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Improving the Power Factor Correction in the Presence of Harmonics by Reducing the Effect of Resonance and Harmonics

Saber M. Saleh*[1], Mohamed E. Arafa[2]
[1]Department of Electrical Power and Machines, Faculty of Engineering, Fayoum University
[2]Middle Egypt electricity zone, Egyptian Electricity Transmission Company, El-Fayoum
Corresponding author, e-mail: sabermssh@gmail.com*, nomiran2013@hotmail.com

Abstract

Harmonics in electrical networks occur as a result of non-linear loads. It has an effect on power factor improvement using capacitors in terms of increasing the unbalance current between units. In addition, the occurrence of resonance and result in the exit of capacitors from service by the protective relays to protect the units from collapse. The main objective of this research is the real-time study of improving the power factor with reducing the effect of the resonance and harmonics on the power system. This reduction can be done using filters, consist of reactors and capacitors connected in series or in parallel or series and parallel together to reduce the current harmonics or voltage harmonics. Single Tuned filter type (passive filter) is used which presents very low impedance at the tuning frequency, through which all current of that particular frequency will be diverted. This research presents two practical power systems 11kV source in Fayoum substation and 13.8kV source in New Badr substation connected to power factor Improvement circuit. These models simulated by Matlab at different unbalance currents and harmonics. Also, it presents the design of the series reactor and the harmonics filter which satisfy the minimum effect of resonance and harmonics.

Keywords: *capacitor bank, resonance, harmonics*

1. Introduction

In the past several decades, there has been a rapid growth in the power grid all over the world which eventually led to the installation of a huge number of new substations, transmission and distribution lines. This growth has led to increasing in the nonlinear loads which cause voltage and current harmonics in the electrical network which have a significant effect on the electrical equipment [1]. Harmonics in electrical networks occur as a result of non-linear loads and the resulting effect is more significant at power factor improvement using capacitors in terms of increasing the unbalance current between units in addition to the occurrence of resonance and result in the exit of capacitors from service using the protective relays (over current relays) to protect the units from damage [2-5]. Also, the distortion which produced in the voltage and current waveforms by harmonics causes increasing of the losses in power and reduces the lifetime of the electrical equipment [6-9].

Detuned Filter Reactors are used in series with capacitor banks in power factor correction units. By using these types of detuned reactors it is possible to avoid negative effects on the power system. The detuning factor (P %) is proportional to the resonance frequency and can be calculated from the following equations and the Table 1 shows the available detuning factors and their resonance frequencies [10-14].

$$\mathrm{Fres} = \frac{\mathrm{Fn}}{\sqrt{\frac{\mathrm{P\,\%}}{100}}}$$

$$\mathrm{P} = \left(\frac{\mathrm{Fn}}{\mathrm{Fres}}\right)^2 * 100$$

Where:

Fn is the fundamental frequency.
Fres is the resonance frequency.

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Table 1. Detuning Factor and Resonance Frequency

Detuning Factor P %	Resonance Frequency Fres
5 %	224 Hz
5.5 %	213 Hz
5.67 %	210 Hz
6 %	204 Hz
7 %	189 Hz
8 %	177 Hz
12.5 %	141 Hz
14 %	134 Hz

This technical paper has the purpose of analyzing this problem, starting from the definition of power factor correction, studying the effects of harmonics on power system, studying the harmonic filtering techniques and the steps of designing the detuning filter (series reactor) to solve the problem of resonance and also the steps of designing the single tuned filter (passive filter) to solve the problem of harmonics in two substations. The first one found in Egypt which called Fayoum substation which has parameters of (11 kV secondary source of 25 MVA power transformer operates on 50Hz frequency) and the second one lies in Saudi Arabia which called New Badr substation which has parameters of (13.8 kV secondary source of 73 MVA power transformer operates on 60Hz frequency). Also, Simulation of this model presented using (Matlab) software at different unbalance currents and harmonics [8, 9].

2. Cases of Study

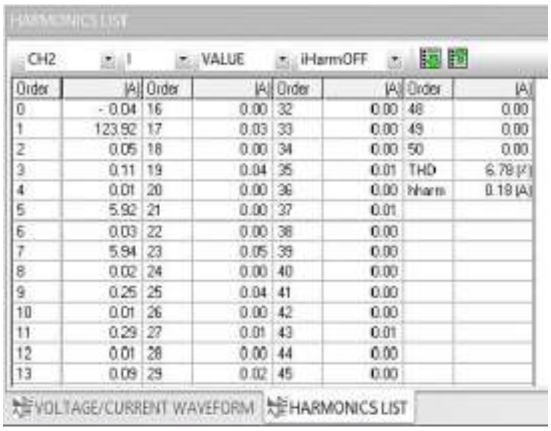
Case 1: (Fayoum Substation 66 KV)

The current THD measurements are practically taken as listed in Table 2, 3, and 4 since December 2014 for medium voltage (11KV) outgoing feeder for one day in Fayoum substation which consists of four (step down) transformers with technical information for each transformer as:

Apparent power = 25 MVA.
Turns Ratio = 66/11 KV.
Frequency = 50 Hz.
Medium Voltage Capacitor Banks up to 5.4 MVAR containing two steps.
Short Circuit Impedance (Z %) = 10%.

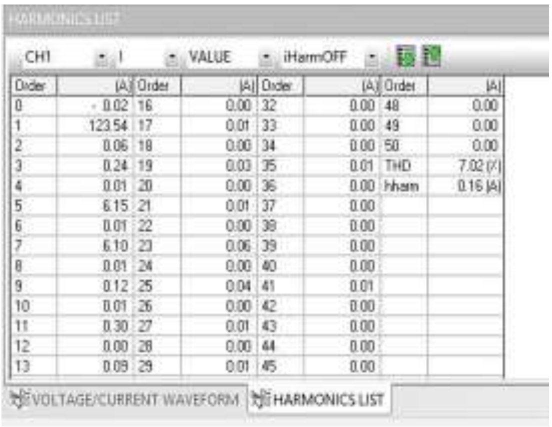
The instrument which used to measure harmonics is Power Quality analyzer called (HIOKI power analyzer PW3198).

Table 2. THDi for Phase R



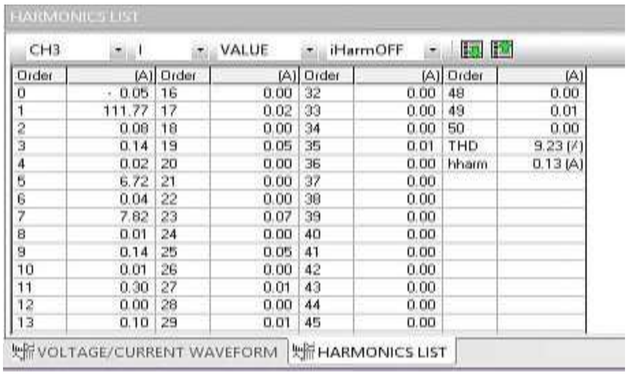
Order	[A]	Order	[A]	Order	[A]	Order	[A]
0	- 0.04	16	0.00	32	0.00	48	0.00
1	123.92	17	0.03	33	0.00	49	0.00
2	0.05	18	0.00	34	0.00	50	0.00
3	0.11	19	0.04	35	0.01	THD	6.78 [%]
4	0.01	20	0.00	36	0.00	Iharm	0.19 [A]
5	5.92	21	0.00	37	0.01		
6	0.03	22	0.00	38	0.00		
7	5.94	23	0.05	39	0.00		
8	0.02	24	0.00	40	0.00		
9	0.25	25	0.04	41	0.00		
10	0.01	26	0.00	42	0.00		
11	0.29	27	0.01	43	0.01		
12	0.01	28	0.00	44	0.00		
13	0.09	29	0.02	45	0.00		

Table 3. THDi for Phase S



Order	[A]	Order	[A]	Order	[A]	Order	[A]
0	- 0.02	16	0.00	32	0.00	48	0.00
1	123.54	17	0.01	33	0.00	49	0.00
2	0.06	18	0.00	34	0.00	50	0.00
3	0.24	19	0.03	35	0.01	THD	7.02 [%]
4	0.01	20	0.00	36	0.00	Iharm	0.16 [A]
5	6.15	21	0.01	37	0.00		
6	0.01	22	0.00	38	0.00		
7	6.10	23	0.06	39	0.00		
8	0.01	24	0.00	40	0.00		
9	0.12	25	0.04	41	0.01		
10	0.01	26	0.00	42	0.00		
11	0.30	27	0.01	43	0.00		
12	0.00	28	0.00	44	0.00		
13	0.09	29	0.01	45	0.00		

Table 4. THDi for Phase T



Order	(A)	Order	(A)	Order	(A)	Order	(A)
0	0.05	16	0.00	32	0.00	48	0.00
1	111.77	17	0.02	33	0.00	49	0.01
2	0.08	18	0.00	34	0.00	50	0.00
3	0.14	19	0.05	35	0.01	THD	9.23 (%)
4	0.02	20	0.00	36	0.00	hharm	0.13 (A)
5	6.72	21	0.00	37	0.00		
6	0.04	22	0.00	38	0.00		
7	7.82	23	0.07	39	0.00		
8	0.01	24	0.00	40	0.00		
9	0.14	25	0.05	41	0.00		
10	0.01	26	0.00	42	0.00		
11	0.30	27	0.01	43	0.00		
12	0.00	28	0.00	44	0.00		
13	0.10	29	0.01	45	0.00		

Case 2: (New Badr Substation 110 KV)

The harmonic current measurements are practically identified in New Badr substation as listed in tables 5, 6, and 7 which consists of (step down) transformers with technical information as follow:

Apparent power = 73 MVA.

Turns Ratio = 110/13.8 kV.

Frequency = 60 Hz.

Medium Voltage Capacitor Banks up to 2x7 MVAR containing two steps.

Short Circuit Impedance (Z %) = 22%.

The instrument which used to measure harmonics is Power Quality analyzer called (Chauvin Arnoux type CA8334).

These measurements were taken since January 2010 for two medium voltage (13.8KV) incomers for one day and the results of these measurements can be shown as follow [5]:

Tables 5. Voltage THD of Two 13.8 kV Incoming Feeders
Maximum Voltage harmonics as % of Fundamental

Incomer Ref.	**uthd**			**Vthd**		
	L2	**L2**	**L3**	**L1**	**L2**	**L3**
IC-1	0.70	0.60	0.80	0.10	0.10	0.10
IC-2	0.70	0.80	0.90	0.10	0.30	0.30

THDu – Total Harmonic Voltage Distortion, Phase to phase
THDv – Total Harmonic Voltage Distortion, Phase to Neutral

Tables 6. Current THD of two 13.8 kV Incoming Feeders
Maximum Current harmonics as % of Fundamental

Incomer Ref.	Incomer 1			Incomer 2		
	L1 Amps	L2 Amps	L3 Amps	L1 Amps	L2 Amps	L3 Amps
THDi %	3.30	3.40	3.50	5.30	5.40	5.50

THDi – Total Harmonic Current Distortion

Tables 7. Three Phase Current THD of Two 13.8 kV Incoming Feeders
Current Harmonics in Amps measured

Incomer Ref.	Incomer 1			Incomer 2		
	L1 Amps	L2 Amps	L3 Amps	L1 Amps	L2 Amps	L3 Amps
Ah01	319.10	320.10	321.20	323.50	328.40	330.60
Ah03	1.91	0.96	2.57	2.26	0.99	2.31
Ah05	9.25	9.60	9.64	15.53	15.76	16.20
Ah07	4.15	5.12	4.50	6.47	7.55	7.60
Ah11	2.23	2.24	1.93	3.24	3.61	2.98
Ah13	1.28	0.84	1.28	1.62	1.31	1.65

As may be noted from enclosed results, all higher order harmonics are present in the system as follow:

The maximum total harmonic voltage distortion for the phase to phase voltage, THDu measured is 0.9% as per the measurement results enclosed on IC-2.

The maximum total harmonic current distortion, THDi measured is 5.5% as per the measurement results enclosed on IC-2.

3. Research Methodology

Case 1: (Fayoum Substation 66 KV)

A. Designing of Detuning Filter

For 5.4 MVAR & 11 kV capacitor bank (type Tepco) as shown in Figure 1 and constructed for Fayoum substation harmonic resonance problem and the operation is only for the 3.6 MVAR step.

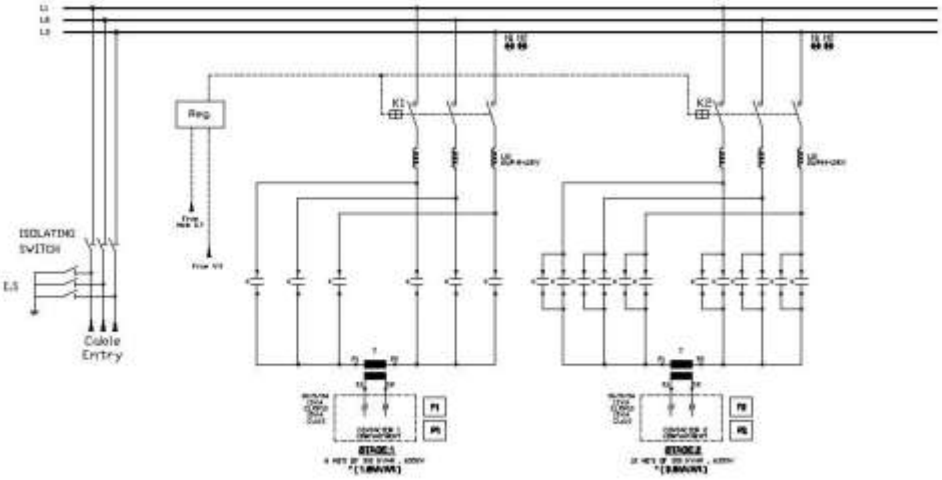


Figure 1. 11 kV Capacitor Bank (Tepco)

$$\text{Rated current at 11 kV bus}(\mathrm{I_C}) = \frac{\frac{\text{Total kVA}}{\sqrt{3}}}{\text{LINE VOLTAGE}} = \left[3.6 * \frac{1000}{\sqrt{3} * 11}\right] = 188.951\ \mathrm{A}$$

It is proposed to connect series reactor of rating 7% of capacitor bank rating, at each of the three phases so, as to protect capacitors against inrush current.

$$\mathrm{V_L} = \frac{7}{100} * \frac{11}{\sqrt{3}} = 444.559\mathrm{V}\ \text{ at } 7\%$$

$$\mathrm{XL_{(SR)}} = \frac{\mathrm{V_L}}{\mathrm{I_C}} = \frac{444.559}{188.951} = 2.35\ \Omega$$

$$\mathrm{L} = \frac{\mathrm{X_L}}{2\pi \mathrm{f}} = \frac{2.35}{2 * \pi * 50} = 7.48\ \mathrm{mH}$$

$\mathrm{V_L}$ = voltage drop per phase across the series reactor at 11 kV

$\mathrm{I_{SR}}$ = series reactor current rating $= \mathrm{I_C} * 1.3 = 188.951 * 1.3 = 245.64\ \mathrm{A}$

A factor of 1.3 has been considered while calculating the rated reactor current latitude given on capacitor MVAR in capacitor specification, then the rated current of filter chosen 250 A.

B. Determining the Effective Harmonics

$$\mathrm{n} = \sqrt{\frac{\mathrm{MVA_{S.C}}}{\mathrm{MVA_C}}}$$

n= harmonic of resonance

$\mathrm{MVA_{S.C}} = \text{short circuit MVA of 11 kV bus from short circuit study}$

$= 600 \text{ at } 31.5 \text{ kA \& } 3.6 MVAr$

$\mathrm{MVA_C} = \text{capacitive MVA on the 11 kV bus due to capactive bank} = 3.6$

$$n = \sqrt{\frac{600}{3.6}} = 12.90994 \approx 13$$

Therefore, at 13th harmonic resonance will occur, but the magnitude of 13th harmonic in the system is negligible so system study is safe.

Since the magnitude of 5th and 7th harmonic frequency is significantly high in the power system network, hence it is necessary to check that the resonance doesn't occur for these values.

The power transformer 25 MVA, 66/11 kV having an impedance of 10% acts as the source.

$$\mathrm{Z_S} = [\left(\frac{\mathrm{kV^2}}{\mathrm{MVA_{TR}}}\right) * \mathrm{Z}]$$

Where:

$\mathrm{Z_s} = \text{source impedance at transformer secondary}$

$\mathrm{Z} = \text{impedance of the transformer on its own base}$

$\mathrm{kV} = \text{voltage level at transformer secondary}$

$\mathrm{MVA_{TR}} = \text{MVA rating of power transformer}$

$$\mathrm{Z_S} = \left[\left(\frac{11^2}{25}\right) * 0.10\right] = 0.484\ \Omega$$

$$\mathrm{Z_S} = \mathrm{X_L} = 0.484\ \Omega$$

$$\mathrm{n\,X_L} = \mathrm{X_c}/\mathrm{n}$$

For 5th harmonic, inductive reactance of transformer will be 5 times.

$$\mathrm{n\,X_L} = 5 * 0.484 = 2.42\Omega$$

For 7th harmonic, inductive reactance of transformer will be 7 times.

$$\mathrm{n\,X_L} = 7 * 0.484 = 3.388\Omega$$

At 11 kV, capacitance reactance is given by:

$$\mathrm{X_C}'' = \frac{\mathrm{kV_B}^2}{\mathrm{Q_C}'} =$$

$\mathrm{X_C}'' = \text{Total capacitive reactance at 11 kV}$

$\mathrm{kV_B} = \text{Voltage level at 11 kV bus}$

$\mathrm{Q_C}' = \text{reactive power yield of capacitor bank connected to 13.8 kV bus}$

$$\mathrm{X_C}'' = \frac{11^2}{3.6} = 33.611\ \Omega$$

For 5th harmonic, inductive reactance of transformer will be 1/5 times.

$$\mathrm{X_C}/\mathrm{n} = 1/5 * 33.611 = 6.722\Omega$$

For 7th harmonic, inductive reactance of transformer will be 1/7 times.

$$\mathrm{X_C}/\mathrm{n} = 1/7 * 33.611 = 4.8\ \Omega$$

$\therefore$ For 5^{th}th harmonic $\mathrm{n\,X_L} \neq \mathrm{X_c}/\mathrm{n}$

$\therefore$ For 7^{th} harmonic $\mathrm{n\,X_L} \approx \mathrm{X_c}/\mathrm{n}$

Maybe critical resonance occurs at 7th harmonic, that mean the resonance may occur during normal operation (because the 7th harmonics is one of the positive sequence harmonics) or any types of faults.

C. Designing of Harmonic Filter

For a capacitor bank installed for reactive power compensation at a 3.6MVAR reactive power and 11KVapplication is to be tuned to the seventh harmonic. It's needed to determine the required reactor size and verify whether capacitor bank operation parameters fall within IEEE-18 recommended limits [7, 12, 15].

For THD equals to 7% as shown in technical measurements and assuming that the most of this THD caused by 7th harmonic the parameters of the passive filter can be determined according to IEEE-18 as following:

Using the preceding methodology and (by ignoring the resistance) the capacitor bank reactance (fundamental at 50 Hz) can be determined by the following equation:

$$\mathrm{X_{C1}}'' = \frac{\mathrm{kV_B}^2}{\mathrm{Q_C}} =$$
$$\mathrm{X_{C1}}'' = \frac{11^2}{3.6} = 23.61\ \Omega$$

Calculating of the series reactor required (by ignoring the resistance):

$$\mathrm{X_{L1}}'' = \frac{\mathrm{X_{C1}}}{\mathrm{n}^2}$$
$$\mathrm{X_{L1}}'' = \frac{33.61}{7^2} = 0.686\ \Omega$$

Determine whether capacitor-operating parameters fall within IEEE-18 recommended limits. RMS current through the filter:

$$\mathrm{I_1}'' = \frac{\mathrm{kV_B}}{\mathrm{X_{C1}} - \mathrm{X_{L1}}}$$
$$\mathrm{I_1}'' = \frac{11000/\sqrt{3}}{(33.61 - 0.686)} = 192.9\ \mathrm{A}$$
$$\mathrm{I_7}'' = \frac{\mathrm{THD\ x\ MVA}}{\sqrt{3}\mathrm{kV_B}} =$$
$$\mathrm{I_7}'' = \frac{(\frac{7}{100})\ \mathrm{x}\ 25\mathrm{e}6}{\sqrt{3}\ \mathrm{x}\ 11\mathrm{e}3} = 91.85\ \mathrm{A}$$
$$\mathrm{X_{C7}}'' = \frac{\mathrm{X_{C1}}}{\mathrm{n}}$$
$$\mathrm{X_{C7}}'' = \frac{33.61}{7} = 4.8\ \Omega$$

Peak and RMS voltages through the capacitor:

$$\mathrm{Vc_{peak}} = \sqrt{2}\ [\mathrm{V_{c1}} + \mathrm{V_{ch}}]$$
$$\mathrm{Vc_{peak}} = \sqrt{2}\ [\mathrm{I_1X_{C1}} + \mathrm{I_{7X_{C7}}}]$$
$$\mathrm{Vc_{peak}} = \sqrt{2}\ [192.9\mathrm{x}33.61 + 91.85\mathrm{x}4.8]$$
$$\mathrm{Vc_{peak}} = 9792.4\ \mathrm{V}$$
$$\mathrm{Vc_{rms}} = \sqrt{(\mathrm{V_{c1}}^2 + \mathrm{V_{ch}}^2)}$$
$$\mathrm{Vc_{rms}} = \sqrt{((192.9\mathrm{x}33.61)^2 + (91.85\mathrm{x}4.8)^2)}$$
$$\mathrm{Vc_{rms}} = 6498.34\ \mathrm{V}$$
$$\frac{\mathrm{Vc_{rms}}}{\mathrm{Vc_{rms\ rated}}} = \frac{6498.34}{\left[\frac{11000}{\sqrt{3}}\right]} = 1.02\ \mathrm{p.u}$$

(Below 1.1 p.u limit of IEEE-18)

$$\frac{\mathrm{Vc_{peak}}}{\mathrm{Vc_{peak\ rated}}} = \frac{9792.4}{\sqrt{2}\left[\frac{11000}{\sqrt{3}}\right]} = 1.09\ \mathrm{p.u}$$

(Below 1.2 p.u limit of IEEE-18)

The RMS current through the reactor is the summation of all RMS currents that will flow through the filter. The assumption here is that only the seventh harmonic is involved:

$$\mathrm{Ic_{rms}} = \sqrt{(\mathrm{I_{c1}}^2 + \mathrm{I_{ch}}^2)}$$

$$\mathrm{Ic_{rms}} = \sqrt{((192.9)^2 + (91.85)^2)}$$

$$\mathrm{Ic_{rms}} = 213.65\ \mathrm{A}$$

$$\frac{\mathrm{Ic_{rms}}}{\mathrm{Ic_{rms\ rated}}} = \frac{213.65}{\left[\frac{3.6e6}{11000\sqrt{3}}\right]} = 1.13\ \mathrm{p.u}$$

(Below 1.35 p.u limit of IEEE-18)

Reactive power delivered by the capacitor bank is:

$$\mathrm{MVAR\ per\ phase} = [\mathrm{Vc_{rms}} * \mathrm{Ic_{rms}}\ ]$$

$$\mathrm{MVAR\ per\ phase} = [6498.34 * 213.65\ ] = 1.388$$

$$\mathrm{MVAR\ three\ phase} = [3 * 1.388\ ] = 4.164$$

$$\frac{\mathrm{Ic_{rms}}}{\mathrm{Ic_{rms\ rated}}} = \frac{4.164e6}{[3.6e6]} = 1.157\ \mathrm{p.u}$$

(Below 1.35 p.u limit of IEEE-18)

Case 2: (New Badr Substation 110 KV)

Designing of Detuning Filter

For 7 MVAR & 13.8 kV capacitor bank (type Nokian) as shown in Figure 2 and constructed for Badr substation harmonic resonance problem.

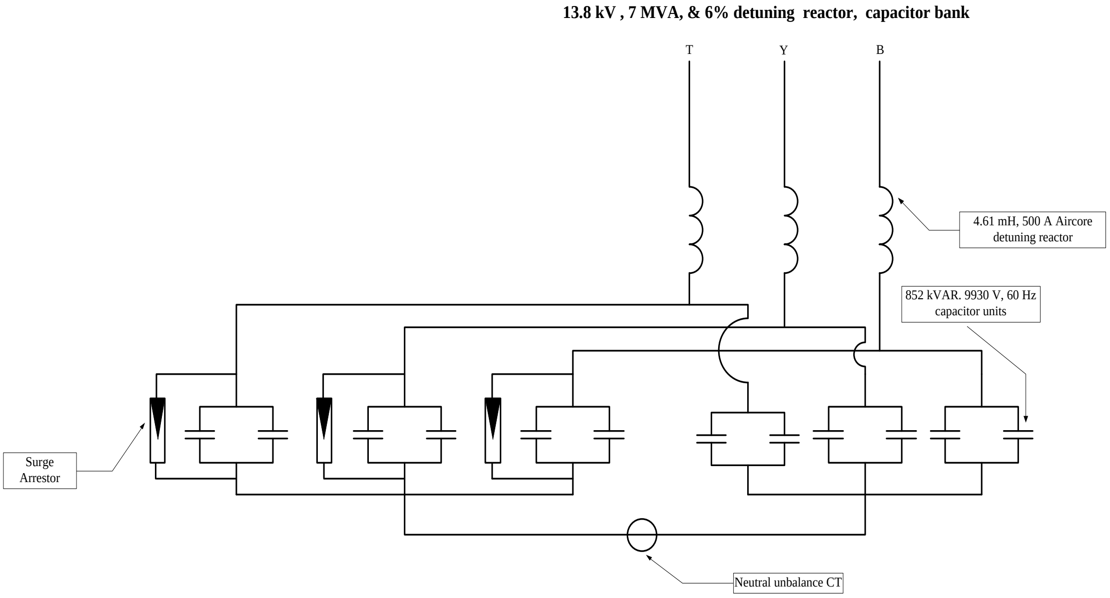


Figure 2. 13.8 kV Capacitor Bank (Nokian)

$$\frac{V_C}{V_{ph}} = \frac{X_C}{X_C + X_L} \text{ at 6\% dtuning reactor}$$
$$\frac{V_C}{V_{ph}} = \frac{X_C}{X_C + 0.06 * X_C} = 1.0638$$
$$V_C = 1.0638 * V_{ph} = 1.0638 * \frac{13.8}{\sqrt{3}} = 8.4757 \text{ kV Chosen } 9.93 \text{ kV}$$

For series reactor detuning 6%:

$$\text{Rated MVAr} = 7 * 0.06 + 7 = 7.42 \text{ MVAr Chosen } 10.22 \text{ MVAr}$$
$$\text{So, each} \frac{\text{MVAr}}{12} = \frac{10.22}{12} = 0.851667 \approx 0.852 \text{ MVAr}$$
$$\frac{{kV_R}^2}{Q_R} = \frac{1}{WC} = \frac{1}{2\pi fC}$$
$$\frac{(9.93)^2}{0.852} = \frac{1}{2 * \pi * 60 * C}$$
$$C = 22.91\ \mu F$$
$$kV_R = \text{voltage rating of capacitor}$$
$$Q_R = \text{Reactive power rating of capacitor MVAr}$$
$$Q' = [\frac{kV_B}{kV_R}]^2 * Q_R$$
$$kV_B = \text{Voltage level at the bus (phase voltage)}$$
$$Q' = \text{reactive power yield at the bus voltage}$$
$$Q' = [\frac{13.8/\sqrt{3}}{9.93}]^2 * 0.852 = 0.5485 \text{ MVAr}$$

For 12 capacitor:

Q'=12*0.5485=6.582 MVAr

$$\text{Rated current at 13.8 kV bus} = \left[6.582 * \frac{1000}{\sqrt{3} * 13.8}\right] = 275.3718 \text{ A}$$

Calculation of series reactor to be connected in series with capacitor bank. It is proposed to connect series reactor of rating 6% of capacitor bank rating, at each of the three phases so, as to protect capacitors against inrush current.

Since series reactor operates in series with the capacitor bank, it carries the same current as capacitor bank. As a result, the voltage drop across it is also a percent of the phase voltage across capacitor bank.

$$\text{Rated current at 13.8 kV bus}(I_C) = \frac{\frac{\text{Total kVA}}{\sqrt{3}}}{\text{LINE VOLTAGE}} = \left[6.582 * \frac{1000}{\sqrt{3} * 13.8}\right] = 275.3718 \text{ A}$$
$$V_L = \frac{6}{100} * \frac{13.8}{\sqrt{3}} = 478.046\text{V at } 6\%$$
$$XL_{(SR)} = \frac{V_L}{I_C} = \frac{478.046}{275.3718} = 1.7\Omega$$
$$L = \frac{X_L}{2\pi f} = \frac{1.7}{2 * \pi * 60} = 4.6 \text{ mH}$$
$$V_L = \text{voltage drop per phase across the series reactor at 13.8 kV}$$
$$I_{SR} = \text{series reactor current rating} = I_C * 1.3 = 275 * 1.3 = 357.5 \text{ A}$$

A factor of 1.3 has been considered while calculating the rated reactor current latitude given on capacitor MVAR in capacitor specification Chosen 500 A.

D. Determining the Effective Harmonics

$$\mathrm{MVA_{S.C}} = \text{short circuit MVA of 13.8 kV bus from short circuit study}$$
$$= 598 \text{ at } 25 \text{ kA} \ \& \ 7MVAr$$
$$\mathrm{MVA_C} = \text{capacitive MVA on the 13.8 kV bus due to capactive bank} = \ 6.582$$
$$\mathrm{n} = \sqrt{\frac{598}{6.582}} = 9.531713 \approx 10$$

Therefore, at 10th harmonic resonance will occur, but the magnitude of 10th harmonic in the system is negligible so system study is safe.

Since the magnitude of 5th and 7th harmonic frequency is significantly high in the power system network, hence it is necessary to check that the resonance doesn't occur for these values.

The power transformer 73 MVA, 110/13.8 kV having an impedance of 22% acts as the source.

$$\mathrm{Z_S} = [\left(\frac{\mathrm{kV^2}}{\mathrm{MVA_{TR}}}\right) * \mathrm{Z}]$$
$$\mathrm{Z_S} = \left[\left(\frac{13.8^2}{73}\right) * 0.22\right] = 0.5739\ \Omega$$
$$\mathrm{Z_S} = \mathrm{X_L} = 0.5739\ \Omega$$
$$\mathrm{n\,X_L} = \mathrm{X_c/n}$$

For 5th harmonic, inductive reactance of transformer will be 5 times i.e.

$$\mathrm{n\,X_L} = 5 * 0.5739 = 2.86964\Omega$$

For 7th harmonic, inductive reactance of transformer will be 7 times i.e.

$$\mathrm{n\,X_L} = 7 * 0.57392 = 4.0\Omega$$

At 13.8 kV, capacitance reactance is given by:

$$\mathrm{X_C}'' = \frac{\mathrm{kV_B}^2}{\mathrm{Q_C}'} =$$
$$\mathrm{X_C}'' = \frac{13.8^2}{6.58202} = 28.93336\ \Omega$$

For 5th harmonic, inductive reactance of transformer will be 1/5 times i.e.

$$\mathrm{X_C/n} = 1/5 * 28.933362 \ = 5.786672\Omega$$

For 7th harmonic, inductive reactance of transformer will be 1/7 times i.e.

$$\mathrm{X_C/n} = 1/7 * 28.93336 \ = 4.\Omega$$
$$\therefore \text{For } 5^{\mathrm{th}}\text{th harmonic } \ \mathrm{n\,X_L} \neq \mathrm{X_c/n}$$
$$\therefore \text{For } 7^{\mathrm{th}} \text{ harmonic } \mathrm{n\,X_L} = \mathrm{X_c/n}$$

Maybe critical resonance occurs at 7th harmonic, that mean the resonance may occur during normal operation (because the 7th harmonics is one of the positive sequence harmonics) or any types of faults.

E. Designing of Harmonic Filter

For a capacitor bank installed for reactive power compensation at a 7MVAR reactive power and 13.8 kV applications is to be tuned to the seventh harmonic. It's needed to determine the required reactor size and verify whether capacitor bank operation parameters fall within IEEE-18 recommended limits [7, 12, 15].

For THD equals to 5.5% as shown in technical measurements and assuming that the most of this THD caused by 7th harmonic the parameters of the passive filter can be determined according to IEEE-18 as following:

Using the preceding methodology and (by ignoring the resistance) the capacitor bank reactance (fundamental at 60 Hz) can be determined by the following equation:

$$X_{C1}{}^{''} = \frac{kV_B{}^2}{Q_C} =$$

$$X_{C1}{}^{''} = \frac{13.8^2}{6.58202} = 28.93336\ \Omega$$

Calculating of the series reactor required (by ignoring the resistance):

$$X_{L1}{}^{''} = \frac{X_{C1}}{n^2}$$

$$X_{L1}{}^{''} = \frac{28.93336}{7^2} = 0.59\ \Omega$$

Determine whether capacitor-operating parameters fall within IEEE-18 recommended limits. RMS current through the filter:

$$I_1{}^{''} = \frac{kV_B}{X_{C1} - X_{L1}}$$

$$I_1{}^{''} = \frac{13800/\sqrt{3}}{(28.93336 - 0.59)} = 281.1\ \text{A}$$

$$I_7{}^{''} = \frac{\text{THD x MVA}}{\sqrt{3}kV_B} =$$

$$I_7{}^{''} = \frac{(\frac{5.5}{100})\ \text{x}\ 73\text{e}6}{\sqrt{3}\ \text{x}\ 13.8\text{e}3} = 167.9\ \text{A}$$

$$X_{C7}{}^{''} = \frac{X_{C1}}{n}$$

$$X_{C7}{}^{''} = \frac{28.93336}{7} = 4.133\ \Omega$$

Peak and RMS voltages through the capacitor:

$$Vc_{peak} = \sqrt{2}\ [V_{c1} + V_{ch}]$$

$$Vc_{peak} = \sqrt{2}\ [I_1X_{C1} + I_{7X_{C7}}]$$

$$Vc_{peak} = \sqrt{2}\ [281.1\text{x}28.93336 + 167.9\text{x}4.133]$$

$$Vc_{peak} = 12479.31\ \text{V}$$

$$Vc_{rms} = \sqrt{(V_{c1}{}^2 + V_{ch}{}^2)}$$

$$Vc_{rms} = \sqrt{((281.1\text{x}28.93336)^2 + (167.9\text{x}4.133)^2)}$$

$$Vc_{rms} = 8162.7\ \text{V}$$

$$\frac{Vc_{rms}}{Vc_{rms\ rated}} = \frac{8162.7}{\left[\frac{13800}{\sqrt{3}}\right]} = 1.02\ \text{p.u}$$

(Below 1.1 p.u limit of IEEE-18)

$$\frac{Vc_{peak}}{Vc_{peak\ rated}} = \frac{12479.31}{\sqrt{2}\left[\frac{13800}{\sqrt{3}}\right]} = 1.1\ \text{p.u}$$

(Below 1.2 p.u limit of IEEE-18)

The RMS current through the reactor is the summation of all RMS currents that will flow through the filter. The assumption here is that only the seventh harmonic is involved:

$$\mathrm{Ic_{rms}} = \sqrt{(\mathrm{I_{c1}}^2 + \mathrm{I_{ch}}^2)}$$
$$\mathrm{Ic_{rms}} = \sqrt{((281.1)^2 + (167.9)^2)}$$
$$\mathrm{Ic_{rms}} = 327.43\ \mathrm{A}$$
$$\frac{\mathrm{Ic_{rms}}}{\mathrm{Ic_{rms\ rated}}} = \frac{327.43}{\left[\frac{6.582e6}{13800\sqrt{3}}\right]} = 1.189\ \mathrm{p.u}$$

(Below 1.35 p.u limit of IEEE-18)

Reactive power delivered by the capacitor bank is:

$$\mathrm{MVAR\ per\ phase} = [\mathrm{Vc_{rms}} * \mathrm{Ic_{rms}}\ ]$$

$$\mathrm{MVAR\ per\ phase} = [8162.7 * 327.43\ ] = 2.673$$
$$\mathrm{MVAR\ three\ phase} = [3 * 2.673\ ] = 8.019$$
$$\frac{\mathrm{Ic_{rms}}}{\mathrm{Ic_{rms\ rated}}} = \frac{8.019e6}{[6.582e6]} = 1.22\ \mathrm{p.u}$$

(Below 1.35 p.u limit of IEEE-18)

4. Results and discussion

The parameters of the detuning and harmonic filters for the two substations can be summarized in Table 8 as following:

Table 8. Parameters of Detuning and Harmonic Filters

Fayoum Substation Detuning Filter Parameters	Harmonic Filter Parameters	New Badr Substation Detuning Filter Parameters	Harmonic Filter Parameters
P% = 7	XL = 0.69 Ω	P% = 6	XL = 0.59 Ω
L = 7.48 mH		L = 4.6 mH	
VL = 444 V	XC = 4.8 Ω	VL = 478 V	XC = 4.13 Ω
ISR = 245 A		ISR = 357 A	

The simulation model is shown in Figure 3 for 11 KV capacitor bank in Fayoum substation shows the power factor improvement circuit in the presence of harmonics and unbalance currents [16].

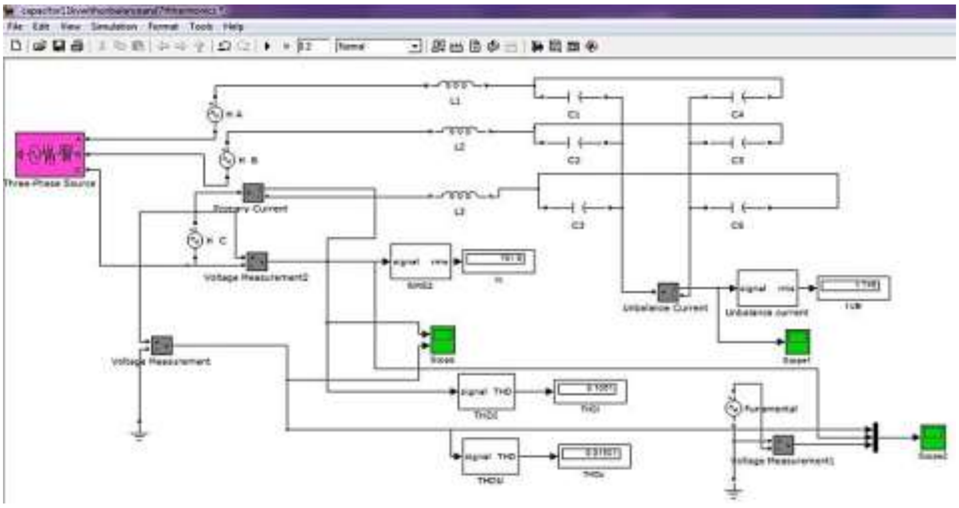


Figure 3. Simulation model for 11 KV PFI circuit with 7th harmonic

From this model at 1.5% voltage THD, the effect of harmonics is significant on the current and voltage waveforms which captured by the scopes as shown in Figure 4 and actually sensed by FFT analysis as shown in Figure 5.

Using the single tuned harmonic filter the voltage THD became 0.11% and the distortion of the voltage and current waveforms has been removed as shown in Figure 6 and 7.

This simulation model applied to the 13.8 kV capacitor bank and other medium voltages with various orders of harmonics and the results satisfied the same concept. Also, the effect of harmonics on the values of unbalance currents has been studied for the 11 kV and 13.8 kV capacitor banks at various values of THD and tested by the simulation model which given the results are shown in Table 9. From this table, the effect of harmonics on the unbalance currents can be sensed and the increase of unbalance currents due to the increase of THD is sensed by protective relays. If the value of unbalance current has exceeded the setting value these relays would take action (trip power contactors and circuit breaker) to protect the units of the capacitor bank from damage.

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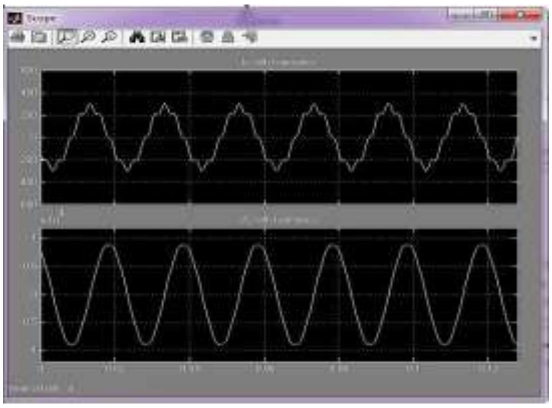

Figure 4. Current and Voltage waveforms with harmonics effect

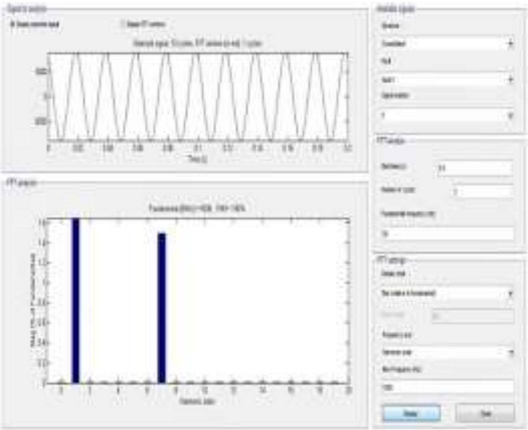

Figure 5. FFT analysis of voltage THD (1.5%)

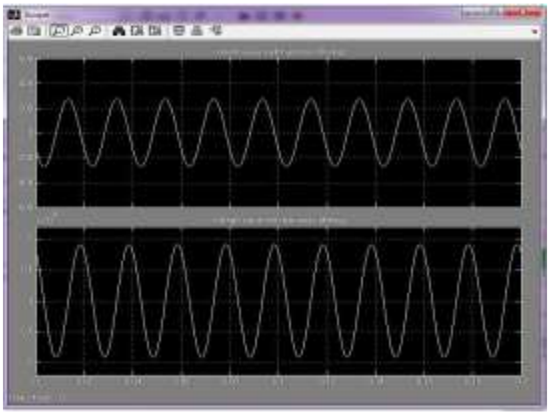

Figure 6. Current and Voltage waveforms after using single tuned harmonic filter

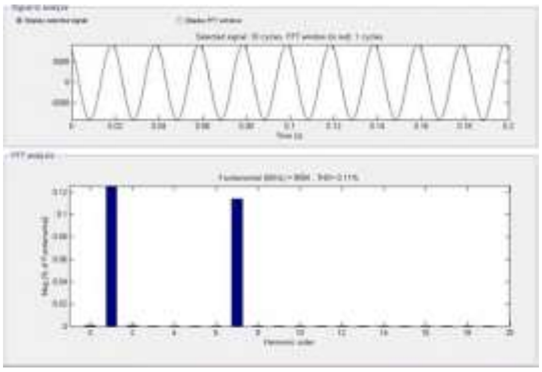

Figure 7. FFT analysis of voltage THD (0.11%) due to filtering

Table 9. THD and Unbalance Current

Fayoum Substation			New Badr Substation		
THDv %	THDi %	Unbalance current (Ampere)	THDv %	THDi %	Unbalance current (Ampere)
0.2	1.4	1.739	0.2	2.5	2.635
0.4	2.8	1.740	0.4	5.0	2.638
0.6	4.2	1.741	0.6	7.5	2.642
0.8	5.6	1.742	0.8	10.01	2.648
1.0	7.0	1.743	1.0	12.5	2.655
1.2	8.4	1.745	1.2	15.01	2.664
1.4	9.8	1.747	1.4	17.52	2.675
1.6	11.3	1.750	1.6	20.01	2.688
1.8	12.7	1.753	1.8	22.51	2.702
2.0	14.14	1.756	2.0	25.01	2.717
2.2	15.55	1.760	2.2	27.50	2.734
2.4	16.97	1.764	2.4	30.02	2.753
2.6	18.38	1.768	2.6	32.53	2.773
2.8	19.8	1.773	2.8	35.03	2.795
3.0	21.21	1.778	3.0	37.53	2.817
3.2	22.62	1.783	3.2	40.04	2.842
3.4	24.04	1.789	3.4	42.50	2.867
3.6	25.45	1.795	3.6	45.03	2.894
3.8	26.87	1.801	3.8	47.56	2.923
4.0	28.28	1.807	4.0	50.01	2.952

5. Conclusion and future work

Harmonics in electrical networks occur as a result of non-linear loads such as welding machines, induction furnaces, and Static converters. The resulting effect is significant on the unbalance currents to flow through the neutral points of the star connection of capacitor bank units and these currents can be sensed by the current transformer (C.T) in addition to the occurrence of resonance. If the value of unbalance current has exceeded the setting value the protective relays would take action (trip power contactors and circuit breaker) to protect the units of the capacitor bank from damage. The common unbalance current setting for Tepco, Egemac, Schneider and Nokian capacitor banks is (2.5 Ampere as Alarm) and (3.0 Ampere as Trip). This research presented a study to improve the power factor by reducing the effect of resonance and harmonics on the power system. This reduction can be done using filters, consist of reactors and capacitors connected in series or in parallel or series and parallel together and the purpose is to reduce the current harmonics or voltage harmonics. Here Single Tuned filter type (passive filter) is used which presents very low impedance at the tuning frequency, through which all current of that particular frequency will be diverted. This research presented a model of a practical power system for medium voltage (11kv) source in Fayoum substation and (13.8kv) source in New Badr substation connected to power factor improvement circuit and Simulation of this model using (Matlab) software. Also, it presented the design of the series reactor and the harmonics filter which satisfy the minimum effect of resonance and harmonics. Finally a Total Harmonic Distortion (THD), the more losses in the power and the more quickly damage and malfunctioning of electrical equipment.

This paper presented a study to improve power factor with reducing the effect of resonance and harmonics on the power system where the THD percentage and the effective harmonic degree (order of harmonic) are assumed to be constant values. The future work will be a study on variable values of THD percentage and the effective harmonic degree for 24 hours daily. To reduce the effect of these variable values a new design of a smart harmonic filter will be designed to make automatic compensation during the variation of harmonics values. Also, this model will be connected with the model of automatic power factor regulator to avoid operating on capacitor bank during high values of THD.

References

[1] VE Wagner, JC Balda, DC Griffitki, A McEachern, TM Barnes, DP Hartmann, DJ Phileggi, AE Emannuel, WF Horton, WE Reid, RJ Ferraro, WT Jewell. Effects of harmonics on equipment. *IEEE Trans. Power Delivery*. 1993; 8: 672-680.

[2] Francisco C De La Rosa. Harmonics and Power Systems. Taylor & Francis Group, LLC. 2006.

[3] ANSI/IEEE Std. 519-1992. *IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems.* IEEE; 1992.

[4] ABB Technical Application Paper. Power factor correction and harmonic filtering in electrical plants. 2008.
[5] Areva T&D. *Harmonic Analysis report Harmonic measurement carried out on 13.8 kV Incomers at Old Badr S/S of M/S SEC-Saudi Arabia*. NOKIAN CAPACITORS. Report number: TV88500-2x13.8 kV/7MVAR. 2011.
[6] Team of experienced international experts. 60364. *Electrical installation guide 2008.* Schneider Electric; 2008.
[7] JN Fiorina. Inverters and harmonics (case studies of non-linear loads). Cahier Technique Merlin Gerin. 1993; 159.
[8] JN Fiorina. Harmonics upstream of rectifiers in UPS. Cahier Technique Merlin Gerin. 1993; 159.
[9] E Bettega, J Fiorina. Active Harmonic Conditioners and Unity Power Factor Rectifiers. Cahier technique Schneider Electric. 1999; 183.
[10] Y Hsiao. Design of Filters for Reducing Harmonic Distortion and Correcting Power Factor in Industrial Distribution Systems. *Tamkang Journal of Science and Engineering*. 2001; 4: 193-199.
[11] P Chao, K Lingguo, L Zhenxin, Z Qing, W Zezhong. *Analysis Based on Improved Method for Transformer Harmonic Losses.* The 2012 International Conference on Future Energy, Environment, and Materials, Energy Procedia. 2012; 16: 1845-1851.
[12] T Hoevenaars, K LeDoux, M Colosino. *Interpreting IEEE Std 519 and Meeting its Harmonic Limits in VFD Applications.* IEEE Industry Applications Society 50th Annual in Petroleum and Chemical Industry Conference. 2003; 1: 145-150.
[13] KC Agrawal. Industrial Power Engineering and Applications Handbook. Fourth ed. Newnes Power Engineering Series. 2001.
[14] C Collombet, JM Lupin, J Schonek. Harmonic disturbances in networks, and their treatment. Cahier Technique Schneider Electric. 1999; 152.
[15] IEEE Std. 18–2002. *IEEE Standard for Shunt Power Capacitors.* IEEE; 2002.
[16] Mathworks. Three Phase Harmonic Filter Toolbox: User's Guide (r2014b). 2014.