Mitigation of Harmonic Distortion in a Power System Feeding Nonlinear Loads Using Shunt Passive Single Tuned Filters

Adel Ridha Othman
Electromechanical Engineering Department, University of Technology, Baghdad, Iraq 50063@uotechnology.edu.iq

Abstract. In this paper a distribution system of 2 MVA, 11 KV standalone generator is feeding a group of six branches of pulse width modulation (PWM) drive nonlinear loads, such a distribution power system is used in oil fields drilling rigs, each branch is fed through a step down transformer of 11/0.4 KV and of capacity proportional to its branch load rating. For this group of nonlinear loads, the total current harmonic distortion (ITHD) and total voltage harmonic distortion (VTHD) are calculated at the point of common coupling (PCC#1) which show that the system failed to meet IEEE Std 519 harmonic limits. A shunt passive single tuned filters are designed to mitigate (ITHD) and (VTHD). The addition of these filters to this power system were effective in making it compliance with IEEE Std 519.

1. Introduction
In an ideal power system the electrical power must be supplied with a sinusoidal voltage and current wave shape but due to the increased use of power electronics which are considered as nonlinear loads such as adjustable speed drive (ASD) and also the magnetization current drawn by transformers, there will be a current wave shape distortion and when this distorted current passes through the impedance that is between the nonlinear load and the system source, harmonic voltages are produced by impedance in the system for each harmonic. These voltages sum and when added to the nominal voltage produce voltage distortion. To overcome the harmonic distortion problem which cause many bad effect on power system, harmonic mitigation is important for both utilities and customers so shunt passive filters have been used to mitigate harmonic distortion [1].

2. Harmonic Sources
The sources of harmonics in power system are a lot and they have a common specification which is the nonlinear voltage – current relationship. The nonlinear load permit the current to flow through it discontinuously and doesn’t correspond the voltage waveform. The nonlinear loads includes transformers and solid state devices for motor drives. These solid state harmonic producing devices is specified by the pulse number (p) and equation (1) calculates the characteristic harmonics (h) of the solid state device [2].

\[ h = (n \times p) \pm 1 \quad n \text{ is an integer} = 1, 2, 3, ... \]  

3. Voltage Total Harmonic Distortion (VTHD)
As given in equation (2), it is the ratio of the root-sum-square of the harmonics of the voltage to the root-mean-square of the fundamental voltage [3].
\[
V_{THD} = \left( \sum_{n=2}^{\infty} (V_n) \right)^{\frac{1}{2}} \cdot (V_1)^{-1} \times 100\%
\]  

(2)

4. Current Total Harmonic Distortion (ITHD)

As given in equation (3), it is the ratio of the root-sum-square of the harmonics of the current to the root-mean-square of the fundamental current [3].

\[
ITHD = \left( \sum_{h=2}^{\text{max}} (I_h)^2 \right)^{\frac{1}{2}} \cdot (I_1)^{-1} \times 100\%
\]  

(3)

4.1. Current Total Demand Distortion

As given in equation (4), it is the ratio of the root-sum-square of the harmonics of the current to the maximum demand load current

\[
ITDD = \left( \sum_{h=2}^{\text{max}} (I_h)^2 \right)^{\frac{1}{2}} \cdot (I_L)^{-1} \times 100\%
\]  

(4)

5. Harmonics and Power Factor (PF)

PF is a measure of how effectively a load consumes electricity to do work. The higher the PF, the more work produced for a given voltage and current. PF is measured as the ratio between real power in kilowatts and apparent power in kilovoltamperes. For linear loads, which are defined as resistive, inductive, or capacitive, the apparent power in kilovoltamperes (S) is the phasor sum of the reactive power in kilovoltamperes reactive (Q) and the real power in kilowatts (P). The PF is \(P/S = \cos \phi\), where \(\phi\) is the angle between S and P. This angle is the same as the displacement angle between the voltage and the current for linear loads and is therefore often referred to as displacement power factor (DPF).

For nonlinear loads, the power phasor relationship becomes three dimensional with distortion reactive power \(H\) combining with both \(Q\) and \(P\) to produce the apparent power \(S\) which is the power system must deliver as given in equation (5).

\[
S = (P^2 + Q^2 + \frac{H^2}{2})^{1/2}
\]  

(5)

PF remains the ratio of kilowatts to kilovoltamperes, but the kilovoltamperes now has a harmonic component. True power factor (TPF) becomes the combination of DPF and distortion PF. DPF is still equal to \(\cos \phi\), with \(\phi\) being the angle between the fundamental current and voltage. DPF can be either leading or lagging. Distortion PF is then TPF (kW/kVA) divided by DPF. Distortion PF is neither leading nor lagging. For typical nonlinear loads, the DPF will be near unity. TPF, however, is normally very low because of the distortion component. [4]

6. Passive Filters

A shunt filter is said to be tuned to the frequency that makes its inductive and capacitive reactances to be equal. The quality of the filter (Q) specify the sharpness of filter tuning so it may be either of high or low Q type. If (Q) is high then the filter is sharply tuned to one of the harmonic frequencies and it is called single tuned filter STF [5].

6.1. Single Tuned Filter (STF)

The single tuned filter (STF) is an R-L-C series filter and it is either a low pass or a band pass. The inductive and capacitive reactances of the STF at the tuned frequency are calculated from equations (6), equation (7) and equation (8) [1][5].
\[ Z = j \omega_n L + \frac{1}{j \omega_n C} = R \]  
\[ \omega_n = (L/C)^{-\frac{1}{2}} \]  

If \( X_0 \) is the reactance of the capacitor or the reactor of the filter at its tuned frequency (\( \omega_n \))

\[ X_0 = \omega_n L = \frac{1}{\omega_n C} = (L/C)^{-\frac{1}{2}} \]  

The quality factor \( Q \) of the filter reactor is given in equation (9)

\[ Q = \frac{X_0}{R} = \left(\frac{L}{C}\right)^{\frac{1}{2}} \cdot (R)^{-1} \]  

Equation (10) gives the detuning of the filter from the resonance frequency which is represented by a factor \( \delta \)

\[ \delta = \frac{\omega - \omega_n}{\omega_n} \]  

\( \delta \) depends on (i) variation in supply frequency; (ii) variations of L and C caused by aging and temperature and (iii) tolerances and finite step of tuning steps.

The variation of L and C values by 2% causes detuning as a change in frequency by 1%, so \( \delta \) can be calculated from equation (11)

\[ \delta = \frac{\Delta f}{f_n} + \frac{1}{2} \left( \frac{\Delta L}{L} + \frac{\Delta C}{C} \right) \]  

7. IEEE Std 519 Harmonic Limits

IEEE Std 519 was first introduced in 1981 to provide direction on dealing with harmonics introduced by static power converters and other nonlinear loads so that power quality problems could be averted. It is being applied by consulting engineers and enforced by Utilities more frequently in recent years as the use of Variable Frequency Drives (VFD) and other non-linear loads has grown [3]. Referring to IEEE Std 519 tables and for the voltage of the simulated system which is 11 KV so the voltage total harmonic distortion (VTHD) limit is 5% [6]. To define current distortion limits, IEEE Std 519 uses a short circuit ratio to establish a customer’s size and potential influence on the voltage distortion of the system. The short circuit ratio (I_{SC}/I_L) is the ratio of short circuit current (I_{SC}) at the point of common coupling (PCC) with the utility to the customer’s maximum load or demand current (I_L). Lower ratios or higher impedance systems have lower current distortion limits to keep voltage distortion at reasonable levels [3].
8. Simulation of the Power System without Filters

The one line diagram of the simulated power system without filters is shown in figure 1. The simulation results at PCC#1 of the voltage and current waveforms are shown in figure 2 and Figure 3 respectively. Figure 4 and Figure 5 show the harmonic spectrum of the voltage and current respectively at PCC#1.

Figure 1. The Simulated Power System without Filters.

Figure 2. Voltage Waveform at PCC#1.  
Figure 3. Current Waveform at PCC#1.
Table 1 shows the calculated parameters at PCC#1 of the simulated power system. Table 2 shows the voltage individual harmonic components, the absolute value and in percentage of its fundamental component values at PCC#1. Table 3 shows the current individual harmonic components, the absolute and in percentage of its fundamental component values at PCC#1. Table 4 shows both of the total harmonic distortion and individual harmonic distortion values of both of the voltage and current at PCC#1, these values are compared to IEEE Std 519 limit values of VTHD and ITHD, it is shown that the VTHD and the 5’th harmonic component of the voltage are failed to compliance with IEEE Std 519. Also the ITHD, the 5’th and 11’th harmonic components of the current are failed to compliance with IEEE Std 519.

Table 1. Calculated Parameters at PCC#1

| Parameter                          | Value          |
|------------------------------------|----------------|
| Total Current $I_L$ (A)            | 22.8           |
| Short Circuit Current $I_{SC}$ (KA)| 0.7            |
| Short Circuit to Load Current Ratio, $I_{SC}/I_L$ | 30.0           |
| Displacement Power Factor (DPF)    | 0.968 lag.     |
| True Power Factor (TPF)            | 0.927          |
| Apparent Power S (KVA)             | 436.3          |
| Reactive Power (Q) (KVAR)          | 163.4          |
| Active Power (P) (KW)              | 404.6          |
### Table 2. Voltage Individual Harmonic Distortion Components

| Harmonic # | $V_{LL}$ rms | $V_{LL}$ % Fund. | Harmonic # | $V_{LL}$ rms | $V_{LL}$ % Fund |
|------------|--------------|------------------|------------|--------------|-----------------|
| 1          | 10980.03     | 100.00           | 30         | 0.04         | 0.00            |
| 2          | 0.06         | 0.00             | 31         | 69.41        | 0.63            |
| 3          | 0.14         | 0.00             | 32         | 0.05         | 0.00            |
| 4          | 0.02         | 0.00             | 33         | 0.25         | 0.00            |
| 5          | 503.75       | 4.59             | 34         | 0.06         | 0.00            |
| 6          | 0.05         | 0.00             | 35         | 63.29        | 0.58            |
| 7          | 198.66       | 1.81             | 36         | 0.09         | 0.00            |
| 8          | 0.03         | 0.00             | 37         | 64.02        | 0.58            |
| 9          | 0.13         | 0.00             | 38         | 0.06         | 0.00            |
| 10         | 0.05         | 0.00             | 39         | 0.21         | 0.00            |
| 11         | 214.81       | 1.96             | 40         | 0.03         | 0.00            |
| 12         | 0.04         | 0.00             | 41         | 57.36        | 0.52            |
| 13         | 158.68       | 1.45             | 42         | 0.07         | 0.00            |
| 14         | 0.01         | 0.00             | 43         | 57.05        | 0.52            |
| 15         | 0.11         | 0.00             | 44         | 0.07         | 0.00            |
| 16         | 0.03         | 0.00             | 45         | 0.17         | 0.00            |
| 17         | 110.85       | 1.01             | 46         | 0.08         | 0.00            |
| 18         | 0.04         | 0.00             | 47         | 57.72        | 0.53            |
| 19         | 115.72       | 1.05             | 48         | 0.12         | 0.00            |
| 20         | 0.05         | 0.00             | 49         | 55.25        | 0.50            |
| 21         | 0.19         | 0.00             | 50         | 0.09         | 0.00            |
| 22         | 0.02         | 0.00             |            |              |                 |
| 23         | 83.10        | 0.76             |            |              |                 |
| 24         | 0.05         | 0.00             |            |              |                 |
| 25         | 78.05        | 0.71             |            |              |                 |
| 26         | 0.02         | 0.00             |            |              |                 |
| 27         | 0.17         | 0.00             |            |              |                 |
| 28         | 0.02         | 0.00             |            |              |                 |
| 29         | 78.79        | 0.72             |            |              |                 |
Table 3. Current Individual Harmonic Distortion Components.

| Harmonic # | $I_{LL}$ rms | $I_{LL}$ % Fund. | Phase (degr.) | Harmonic # | $I_{LL}$ rms | $I_{LL}$ % Fund. | Phase (degr.) |
|------------|--------------|------------------|---------------|------------|--------------|------------------|---------------|
| 1          | 21.83        | 100.00           | -16.39        | 30         | 0.00         | 0.00             |               |
| 2          | 0.00         | 0.00             |              | 31         | 0.12         | 0.56             | 16.87         |
| 3          | 0.01         | 0.02             |              | 32         | 0.00         | 0.00             |               |
| 4          | 0.00         | 0.00             |              | 33         | 0.00         | 0.00             |               |
| 5          | 5.99         | 27.45            | 85.24         | 34         | 0.00         | 0.00             |               |
| 6          | 0.00         | 0.00             |              | 35         | 0.10         | 0.45             | 61.28         |
| 7          | 1.68         | 7.72             | 135.39        | 36         | 0.00         | 0.00             |               |
| 8          | 0.00         | 0.00             |              | 37         | 0.09         | 0.42             | 77.03         |
| 9          | 0.00         | 0.00             |              | 38         | 0.00         | 0.00             |               |
| 10         | 0.00         | 0.00             |              | 39         | 0.00         | 0.00             |               |
| 11         | 1.15         | 5.27             | -177.74       | 40         | 0.00         | 0.00             |               |
| 12         | 0.00         | 0.00             |              | 41         | 0.07         | 0.33             | 111.57        |
| 13         | 0.72         | 3.28             | -166.72       | 42         | 0.00         | 0.00             |               |
| 14         | 0.00         | 0.00             |              | 43         | 0.07         | 0.31             | 132.97        |
| 15         | 0.00         | 0.00             |              | 44         | 0.00         | 0.00             |               |
| 16         | 0.00         | 0.00             |              | 45         | 0.00         | 0.00             |               |
| 17         | 0.38         | 1.73             | -110.16       | 46         | 0.00         | 0.00             |               |
| 18         | 0.00         | 0.00             |              | 47         | 0.06         | 0.28             | 170.55        |
| 19         | 0.35         | 1.60             | -94.35        | 48         | 0.00         | 0.00             |               |
| 20         | 0.00         | 0.00             |              | 49         | 0.06         | 0.26             | -170.91       |
| 21         | 0.00         | 0.00             |              | 50         | 0.00         | 0.00             |               |
| 22         | 0.00         | 0.00             |              |            |              |                  |               |
| 23         | 0.21         | 0.94             | -62.25        |            |              |                  |               |
| 24         | 0.00         | 0.00             |              |            |              |                  |               |
| 25         | 0.18         | 0.80             | -35.35        |            |              |                  |               |
| 26         | 0.00         | 0.00             |              |            |              |                  |               |
| 27         | 0.00         | 0.00             |              |            |              |                  |               |
| 28         | 0.00         | 0.00             |              |            |              |                  |               |
| 29         | 0.15         | 0.69             | -0.95         |            |              |                  |               |

Table 4. Compliance with IEEE Std 519

| The Calculated Parameter | Harmonic No. | Calculated Value [%] | IEEE Std 519 Limit [%] |
|--------------------------|--------------|----------------------|------------------------|
| Voltage Harmonic Distortion (VTHD) | ------ | 6.01 | 5.0 | FAIL |
| Maximum individual Voltage Harmonic | 5 | 4.6 | 3.0 | FAIL |
| Current Total Harmonic Distortion (ITHD) | ------ | 29.33 | 8.0 | FAIL |
| Maximum Individual Current Harmonic < 11 | 5 | 27.45 | 7.0 | FAIL |
| Maximum Individual Current Harmonic 11 to 16 | 11 | 5.27 | 3.5 | FAIL |
| Maximum Individual Current Harmonic 17 to 22 | 17 | 1.73 | 2.5 | PASS |
| Maximum Individual Current Harmonic 23 to 34 | 23 | 0.94 | 1.0 | PASS |
| Maximum Individual Current Harmonic > 35 | 35 | 0.45 | 0.5 | PASS |
9. Single Tuned Filter (STF) Design
The single tuned filters that have to be connected to the PCC#1 consist of two resonant arms for the 5'th and 11'th harmonics components.

9.1. 5'th harmonic STF Design
From table 1 the
TPF = 0.927 (True Power Factor)
Active power = 404.6 KW
So the actual phase angle \( \Phi_{\text{TPF}} = \arctan(0.927) = 22^\circ \)
If the required PF is to be equal 1 then \( \Phi_{\text{Required}} = \text{zero deg.} \) and \( \tan(\Phi_{\text{Required}}) = \text{zero} \)
The required compensation reactive power = load (KW) \( \times \tan(\Phi_{\text{TPF}} - \Phi_{\text{Required}}) \)
\[ = 404.6 [0.4 - \text{zero}] = 161.84 \text{ KVAR} \]
\[ X_C = \frac{V_L^2}{\text{VAR}} = \frac{11^2 \times 10^6}{161.84 \times 10^3} = 747 \Omega \]
\[ X_C = \frac{1}{2\pi fC} \]
So \( C = \frac{1}{2\pi X_C} = \frac{1}{2\pi \times 50 \times 747} = 4.263 \mu f \)
If the capacitance is to be divided between the two filters branches as two-third of the capacitance value in 5'th harmonic branch and one-third of the capacitance value in the 11'th harmonic branch so
\[ C_5 = 2.842 \mu f \]
And
\[ C_{11} = 1.421 \mu f \]
Now
\[ X_{C5} = \frac{10^6}{2\pi \times 250 \times 2.842} = 224.117 \Omega \]
\[ X_{L5} = X_{C5} \] at resonance frequency
So
\[ X_{L5} = 224,117 \Omega \]
\[ L_5 = \frac{224,117}{2\pi \times 250} = 0.142 \text{ H} \]
Now if the
The capacitor temperature coefficient \( \frac{\Delta C}{C} = 0.05 \% \) per degree Celsius
The inductor temperature coefficient \( \frac{\Delta L}{L} = 0.01 \% \) per degree Celsius
The frequency tolerance \( \frac{\Delta f}{f_n} = \pm 1\% \)
So \( \delta \) can be calculated from equation (11)
\[ \delta = \frac{\Delta f}{f_n} + \frac{1}{2} \left( \frac{\Delta L}{L} + \frac{\Delta C}{C} \right) \]
\[ \delta \left( \frac{1}{100} \right) \left[ 1 + 0.5 (0.05 \times 20 + 0.01 \times 20) \right] = 0.016 \]
The optimum quality factor (Q) which results in the lowest harmonic voltage is then obtained from the following equation [5].

\[ Q = \frac{1 + \cos \phi_{s_y}}{2 \delta \sin \phi_{s_y}} \]

Where \( \phi_{s_y} \) is the phase angle of the system impedance which is less than 75° at any frequency. So

\[ Q = \frac{1 + \cos 75}{2 \times 0.016 \times \sin 75} = 40.738 \]

\[ R_5 = \frac{X_{L5}}{Q} = \frac{224.117}{40.738} = 5.5 \, \Omega \]

9.2. 11’th harmonic STF Design

\[ C_{11} = 1.421 \, \mu f \]

\[ X_{C11} = \frac{10^6}{2 \pi \times 550 \times 1.421} = 203.743 \, \Omega = X_{L11} \]

\[ L_{11} = \frac{2 \pi \times 550}{203.743} = 0.0589 \, \text{H} \]

\[ R_{11} = \frac{X_{L11}}{Q} = \frac{203.743}{40.738} = 5 \, \Omega \]

10. Simulation of the Power System with Filters

A 5’th harmonic shunt passive STF and an 11’th harmonic shunt passive STF are designed to mitigate the VTHD and ITHD of this system to be compliance with IEEE Std 519. The power system is simulated with the two branches of the STF (5’th and 11’th) are connected to PCC#1. Table 5 shows the filters parameters C, L and R.

| The Filter        | C (\( \mu f \)) | L (H) | R (\( \Omega \)) |
|-------------------|---------------|-------|-----------------|
| 5’th Harmonic STF | 2.842         | 0.142 | 5.5             |
| 11’th Harmonic STF| 1.421         | 0.0589| 5               |

The simulation results at PCC#1 of the voltage and current waveforms is shown in figures 6 and Figure 7 respectively. The harmonic spectrum of the voltage and current are shown in Figure 8 and Figure 9 respectively.
Table 6 shows the calculated parameters at PCC#1 of the simulated power system. Table 7 shows the voltage individual harmonic components, the absolute and in percentage of its fundamental component values at PCC#1. Table 8 shows the current individual harmonic components, the absolute and in percentage of its fundamental component values at PCC#1. Table 9 shows both of the total harmonic distortion and individual harmonic distortion values of both of the voltage and current at PCC#1, these values are compared to IEEE Std 519 limit values of VTHD and ITHD, it is shown that the power system is compliance with IEEE Std 519 for both of the voltage and current waveforms.
Table 6. Calculated Parameters at PCC#1.

| Parameter                                      | Value       |
|------------------------------------------------|-------------|
| Total Current $I_L$ (A)                        | 21.7        |
| Short Circuit Current $I_{SC}$ (KA)            | 0.7         |
| Short Circuit to Load Current Ratio, $I_{SC}/I_L$ | 30.2        |
| Displacement Power Factor (DPF)                | 0.978 lag.  |
| True Power Factor (TPF)                        | 0.976       |
| Apparent Power S (KVA)                         | 415.0       |
| Reactive Power (Q) (KVAR)                      | 90.3        |
| Active Power (P) (KW)                          | 405.0       |

Table 7. Voltage Individual Harmonic Distortion Components.

| Harmonic # | $V_{LL}$ RMS | $V_{LL}$ % Fund. | Harmonic # | $V_{LL}$ RMS | $V_{LL}$ % Fund. |
|------------|--------------|------------------|------------|--------------|------------------|
| 1          | 10997.81     | 100.00           | 30         | 0.10         | 0.00             |
| 2          | 0.37         | 0.00             | 31         | 27.23        | 0.25             |
| 3          | 0.26         | 0.00             | 32         | 0.02         | 0.00             |
| 4          | 0.26         | 0.00             | 33         | 0.17         | 0.00             |
| 5          | 6.33         | 0.06             | 34         | 0.29         | 0.00             |
| 6          | 0.33         | 0.00             | 35         | 26.91        | 0.24             |
| 7          | 117.79       | 1.07             | 36         | 0.34         | 0.00             |
| 8          | 0.22         | 0.00             | 37         | 22.72        | 0.21             |
| 9          | 0.10         | 0.00             | 38         | 0.17         | 0.00             |
| 10         | 0.07         | 0.00             | 39         | 0.30         | 0.00             |
| 11         | 86.85        | 0.79             | 40         | 0.14         | 0.00             |
| 12         | 0.23         | 0.00             | 41         | 25.75        | 0.23             |
| 13         | 44.40        | 0.40             | 42         | 0.21         | 0.00             |
| 14         | 0.11         | 0.00             | 43         | 24.08        | 0.22             |
| 15         | 0.12         | 0.00             | 44         | 0.41         | 0.00             |
| 16         | 0.13         | 0.00             | 45         | 0.50         | 0.00             |
| 17         | 56.11        | 0.51             | 46         | 0.17         | 0.00             |
| 18         | 0.18         | 0.00             | 47         | 23.10        | 0.21             |
| 19         | 46.47        | 0.42             | 48         | 0.24         | 0.00             |
| 20         | 0.10         | 0.00             | 49         | 24.84        | 0.23             |
| 21         | 0.15         | 0.00             | 50         | 0.30         | 0.00             |
| 22         | 0.30         | 0.00             |            |              |                  |
| 23         | 33.63        | 0.31             |            |              |                  |
| 24         | 0.13         | 0.00             |            |              |                  |
| 25         | 37.85        | 0.34             |            |              |                  |
| 26         | 0.26         | 0.00             |            |              |                  |
| 27         | 0.36         | 0.00             |            |              |                  |
| 28         | 0.11         | 0.00             |            |              |                  |
| 29         | 26.18        | 0.24             |            |              |                  |
### Table 8. Current Individual Harmonic Distortion Components

| Harmonic # | I_{LL} rms | I_{LL} % Fund. | Phase (degr.) | Harmonic # | I_{LL} rms | I_{LL} % Fund. | Phase (degr.) |
|------------|------------|----------------|---------------|------------|------------|----------------|---------------|
| 1          | 21.70      | 100.00         | -13.99        | 26         | 0.00       | 0.00           | 0.00          |
| 2          | 0.00       | 0.02           | 0.00          | 27         | 0.00       | 0.00           | 0.00          |
| 3          | 0.01       | 0.03           | 0.00          | 28         | 0.00       | 0.00           | 0.00          |
| 4          | 0.00       | 0.01           | 0.05          | 29         | 0.00       | 0.23           | -98.15        |
| 5          | 0.07       | 0.33           | -5.36         | 30         | 0.00       | 0.00           | 0.00          |
| 6          | 0.00       | 0.01           | 0.05          | 31         | 0.05       | 0.22           | -77.53        |
| 7          | 1.00       | 4.61           | -176.51       | 32         | 0.00       | 0.00           | 0.00          |
| 8          | 0.00       | 0.01           | 0.00          | 33         | 0.00       | 0.00           | 0.00          |
| 9          | 0.00       | 0.00           | 0.00          | 34         | 0.00       | 0.00           | 0.00          |
| 10         | 0.00       | 0.00           | 0.04          | 35         | 0.04       | 0.19           | -65.47        |
| 11         | 0.47       | 2.15           | 144.85        | 36         | 0.00       | 0.00           | 0.00          |
| 12         | 0.00       | 0.00           | 0.03          | 37         | 0.03       | 0.15           | -49.83        |
| 13         | 0.20       | 0.93           | 160.07        | 38         | 0.00       | 0.00           | 0.00          |
| 14         | 0.00       | 0.00           | 0.00          | 39         | 0.00       | 0.00           | 0.00          |
| 15         | 0.00       | 0.00           | 0.00          | 40         | 0.00       | 0.00           | 0.00          |
| 16         | 0.00       | 0.00           | 0.03          | 41         | 0.03       | 0.15           | -23.42        |
| 17         | 0.19       | 0.88           | -160.74       | 42         | 0.00       | 0.00           | 0.00          |
| 18         | 0.00       | 0.00           | 0.03          | 43         | 0.03       | 0.13           | -17.33        |
| 19         | 0.14       | 0.65           | -163.48       | 44         | 0.00       | 0.00           | 0.00          |
| 20         | 0.00       | 0.00           | 0.00          | 45         | 0.00       | 0.00           | 0.00          |
| 21         | 0.00       | 0.00           | 0.00          | 46         | 0.00       | 0.00           | 0.00          |
| 22         | 0.00       | 0.00           | 0.02          | 47         | 0.02       | 0.11           | 14.49         |
| 23         | 0.08       | 0.38           | -121.43       | 48         | 0.00       | 0.00           | 0.00          |
| 24         | 0.00       | 0.00           | 0.03          | 49         | 0.03       | 0.12           | 20.90         |
| 25         | 0.09       | 0.39           | -115.78       | 50         | 0.00       | 0.00           | 0.00          |

### Table 9. Compliance with IEE Std 519

| The Calculated Parameter                        | Harmonic No. | Calculated Value [%] | IEEE Std 519 Limit [%] |
|------------------------------------------------|--------------|----------------------|-----------------------|
| Voltage Harmonic Distortion (VTHD)              | -----        | 1.7                  | 5.0                   | PASS                  |
| Maximum individual Voltage Harmonic            | 7            | 1.1                  | 3.0                   | PASS                  |
| Current Total Demand Distortion (ITDD)         | -----        | 5.3                  | 8.0                   | PASS                  |
| Maximum Individual Current Harmonic < 11       | 7            | 4.6                  | 7.0                   | PASS                  |
| Maximum Individual Current Harmonic 11-16      | 11           | 2.1                  | 3.5                   | PASS                  |
| Maximum Individual Current Harmonic 17-22      | 17           | 0.9                  | 2.5                   | PASS                  |
| Maximum Individual Current Harmonic 23-34      | 25           | 0.4                  | 1.0                   | PASS                  |
| Maximum Individual Current Harmonic > 35       | 35           | 0.2                  | 0.5                   | PASS                  |
11. Conclusion
The 5'th harmonic shunt passive STF and the 11’th harmonic shunt passive STF have mitigated the VTHD and ITHD of this system to be compliance with IEEE Std 519. So the single tuned filters which have been used were effective in mitigating the distortion of both of the current and the voltage at the point of common coupling.

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