Single Tuned Filter Design for Mitigating Harmonic Distortion in (30 KV) ALTAHRER Substation

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Abstract

Nowadays, due to the fast growth of electronic devices, harmonic issues have become a main matter for current day electrical operators. Some of the causes of harmonics are: a) ripples in voltage waveform of machines, b) flux distortion in the synchronous machines, c) transformer magnetizing currents, d) non-linear loads such as static power converters, arc furnaces, and e) static-var compensators as suppliers of continuously variable var sources. The harmonic filtering is one of the solutions for preventing the worrying harmonics from entering the rest of the system. There are basically two types of filters: i) passive, where the filter components are passive elements such as resistor, inductor, and capacitor, and ii) active, where the filter has a controlled current or voltage source. This paper introduces a single-tuned passive filter to minimize the harmonic distortion of ALTAHRER substation (30KV). The offered filter and studied system modeling are built by ETAP software. Results show the effectiveness of the proposed filter in mitigating total harmonic distortion of studied system.

Keywords: Total harmonic distortion, Single tuned filter, ALTAHRER Substation

INTRODUCTION

Significance of harmonics was known in 1920s and early 1930s when distorted voltage and current waveforms were detected on transmission lines [1]. The power system harmonic issue has been traced to one core factor, the substantial growth in nonlinear loads [2]. Recent decades showed an increase in nonlinear devices, which meant a rise in power system harms resulted from harmonics, such as: distort current and voltage waveforms, resonance problems, system losses and decrease the convenient life of electrical equipment. It is expected that through the next 10 years more than 60% of the loads on utility systems will be nonlinear, which means more importance of the study of harmonics and their reduction methods. Significance of harmonic lessening methods comes from the fact that the nonlinear loads which are a source of generation of harmonics are themselves relatively less tolerant to poor power quality that originates from harmonic emission from these loads. Harmonic mitigation
techniques main idea is to lessen harmonic distortions into permissible levels making the system apparatus work in an appropriate environment [3].

However, Libyan network in the recent years, witnessed an increase in the nonlinear loads, consequently an increase in power quality issues (one of them harmonics), so immediate studies and modern practical solutions need to be done. Several methods have been presented to mitigate harmonic distortions such as [4-11]. However, no studies focused on harmonic distortion issues for General Electricity Company of Libya (GECOL) have been found in the literature.

In this paper, two single-tuned passive filters for mitigating the harmonic distortion in ALTAHRER substation (30KV) are designed. The proposed technique and studied system modeling are built by ETAP (Electric Transient Analyzer Program) software. Results show the effectiveness of the proposed technique in mitigating THD for studied system.

Harmonics Definition
IEEE Standards 519-2014 has defined harmonics as: a component of order greater than one of the Fourier series of periodic quantity. For example, in 60Hz system, the harmonic order 5, also known as the “fifth harmonic” is 300Hz [12]. Figure 1 shows fundamental, 3rd, 5th, 7th and resultant waveforms.

Harmonic Causes
Harmonics appear in power system due to nonlinear loads energized by sinusoidal sources or linear loads with non-sinusoidal sources. The difference between linear and nonlinear loads, is that linear loads are characterized so that an application of a sinusoidal voltage results in a sinusoidal flow of current, which means it displays constant steady-state impedance during the applied sinusoidal voltage, but in a nonlinear device, the application of a sinusoidal
voltage does not result in sinusoidal flow of current (current flow may be discontinuous of flow in pulses), so it does not exhibit constant impedance during the entire cycle of applied sinusoidal voltage. Some examples of loads that produce harmonics are: adjustable speed drives (ASD), arc furnace, switching mode power supplies, computers, copy machines, mobile chargers, television sets and home appliances, battery charging and fuel cells, rectifiers, and Inverters [13].

**Problems Caused By Harmonic**
There are some issues produced by harmonics [14]:

1. Troubles caused by harmonic currents:
   1.1 Overloading of neutrals
   1.2 Overheating of transformers
   1.3 Nuisance tripping of circuit breakers
   1.4 Over-stressing of power factor correction capacitors
   1.5 Skin effect

2. Troubles caused by harmonic voltages:
   2.1 Voltage distortion of Induction motors
   2.2 Zero-crossing noise

**Single Tund Passive Filter**
The filter also known as band pass filter is designed based on three non-intricate quantities. The filter contains a series of $RLC$ configuration, which is tuned to resonate single harmonic frequency. Following figure shows the typical configuration of single tuned filter.

![Basic configuration of Single-tuned passive filter](image)

**Single Tund Passive Filter Design Equations**
The impedance behavior can be explained as

$$Z_f(s) = \frac{(LCs^2 + RCS + 1)}{Cs} \quad (1)$$
Single Turned Filter Design for mitigating Harmonic Distortion in ALTAHRER Substation (30 KV)

Where:

\[ s = \text{the Laplace operator}, \quad L = \text{the filter inductance}, \quad \text{and } C = \text{the filter capacitance}. \]

In order to determine the single-tuned filter parameter, the reactive power \((Q_C)\) of the filter's capacitor need to be calculated. \(Q_C\) is used to correct the power factor of the system, thus its value depends on the desired value of the studied system. The following equation is used to calculate \(Q_C\).

\[
P_{\text{old}} / \left( P_{\text{old}}^2 + (Q_{\text{old}} + Q_C)^2 \right)^{0.5} = PF_{\text{desired}} \tag{2}
\]

Where:

\(P_{\text{old}} = \text{active power drawn by the load without connecting filter}, \quad Q_{\text{old}} = \text{reactive power drawn by the load without connecting filter}, \quad \text{and } PF_{\text{desired}} = \text{power factor with connecting filter}.\)

The following equations use to compute the capacitor and inductor values of the filter:

\[
C = Q_C / (2\pi f V^2) \tag{3}
\]

Where:

\[
L = 1 / (2\pi f h)^2 C \tag{4}
\]

Where:

\(f = \text{the fundamental frequency}, \quad V = \text{the line voltage with the connecting filter}, \quad \text{and } h = \text{the harmonic order}.\)

By determining the main filter parameters, another parameter should be considered, which the quality factor. The quality factor determines the bandwidth and the filtering deepness at the notch frequency \([15]\). The quality factor \(Q\) has a practical value between 30 and 60.

By choosing the desired value of \(Q\), \(R\) can be determined by following equation:

\[
Q = \left[ \sqrt{L/C} \right] / R \tag{5}
\]

**ALTAHRER 30KV Substation Overview**

ALTAHRER substation (30kV) substation is considered a medium voltage substation in GECOL; it is located in ALTAHRER Company for steel manufacture, ALBURJ region, Zliten, Libya. ALTAHRER substation consists of two bus bars connected together, which are fed by ALBURJ substation (220/30 kV). ALTAHRER substation is loaded by ALTAHRER steel factory loads, which are: four arc furnaces, casting machine, rolling machine and other various loads such as computers, lights, air conditioners. Figure 3 shows the single line diagram of ALTAHRER substation (30 kV) and ALBURJ substation (220/30 kV) which is built by ETAP.
Collected Data of ALTAHRER Substation

Loads connected to ALTAHRER substation are steel factory loads, Actual recorded data of those loads are shown in Table 1 [16].

Table 1: Actual recorded data of loads connected to ALTAHRER substation

<table>
<thead>
<tr>
<th>Load</th>
<th>Apparent power (KVA)</th>
<th>Rated voltage (kV)</th>
<th>Power factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arc furnace 1</td>
<td>6300</td>
<td>11</td>
<td>0.85</td>
</tr>
<tr>
<td>Arc furnace 2</td>
<td>6300</td>
<td>11</td>
<td>0.85</td>
</tr>
<tr>
<td>Arc furnace 3</td>
<td>6300</td>
<td>11</td>
<td>0.85</td>
</tr>
<tr>
<td>Arc furnace 4</td>
<td>6300</td>
<td>11</td>
<td>0.85</td>
</tr>
<tr>
<td>Rolling machine</td>
<td>5000</td>
<td>6</td>
<td>0.85</td>
</tr>
<tr>
<td>Casting machine</td>
<td>2000</td>
<td>0.4</td>
<td>0.85</td>
</tr>
<tr>
<td>Various loads</td>
<td>100</td>
<td>0.4</td>
<td>0.85</td>
</tr>
</tbody>
</table>

Figure 3: Single line diagram of ALTAHRER substation and ALBURJ substation
Harmonic Analysis of ALTAHRER Substation

Before running the harmonic analysis simulation, a load flow analysis of studied system (ALTAHRER AND ALBURJ) is done to make sure that bus bars, transformers and other system apparatuses are working on their rated values.

Load Flow Calculations

Load flow calculations are achieved by ETAP simulation. Loads of studied system is considered maximum value. Simulation calculations of load flow are presented in and Table 2 and Figure 4.

Table 2: load flow calculations

<table>
<thead>
<tr>
<th>Load</th>
<th>Apparent power (kVA)</th>
<th>Active power (kW)</th>
<th>Reactive power (kvar)</th>
<th>Current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arc furnace 1</td>
<td>6000</td>
<td>5100</td>
<td>3161</td>
<td>3464</td>
</tr>
<tr>
<td>Arc furnace 2</td>
<td>6000</td>
<td>5100</td>
<td>3161</td>
<td>3464</td>
</tr>
<tr>
<td>Arc furnace 3</td>
<td>6000</td>
<td>5100</td>
<td>3161</td>
<td>3464</td>
</tr>
<tr>
<td>Arc furnace 4</td>
<td>6000</td>
<td>5100</td>
<td>3161</td>
<td>3464</td>
</tr>
<tr>
<td>Casting machine</td>
<td>1981</td>
<td>1684</td>
<td>1044</td>
<td>2860</td>
</tr>
<tr>
<td>Rolling machine</td>
<td>3938</td>
<td>3347</td>
<td>2075</td>
<td>378.9</td>
</tr>
<tr>
<td>Various loads</td>
<td>101</td>
<td>75.7</td>
<td>66.8</td>
<td>3</td>
</tr>
</tbody>
</table>

Figure 4: Studied system with load flow calculations
Harmonic Loads Analysis of ALTAHRER Substation

After making sure that studied system apparatuses are working on their rated values, harmonic load analysis has been performed. Figure 5 illustrates the harmonic distortion of studied system. IEEE Std. 519-2014 [12], states that, if bus voltages is equal to or between 1kV and 69kV the individual harmonic percent should not exceed 3% of rated frequency voltage whereas the total harmonic distortion (THD %) should not exceed 5% of rated frequency voltage.

It can be seen from results that the THDV% in ALBURJ bus bar 220 kV (0.261 %) has not exceeded the permissible level stated by IEEE, while the THDV% in ALBURJ bus bars (5.05 %, 5.09 %) and ALTAHRER bus bar (5.32 %) has exceeded the permissible level stated by IEEE Std 519-2014.

Following Table displays the bus bars THDV% calculations of the studied system.

<table>
<thead>
<tr>
<th>Bus bar</th>
<th>THD V %</th>
<th>V (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALTAHRER 30 kV</td>
<td>5.32</td>
<td>30.77</td>
</tr>
<tr>
<td>ALBURJ 30 kV</td>
<td>5.05</td>
<td>31</td>
</tr>
<tr>
<td>ALBURJ 30 kV 2</td>
<td>5.09</td>
<td>31.07</td>
</tr>
<tr>
<td>ALBURJ 220 kV</td>
<td>0.261</td>
<td>220</td>
</tr>
</tbody>
</table>
Individual Harmonic Distortions

In order to minimize harmonic distortion, the highest individual harmonic distortion has to be known. Figures 6, 7 and 8 display the harmonic spectrum for ALTAHRER substation, ALBURJ bus and ALBURJ 30kV bus 2.

![Harmonic spectrum of ALTAHRER substation](image)

It can be seen from above figure that 7\textsuperscript{th} and 11\textsuperscript{th} are the highest individual harmonics distortion levels, therefore 7\textsuperscript{th} and 11\textsuperscript{th} individual harmonics level need to be reduced.
As ALTAHRER bus is fed by ALBURJ buses and it has high distortion levels of 7\textsuperscript{th} and 11\textsuperscript{th} harmonic order, therefore the 7\textsuperscript{th} and 11\textsuperscript{th} of ALBURJ buses are the highest level, as shown in Figure 6, 7.

Criteria for Choosing Appropriate Harmonic Mitigation Method

There are several methods for reducing harmonic distortions. The most common practice mitigation technique is the installation of passive harmonic filters. They exhibit the best relation between cost and benefit among all other mitigation techniques when dealing with medium and high voltages, especially at levels higher than 10kV. They supply reactive power to the system while being highly effective in attenuating harmonic components. From various types of passive filters the simplest and cheapest filter is the single tuned filter [14], therefore it has been chosen to reduce THD of the studied system. As founded in harmonic analysis of studied system, the 7\textsuperscript{th} and 11\textsuperscript{th} individual harmonic distortion were the highest harmonic distortion level, so two single-tuned passive filters have been chosen, in order to reduce their distortion level. The two single-tuned filters are connected to ALTAHRER substation 30kV bus bar.
Working Principle of Single-Tuned Passive Filter

The working principle of the single tuned filter is that its inductive and capacitive reactance are equal in the tuned frequency \((X_L = X_C)\), therefore it provides a low resistance path for the harmonic current to pass through. Practically single-tuned filters are not tuned exactly to the intended harmonic. They are instead detuned to lower frequency value. This detuning can prevent the harmonic component to be amplified due to the resonance that arises in the lower vicinity of the driving point impedance after the single-tuned filter is installed, so the single tuned filter is detuned by 5% of the harmonic suppressed \([17]\), so the single-tuned filter for the 7th and the 11th harmonic are tuned to 6.7 Hz and 10.5 Hz respectively. The filters resistance must be as low as possible so in the tuning frequency it does not retards the harmonic current to pass through the filter.

Two Proposed Single-Tuned Passive Filters Design

In order to design a single-tuned passive filter, its parameters \((R, L, \text{ and } C)\) need to be calculated. Therefore the following steps are performed to calculate the two filters parameters.

Step 1: is calculating the power factor of ALTAHRER substation:

As ALTAHRER substation draws 33824 kVA, thus the power factor is calculated by eq. (2), which equals to 0.83, while the desired value should be equal to 0.9, so the reactive power should be reduced.

Step 2: is estimating the reactive power of two proposed filters:

By using eq. (2), the reactive power \((Q_C)\) is calculated as following:

\[
\frac{28042.7k}{\sqrt{(28042.7k)^2 + (Q_{\text{New}})^2}} = 0.9
\]

So:

\[
Q_{\text{New}} = 13581.7 \text{ kvar}
\]

\[
Q_{\text{New}} = 18913.8 - Q_C = 13581.7 \text{ kvar} \quad \text{So} \quad Q_C = 5332.1 \text{ kvar}
\]

Therefore the two filters must have a resultant \(Q_c\) that equals to 5300 kvar, it has been chosen to divide them as follows \(Q_{C7} = 3000 \text{ kvar}\), and \(Q_{C11} = 2300 \text{ kvar}\).

Step 3: is calculating the capacitor, inductor and resistor of the first filter (7th harmonic order):

By equation (3) \(C = 10.61 \mu F\)

By equation (4) \(L = 21.273 \text{ mH} \quad \text{so}, \quad XL = 2\pi f L = 6.683\Omega\)

Q (quality factor) for most practical uses is 60.

By equation (5) \(R = 0.007\Omega\)
Step 4: is calculating the capacitor, inductor and resistor of the second filter (11th harmonic order):
By equation (3) \( C = 8.135 \, \mu F \)

By equation (4) \( L = 11.297 \, mH \) so, \( XL = 2\pi f L = 3.549 \, \Omega \)

Q (quality factor) for most practical uses is 60 and by equation (5) \( R = 0.62 \, \Omega \)

Theoretically, connecting two single-tuned filters with those parameters will reduce the harmonic distortion into permissible levels.

**Harmonic Analysis of Studied System with Connecting Two Designed Filters**

After calculating the suggested filters parameters, two filters are connected to ALTAHRER bus bar. The studied system with connecting two proposed filters simulation is carried out. The simulation results are demonstrated in Figure 9 and Table 7.

![Figure 9: THD% and voltage of the system with connecting filters](image_url)

It can be seen from results that the THD\(_V\) % in ALBURJ bus bar 220 kV (0. %) is in permissible level that is stated by IEEE. Also, the THD\(_V\) % in ALBURJ bus bars (4.22, 4.26 %) and ALTAHRER bus bar (4.45 %) has become in the permissible level stated by IEEE Std 519-2014. Table 4 shows the harmonic analysis results with connecting two filters.
Single Turned Filter Design for mitigating Harmonic Distortion in ALTAHRER Substation (30 KV)

Table 4: THDV and voltage on the system bus bars with filters

<table>
<thead>
<tr>
<th>Bus bar</th>
<th>THDV %</th>
<th>V (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALTAHRER 30 kV</td>
<td>4.45</td>
<td>30.88</td>
</tr>
<tr>
<td>ALBURJ 30 kV</td>
<td>4.22</td>
<td>31.1</td>
</tr>
<tr>
<td>ALBURJ 30 kV 2</td>
<td>4.26</td>
<td>31.18</td>
</tr>
<tr>
<td>ALBURJ 220 kV</td>
<td>0.213</td>
<td>220</td>
</tr>
</tbody>
</table>

It can be noted that the individual harmonic distortion levels of the 7th and 11th have been minimized in all the system bus bars. Figure 10 shows the individual harmonic distortion level in ALTAHRER substation bus bar.

Reducing high distortions in ALTAHRER substation of the 7th and 11th harmonic order reduces their level in ALBURJ bus bars. Figures 10, and 11 show harmonic distortion levels in ALBURJ (30kV) and ALBURJ (30kV) bus 2.

Figure 10: Harmonic spectrum of ALTAHRER substation with filtering

Figure 11: Harmonic spectrum of ALBURJ bus with filtering
To illustrate the effectiveness of the two proposed filters, a comparison of the harmonic distortion levels is compared with and without connecting filters; Table 5 shows results with and without connecting filters.

<table>
<thead>
<tr>
<th>Filtering</th>
<th>THD</th>
<th>5th harm.%</th>
<th>7th harm.%</th>
<th>11th harm.%</th>
<th>13th harm.%</th>
<th>17th harm.%</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALTAH ER bus</td>
<td>without</td>
<td>5.32</td>
<td>1.11</td>
<td>2.83</td>
<td>2.04</td>
<td>0.305</td>
</tr>
<tr>
<td></td>
<td>with</td>
<td>4.45</td>
<td>1.41</td>
<td>1.3</td>
<td>1.73</td>
<td>0.26</td>
</tr>
<tr>
<td>ALBURJ bus1</td>
<td>without</td>
<td>5.05</td>
<td>1.045</td>
<td>2.68</td>
<td>1.94</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>with</td>
<td>4.22</td>
<td>1.33</td>
<td>1.23</td>
<td>1.64</td>
<td>0.25</td>
</tr>
<tr>
<td>ALBURJ bus 2</td>
<td>without</td>
<td>5.09</td>
<td>1.059</td>
<td>2.71</td>
<td>1.95</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>with</td>
<td>4.26</td>
<td>1.34</td>
<td>1.25</td>
<td>1.66</td>
<td>0.25</td>
</tr>
</tbody>
</table>

It has been focused on these harmonics (5, 7, 11, 13, and 17) because they are the most harmful harmonics, and preserving them into low levels keeps the system in the safe side. From Table 5 it can see that the THD% for all the bus bars has become under 5% and the distortion percent for individual harmonics has become under 2% after connecting the filters, so the proposed filters has a positive impact on the system.

**Conclusions**

This paper has offered a design of two single turned passive filters for mitigating the harmonic distortion of actual system, which is ALTHARER substation (30 kV). The harmonic distortion analysis of the studied system is carried out without and with the connecting of offered two filters. Results show that THDV % of ALTHARERE substation without filters violent the IEEE standard. On the other hand, by connecting the designed filters the THDV % of ALTHARER substation is reduced which led to be in the allowed margin of IEEE standers. Furthermore, by connecting the designed two filters the 7th and 11th individual harmonics distortion levels are minimized which leads to improve current and
Single Turned Filter Design for mitigating Harmonic Distortion in ALTAHRER Substation (30 KV)

voltage wave form. Results show the effectiveness of designee filters to mitigate the harmonic distortion of the studied system.

REFERENCES

تصميم مرشح أحادي الضبط لتخفيف التشوه التوافقي في محطة التحرير الفرعية (30 ك ف) 

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ملخص البحث 
في الوقت الحاضر، نظرًا للنمو السريع للأجهزة الإلكترونية، أصبحت مشكلات التوافقيات مسألة رئيسية لمشغلي الكهرباء في الوقت الحالي. بعض أسباب التوافقيات هي: أ) تمتلكات في شكل موجة الجهد للإلكترود، ب) تشوهات تدفق القبضة في الآلات المترامدة، ج) التيارات الممغنطة للمحول، د) الإخلال غير الخطيية مثل محولات الطاقة الثابتة، أفران الفوام، و) معاوضات القدرة الغير فعالة المتغيرة. يعد فلترة التوافقيات أحد الحلول لمنع التوافقيات المنتشرة في دخل بقية النظام. يوجد نوعان أساسيان من المرشحات: 1) مرشح غير فعال، حيث تكون مكونات المرشح عناصر سلبية مثل المقاومة، والملف، والمكلف، و 2) فعال، حيث يحتوي المرشح على تيار أو مصدر جهد متتالي فيه. يقيد هذا المشروع مرشحًا منفردًا أحادي الضبط لتقليل التشوه التوافقي لمحطة التحرير الفرعية (30 كيلو فولت). تم إنشاء المرشح المقترح ومحاكاة النظام المدرسو بواسطة برنامج ETAP بينت النتائج فاعلة المرشح المقترح في التخفيف من التشوه التوافقي الكلي للنظام المدرسو. 

الكلمات المفتاحية: تشوه التوافقيات الكلي، المرشح أحادي الضبط، محطة التحرير

[16] Genral Electricity Company of Libya 