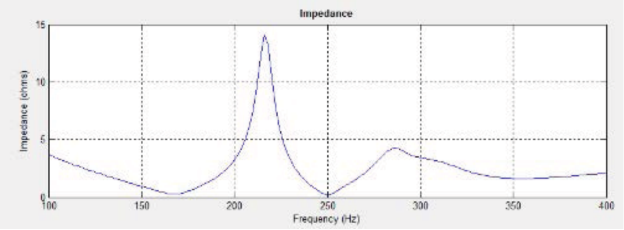

Fig. 14. The network harmonic impedance curve.

Fig.14 shows the network harmonic impedance curve, seen from the node where the harmonic currents [20] are injected, exhibits a maximum of 14 ohms (anti-resonance)in the vicinity of the 4th current. For the 5th harmonic, this impedance is reduced to the reactor resistance. For the 7th harmonic, the low, purely resistive impedance of the damped filter also reduces the individual harmonic voltage. For harmonics higher than the tuning frequency, the damped filter impedance curve reduces the corresponding harmonic voltages. This equipment, therefore, offers an improvement over the second solution (reactor-connected capacitors).

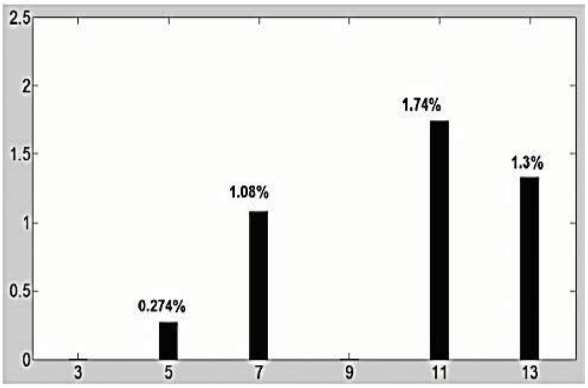

Fig. 15. Harmonic voltage spectrum of a 5.5[KV] network.

TABLE III. HARMONIC VOLTAGE

| Harmonic Voltage | 3 | 5 | 7 | 9 | 11 | 13 |
|---|---|---|---|---|---|---|
| % | - | 0.274% | 1.08% | - | 1.74% | 1.3% |

For the 5.5[KV] network, the individual harmonic voltage ratios of 0.274%(5th harmonic),1.08% (7th harmonic), 1.74%(11th harmonic) and 1.3%(13th harmonic) may be too high for most sensitive loads.

From fig.16: the total voltage distortion of 3.6% is acceptable.

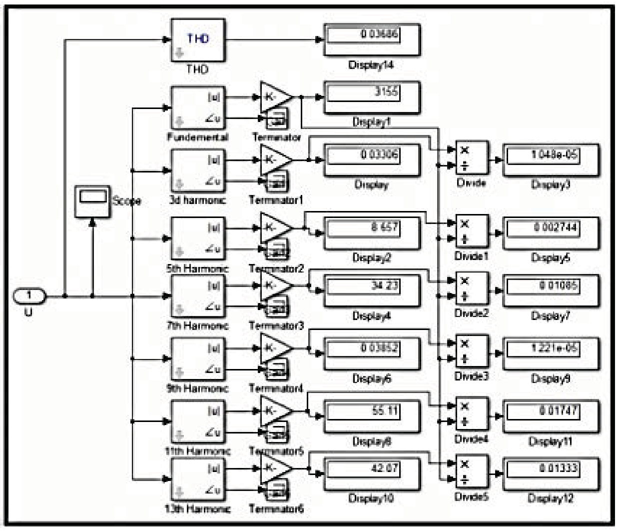

Fig. 16. Value of total harmonic distortion(THDV).

## V. CONCLUSION

In the case of electrical networks, where (THDV). is less (5%), reactive power can be compensated directly by a capacitor bank to compensate for reactive power, but if (THDV).is greater (5%), the filters should be placed in parallel with the capacitor bank to compensate for reactive power. Finally filters should be used to remove electrical networks from harmonic electrical devices and compensating capacitors.

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