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Power Quality and Harmonic Analysis in Three Phase Systems

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Abstract

Problems involving power quality is an often occurrence which comes as nonstandard voltage, frequency or current which result in a complete failure or dysfunction of an end user equipment. Sensitive industrial loads, distribution networks and some very important commercial operation suffer the most from these forms of distortions which may lead an outage which will in turn cost a significant financial loss. With redesigning and restructuring of power systems, the problem involving power quality is going to take a different phase. In developing countries like Nigeria, power frequencies and many other things that determine power quality varies and this will lead to a serious question, it is extremely important to take great steps towards this direction. In order to achieve an acceptable distortion, which is the sole purpose of this thesis by reducing the harmonics as well as improving the overall power quality of the system, three phase filters which filter harmonics were connected in parallel these filters will help in suppressing the higher order harmonics. Variants of Butterworth, Chebyshev and Cauer filters were used in MATLAB SIMULINK. HVDC line was also checked for harmonics and also to correct the overall power factor of the system.

Keywords: Power quality; Harmonics; Harmonic filters; Iron and steel industry; MATLAB/SIMULINK

Introduction

Power Quality or PQ as abbreviated is a general term that is being used to a very large phenomena's in the electrical power systems. Most of the times the term PQ is linked with particular issues with the equipment or the whole system. As an example, equipment might be damaged; some data losses may occur or even a total system failure. The fault time in each of this phenomenon as ranges widely from nanoseconds (as in the case of transients) to a few milliseconds (as in the case of voltage sags or voltage swells) or to steady state disturbances (as in the case of harmonics, inter-harmonics and voltage fluctuations) [1].

The concept of power quality deals with the powering and grounding of sensitive power equipment's in a way that is most suitable to the operation of that particular equipment (IEE Std 1100 & IEEE std 1159) according to these standards, those sensitive materials or equipment's require total protection against any type of disturbance.

Harmonic analysis in power systems

Electrical power engineers are basically using identical components to help them label a three phase systems operation. This three phase system is being converted into three different single phase systems that will be much easier to analyze. This method can be used to analyze the response of the system to harmonic currents but care must be taken in order not to disrupt the basic expectations. This process will allow any unbalanced phase voltages or currents to be changed into balanced sets. The positive sequences all contain three sinusoidal waveforms which are 120 degrees out of phase with each other. The normal phase that is widely used is the A-B-C sequence whose phases are (0, 120, 120 degrees). The waveform of the negative sequence is also moved 120 degrees in phase. Being a negative sequence, these sets have the opposite phase notation A-C-B. In an ideal balanced three phase system, the harmonic sequences can be determined by multiplying the normal positive sequence with the harmonic number h. example; for a second harmonic of magnitude h = 2, we will have 2 X (0, 120, 120), (0, 120, 120) which will yield the negative sequence. These phases are the same hence they will cancel each other out because the harmonic component is an even number 2, phase sequence for all other harmonic components can be found using the same method as a distorted waveform have only odd harmonics [2]. The summary below shows the phase sequences of odd harmonics

- Harmonics of order h = 1, 7, 13, are all positive sequence.
- Harmonics of order h = 5, 11, 17 are all negative sequence.
- Triplens (those who are multiples of 3) h = 3, 9, 15 are called zero sequence

Odd harmonics

Figure 1 shows the graph of an odd harmonic Fourier series. The Fourier series will contain odd harmonics if

$$f(t+\pi) = -f(t)$$

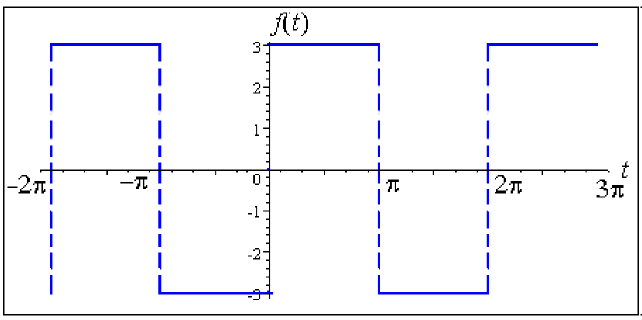

Figure 1: Odd harmonics.

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In this case, the fourier expansion will be in the form of;

$f(t)=\frac{a_0}{2}+(a_1 cost+b_1 sint)+(a_3 cos3t+b_3 sin3t)+(a_5 cos5t+b_5 sin5t)+\ldots$ all of the harmonics are odd.

Even harmonics

The Fourier series as shown in Figure 2 will contain even harmonics if

$$f(t+\pi)=f(t)$$

In this case, the Fourier expansion will be of the form:

$$f(t)=\frac{a_0}{2}+(a_2 cos2t+b_2 sin2t)+(a_4 cos4t+b_4 sin4t)+(a_6 cos6t+b_6 sin6t)+\ldots.$$

Fourier transform

The expression Fourier Transform as defined by prominent mathematicians and scientists is given below. The motivation for the Fourier transform comes from the study of Fourier series. In the study of Fourier series, complicated but periodic functions are written as the sum of simple waves mathematically represented by sines and cosines. The Fourier transform is an extension of the Fourier series that results when the period of the represented function is lengthened and allowed to approach infinity [3]. Basically Fourier Transform is a mathematical operation used to decompose a signal into sine and cosine components Figure 3.

Fundamentally Fourier Transform is a mathematical operation used to break a signal into sine and cosine components. The result of the alteration represents the signal as a function of frequency while the input signals as a function of time. It can refer into 4 categories.

- Aperiodic-Continuous (Fourier transform)
- Periodic-continuous (Fourier Series)
- Aperiodic-Discrete (Discrete-time Fourier Transform)
- Periodic-Discrete (Discrete Fourier Transform)

The Discrete Fourier transform (DFT), which is normally calculated using the so-called Fast Fourier Transform (FFT), has modernized modern society, as it is universal in digital electronics and signal processing Figure 4. DFT defined as

$$F(k\Delta\Omega)=\sum_{n=0}^{N-1} f(n\Delta T)\times e^{\frac{-j2kn}{N}}$$

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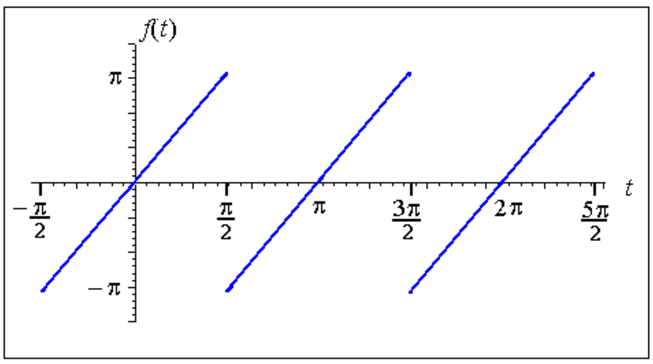

Figure 2: Even harmonics.

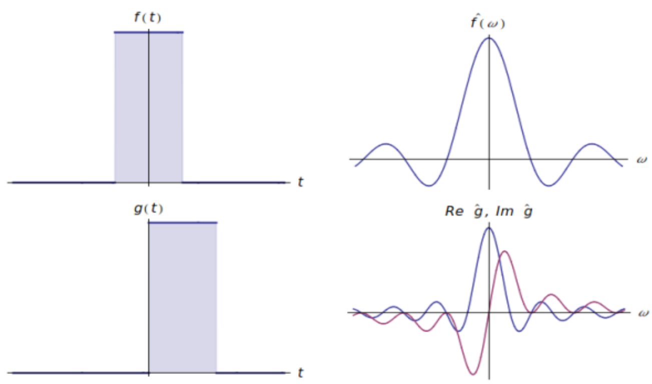

Figure 3: Fourier transform of 2 signals f(t) and g(t).

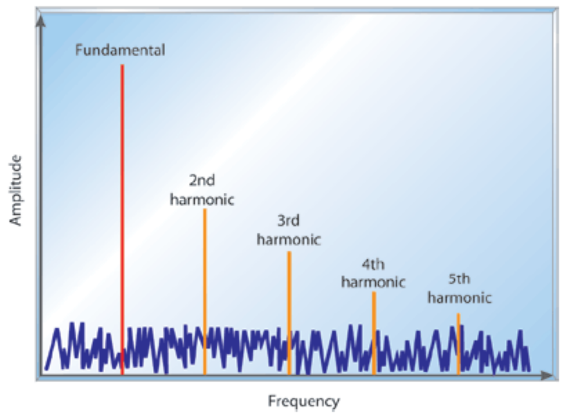

Figure 4: Fourier transform of harmonics.

$$k,n=0,1,\ldots N-1;(\Delta\Omega)=\frac{2}{\Delta T};\Delta T=\frac{T}{N}$$

Power Quality Indices under Harmonic Distortion

Total harmonic distortion

Total harmonic distortion THD can be defined as summation of the all harmonic values (except the fundamental component), the summation is divided by fundamental component. The main purpose is to limit voltage and current harmonics to under a certain value. It is very common in power quality and harmonic standards [4,5]. THD can be computed for both current and voltage waveforms as shown in the equation below;

$$THD_v=\frac{\sqrt{\sum_{h=2}^{\infty} V_h^2}}{V_1}$$

$$THD_I=\frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1}$$

This implies that the ratio between the rms values of current and voltages to their respective fundamentals is defined as the total harmonic distortion. Harmonic waveforms are most visible when observed at the point of common coupling PCC. This PCC is usually at the meters of the customers and can reflect the maximum customer demands weak sources with a high current demand when compared to their rated current will show a greater distortion of the waveform. Total demand distortion is based on the demand or load current I_L over an observable period.

$$TDD = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_L}$$

A Three Phase Harmonic Filter

A three phase harmonic filter is a connection of parallel elements that are useful in a power system in order to decrease the voltage distortion and to correct the power factor. Harmonic elements such as electronic converters produce harmonic currents and harmonic voltages or both at the same time. These distortions are injected into the power system. This will in turn produce a distorted current flow through the impedance of the system which will yield to the production of harmonic voltage distortion. Harmonic filters whether single phase or three phase are used to reduce this distortion by guiding the harmonic currents to the path where there is a relatively low impedance. Harmonic filters are capacitive at the base or fundamental frequency and they can also be used for producing reactive power which will be required by the converters for purpose of power factor correction [6-9]. In order to achieve an acceptable distortion limit, a lot filter banks are usually connected in parallel, the most commonly used of these filters are;

- Band pass filters: these filters are used to filter low order harmonics like the 5^{th}, 7^{th}, 11^{th}, 13^{th} etc. these filters can be in two forms namely; single tuned and double tuned single tuned filter is operated at one frequency while the double tuned filter is operated at two frequencies.
- High pass filters: These filters are used to filters high harmonic frequencies as the name implies. A special type of high pass filter called the C type filter was used in this thesis to provide reactive power and to stop parallel resonance. It enables the filtering of lowest order harmonic that is the 3^{rd} harmonic as well as keeping zero losses at the base frequency.
- Three phase harmonic filters: This filter is built with RLC elements. These RLC values are determined from the form of the filter using the following parameters [10-14]:
- Reactive power at the nominal voltage
- Tuning frequency
- Quality factor.

The four types of filters that can be designed alongside the three phase harmonic filter are shown below

The simplest form of these filters is the single tuned, that is the one that is operated using only one frequency, and Figure 5 shows the quality factor and formulae for calculating the reactive and active powers respectively. The quality factor Q of the fil reactance at the tuning frequency is the same and is given by $Q = \frac{nX_L}{R}$. The quality factor Q indicates the bandwidth B which measures the sharpness of the tuning frequency.

The filter design

The HVDC line in the system's rectifier was gotten from the two 6 pulse thyristor bridges that were connected in series. Connected to the system is also a converter with a 120MVA three phase transformer. Connected to the DC side is a 1000MW resistive load through a 0.5H smoothening reactor Figure 6. The filters comprises of the following four components of the power lib library [15-18]:

- 1. One capacitor bank C1 of 150Mvar designed by a "Three-Phase Series RLC Load",

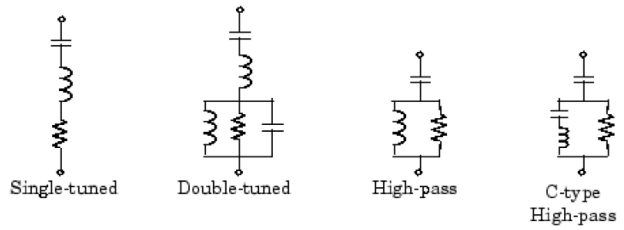

Figure 5: Different types of three-phase RLC harmonic filter.

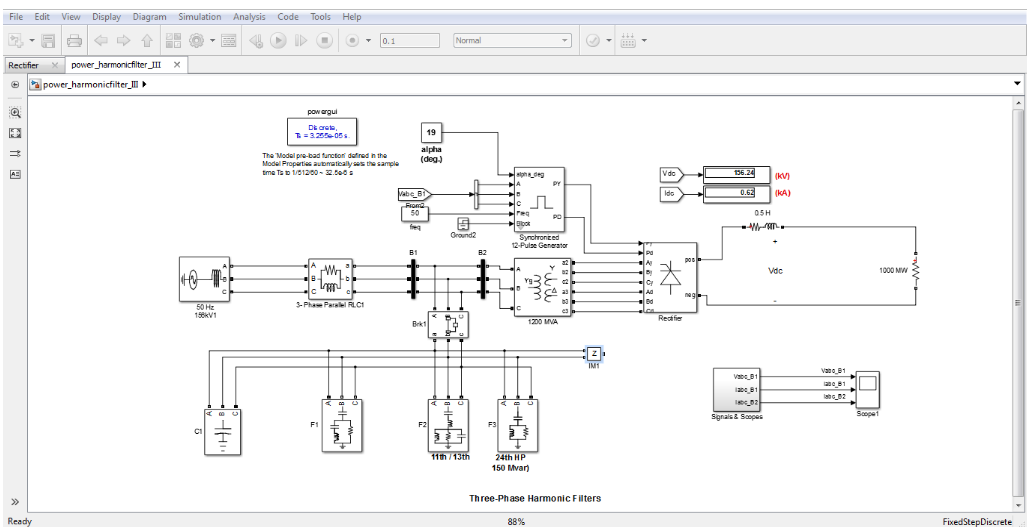

Figure 6: Three Phase Harmonic Filter (Simulink Design).

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- Three filters designed using the "Three-Phase Harmonics Filters" are used in the HVDC line as shown in the Figure 6.
- One c type filter tuned to to the 3rd F1 of 150Mvar
- One double tuned filter 11th/13th F2 of 150Mvar.
- One high-pass filter tuned to the 24th (F3) of 150 Mvar.

The filter is opened and closed with the breaker in the circuit. When the breaker is closed, the current and voltage from B1 will pass through the filter and will subsequently be filtered and can be seen through the scope. However, when the breaker is opened, the filter will be deactivated and will have no effect on the output waveforms of the system.

The following waveforms will show the filter effects on the output waveforms of the system Figure 7.

With the breaker opened and the filter deactivated, a highly distorted waveform was formed as the result of the nonlinear loads in the system. Checking the FFT analysis of the system, we will also see a very high amount of THD which will be way above the accepted IEE-519-1992 limits Figure 8 [19-22].

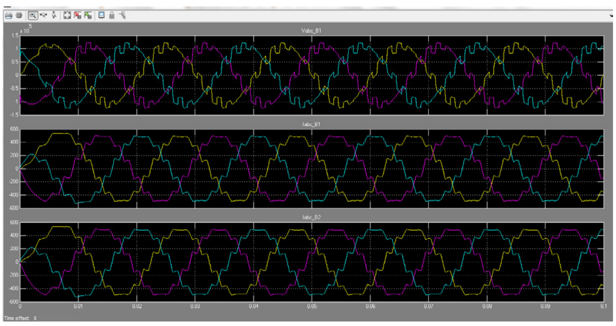

Figure 7: Output Waveforms of The System With Filter Disconnected.

The FFT analysis of the voltage waveform at B1 above shows a highly distorted waveform and an unacceptable level of THD at 17.09% Figure 9.

The FFT also shows a highly distorted current waveform at B1 and an unacceptable level of THD at 9.84% Figure 10. Now, by closing the breaker, the filter will be activated, and the waveforms will be as follows;

The output from VI measurement B1 was connected to the filter, and hence, we can see the voltage and current at B1 were duly filtered to an almost ideal sinewave. The FFT analysis also showed that the THD was significantly reduced to an accepted level Figure 11.

The FFT of the voltage ab B1 shows an almost ideal waveform and the THD was significantly reduced from 17.09% to1.47% which is within the acceptable limits of the IEE-519-1992 Figure 12.

The FFT analysis of the current waveform at B1 also shows that the THD of the current waveform was reduced from 9.84% to 1.77% which is within the acceptable limits of THD Figure 13.

We now check the impedance vs frequency graph of the filter.

The graph above shows that the maximum impedance will be reached at a high frequency of around 700Hz and our filter impedance at fundamental frequency of 50Hz is around 40.5 ohms [23-27].

Then, we can calculate the reactive power of our filter;

$$Q_C = \frac{V^2}{X_C}$$

$$= \frac{(156 \times 10^3)^2}{40.5} \cong 600 Mvar.$$

The 600Mvar reactive power was as the result of the four different 150Mvar filters used in the diagram. For which $(150 Mvar \times 4 = 600 Mvar)$.

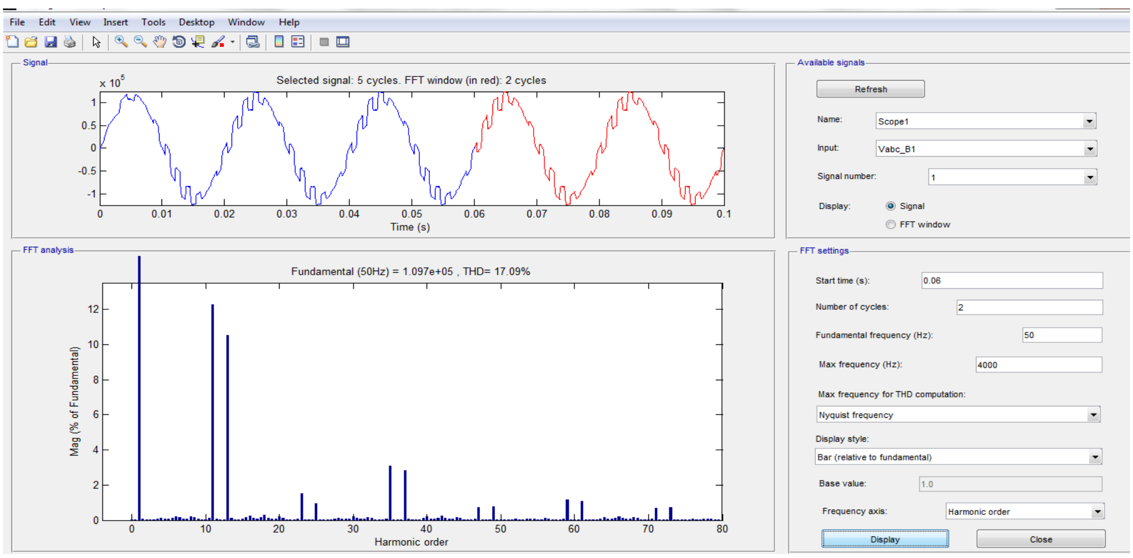

Figure 8: FFT analysis of the voltage with filter disconnected.

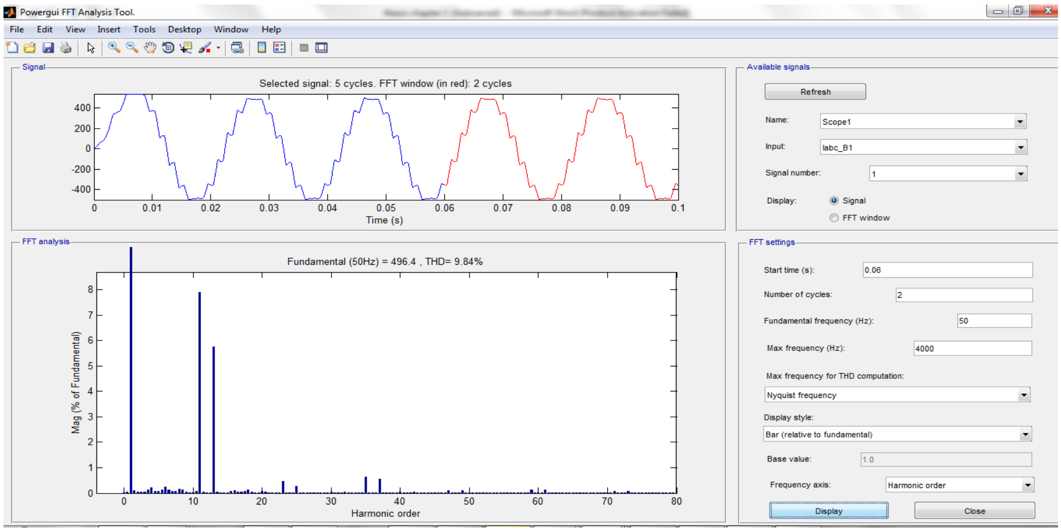

Figure 9: FFT analysis of the current waveform with filter disconnected.

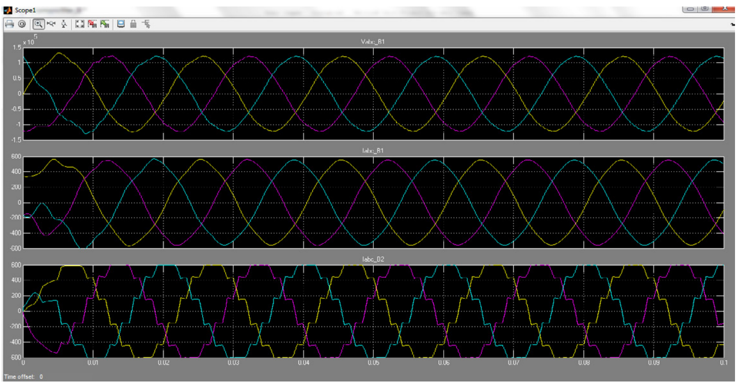

Figure 10: Output waveforms of the system with filter connected at bus B1.

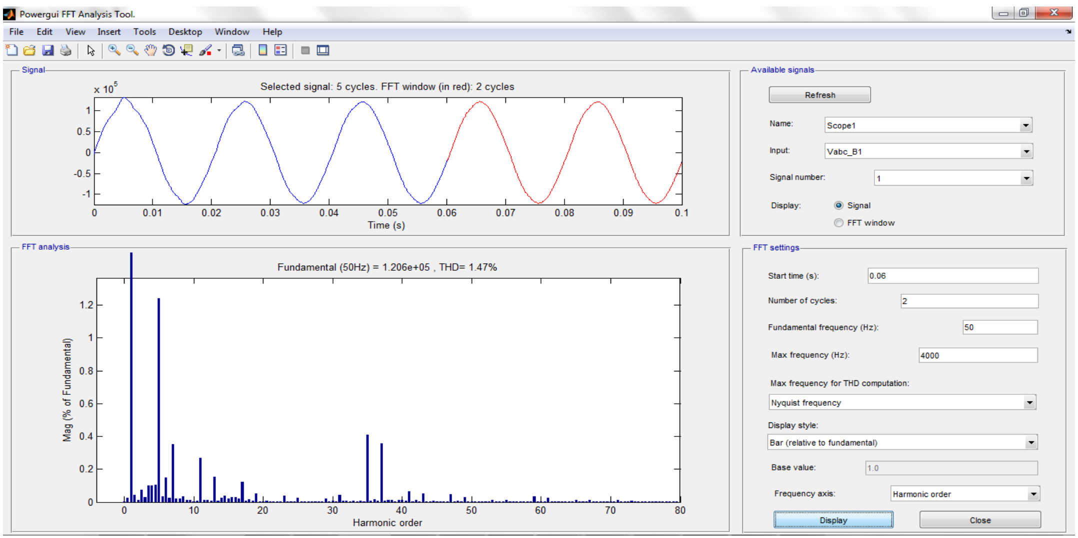

Figure 11: FFT analysis of the voltage with filter connected.

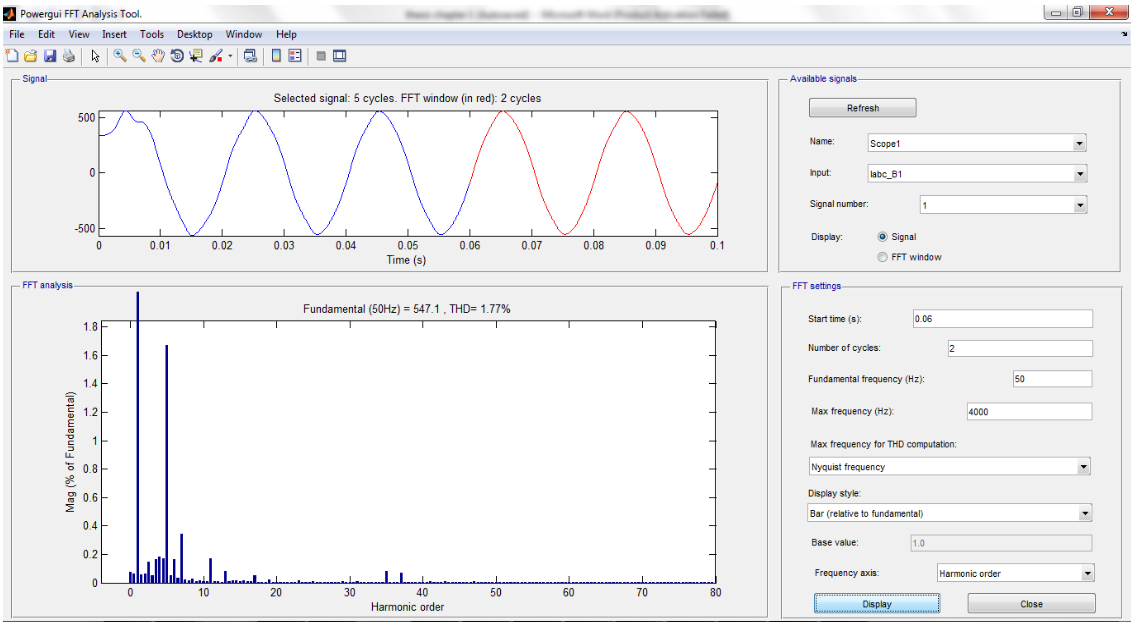

Figure 12: FFT analysis of the current with filter connected.

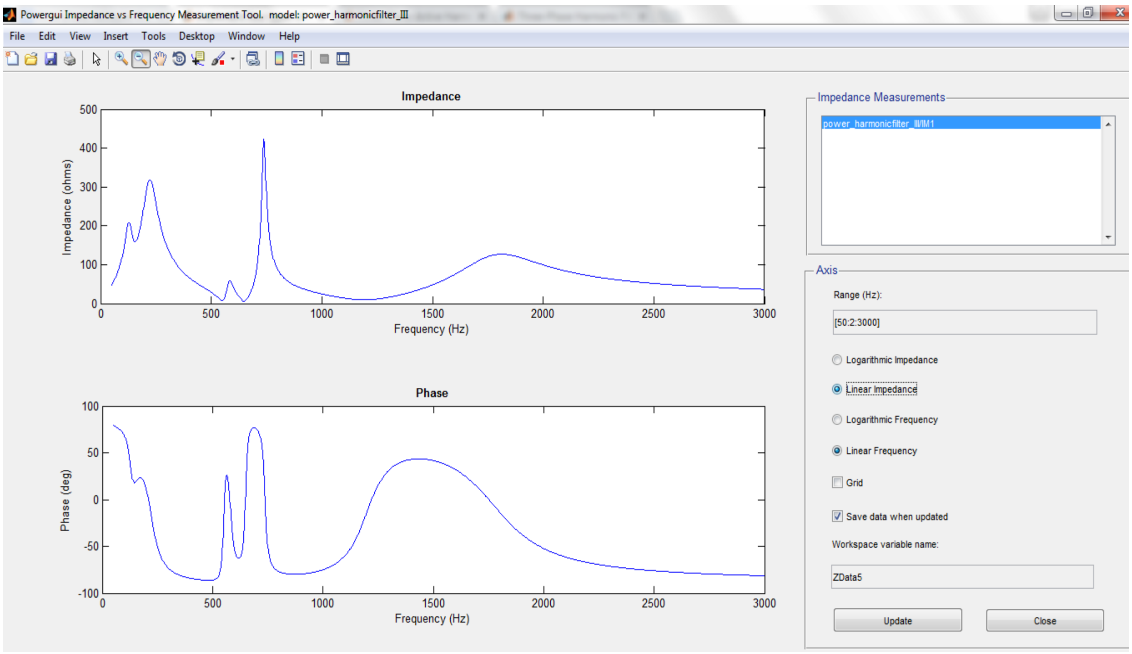

Figure 13: The impedance *Vs*. Frequency graph.

Conclusion

Conclusively, in the whole of this thesis, harmonics was specially discussed as the case study, but some few power quality problems were also explained. The design of the three phase harmonic filter and its simulations was done with MATLAB simulin. Additionally, varieties of three phase filters were briefly discussed. These filters are also used in the HVDC line connected in parallel, all in the hope of achieving an acceptable distortion level. The HVDC line is used with a three phase filter to reduce harmonic distortion as well improving the overall quality of the power system. The results obtained from this thesis show that the filtering system will remove both high and low frequency harmonics from the system.

From the results obtained in this thesis, we can draw a conclusion that the filter is an effective method of mitigating harmonics at different frequencies ranging from 13th to 23rd.

Improvement of power quality and saving energy is very important for industrial plants. The permanent increase of non-linear loads cause rising “network contamination”. Network contamination must be considered equal to environment pollution. In an ideal network, power generators are stabilized and generate pure sine waves. Any deviations of these sine waves are described as “network perturbation”. Many consumers encounter these perturbations. The FFT (Fast Fourier Transform) of these polluted currents and voltages results in a wide range of harmonic frequencies.

Future Work

As shown in this thesis, there are varieties of power quality challenges in modern day industries. After designing and implementing the filters, it is extremely useful to have a monitoring system. Today, power quality monitoring is an essential service many utilities perform for their industrial and other key commercial customers. Because of the technology and software now available this monitoring is highly effective. Not only can a monitoring system provide information about the quality of the power and the causes of power system disturbances, but it can identify problem condition throughout the system before they cause widespread customer complaints, equipment malfunction, and even equipment failures. Many surveys have shown that the majority of problems are localized within customer facilities. Given this fact, monitoring provides a key opportunity for a utility to protect its reputation and improve its relationship with customers and future work.

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