An-Najah National University

Faculty of Graduate Studies

Power System Harmonics Analysis Using Frequency-Domain Impedance Model of Network and Methods of Disposal

By

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Dedication

Dedicated to my family the most valuable thing I obtained in life

Acknowledgment

I would like to thank Almighty God for making this work a reality and bringing me to this level of success.

I acknowledge with gratitude the following people for their valuable contributions towards this study:

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الإقرار

أنا الموقع أدناه مقدم الرسالة التي تحمل العنوان

Power System Harmonics Analysis Using Frequency-Domain Impedance Model of Network and Methods of Disposal

أقر بأن ما شملت عليه الرسالة هو نتاج جهدي الخاص, باستثناء ما تمت الإشارة إليه حيثما ورد, وأن هذه الرسالة ككل أو أي جزء منها لم يقدم من قبل لنيل أي درجة أو لقب علمي أو بحثي لدى أي مؤسسة علمية أو بحثية

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Student's Name: **اسم الطالب: علاء مرداوي**

Signature **التوقيع:**

Date **التاريخ: 23/5/2018**

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Power System Harmonics Analysis Using Frequency-Domain Impedance Model of Network and Methods of Disposal

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Abstract

Power grids can be described as low power quality if they contain distorted currents which are known as harmonics. Harmonics mean that the alternating current (AC) wave contains multiple integers of the fundamental frequency. In the past, this distortion was caused by the elements of the network itself, such as transformers, when they enter the saturation area in periods of high demand for energy. The generators themselves produce waves with a slight degree of distortion because the distribution of the magnetic flux is not optimal. But nowadays, the main reason for the problem is the spread of nonlinear loads, especially power electronic devices, for domestic and commercial use. Several small devices spread through the whole network are participating in the distortion.

Distortion due to harmonics has become very important in the field of power quality studies because of the negative effects of the distortion on equipment and what is accompanied by negative effects such as resonance.

In order to understand the problem of harmonics, an accurate analysis of the network must be carried out in the presence of the sources of harmonics. The main goal of this analysis is to find different values of the distortion and to

compare them with the standards set to the normal level. Also, such studies enable us to study the effectiveness of different procedures followed in eliminating harmonics and controlling their flow.

In this thesis, a frequency-domain model of a distribution network was developed and an analysis was carried out to enable us to calculate the required values of distortion. All this was accompanied by a software simulation of the same network in order to compare the accuracy of the results.

- **Problem statement**

  The spread of nonlinear loads in the electric power systems will result in distortions in the current wave and thus distortion on the voltage, which is called the harmonics. These distorted currents will be injected back into the power supply to cause a negative effect on the power quality that is to increase the losses and reduce the power factor. The network equipment itself will also be subject to damage and downtime due to harmonics. This has necessitated worldwide interest in harmonics studies, including harmonics estimation, elimination and a variety of related areas.

- **Objectives**

  - To learn how to form a frequency-dependent model for network elements depending on the nature of each element and how it behaves with harmonics frequencies.
  - To develop a methodology for harmonics analysis of networks so that this method can be adopted by network operators as a guide to execute of various calculations related to harmonics.

- To study procedures used in harmonics mitigation and to ensure their effectiveness by simulation.
- To present all issues associated with harmonics such as general characteristics, sources, effects, harmonics indices and standards.

- **Methodology**

  A mathematical model for the whole electric network is developed in order to carry out harmonics power flow analysis by hand calculation. Later, the analysis is carried out to evaluate the developing method proposed by using a computer program ETAP12.6.

- **Thesis layout**

  The thesis is organized as follows: **Chapter 1** provides a basic theory about harmonics and related topics such as distortion measurements, harmonics sequences and calculation of electrical quantities of distorted waves. **Chapter 2** deals with the undesirable effects of harmonics as they pass through the various network equipment. It also looks at the effects on the entire network such as resonance. **Chapter 3** covers the sources of harmonics in the electric network with a description of the nature of the harmonics injected during the operation of the device. **Chapter 4** covers a brief discussion on standards for distortion limits. **Chapter 5** models the network elements based on the nature of the interaction of the element with the passage of harmonics in it. Each element will be dealt with separately to get a frequency dependent impedance. **Chapter 6 represents** building a complete harmonics model for a distribution network and conduct an accurate analysis of harmonics frequencies, thus calculate the bus voltages and then calculate the distortion measurements. This is accompanied by simulations of the same network to determine the accuracy of the model and manual analysis. **Chapter 7** covers several procedures that can be used for the mitigation of harmonics. A simulation was done to make sure that they are correct. **Chapter 8** includes appropriate conclusions and suggestions for future work. **Appendix A**: includes MATLAB coding for harmonics voltages calculation. **Appendix B**: includes proof of phase shift ($\Delta\ to\ \Delta/Y\ connection$) method which is used for harmonics cancelation. **Appendix C:** includes filter harmonics currents calculation. **Appendix D:** includes selected examples of harmonics analyzer.

Literature Review:

Shehab Ali, (2011), Provided an easily obtained and simple model for distribution networks without knowing the configuration of the network. This model was known as Norton model. It was found that the model is very useful for analysis even if there is a change in the operating conditions of the supply-side of the system, which in turn changes the nature and value of harmonics currents. The model is useful in knowing the harmonics content of the current source. In this model, we need to measure harmonics voltages and currents at the target point for at least two different operating conditions. Also, the different distortion values cannot be calculated [12].

Nikita Lovinskiy,(2010), developed a network model that reflects the impact of harmonics on distribution networks as a whole and network elements as well. In the model; the impedance of two main components in the distribution networks which are the transformer, and the transmission lines is represented taking into account the phenomena affecting the accuracy of the representation. From this representation, it is possible to conduct an analysis that reveals the effect of harmonics on the network. One of the shortcomings of this analysis is that it deals with nonlinear loads as a percentage of the total load and not as a source of harmonics with its own nature in the generation of harmonics. This makes the accuracy of the analysis mainly dependent on the accuracy of the nonlinear load ratio estimation [17].

Hardik Patil,(2015), presented a model for transmission network model which enables us to implement harmonics calculations using the Matlab software. In his study, he focused on the problem of resonance resulting from shunt capacitors in transmission networks. He found that many buses had already been affected by the resonance phenomenon. But the study did not include actual calculations of harmonics voltages or currents and did not rely on impedances at different frequencies [14].

Ankit Vashi, (2006), studied harmonics in distribution networks. The study focused on the negative impact of harmonics on the quality of power provided to consumers. He raised the issue of harmonics mitigation and the possibility of improving the power quality

in the presence of harmonics. The study found that harmonics have an important effect on the quality of power and cause problems. The study confined the methods of dealing with the problem of harmonics to the use of filters only and did not address other methods. Also, it did not address how to model the network components for the purposes of the study [19].

Hussein et al, (2010), analyzed the propagation of harmonics waves in power system networks and they investigated the effect of harmonics on both utility components and pieces of equipment. They introduced effective procedures which can be used in harmonics mitigation. The study found that the harmonics have a great effect on the system performance and that the procedures which are used in harmonics mitigation have a noticeable feasibility. One of the shortcomings of the study was that it was limited to simulations in the analysis using software and did not address the analysis by accurate calculations [21].

David Heidt, (1994), made a try to solve the problem of harmonics in an iteration method and he entered the frequency effect of the harmonics on the mechanism of analysis. Of the positive things in the analysis, it was through calculations. However, the analysis was not carried out on a real distribution network and the results of the analysis were not very accurate [26].

Leonard Abbott, (2006), analyzed the replacement of constant speed drives with variable ones in an industrial plant and what the benefit was from such replacement. The way he applied was to take real measurements from the grid and compare them with the simulation results of the modified grid. Recommended criteria for the conversion process are suggested. The results of the study found that the process of replacement did not completely eliminate harmonics problems and the author did not address how to solve these problems [20].

Chapter One

Fundamentals of power system harmonics

1.1 Introduction

Generated currents and voltages in electric power systems are assumed theoretically to be pure sinusoidal waves to simplify analysis and calculation. However, despite all the precautions applied in generator design to obtain pure sine wave, it is impossible to obtain such a wave in practice. The AC current wave deviates significantly or less from the ideal sinusoidal wave and its precise description is a complex wave or a distorted wave. The deformation of the current is caused by a number of causes, for example, the irregularity distribution of the magnetic flux in the generator.

This distortion is always presented in electric power grids and is not harmful as long as it does not exceed normal standard levels. However, due to the steady increase in the use of nonlinear loads in electrical distribution networks, the distortion levels on currents and voltages have reached levels that have exceeded normal conditions. As a result, this distortion has become a major source of low power quality and has been accompanied by troubles for power grids.

Distortion occurs on the current and voltage wave when frequencies with an integer multiple of the main frequency (50Hz or 60Hz) are added to the original wave causing the emergence of protrusions and distortions of the pure wave and these frequencies are called harmonics. The main reason for the occurrence of the harmonics problem is the nonlinear loads, which now account for 50% of household loads and a larger proportion of industrial loads.

These harmonics not only affect the distortion of the wave shape. If this were the case, there would not be a problem. Harmonics will cause several problems in the network such as heating of the equipment, the disruption of the work, and perhaps the destruction of the equipment as we shall see in details in later chapters.

The effect of harmonics varies according to the following points:

- The nature of harmonic sources in the network.
- Sites of equipment which generates harmonics in the network.
- Characteristics of the electrical network and its components.

It should be noted that these harmonics exist even before the arising of this type of loads or devices. It was present though with a small percentage in generator voltages and transformer magnetizing current, but the strongest appearance of the harmonics was after the spread of non-linear loads, especially power electronic devices.

Calculating the value of these harmonics is very important in network analysis in terms of power quality issues.

1.2 Nonlinear loads

To distinguish between linear loads and nonlinear loads, in linear load, if a sinusoidal voltage is applied, it behaves as a constant impedance and thus produces a wave current similar to the wave of applied voltage in shape and frequency, i.e. The relationship between current and voltage is a straight line. Pure resistance, inductance, and capacitance are all linear elements and any load formed from these elements is considered as a linear load. Examples of linear loads are the incandescent light bulbs, heating loads, transformers as long as they do not reach saturation and motors.

On the other hand, nonlinear loads do not behave as a constant impedance when applying a sinusoidal voltage. As a result, they do not produce a sinusoidal current, but a distorted current or pulses. This current is very rich in harmonics.

Changes which occurred in the current shape are reflected as distortion in the voltage sinusoidal wave.

Nonlinear loads lose a basic condition for the linear property, which is the homogeneity of the form between voltage and current. Examples of nonlinear loads are adjustable speed drives, electric arc furnaces and fluorescent lamps.

Nonlinear loads are constantly increasing, with a forecast of up to 65% of loads in electric grids and they affect the electric power systems by generating harmonic currents and as a result harmonic voltage.

1.3 Distorted waveforms

The distorted wave that is formed in the electric power systems because of the harmonics existence no longer maintains the sinusoidal waveform because it contains frequencies other than the basic frequency (50Hz).

Fig 1.1, for example, shows a distorted current wave due to the presence of harmonics.

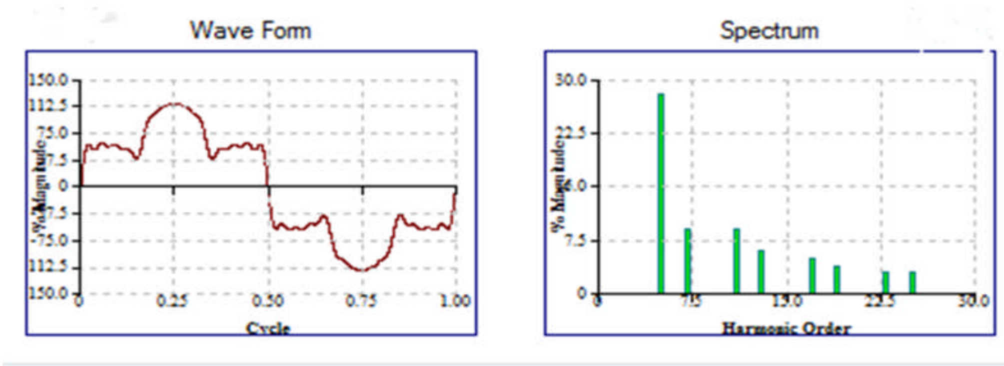


Fig 1.1: Distorted current wave

Joseph Fourier a French mathematician proved that any periodic complex wave could be written as follows:

$$f(t) = I_{avg} + \sum_{h=1}^{\infty} I_h \sin(hw_1 t + \theta_h) \qquad (1.1)$$

where:

f(t): momentary value of the complex wave

I_{avg}: is DC value referred to as average value

I_h : is peak value of each individual harmonic component

θ_h : is harmonic phase angle.

As shown by the above Fourier series, any periodic complex wave can be decomposed by:

- A fundamental wave with a basic frequency f

- A number of other sinusoidal waves whose frequencies are an integer multiple of the basic frequency such as 2f,3f,4f………. etc. These frequencies are called harmonics.

The fundamental wave is called the first harmonic and the second wave is called the second harmonic and the third wave is called the third harmonic and so on. Fig 1.2 shows Fourier series representation of a complex wave

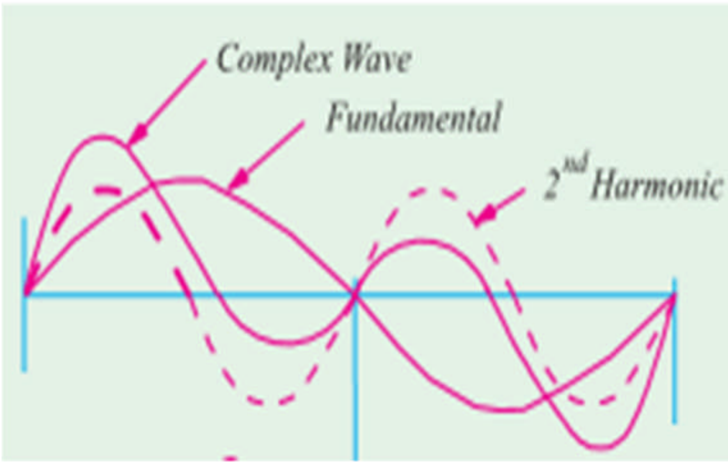


Fig 1.2: Fourier series representation of a complex wave [8]

In the opposite direction of what has been mentioned, any complex wave can be obtained from the superposition of sinusoidal waves of different frequencies and amplitudes. This means that it can be composed of harmonics. Fig 1.3 shows the fundamental and second harmonics summed together to form a resultant complex wave.

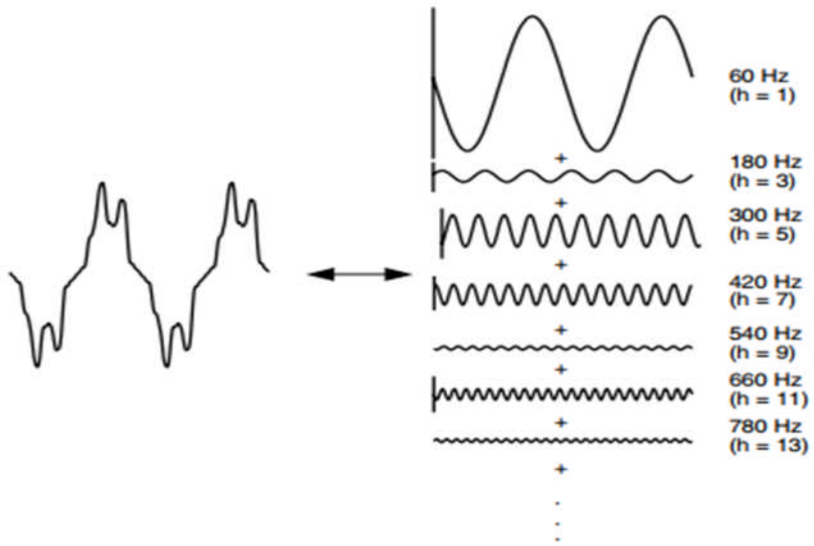


Fig 1.3: Construction of a wave from the fundamental and second harmonics [11]

1.4 Even and odd harmonics

Waves with frequencies 2f ,4f ,6f... are called even harmonics, while waves with frequencies f,3f,5f... are called odd harmonics. To see the effect of the presence of even and odd harmonics on the shape of a distorted wave.

Fig 1.4 shows that effect.

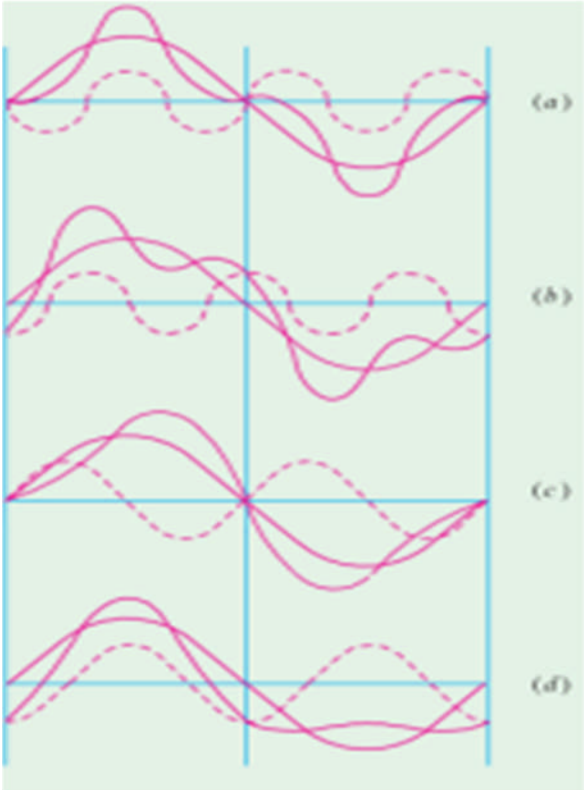


Fig 1.4: The effect of harmonics on the shape of the fundamental wave [11]

Let us add odd harmonics and again even harmonics with the fundamental as in Fig 1.4.

Fig 1.4 (a) shows the fundamental and third harmonic with phase shift = 180°. While Fig 1.4(b) shows the fundamental and third harmonic with phase shift = 90°. Fig 1.4(c) shows the fundamental with second harmonic with phase shift= 0°.While Fig 1.4(d) shows the fundamental with second harmonic with phase shift = 90°.

A careful observation for Fig 1.4 reveals the following [11]:

- Adding odd harmonics leads to make the positive half cycle of the complex wave symmetrical with negative half cycle regardless of phase shift between fundamental and other harmonics.
- Adding even harmonics leads to a complex wave with no symmetry regardless of the phase shift. Note that when phase shift = 0° the first and fourth quarters are inverted (still no symmetry!).

From the above analysis, it can be said that a balanced three-phase system does not have even harmonics because all electrical loads (except half wave rectifier) produce a symmetrical current i.e. the positive half cycle is similar to the negative half cycle (half wave symmetry), also, the three-phase symmetry in the power systems infrastructure and the nature of its configuration make all of its waveforms to be symmetrical even if they contain harmonics.

1.5 Harmonics phase sequence

In a balanced three-phase system under non-sinusoidal conditions, the complex wave of voltage or current in the three phases (A, B, C) is expressed as follows:

$$i_a(t)= \sum_{h=1}^{\infty} I_h \sin(hw_1 t + \theta_h) \qquad (1.2a)$$

$$i_b(t)=\sum_{h=1}^{\infty} I_h \sin(hw_1 t + \theta_h - 120h) \qquad (1.2b)$$

$$i_c(t)=\sum_{h=1}^{\infty} I_h \sin(hw_1 t + \theta_h + 120h) \qquad (1.2c)$$

Based on previous relationships, extending for first five harmonics we get

$$i_a = I_1 \sin(w_1 t + \theta_1) + I_2 \sin(2w_1 t + \theta_2) + I_3 \sin(3w_1 t + \theta_3) + I_4 \sin(4w_1 t + \theta_4) + I_5 \sin(5w_1 t + \theta_5) + \dots \dots \dots \dots$$

$$i_b = I_1 \sin(w_1 t + \theta_1 - 120) + I_2 \sin(2w_1 t + \theta_2 - 240) + I_3 \sin(3w_1 t + \theta_3 - 360) + I_4 \sin(4w_1 t + \theta_4 - 480) + I_5 \sin(5w_1 t + \theta_5 - 600) + \dots \dots \dots \dots$$

$$= i_b = I_1 \sin(w_1 t + \theta_1 - 120) + I_2 \sin(2w_1 t + \theta_2 + 120) + I_3 \sin(3w_1 t + \theta_3) + I_4 \sin(4w_1 t + \theta_4 - 120) + I_5 \sin(5w_1 t + \theta_5 + 120) + \dots \dots \dots \dots$$

$$i_c = I_1 \sin(w_1 t + \theta_1 + 120) + I_2 \sin(2w_1 t + \theta_2 + 240) + I_3 \sin(3w_1 t + \theta_3 + 360) + I_4 \sin(4w_1 t + \theta_4 + 480) + I_5 \sin(5w_1 t + \theta_5 + 600) + \dots \dots \dots \dots$$

$$= i_c = I_1 \sin(w_1 t + \theta_1 + 120) + I_2 \sin(2w_1 t + \theta_2 - 120) + I_3 \sin(3w_1 t + \theta_3) + I_4 \sin(4w_1 t + \theta_4 + 120) + I_5 \sin(5w_1 t + \theta_5 - 120) + \dots \dots \dots \dots$$

From the above, noting the harmonics of the current in the three phases, it is possible to record the following Table 1.1

Table 1.1: Phase sequence of harmonics in a balanced three phase system

Harmonics order	Phase shift angle(degree)			Phase sequence
	Phase A	Phase B	Phase C	
fundamental	0	-120	+120	Positive
h=2	0	+120	-120	negative
h=3	0	0	0	zero
h=4	0	-120	+120	positive
h=5	0	+120	-120	negative
h=6	0	0	0	zero
h=7	0	-120	+120	positive
h=8	0	+120	-120	negative

Hence, in a balanced three-phase system the phase sequence pattern will be as follows:

$3h+1$: positive sequence leads to heating effect

$3h+2$: negative sequence leads to motor torque problems

$3h$: zero sequence leads to heating effect in neutral line only

Where h is harmonics order.

All triplen harmonics are zero sequence and next above harmonics are positive sequence while next below harmonics are negative sequence.

The three phases that represent the third harmonics (3f) are all in the same direction and there is no phase shift between them. Therefore, the currents that bear these harmonics are called zero sequences and this applies to the multiples of the third harmonics (6f, 9f, 12f…….).

Positive and negative sequence harmonics circulate between phases while, zero sequence harmonics do not produce rotating field and are summed together in the neutral line, as a result, circulate between the phase and neutral.

In brief, harmonics have different frequencies and also have different phase sequence.

The situation is different in an unbalanced system where for each harmonic there are positive, negative and zero sequence components [4]. So the analysis has to be done separately for each sequence. The positive, negative and zero sequence impedances differ from one another. As an example, in the case of transmission lines, the zero sequence impedance reaches three times of the positive [3].

1.6 Electric quantities under non-sinusoidal (harmonics) conditions

1.6.1 The R.M.S value

The complex current wave can be expressed as:

$$i(t) = I_1 \sin(wt + \theta_1) + I_2 \sin(2wt + \theta_2) + I_3 \sin(3wt + \theta_3) + I_4 \sin(4wt + \theta_4) \dots \dots \dots \dots + I_k \sin(kwt + \theta_k) \qquad (1.3)$$

As well as complex voltage wave:

$$v(t) = V_1 \sin(wt + \emptyset_1) + V_2 \sin(2wt + \emptyset_2) + V_3 \sin(3wt + \emptyset_3) + V_4 \sin(4wt + \emptyset_4) \dots \dots \dots + V_k \sin(kwt + \emptyset_k) \qquad (1.4)$$

Where the k is the highest harmonics order of interest and typically a value of k = 50 is sufficient in power systems analysis [9].

In linear systems a complex voltage will produce a complex current with different amplitude and phase shift of each harmonic order. Electric power system components are linear in ordinary conditions.

The R.M.S value of complex current wave (or voltage) is:

$$I_{RMS} = \sqrt{\frac{1}{T}\int_{0}^{T} i^2(t)dt} \tag{1.5}$$

$$= \sqrt{average\ value\ of\ i^2\ \ over\ complete\ cycle}$$

Using trigonometric properties for the square of the current under the square root yields to [5,11]:

$$I_{RMS} = \sqrt{\sum_{h=1}^{K} \frac{I_h^2}{2}} \tag{1.6}$$

$$= \sqrt{\sum_{h=1}^{K} I_{hRMS}^2}$$

Hence, the R.M.S value of a complex wave is equal to the square root for the sum of the square of individual harmonics. If the complex wave contains a DC value (it is neglected here for its small value) it is combined with the sum as follows:

$$I_{RMS} = \sqrt{I_{DC}^2 + \sum_{h=1}^{K} I_{hRMS}^2} \tag{1.7}$$

The R.M.S value is a very important value and should be taken into account in heating effects of the current on the network components such as transformers, motors and capacitor banks.

1.6.2 Average (active) power

The average power absorbed by a load equals to:

$$P_{avg} = \frac{1}{T}\int_{0}^{T} v(t)\, i(t)dt \tag{1.8}$$

Equation 1.8 yields to:

$$P_{avg} = \sum_{h=1}^{K} V_{hRMS} I_{hRMS} \cos(\emptyset_h - \theta_h) \tag{1.9}$$

$$= V_{1RMS} I_{1RMS} \cos(\emptyset_1 - \theta_1) + V_{2RMS} I_{2RMS} \cos(\emptyset_2 - \theta_2) + V_{3RMS} I_{3RMS} \cos(\emptyset_3 - \theta_3) + \cdots$$

$$= P_{avg1} + P_{avg2} + P_{avg3} + P_{avg4} + \ldots\ldots\ldots\ldots$$

P_{avg2} , P_{avg3} , P_{avg4} … … are losses usually caused by nonlinear loads and are small in value compared to P_{avg1}[6]. However, they should not be neglected because they are likely to be a significant value of the losses.

1.6.3 Overall power factor

After finding the R.M.S values of voltage and current beside the average power value, the overall power factor value can be found using the equation 1.10[11]:

$$p.f = \frac{total\ watts}{total\ volt\ amperes}$$

$$= \frac{V_{1RMS} I_{1RMS} \cos(\emptyset_1 - \theta_1) + V_{2RMS} I_{2RMS} \cos(\emptyset_2 - \theta_2) + \cdots}{V_{RMS} I_{RMS}} \tag{1.10}$$

Where:

V_{RMS}: R.M.S value of the complex voltage wave

V_{1RMS}: R.M.S value of the fundamental voltage wave

V_{2RMS}: R.M.S value of the second order harmonic voltage wave and so on……….

The following Fig 1.5 shows how the power factor is affected by the increased total harmonics distortion in current THD_i (explained in the following section)

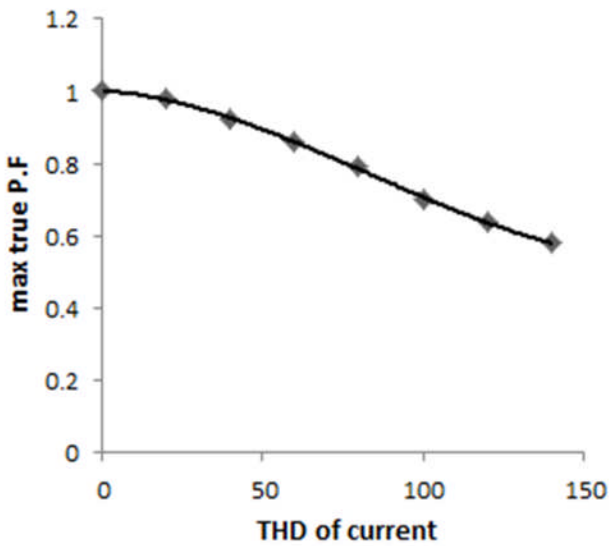


Fig 1.5: Decreasing of power factor with increasing current distortion

It is clear that with the increase of harmonic distortion the value of the power factor decreases.

1.7 Measurement of harmonics distortion

1.7.1 Total harmonics distortion THD

The most commonly used index for quantifying the amount of distortion in a voltage wave (or current) is called total harmonics distortion THD [5]. This index determines the harmonics level content of the wave and the associated deformation. It is used for all levels of voltages: low, medium and high.

According to IEE 519,1992, voltage THD is defined by following formula [5,8,9]:

$$\%THD_v = \frac{\sqrt{\sum_{h=2}^{\infty} V_{hRMS}^2}}{V_{1RMS}} 100\% \tag{1.11}$$

$$= \frac{\sqrt{sum\ of\ square\ of\ harmonics\ R.M.S}}{fundamental\ R.M.S\ value}$$

Normally, harmonics up to 50 order are used to calculate this index due to the very small value of the other higher order harmonics.

The same equation is used for the current THD as follows:

$$\%THD_i = \frac{\sqrt{\sum_{h=2}^{\infty} I_{hRMS}^2}}{I_{1RMS}} 100\% \tag{1.12}$$

For a pure sine wave with only 50 Hz, the THD value = 0. The current THD in loads usually ranges from a few percent to 100 %. While the voltage THD is often less than 5% [5]. The voltage THD if exceeds the normal levels, causes problems for the network and its equipment so IEEE ST.519 recommends standard levels for THD related to voltage and current

It is possible to conclude a relationship between V_{RMS} value and THD_v. The V_{RMS} value of a complex wave as seen:

$$= \sqrt{\sum_{h=1}^{\infty} V_{hRMS}^2}$$

Hence, THD_v in terms of V_{RMS}

$$THD_v = \frac{\sqrt{V_{RMS}^2 - V_{1RMS}^2}}{V_{1RMS}}$$

$$THD_v = \sqrt{\left(\frac{V_{RMS}}{V_{1RMS}}\right)^2 - 1}$$

This yields to [4]:

$$V_{RMS} = V_{1RMS}\sqrt{1 + THD_v^2} \tag{1.13}$$

1.7.2 Individual harmonics distortion (IHD)

The distortion amount associated with individual harmonics component measured by a similar index is given by:

$$\%\, IHD_v = \frac{V_{hRMS}}{V_{1RMS}} 100\% \tag{1.14}$$

This index helps us to plot what is called harmonics magnitude spectrum for the complex (distorted) wave of several loads. Harmonics magnitude spectrum data is an important in harmonics analysis also it gives an indication about the most harmonics orders which contribute in distortion. It will be like the following Fig 1.6

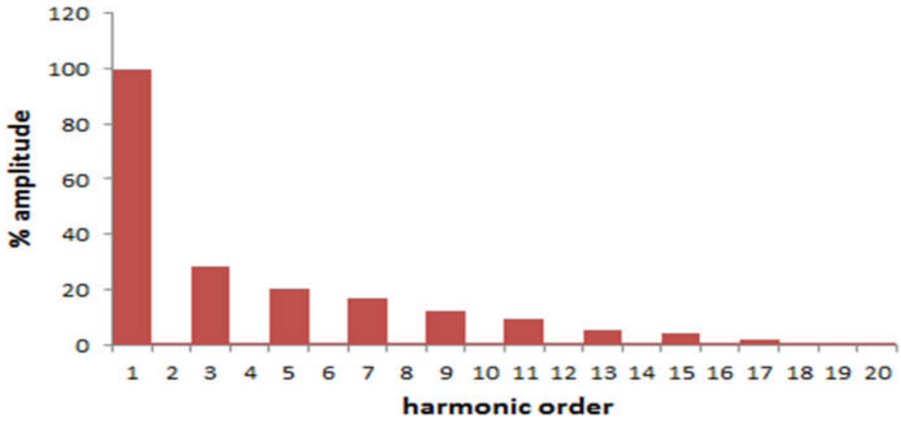


Fig 1.6: Amplitude harmonics spectrum

1.7.3 Total demand distortion (TDD)

Many times The THD index is misleading, as in the case of light loads. When the fundamental current approaches to zero as in light loads case; The resulting THD value will be high, however this THD value is not necessarily of great interest because the associated harmonic currents value is small, even if these harmonics value is a large value according to the fundamental current [5,8].

In order for the index to be more real, its value is referred to a real value instead of a variable value which changes with the change in load. Hence, engineers will not find a better value than the rated current that the electrical networks are designed to carry.

Due to the above explanation, TDD index is found and defined as [3,5,9]:

$$TDD = \frac{\sqrt{\sum_{h=2}^{h=max} I_h^2}}{I_L} \tag{1.15}$$

Where I_L: R.M.S value of the peak or maximum demand load current at fundamental frequency measured at PCC point (see section 1.9).

If the load does not exist, I_L can be expected based on design experience. If the load is present, the maximum (15-25 minutes) readings for the previous 12 months are averaged [8]. In THD calculation, the current value is considered as a snapshot while in TDD, the different operating conditions are taken into account.

1.7.4 K-factor

The presence of harmonics in the network increases the R.M.S value of the current and thus increases the losses and heating effect. In a transformer, the heating effect is more severe because eddy current losses which are produced by harmonics current are proportional to square root of frequencies of these harmonics. Hence high levels of harmonics result in overheating the transformer. Of course normal transformer cannot deal with this case.

An index was defined that gives an indication of the amount of heat that results from the presence of harmonics. This index helps us in derating the transformer to be able to withstand this heat.

K-factor is defined as [5]:

$$K = \frac{\sum_{h=1}^{m} h^2 \left(\frac{I_h}{I_1}\right)^2}{\sum_{h=1}^{m} \left(\frac{I_h}{I_1}\right)^2} \tag{1.16}$$

where m: is the highest harmonics order considered.

The range of the K is from 1 to 50. A more K value means there is a need for a transformer that can handle more heat. In most cases $k \leq 10$ [4].

Table 1.2 shows the available commercial category k-type transformer

Table 1.2: Commercial category k-type transformer [9]

Commercial category
k-4
k-9
k-13
k-20
k-30
k-40

These k-type transformers are specially designed to handle excessive heat which is produced by harmonics. K-factor is taken into consideration in the design stage.

1.8 Skin effects and proximity effect

Skin effect is an AC phenomenon in which the current tends to pass near the outer surface and is not distributed equally in the conductor.

The explanation of this phenomenon is that the AC magnetic flux generates an electromotive force (EMF) value greater in the middle of the conductor than the surface. This difference in EMF generates a current that resists the passage of the original current in the center and assists it in the outside. The total result can be said that the cross section area available to the original current flow has decreased, and thermal effect also is increased.

Skin effect depends on several factors which are frequency, cable construction and cable size. Because of this phenomenon, the conductors are made hollow from the middle to save conductor material.

AC resistance to DC resistance ratio as a function of frequency is shown in Fig 1.7

Fig 1.7: Rac/Rdc as a function of frequency curve

In 2008, Baggin proved that skin effect may be effective even for low frequencies. His work was based on a copper conductor with a diameter of 20mm.The results were as follows:

$$\frac{R_{AC}^{9th}}{R_{DC}} = 2.07\,, \frac{R_{AC}^{3rd}}{R_{DC}} = 1.35$$

Proximity effect occurs because of the mutual inductance existing between two conductors placed near each other. Due to this effect, currents pass far from the nearby conductor as a result, increasing the resistance of the conductor.

1.9 Point of common coupling (PCC)

Point of common coupling is the point of contact between nonlinear loads and linear loads within the industrial plant as shown in Fig 1.8. This point can be reached by both the consumer and the supplier of electricity [3].

Usually, companies have an access to the PCC point to take power measurements and other indicators such as deformation of the wave. No difference if PCC was on the primary or secondary winding of the transformer.

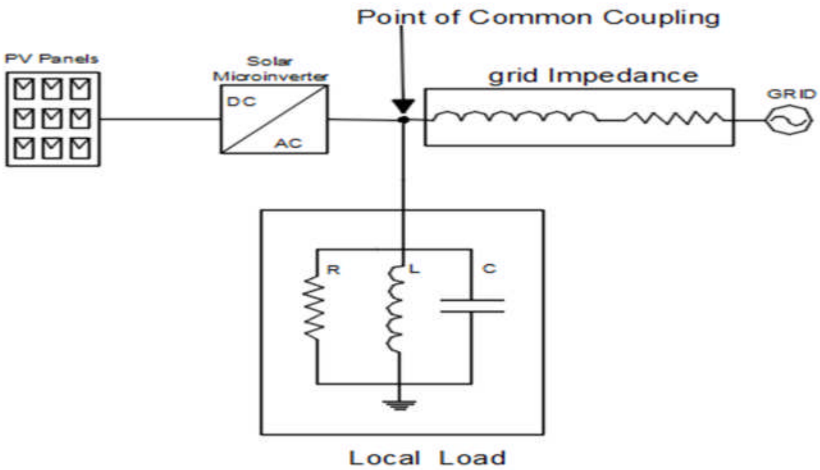


Fig 1.8: Point of common coupling illustration

Chapter Two

Effects of harmonics

2.1 Effect of harmonics on network components

2.1.1 Cables

Harmonics lead to increase conductor losses in the form of heat for three reasons: the first reason is that the R.M.S value of the current increases due to harmonics, which means additional load and additional losses. The R.M.S value is known as:

$$I_{RMS} = \sqrt{I_1^2 + I_2^2 + I_3^2 + \cdots} = I_1\sqrt{1 + (THD_i)^2}$$

As an example of increasing losses only because of the increase in the R.M.S value, it is supposed that THD_i = 38% .Thus the R.M.S value of the current is equal to $I_{RMS} = I_1\sqrt{1 + 0.38^2}$. Neglecting other factors that increase the losses, I^2R will increase by: $\left(\frac{I_1\sqrt{1+0.38^2}}{I_1}\right)^2 100\%$ =14.4% compared to the losses due to the fundamental current only.

The second reason is increasing the resistance due to skin effect and proximity effect which lead to a redistribution of current in the conductor. After calculating the increase in cable resistance due to the passage of harmonics we can derate the cable capacity according to the following equation 2.1[3]:

$$\frac{1}{1 + \sum_{h=1}^{h=max} I_h^2 \frac{R_h}{R_{dc}}} \tag{2.1}$$

For example, if the 6-pulse harmonics pass in the conductor, derating will be typically by 3-6% [3].

From the above discussion it can be said that harmonics lead to reduced power transmission capacity because of increased losses and increased voltage drop through impedances of different system components.

The third reason is that harmonics increase the dielectric losses due to the increased stress on the cable, the side effects of this is extra heat which reduces the life of the cable. Dielectric losses are equal to [12]:

$$\sum_{h=1}^{h=max} C \tan\delta \, w_h V_h^2 \tag{2.2}$$

Where:

C: capacitance

V_h: R.M.S voltage of n^{th} harmonics.

w_h: $2\pi f_h$

$\tan\delta$: the loss factor($\frac{R}{\left(\frac{1}{wC}\right)}$).

The neutral line in the three phase 4-wire systems is worthy of special attention because of the zero sequence currents which are summed algebraically - not vector sum - in the neutral unlike positive and negative sequence harmonics which are eliminated in the neutral line. This is also an undesirable effect of the harmonics for cables causing overload to the conductor.

This problem is evident in commercial buildings because of many nonlinear loads which produce the third harmonics such as fluorescent lamps and computers. The measurements which are made on the commercial buildings showed that there is a need to a neutral cross section area equal to 1.8 of the phase cross section area. For this IEEE 1100_1992 standard recommended that neutral cross section area in a system that feeds nonlinear loads is not less than 173% of the same value for each phase [12].

Suppose that the third harmonics current is : I^{3d} = 70% of fundamental current. Hence, R.M.S phase of the current = $\sqrt{I_1^2 + I_3^2}$ = $\sqrt{1^2 + 0.7^2}$ = 1.22, while neutral current is equal to: $I_3 + I_3 + I_3 = 0.7 + 0.7 + 0.7 = 2.1$. Hence,

$$\frac{I_N}{I_{PH}} = \frac{2.1}{1.22} = 1.72$$

From the above example, the cross-sectional area of the neutral conductor has to be 1.72 of the phase conductor.

It remains to say that harmonics in a cable affect the adjacent cables, especially control and communication cables due to the occurrence of magnetic interference.

2.1.2 Transformer

The harmonics effect in the transformers has a double effect, causing an increase in the copper and iron loses and the overall effect is to increase the heat of the transformer. Heat causes degradation of the insulation and then the entire fail of the transformer.

The transformer losses include the no-load losses which depend on magnetic flux value required for magnetizing the transformer core and the load losses, which depend on the frequency and include the copper losses and the stray flux losses.

The no-load losses (core losses) are divided into:

- Eddy current losses: the increase in eddy losses can be seen from the following equation [3,11]:

$$W_{edd} = K_e B_{max}^2 f^2 \tag{2.3}$$

Where:

f: frequency

B_{max}: maximum leakage flux density

K_e : a factor depends on the width of transformer's conductor.

It is very clear that the loss is proportional to the square of frequency.

●The hysteresis losses: in case of linear load hysteresis losses form 5% of total losses but in case of nonlinear loads this value increases 20 times. The hysteresis losses can be calculated from the following equation 2.4[11]:

$$W_{hys} = K_{hys} B_{max}^{1.6} f v \tag{2.4}$$

Where:

f: frequency

B_{max}: maximum leakage flux density

v : iron size

K_{hys} : hysteresis factor.

With the presence of harmonics, copper losses are also increasing. The R.M.S value of the current is higher and the thermal effect is getting worse. The skin effect has a big role in heating and is more severe than in the case of cables because the conductors are very close to each other in the transformer. Copper losses are given by:

$$P_{cu} = I_{RMS}^2 R_{AC} \tag{2.5}$$

It is found from practical measurements that the resulted full-load losses of transformer feeding nonlinear loads like IT equipment are twice these losses of a transformer feeding linear loads.

If there are high harmonics, special transformers - which are designed on a higher safety margin to handle heat - have be used. They are known as K-factor transformers. If the chance of purchasing of this type is weak, the loading capacity of the transformer has to be reduced if harmonics are present.

Another effect comes from the third harmonics and its multiples. It is known that the transformers which are used in the distribution 4-wire systems comes in $\Delta - Y$ configuration and this makes the Δ of the transformer as a trap for the third harmonics and its multiples. This is accompanied by an additional loss in a form of heating.

2.1.3 Induction motor

Losses are increased by harmonics and are accompanied by a heating effect in the same mechanism that occurs in the transformer. It was found that every 10 degrees increase in motor temperature continuously above the rated temperature reduces the motor life by 50% [12]. The effect of heat depends heavily on the type of the motor if it is squirrel- cage or slip ring, where the first type is more heat tolerant.

There is a more serious effect than thermal effect which is represented in harmonics sequence. It is known that the basis of the work of the induction motor depends on producing a rotating magnetic field in the air gap due to three phase currents. Positive sequence harmonics of the three phases produce a magnetic field revolves in the same direction of the fundamental current and thus assist to generate torque. On the contrary, the negative sequence currents revolve in the opposite direction of the fundamental current and thus produces a reverse torque (braking torque) [12].

This imbalance leads to torque pulsations appearing on the shaft. The higher the harmonics content, the more likely the problem will be and it is possible to stop motor movement.

There are types of motors called flameproof motors which are specifically designed to isolate anything that gets inside the motor enclosure (like explosions) about the outer perimeter [12]. This design has been adopted based on the existence of a pure sinusoidal wave and thus will not become effective in the presence of harmonics because the excess heat of the rotor works to degrade enclosure gradually until it becomes useless in isolating explosions about the outer perimeter.

2.1.4 Capacitors

Capacitors are often present in industrial and commercial systems for the purpose of power factor improving, such as installing capacitors in fluorescent lamps. The effect of harmonics on capacitors is often destructive. The location and size of the capacitor play a large role in the extent of the impact of harmonics on the network.

Problems caused by harmonics are listed below:

- The higher the frequency of the harmonics, the lower the capacitive impedance value (inverse relationship). This means increasing the value of the current which will be drawn by the capacitor and burning it, i.e. the capacitor behaves as a sink for the current.
- It is possible, at certain frequencies, resonance occurs between the inductance of the network and capacitors and this produces a huge current or voltages depending on the configuration of harmonics path flow (the phenomenon will be addressed later).
- The voltage harmonics increase dielectric losses and increase thermal effect. In the capacitor, dielectric losses = $\sum_{h=1}^{h=max} C \tan\delta \, w_h V_h^2$
- Excessive harmonics result in humming noise as human ear is sensitive to high frequencies such as those resulting from the fifth harmonics (300 Hz).

2.2 Resonance

One of the most negative effects associated with harmonics is the occurrence of what is known as resonance. Resonance occurs when capacitive reactance ($X_C = \frac{1}{2\pi fC}$) equals with the inductive reactance ($X_L = 2\pi fL$) at a certain frequency of the harmonics frequencies. Capacitive reactance decreases with the frequency increase in contrast to inductive reactance which increases with the frequency increase and at a certain frequency the two values are equal leading to resonance case. The resonance results in a very large current or voltage that causes some components of the network to collapse.

The presence of capacitors in the network has become common both in the nature of equipment such as cables or in many of the devices commonly used in networks such as reactive power compensators.

The resonance circuit can be created between capacitors which are used for improving the power factor or capacitors of lines with load inductance whether being the capacitors and inductance in a parallel or series connection.

2.2.1 Parallel resonance

The impedance of power grids is mainly inductive. When the capacitors which are connected with the networks act as in parallel with the inductance of the network, a parallel resonance occurs as shown in Fig 2.1.

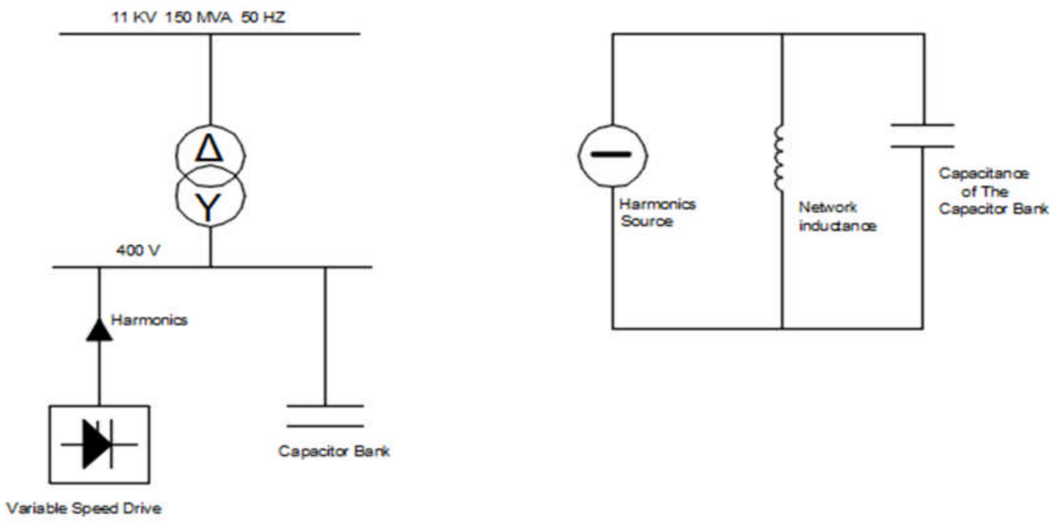


Fig 2.1: Parallel resonance

The whole combination impedance -neglecting the resistance- is given by

$$Z_{par} = \frac{j2\pi fL \frac{1}{j2\pi fC}}{j2\pi fL + \frac{1}{j2\pi fC}} \tag{2.6}$$

At a specific frequency, capacitive reactance is equal to inductive reactance and this makes the denominator value equals to zero. In other words, the impedance is a very large value (∞) that creates a very large voltage.

$$\text{At resonance, } 2\pi fL - \frac{1}{2\pi fC} = 0 \text{ or } f_r = \frac{1}{2\pi\sqrt{LC}} \tag{2.7}$$

Where f_r: is the frequency at which resonance occurs.

Sometimes capacitance and inductance are not available, hence, another formula can be used to determine the resonance harmonics frequency [8]:

$$h_r = \sqrt{\frac{KVA_{sc}}{Kvar_{cap}}} = \sqrt{\frac{KVA_{tr} * 100}{Kvar_{cap} * Z_{tr}(\%)}} \qquad (2.8)$$

Where:

*h*r: resonant harmonic

$kVAR_{cap}$: is kVAR rating of capacitor banks.

kVA_{sc}: is short circuit capacity of the system at the point of application of capacitors.

Z_{tr}: is the transformer impedance.

2.2.2 Series resonance

In this type, capacitive reactance and inductive reactance appear in series connection to the source of harmonics as seen in Fig 2.2. At resonance the combination impedance equals very small value (=R). Hence, the value of the current rises so much that it can exceed the natural levels.

$$Z_{ser} = R + j\left(2\pi f L - \frac{1}{2\pi f C}\right) \qquad (2.9)$$

At resonance,

$$2\pi f L - \frac{1}{2\pi f C} = 0 \quad \text{or} \quad f_r = \frac{1}{2\pi\sqrt{LC}}$$

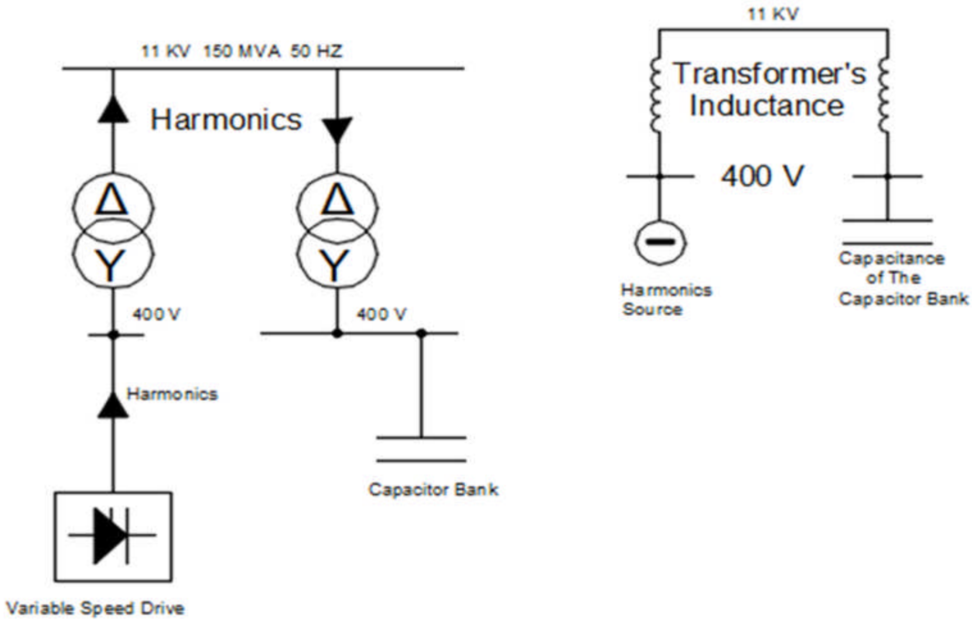


Fig 2.2: Series resonance

2.3 Power factor

The power factor expresses the ratio of the actual power consumption to the total power transmitted. In power systems that contain only linear loads, the vector relationship between power components is as follows:

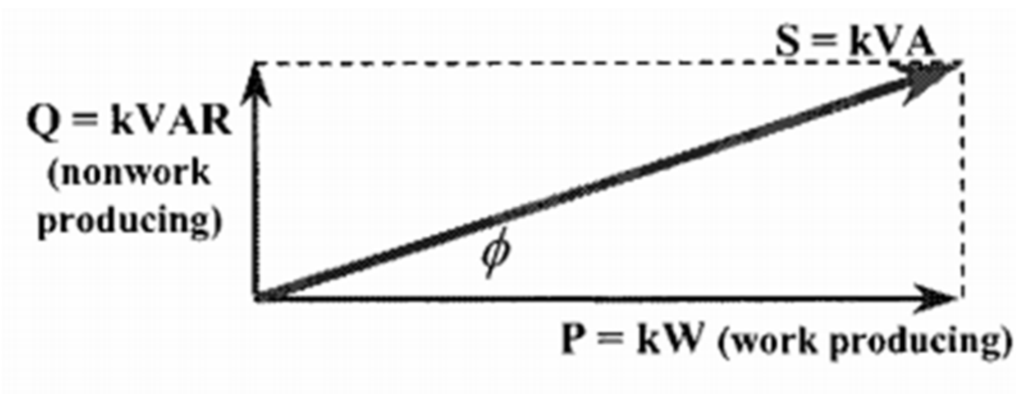


Fig 2.3: Power factor components in system with linear load[12]

Here,

$$S = \sqrt{P^2 + Q^2} = \sqrt{kW^2 + kVAr^2} \quad (2.10)$$

$$p.f = \frac{P}{S} = \frac{kW}{kVA} \quad (2.11)$$

This power factor for pure sinusoidal wave called displacement power factor. It is wrong to use the same relationship of power factor which is mentioned in equation 2.11 to a system that contains nonlinear loads because the displacement power factor only reflects the shift between the current and the voltage of the fundamental frequency. In a distorted wave, there are other frequency components.

The presence of harmonics leads to a case with two power factors. One is the power factor of the fundamental component which is called displacement power factor (DPF) and another is the power factor of harmonics components which is called distortion power factor [12]. The overall power factor includes the both is called true power factor (TPF). Fig 2.4 shows the new relationship between power components:

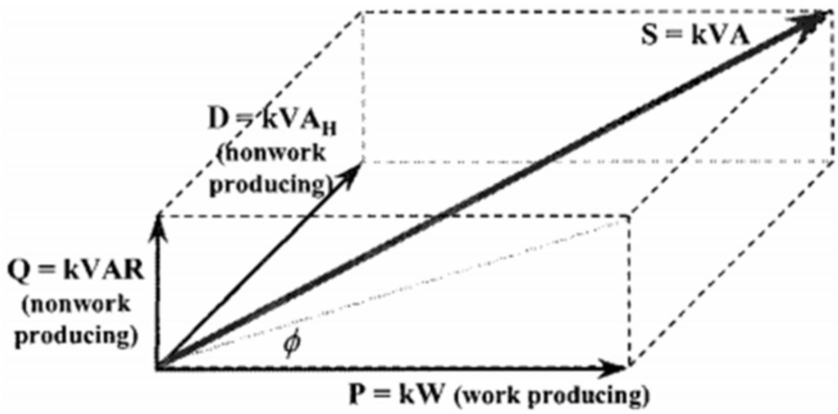


Fig 2.4: Power factor components in system with nonlinear load [12]

Here, the apparent power will be modified as [1,12]:

$$S = \sqrt{P^2 + Q^2 + D^2} = \sqrt{kW^2 + kVAr^2 + kVArd^2} \qquad (2.12)$$

$$p.f = \frac{P}{S} \neq \frac{kW}{kVA}$$

$$S = V_{RMS} I_{RMS} = \sqrt{\sum_{h=1}^{\infty} V_h^2} \sqrt{\sum_{h=1}^{\infty} I_h^2} = V_{1RMS}\sqrt{1 + THD_v^2}\, I_{1RMS}\sqrt{1 + THD_i^2}$$

$$p.f_{true} = \frac{P}{S} = \frac{P_1}{S_1\sqrt{1 + THD_v^2}\sqrt{1 + THD_i^2}} \qquad (2.13)$$

$$= p.f_{displacement}\ p.f_{distortion}$$

In equation 2.13, we assume that $P = P_1$. This is true since in most cases, the average power associated with harmonics($h>2$) is small portion of the fundamental average power.

2.4 Other effects of harmonics

There are many other undesirable effects of harmonics such as:

Metering instrumentation will produce faulty readings with harmonics as these devices are designed to operate on a pure sine wave only and calibrated to responding R.M.S values. Harmonics increase the R.M.S current values to the same power and this causes an error.

Circuit breakers and fuses work on the thermal effect of R.M.S value of current. Increasing R.M.S value leads to the work of these devices incorrectly. Consequently, derating may be needed. Residual current circuit breakers (RCCB) may fail in operation because a difference in value will appear between phase current and neutral current.

Harmonics frequencies may induce noise in the Neighbor communication systems. This interface leads to problems.

Chapter Three

Sources of harmonics

When talking about the problem of harmonics in electric power systems, the harmonic currents have the great influence because different loads generate harmonic currents during their operation.

The reason for the emergence of harmonics is to pull the current in a non-sinusoidal shape in the grid of electricity, that is, the device pulls a current which is not similar to the voltage shape which is applied to it.

In the past, equipment with an iron core was the main reason for the production of harmonics but with the need to use energy-saving devices, power electronic devices became the main source of harmonics generation.

Each device has its own signature in terms of the nature of harmonics (spectrum and order) and in sum all devices share the problem of harmonics. The harmonics generating sources include one phase devices like the fluorescent lamp and three phase devices like the variable speed drives. These types of equipment which produce harmonics also are adversely affected by harmonics voltages and currents. The most common sources of harmonics will be introduced.

3.1 Power converters

Power electronics have spread widely and rapidly due to the tremendous progress that has been made in improving its specifications and operating mechanism.

The 6-pulse converter is the most frequent and it is used in control of motors, fuel cells and batteries. Whether the operation of the 6-pulse converter is confined to rectifying wave (AC to DC) only or it also includes inverting wave (DC to AC), the rectifying process is the main source for generating harmonics. The 6-Pulse converter topology is shown in Fig 3.1 where L >>

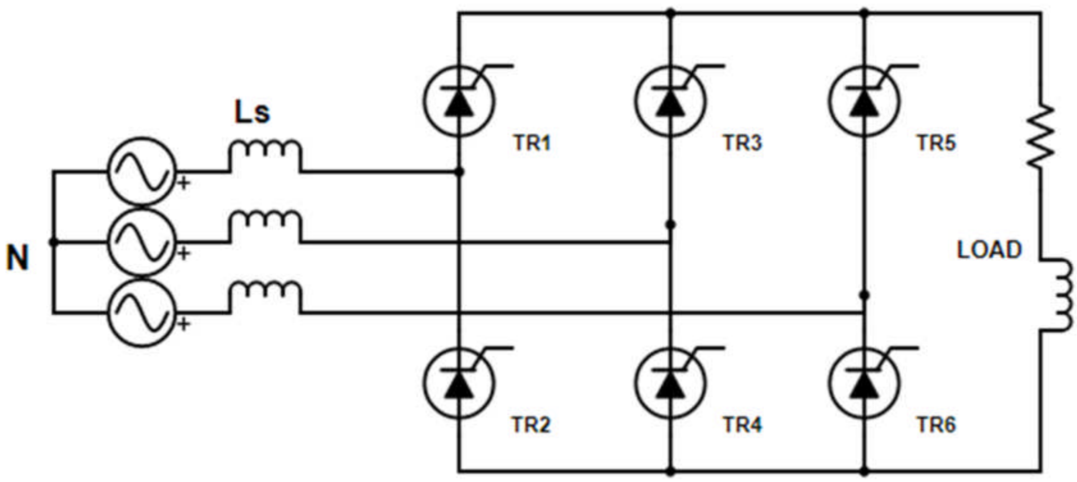


Fig 3.1: Typical 6-pulse converter

It can be seen with reference to Fig 3.1, the converter comprises six thyristors in a full wave bridge configuration. In the circuit two thyristors are fired at the same time and remain fired until are reversed biased by the circuit itself. The firing pattern is as in the Table 3.1

Table 3.1: Firing pattern of the 6-pulse converter [1,3]

	Firing sequence					
conducted thyristor	4,5	1,4	6,1	3,6	2,3	5,2
thyristor to be fired	1	6	3	2	5	4
thyristor to be turn off	5	4	1	6	3	2

The input current wave which is produced by this sequence has the following values and shape respectively:

Table 3.2: Input current value of a 6-pulse converter

Current value	period
$+I_d$	$120°$
0	$60°$
$-I_d$	$120°$
0	$60°$

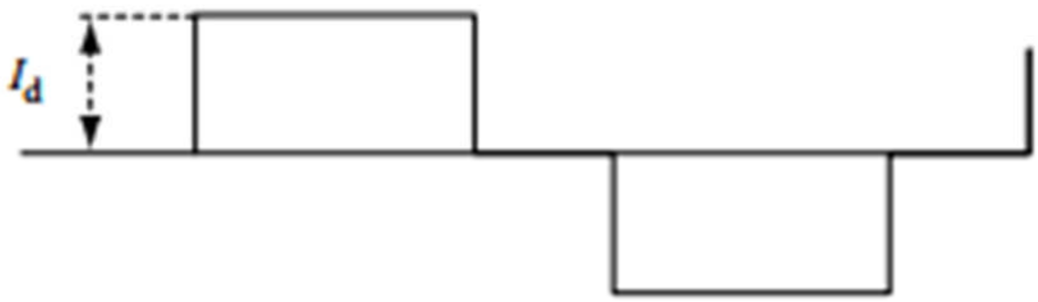


Fig 3.2: Input current shape of a 6-pulse converter

As seen the resulted input current wave is some non-sinusoidal distorted wave rich in harmonics. This happens because the converter allows the current to pass through parts of the cycle in the form of short pulses.

This distorted wave can be analyzed using Fourier series as follows [3]:

$$I_{ac} = \frac{2\sqrt{3}}{\pi} I_d \left(\cos\theta - \frac{1}{5}\cos 5\theta + \frac{1}{7}\cos 7\theta - \frac{1}{11}\cos 11\theta + \frac{1}{13}\cos 13\theta + \cdots\right) \quad (3.1)$$

$$\theta = 2\pi f_1 t \quad (3.2)$$

A note of great significance can be deduced from the previous series; the harmonics in the current wave follow this pattern

$$h = Pn \pm 1 \quad (3.3)$$

Where h: harmonics order, P: pulse number, n: integer number.

i.e. harmonics include only odd order (50Hz,250Hz,350Hz,550Hz, ….) except triple order and their multiples (150Hz,300Hz,450Hz….). This relationship is valid for one phase and three phase converters.

The reason for the absence of even order is that the current wave has half wave symmetry. While the absence of the triple order and its multiples is due to the fact that the converter is connected to a $\Delta - Y\ or\ \Delta - \Delta$ transformer, which makes Δ as a trap for triple order.

The second observation is that the value of the harmonics current decreases inversely by increasing the order as the following pattern:

$$I_h = \frac{1}{h} I_1 \tag{3.4}$$

The Table 3.3 shows theoretical and typical values of 6-pulse converter harmonics

Table 3.3: Theoretical and typical values of a 6-pulse converter [9]

h	5	7	11	13	17	19	23	25
$1/h\ rule$	0.2	0.143	0.091	0.077	0.059	0.053	0.043	0.04
Typical	0.173	0.111	0.045	0.029	0.015	0.01	0.009	0.008

A theoretical total harmonics distortion THD_i for a 6-pulse converter can be calculated as follows:

$$\%THD_i = \sqrt{20^2 + 14.29^2 + 9.09^2 + 7.69^2 + 5.88^2 + \cdots} = \sqrt{808.21} = 28.43\%.$$

Frequencies and magnitudes of the harmonics in this converter depend on its type, operating point and nature of load variations. This converter is considered as a current source of harmonics.

3.2 Electric arc furnaces

These devices are used in scrap smelting and during their work produce the worst harmonics of the network. Arc furnaces are considered loads with a low power factor. The operation of the arc furnaces includes two stages which are called smelting and refining stages and there are a large number of harmonics produced in both stages.

The harmonics of these devices cannot be expected as in the case of a power converter due to the change of arc feed material. The resulting harmonics take a non-continuous pattern which includes integer and non-integer orders. Fig 3.3 shows a current wave in one of phases:

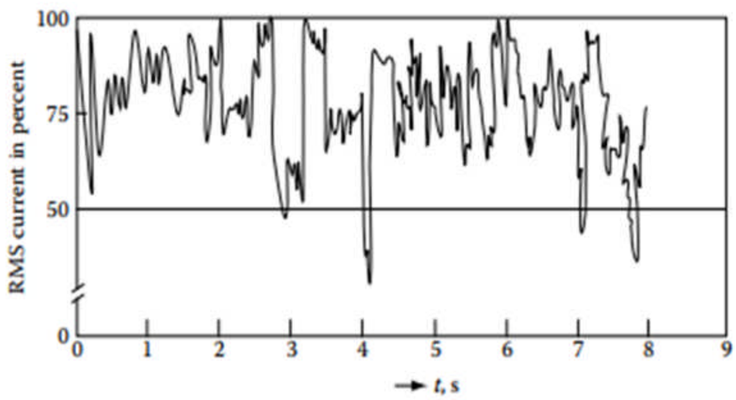


Fig 3.3: Melting current in one-phase supply of an arc furnace [1]

Measurements showed that the amplitude value of harmonics decreases as the harmonics order increases and also the integer order harmonics predominant the non-integer harmonics.

Harmonic currents of the arc furnace as percentage of the fundamental amplitude are shown in Table 3.4

Table 3.4: The harmonics content of the current of the arc furnace [1]

	h				
	2	3	4	5	7
Initial melting stage	7.7	5.8	2.5	4.2	3.1
Refining stage	0	2	0	2.1	0

It is possible that these values vary for other types of arc furnaces, but the values of Table 3.4 remain useful for studies in the case that measurements cannot be made. Arc furnaces are ranging from small equipment with small capacity (2-4MVA) to huge units with large capacity (100MVA) that deal with tens of tons.

3.3 Fluorescent lamp lighting

Lighting especially fluorescent lamps constitute about (40-60) % of the consumer loads and the reason for the high demand of them is their energy-saving compared to other normal types. A 60watt filament lamp can be replaced by a 10watt fluorescent lamp. Practical experience showed that the harmonics current, especially the third order, in these lamps may reach 30% of the value of the fundamental frequency current.

Fig 3.4 and 3.5 show a typical fluorescent lamp current waveform shape with magnetic ballast and electronic ballast respectively.

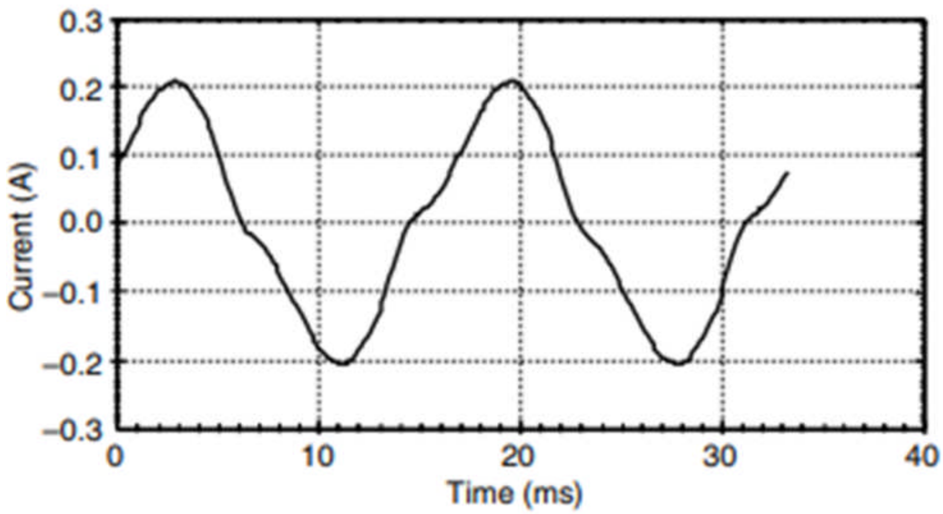


Fig 3.4: Current waveform shape of the fluorescent lamp with magnetic ballast [8]

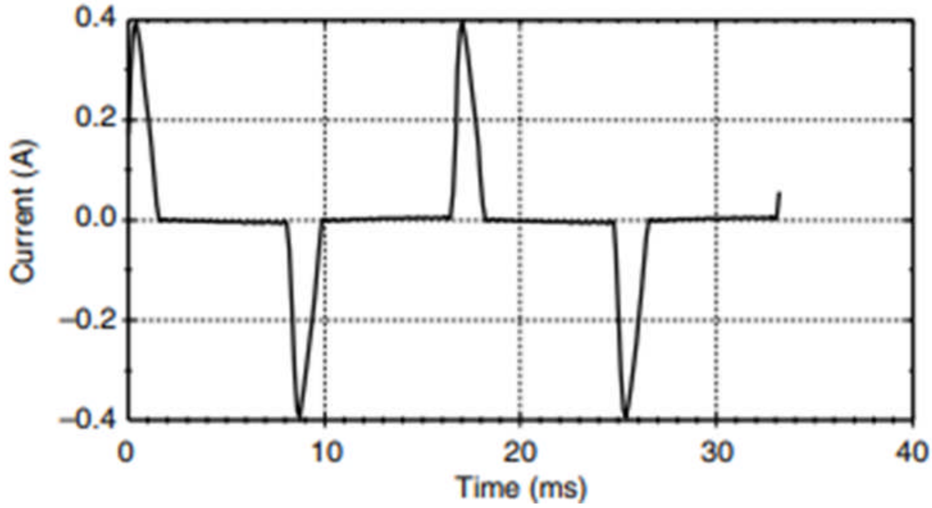


Fig 3.5: Current waveform shape of the fluorescent lamp with electronic ballast [8]

As seen from the figures, the nature of harmonics and the amount of distortion depend on the type of the ballast which is used. There are two types of fluorescent lamps [12]:

- With magnetic ballast: THD_i =12.8%, 3^{rd} order harmonics and it's multiples are equal to 20% of the fundamental.

- With electronic ballast: THD_i =16.3%, 3^{rd} order harmonics and it's multiples are equal to 8%-25% of the fundamental.

A typical magnitude spectrum of the fluorescent lamp with electronic ballast is shown in Table 3.5.

Table 3.5: The harmonics content of the current of the florescent lamp with electronic ballast

Harmonics order	Magnitude(%)	Harmonics order	Magnitude(%)
fundamental	100	9	2.4
2	0.2	11	1.8
3	19.9	13	0.8
5	7.4	15	0.4
7	3.2	17	0.1

Note from Table 3.5 that the third and fifth order harmonics are dominant also the table reveals that the harmonics pattern of the fluorescent lamp waveform is not periodic and as a result, this waveform cannot be analyzed by Fourier series.

3.4 Transformer

It is common knowledge that the transformer is considered as a linear device in normal conditions and the small amount of harmonics produced from it can be neglected. This is true as long as the transformer works in the linear region and did not enter into the saturation. If the transformer became saturated, then it is considered as a source of harmonics, especially the third and fifth order harmonics.

For practical and economic considerations, the transformer's operating point is close to the end of the linear region. This means that a slight increase in the input voltage may cause the transformer to enter the saturation area and consequently generate harmonics. For example, in the morning the loads are low and the voltage is high and this causes the formation of harmonics. Also, the periods of high energy demand cause saturation of the transformer.

An explanation can be found in Fig 3.6:

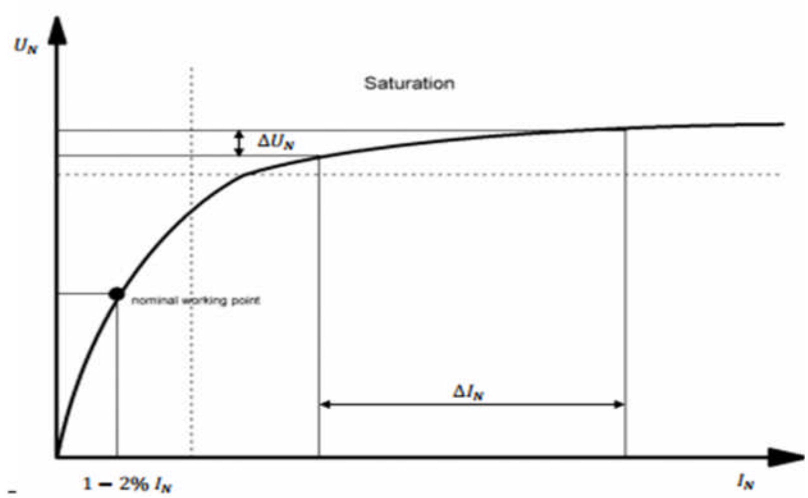


Fig 3.6: Principal of harmonics generating in the transformer

In the normal case, a small increase in voltage leads to a small increase in the magnetizing current. But above the rated values we completely lose the linear relationship. Hence, a small increase in voltage leads to a large increase in current. Typical harmonics spectrum magnitude of the transformer magnetizing current is shown in Table 3.6.

Table 3.6: Typical harmonics spectrum magnitude of the transformer magnetizing current [4]

Harmonics order	Magnitude(%)	Harmonics order	Magnitude(%)
fundamental	100	13	2.1
3	63.5	15	0.9
5	35.9	17	0.4
7	18	19	0.1
9	10.1	23	0.2
11	5.4	25	0.2

Although the rotating machines (motors and generators) are similar to the transformer in the working mechanism in terms of the production of the magnetic field, their curves are more linear than the transformer and this makes the resulting harmonics of no importance.

3.5 Household appliances

Many home appliances are sources of harmonics in distribution networks. Examples include computers (PC), lumination control equipment known as dimmers, radios and televisions. These devices produce harmonics because they contain an electronic control device, i.e., in other words, they contain power electronics in one form or another.

A typical TV current wave is shown in Fig 3.7

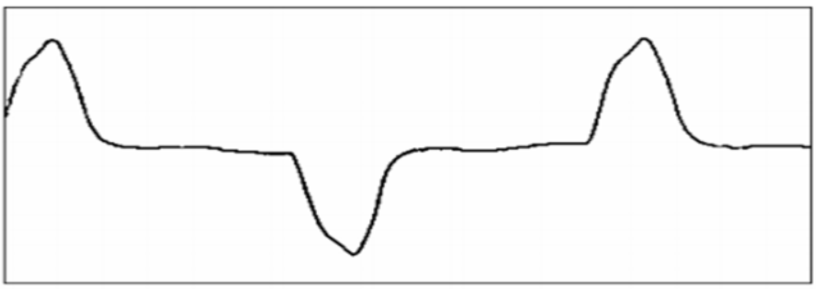


Fig 3.7: Typical TV current waveform [12]

These devices become a big problem in commercial buildings where these devices are widely available. The measurements found that computers produce a third harmonics current about 80% of the fundamental current.

Chapter Four

Harmonics standards

Most standards provide the allowed limits for harmonics to protect electrical network equipment and components from the effects which are resulted from these voltage and current harmonics.

Standard IEEE 519 _1992 is the most famous specification for harmonics distortion. This standard sets maximum limits for the allowable harmonics distortion to appear in the current and voltage waves at the point of connection of the device to the network (PCC).

The IEEE limits for voltage and current distortions are shown in the following tables:

Table 4.1: Current distortion values for general distribution networks (120V-69kV) [6,9]

I_{SC}/I_L	$h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	TDD
< 20	4	2	1.5	0.6	0.3	5
20-50	7	3.5	2.5	1	0.5	8
50-100	10	4.5	4	1.5	0.7	12
100-1000	12	5.5	5	2	1	15
> 1000	15	7	6	2.5	1.4	20

Table 4.2: Current distortion values for general distribution networks (69kV-161kV) [6,9]

I_{SC}/I_L	$h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	TDD
< 20	2	1	0.75	0.3	0.15	2.5
20-50	3.5	1.75	1.25	0.5	0.25	4
50-100	5	2.25	2	0.75	0.35	6
100-1000	6	2.75	2.5	1	0.5	7.5
> 1000	7.5	3.5	3	1.25	0.7	10

Table 4.3: Current distortion values for general distribution networks ($> 161kV$)[6,9]

I_{SC}/I_L	$h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	TDD
< 50	2	1	0.75	0.3	0.15	2.5
≥ 50	3	1.5	1.15	0.45	0.22	3.75

Here,

I_{SC}: maximum short circuit current available at PCC point

I_L: maximum fundamental demand load current at PCC point. It is calculated as the average current of the preceding 12 months.

These two values may need short circuit and load flow calculations to find them.

According to these tables it is clear that:

- Even harmonics are limited to 25% of the odd harmonics limits shown above.
- Current distortions that result in a dc offset like half wave rectifiers are not allowed.
- All power generation equipment are limited to these values of current distortion, regardless of actual I_{SC}/I_L.

It is clear from the tables that in the case of strong networks with high S.C capacity, higher values of current distortion are allowed to exceed. This is true because the higher capacity of short circuit current value means lower value of the network impedance. This means that the voltages of bus bars are less affected by the flow of harmonics.

According to the voltage distortion, Table 4.4 shows the distortion ratios ($\%IHD_v, \%THD_v$) under normal operating conditions that last for more than hour. Knowing that these values are allowed to exceed 50% increase in transit periods such as starting motors and starting operation of transformers.

Table 4.4: Voltage distortion value for general distribution networks [6,9]

Voltage distortion limits (% of V_1)		
Bus voltage at PCC	IHD_v(%)	THD_v(%)
69kV and below	3	5
69kV through 161kV	1.5	2.5
161kV and above	1	1.5

The above specification is concerned with the network as a whole and the point of connection with the subscribers, but there are other specifications concerned with the same device in the sense of whether the harmonics emitted by this device are allowed or not without looking at the network.

IEC 61000-3-2 has been developed to address this issue. This standard deals with most household and commercial appliances with a current of less than 16 A and this specification does not consider THD but looks at the individual distortion [2,8].

Table 4.5: Maximum permissible harmonics current for devices [8]

Harmonics order	Maximum permissible harmonics current (A)
Odd harmonics	
3	2.3
5	1.14
7	0.77
9	0.4
11	0.33
13	0.21
$15 \leq h \leq 39$	0.15(15/h)
Even harmonics	
2	1.08
4	0.43
6	0.3
$8 \leq h \leq 40$	0.23(8/h)

These limits are applied through the following steps:

- The point of connection(PCC) is selected.
- The device's harmonics are determined and calculated at (PCC).
- Remedial procedures are designed and implemented.
- Measurements are taken to see new results.

IEEE 519_1992 is really a recommendation and not a set of compulsory requirements, i.e., it does not mean that the limits in the tables should not be exceeded at all. It does not force the user to use a certain type of converters or devices with certain harmonics ratios, but to instruct the user to take certain procedures for processing, for example, using a filter.

In IEEE 519_1992, Both the user and the utility are responsible for the harmonics. The user has to determine the harmonics of the current by choosing the appropriate device type or other actions while the utility must control the harmonics of voltages.

Sometimes it is not necessary to conduct a detailed study of network harmonics to determine the compatibility of the network with the limits required for harmonics. Instead, a quick method of governance can be followed provided that the short circuit capacity (S.C) of the network is much greater than kVA demand of all nonlinear loads connected to the network.

The method is done in the following steps [9]:

- The short circuit at concerned point (PCC) is calculated.
- kVA capacity for all nonlinear loads at (PCC) is calculated.
- Up to the last nonlinear load, the following relationship is applied

$$S_T = \sum_{i=1} S_i W_i \quad (4.1)$$

S_i: is the kVA demand of i^th nonlinear load.

W_i: is the Weighting Factor.

Limits are acceptable if the following condition applies:

$$\frac{S_T}{S_{SC}} 100\% < 0.1\%$$

Values for W_i are shown in Table 4.6

Table 4.6: Weighting factors for the famous loads[9]

Load type	W_i
semi converter	2.5
6-pulse converter without choke	2
6-pulse converter with choke	1
6-pulse converter with too large inductor	0.8
12-pulse converter	0.5

Chapter Five

Network components modeling for harmonics analysis

5.1 Introduction

A harmonics analysis study is very necessary if the nonlinear loads reach 20% of the total load in the network. This study should be done to find out the effect of harmonics on the network and avoid possible damage. In harmonics analysis, there is a need to model the different network elements such as transmission lines, transformers, loads, etc., to develop an accurate frequency-dependent model for the whole network.

Based on the nature and method of interaction of each element with the passage of harmonic frequencies, several typical models of each element were reached.

This chapter will discuss how the main elements of the network are represented for use in frequency analysis studies.

5.2 Overhead transmission lines and cables

The most common model for the representation of overhead transmission lines and cables is the π-model, which consists of series impedance with shunt admittance divided into two equal halves on the beginning and end of the line.

In the case of short lines, the shunt admittance is ignored and reduced to only resistance and inductance in series, while in the long line the shunt admittance is considered. Overhead line considered long if it exceeds $150/h$

miles, underground cable is considered long if it exceeds 90/*h* miles. where *h* is harmonics order [1].

Fundamental frequency impedance of the lines is calculated based on how the conductors are arranged, type of the conductor material, size of conductor and the temperature. According to German specifications, the fundamental frequency resistance values of cables are as in Table 5.1.

Table 5.1: Resistance values of cables according to cross-sectional area and type

cross-sectional area(mm^2)	R at 20°C (Ω/km)		cross-sectional area(mm^2)	R at 20°C (Ω/km)	
	Aluminum	Copper		Aluminum	Copper
1.5	-	11.9	70	0.433	0.255
2.5	12.2	7.13	95	0.319	0.188
4	7.58	4.45	120	0.252	0.15
6	5.05	2.98	150	0.202	0.12
10	3.03	1.78	185	0.165	0.096
16	1.9	1.12	240	0.123	0.074
25	1.21	0.714	300	0.101	0.0594
35	0.866	0.51	400	0.076	0.0446
50	0.606	0.357	500	0.0606	0.0357

While The fundamental frequency reactance values of the cable are also shown in the Table 5.2

Table 5.2: Reactance values of cables according to cross-sectional area

Cross-sectional area(mm2)	Low voltage X (Ω/km)	medium voltage X (Ω/km)
6	0.102	-
10	0.095	0.142
16	0.090	0.132
25	0.086	0.122
35	0.083	0.112
50	0.081	0.106
70	0.079	0.101
95	0.077	0.097
120	0.077	0.095
150	0.077	0.092
185	0.076	0.090
240	0.076	0.088
300	0.075	0.088

In the case of harmonics existence, the two most important factors to be considered in the impedance calculations are:

- The effect of the harmonics frequency
- And the effect of the length of the line

The effect of the length of the line is not to neglect the value of shunt admittance in case that the line is long and hence, there is a chance of occurrence of resonance between the shunt admittance and the inductance of the network.

The effect of frequency of harmonics is to increase the value of the reactance ($2\pi fL$) of the line. Also to increase resistance value due to skin effect and proximity effect.

The resistance with the skin effect is modified as in the following relationships:

In case of lines [9]:

$$R_{new} = R_{50Hz}\left(1 + \frac{0.646h^2}{192 + 0.518h^2}\right) \quad (5.1)$$

In case of cables [9]:

$$R_{new} = R_{50Hz}\left(0.187 + 0.532(h)^{\frac{1}{2}}\right) \quad (5.2)$$

To facilitate calculations, we can use the following Fig 5.1

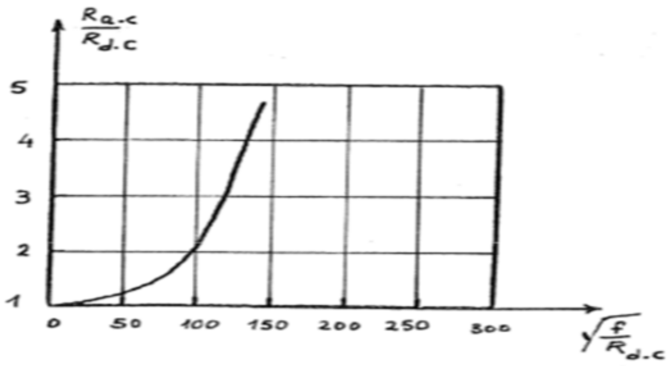


Fig 5.1: A plot relates Ac resistance of lines with frequency

For example, for (240 mm^2) copper cables the fundamental resistance (R_{DC}) = 0.074 Ω/Km. At fifth harmonics order (f = 5*50=250 Hz), $\sqrt{\frac{f}{R_{DC}}} = 58.12$. From the plot $\frac{R_{AC}}{R_{DC}}$ =1.2. This gives $R_{AC} = 0.089$ Ω/Km.

The reactance value at a certain harmonics order frequency can be found as follows [5]:

$$X_h = hX \quad (5.3)$$

Where X The line reactance at 50 Hz which can be obtained from the manufacturer's tables or standard specifications.

5.3 Transformers

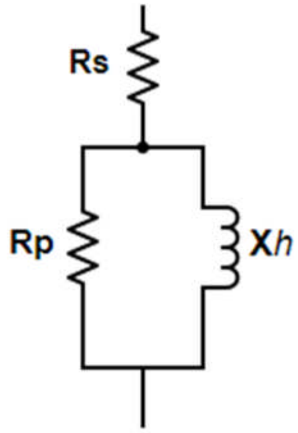
It is possible to use the ordinary model of the transformer which is used in all references for harmonics flow analysis. The results which will be obtained will not go far from the correct results. Experiments and practical measurements showed that the ordinary model remains acceptable - despite the neglect of the phenomena associated with the passage of harmonics in the transformer- up to the 13^{rd} harmonics. Hence, a special model for harmonics flow analysis is needed.

The transformers effect on the harmonics flow by means of two ways:

- The transformer can provide $\pm 30°$ phase shift for the harmonics currents and voltages, this phase shift is related to the way in which the windings are connected $Y\ or\ \Delta$ and the harmonics sequence.
- The transformer series impedance develop a voltage drop which is reflected in the harmonics voltage wave shape later.

Here, the most accurate two models of transformer according [9,13] to are shown. The first one is model (A) shown in Fig 5.2

Fig 5.2: Transformer model (A) for harmonics analysis



Where:

$$Z_{Tr} = R_{Tr} + jX_{Tr} \tag{5.4}$$

$$R_s = R_{Tr} \tag{5.5}$$

$$X_h = hX_{Tr} \tag{5.6}$$

$$R_p = 80X_{Tr} \tag{5.7}$$

The equivalent impedance is calculated by applying parallel and series formulas as follows:

$$Z_{TOT} = R_s + \frac{h^2 X_{Tr}^2 R_p}{R_p^2 + h^2 X_{Tr}^2} + \mathrm{j}\frac{hX_{Tr} R_p^2}{R_p^2 + h^2 X_{Tr}^2}\ , h \neq 1 \tag{5.8}$$

The second is model (B) consists of a modified resistance with inductance in series according to Fig 5.3 [9]:

Fig 5.3: Transformer model (B) for harmonics analysis

At harmonics frequencies, the inductance is related to specific harmonics order as follows

$$X_h = hX_{Tr} \tag{5.9}$$

While the resistance value is adjusted by multiplying it by a factor according to Fig 5.4

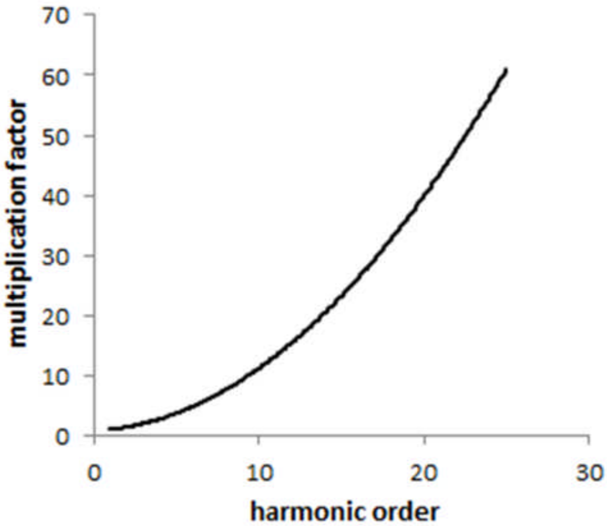


Fig 5.4: Increase in transformer resistance with frequency [1,3]

The multiplication factor for resistance adjustment is tabulated as in the Table 5.3

Table 5.3: Multiplication factor for transformer's resistance adjustment with frequency change

Harmonics order	Resistance factor	Harmonics order	Resistance factor
1	1	13	17
2	1.5	14	21
3	2	15	23
4	3	16	27
5	4	17	29
6	5	18	33
7	6	19	37
8	8	20	40
9	10	21	43
10	11	22	47
11	12	23	53
12	16	24	56

The initial values of resistance and inductance are obtained from the open-circuit and short-circuit tests. However, we can obtain the impedance of transformer $Z_{Tr}\%$ from the nameplate of the transformer or using Fig 5.5 which relates X/R and transformer capacity, then the values of R_{Tr} and X_{Tr} are obtained by using the following equations[1]:

$$R_{Tr} = \frac{Z_{Tr}\%}{\sqrt{\frac{X}{R}^2 - 1}} \tag{5.10}$$

$$X_{Tr} = R_{Tr}\left(\frac{X}{R}\right) \tag{5.11}$$

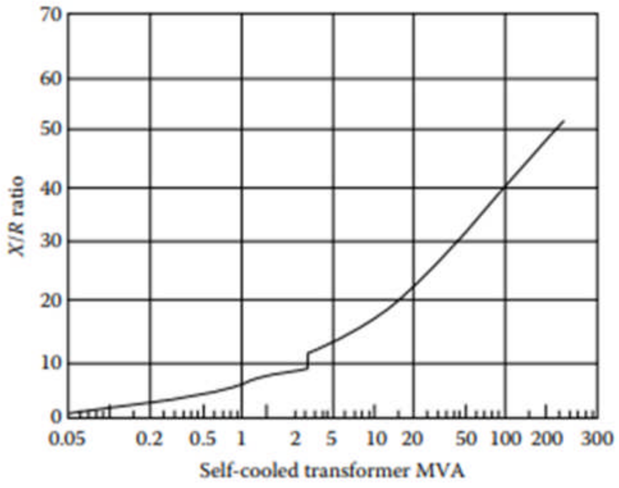


Fig 5.5: X/R value with the capacity of transformer curve [1]

5.4 Rotating machines

The rotating machines term includes both synchronous and induction machines. The synchronous machines are usually used as generators while induction machines are usually used as motors.

In harmonics flow studies, both the generator and the motor are represented as passive load shunted between the bus they are connected to and ground. This is true because they do not contribute in harmonics generation.

In case of synchronous machines, Negative sequence impedance Z_2 is taken or the average of both direct X_d and quadrature X_q reactance can be taken to a reasonable degree of accuracy [5].

The reactance should be scaled up according to the frequency as follows [5]:

$$X_h = hX_{50Hz} \tag{5.12}$$

While the resistance is adjusted to include losses which are caused by skin effect and eddy currents as follows [3]:

$$R_h = R_{50Hz}\left(1 + 0.1\left(\frac{h}{f}\right)^{1.5}\right) \tag{5.13}$$

So, the impedance becomes as follows:

$$Z_h = R_h + \mathrm{j}X_h \tag{5.14}$$

In the case of induction machines, the locked rotor impedance Z_{LR} is taken in the harmonics flow analysis.

The reactance is scaled up directly in accordance with the frequency as follows [3,5]:

$$X_h = hX_{LR} \tag{5.15}$$

The resistance is modified to include eddy currents and skin effect losses as follows [5]:

$$R_h = h^{\propto} R_{50Hz}\,, 0.5 < \propto < 1.5 \tag{5.16}$$

Total impedance becomes as follows:

$$Z_h = R_h + \mathrm{j}X_h \tag{5.17}$$

It should be noted that reactance decreases-contrary to what is expected- with very high frequencies due to saturation, hence, the equation 5.17 will be less correct [3]. If only fundamental impedance (Z_{50Hz}) value is available special curves like that shown in Fig 5.6 can be used to find reactance (X_{50Hz}) and resistance (R_{50Hz}) values.

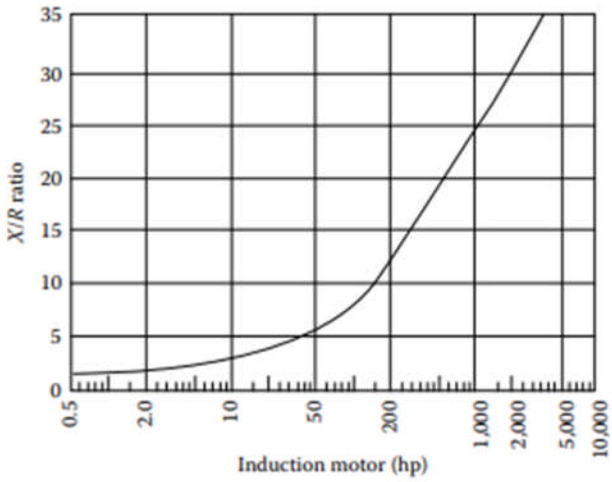


Fig 5.6: X/R value with the capacity of machine curve [1]

Finally, in the case of a salient pole synchronous machines type, the negative sequences currents generate a second order harmonics currents in the magnetic field, which in turn generate a third order harmonics currents in the stator. Here, if the system is unbalanced, more complex model is required to represent this type of machine in harmonics flow analysis.

5.5 Loads

In the case that the load is not a source of harmonics and does not participate in their generation, then it can be represented by linear elements to form an impedance depending on frequency.

Load are classified to three types: passive load (typically domestic), motive load and power electronics load [2]. The first two types can be represented by a linear model for harmonics analysis, but the last type is different since it presents a variable L, R, C elements and it has non-linear characteristics.

There is no absolute acceptable model for load representation. To conclude an acceptable model, several measurements were made and three models were reached. They are: model(A), model(B) and model(C) shown respectively:

Model (A) [3,5,7]:

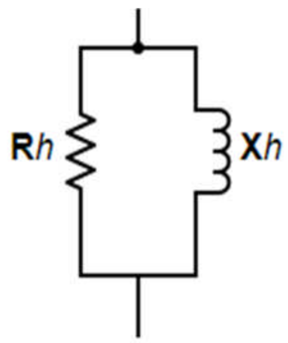


Fig 5.7: Load model (A) for harmonics analysis

$$R_h = \frac{V^2}{P} \tag{5.18}$$

$$X_h = h\frac{V^2}{Q} \tag{5.19}$$

Model (B)[2]:

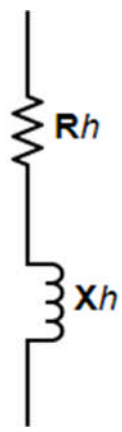


Fig 5.8: Load model (B) for harmonics analysis

$$R_h = \sqrt{h}\frac{V^2}{P} \tag{5.20}$$

$$X_h = h\frac{V^2}{Q} \tag{5.21}$$

Model (C) [3,5]:

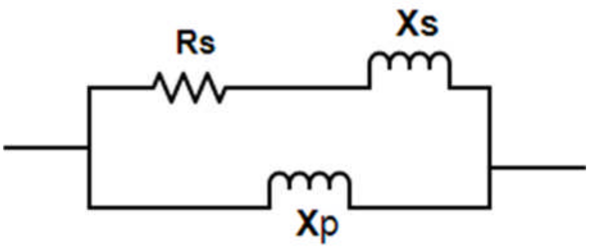


Fig 5.9: Load model (C) for harmonics analysis

$$R_S = \frac{V^2}{P} \tag{5.22}$$

$$X_P = \frac{hR_S}{6.7\frac{Q}{P} - 0.74} \tag{5.23}$$

$$X_S = 0.073hR_S \tag{5.24}$$

In each model, resistance slightly changes with frequency change since there are no skin effect nor eddy currents like in transformers and other components.

5.6 Capacitors

There is a need to know the capacity of the capacitor in (kVAR or MVAR) and the rated voltage in (kV_{LL}) to calculate the capacitor reactance as follows:

$$X_{50Hz} = \frac{{kV_{LL}}^2}{MVAR} \tag{5.25}$$

The capacitor reactance changes with the harmonics frequencies as follows:

$$X_h = \frac{X_{50Hz}}{h} \tag{5.26}$$

5.7 Reactors

With frequency change, both resistance and reactance change as follows:

Reactance change linearly with frequency

$$X_h = hX_{50Hz} \tag{5.27}$$

While resistance change as follows [3]:

$$R_h = \frac{1 + 0.055h^2}{1.055} R_{50Hz} \;\; in\ case\ of\ copper\ reactor \tag{5.28}$$

$$R_h = \frac{1 + 0.115h^2}{1.15} R_{50Hz} \;\; in\ case\ of\ aluminium\ reactor \tag{5.29}$$

5.8 Connection point

The connection point is considered a zero-voltage circuit at harmonics frequencies. It is effective in providing voltages only at the fundamental frequency. Hence, the connection point is represented only by its impedance [5]. Connection point impedance calculation procedure is as follows:

$$Z_{grid} = \frac{V_{LL}^2}{short\ circuit\ MVA} \tag{5.30}$$

Where:

$$short\ circuit\ MVA = \sqrt{3}V_{LL} short\ circuit\ current \tag{5.31}$$

Chapter Six

Harmonics study of balanced distribution networks in frequency domain

6.1 Introduction

In order to identify the impact of harmonics on the power grid, especially the distortion of voltages and currents, there is a need to analyze the distorted waveforms by using a technique called harmonics analysis. Harmonics analysis is widely used in design and troubleshooting.

Harmonics analysis calculations are of great importance for the following reasons:

- It helps us to know how dangerous if a resonance occurs between power factor correction banks and the inductance of the network.
- It determines the distortion in voltages and currents, and its compatibility with the natural limits.
- It assists in the design of methods to eliminate harmonics such as using filters.

The network response for harmonics can be studied through:

- Direct measurements using dedicated devices such as a Harmonics Analyzer Fluke 434/435. These devices reflect the conditions of the network at the time in which measurements were made and do not necessarily give the worst situation for the system.

- Computer simulation using sophisticated software and this track is adopted if the network is extended and containing a large number of buses. These programs are fast to take the results
- Manual calculations, which are the preferred method if the network is not too large to make this method complex. It is common that the results of manual calculations deviate somewhat from the accurate results because of the low probability of access to a comprehensive model for the system which gives the exact results. This point was exceeded in this thesis because the model of each element was carefully selected to form a complete model for the system in which all the individual models fit together.

6.2 Electric grid overview

The selected electric grid can be described as follows:

A utility supplies a distribution network through a 66kV/11kV transformer. Loads in the system are distributed at two buses as follows:

A 6-pulse converter is connected at one bus in parallel with another passive load.

An induction motor is connected to the other bus.

The two buses are linked by a 11kV/4.16kV transformer. Capacitor banks exist on both buses for power factor correction. Fig 6.1 shows the schematic diagram of the network.

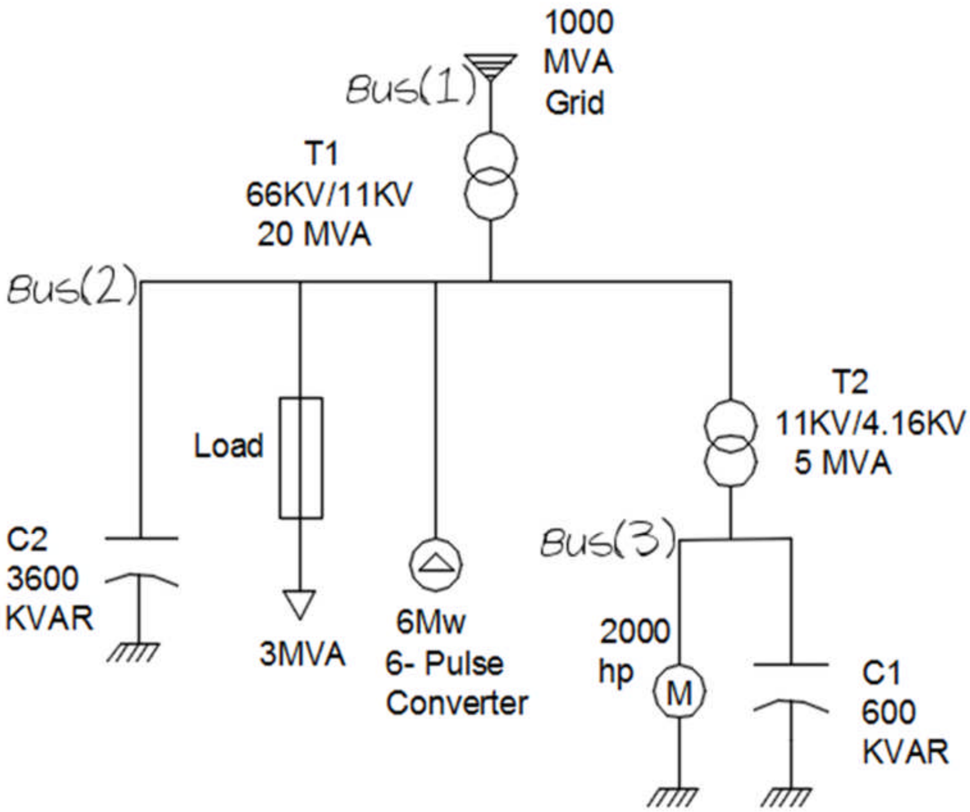


Fig 6.1: Schematic diagram of the distribution network

The system data are as follows:

Utility (grid) 66kV, X/R =10 , infinite bus, $S_{S.C}$=1000MVA

Transformers T1: 66kV-Δ /11kV-Y , 20MVA , Z=6%, X/R=20.

T2: 11kV-Y /4.16kV-Y , 5MVA , Z=6%, X/R=12.

Passive load(bus#2) 3 MVA, P.F=0.9 lag.

Induction motor(bus#3) 2000 hp , P.F=0.926 lag , X'' =15.257% , η=93.94% ,X/R=30.8 .

P.F correction banks C1: 600 kVAR

C2: 3600 kVAR.

6-Pulse converter 6 MW, P. F=0.85 lag.

6.3 Harmonics modeling of system component

The calculation will be done using per unit quantities. $S_{base} = 10MVA$ is taken for all regions.

Bus#1 region:

$$V_b = 66kV$$

$$I_B = \frac{S_b}{\sqrt{3}V_b} = \frac{10MVA}{\sqrt{3}(66kV)} = 87.477A$$

$$Z_b = \frac{V_b^2}{S_b} = \frac{(66kV)^2}{10MVA} = 435.6\Omega$$

Bus#2 region:

$$V_b = 11kV$$

$$I_B = \frac{S_b}{\sqrt{3}V_b} = \frac{10MVA}{\sqrt{3}(11kV)} = 524.86A$$

$$Z_b = \frac{V_b^2}{S_b} = \frac{(11kV)^2}{10MVA} = 12.1\Omega$$

Bus#3 region:

$$V_b = 4.16kV$$

$$I_B = \frac{S_b}{\sqrt{3}V_b} = \frac{10MVA}{\sqrt{3}(4.16kV)} = 1387.86A$$

$$Z_b = \frac{V_b^2}{S_b} = \frac{(4.16kV)^2}{10MVA} = 1.731\Omega$$

The base data is tabulated in Table 6.1

Table 6.1: The per unit values of bus regions

Bus#1	
Base voltage	66kV
Base current	87.477A
Base impedance	435.6 Ω
Bus#2	
Base voltage	11kV
Base current	524.86A
Base impedance	12.1 Ω
Bus#3	
Base voltage	4.16kV
Base current	1387.86A
Base impedance	1.731 Ω

There is a need to perform load flow analysis of the network at the fundamental frequency. This analysis gives us the following values which will be required in the harmonics analysis:

- The buses fundamental voltage values and associated phase angles. The voltage values are important in calculating THD, while phase angles are important in the case when more than one source of harmonics exist. Since in this case study only one source of harmonics is present, phase angles are not of importance [9].
- The value of the fundamental current in the line that feeds the nonlinear load (harmonics source), This value will be used to estimate the current value of the harmonics source for each harmonics order (As we shall see later).

The fundamental load flow study is carried out by ETAP 12.6 software. Voltage, current values and phase angle are shown in Fig 6.2.

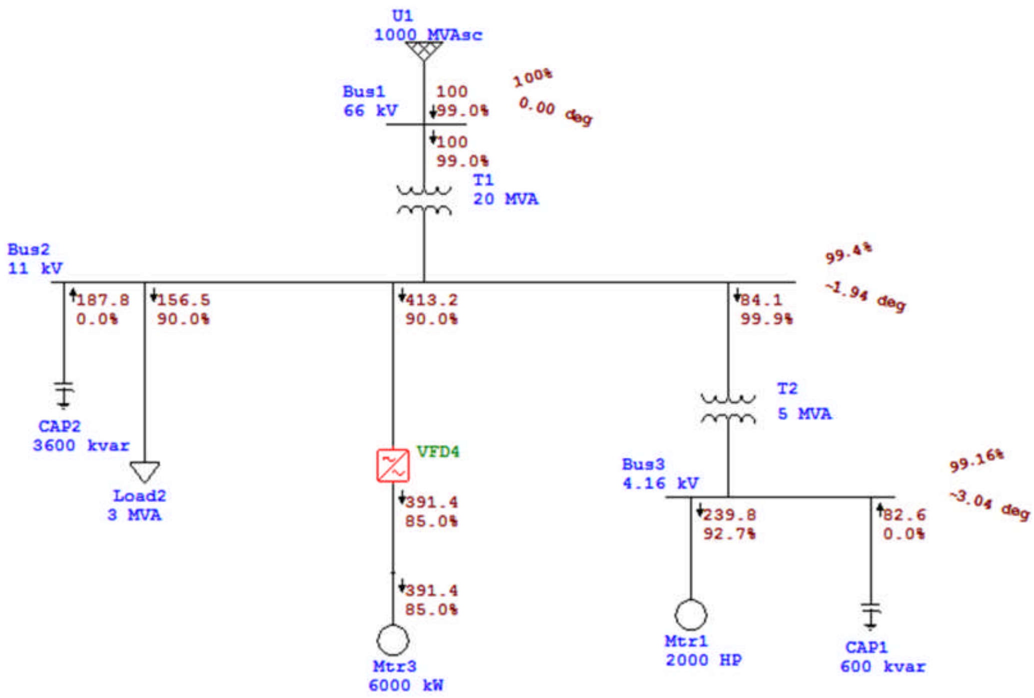


Fig 6.2: Load flow study results obtained by ETAP 12.6

The fundamental current of harmonics source is found to be equal to 413.2A. Moreover, all bus fundamental voltages percentage values are shown in Table 6.2

Table 6.2: Bus voltages percentage values

Bus#1	100%
Bus#2	99.4%
Bus#3	99.16%

The harmonics source was modeled as a constant power load in the fundamental load flow study. This means that it consumes power from the grid and do not inject harmonics to the grid.

The next step is to model every component in frequency domain. As stated before, there are more than one model for each component. Choosing the most suitable model is an important step.

Connection point:

As mentioned earlier in Chapter 5, the grid does not contribute in the generation of the harmonics and for this reason, it is represented by its impedance in harmonics studies.

$$grid\ impedance = \frac{V^2}{MVA_{S.C}}$$

$$Z_b = \frac{V^2}{MVA_b}$$

$$Z_{p.u} = \frac{MVA_b}{MVA_{S.C}} = \frac{10}{1000} = 0.01$$

$$R_{p.u} = \frac{Z_{p.u}}{\sqrt{\left(\frac{X}{R}\right)^2 + 1}} = \frac{0.01}{\sqrt{(10)^2 + 1}} \cong 0.001 p.u$$

$$X_{p.u} = R\left(\frac{X}{R}\right) = 0.01 p.u$$

Hence, the fundamental impedance of the grid $Z_{p.u} = R + jX = 0.001 + j0.01\ p.u$. As stated before, grid impedance is represented by an impedance which consists of resistance and reactance in series. The value of resistance will be constant with frequency change unlike reactance which linearly changes with frequency ($X_h = hX_{50Hz}$).

The per unit values of resistance and reactance for each harmonics frequency order is tabulated in Table 6.3

Table 6.3: Per unit harmonics impedance values of the grid for each harmonic order

harmonic order(h)	$R_g(p.u)$	$X_g(p.u)$
$h = 5$	0.001	0.05
$h = 7$	0.001	0.07
$h = 11$	0.001	0.11
$h = 13$	0.001	0.13

Transformers:

Transformers are represented by using model (A) as shown in Fig 5.2. In this model, the transformer is represented by a combination of series and parallel impedances between the two buses connected by the transformer.

The calculation of the Harmonics impedance of the transformer is done as follows:

- The first step is to find the per unit value of the fundamental impedance of the transformer on the new base values.
- The second step is using the equations 5.4,5.5,5.6 and 5.7 to find harmonic resistances and harmonic reactances.
- The third step is to find the equivalent harmonic impedance for each harmonic order using equation 5.8.

Transformer T1:

The fundamental impedance of the transformer can be calculated as:

$$Z_{p.u} = \frac{Z\%(S_b)}{S_{Tr}} = \frac{0.06(10)}{20} = 0.03p.u$$

$$R_{p.u} = \frac{Z_{p.u}}{\sqrt{\left(\frac{X}{R}\right)^2 + 1}} = \frac{0.03}{\sqrt{(20)^2 + 1}} = 0.0015p.u$$

$$X_{p.u} = R_{p.u}\left(\frac{X}{R}\right) = 0.015(20) = 0.03p.u$$

$$Z_{Tr} = R_{Tr} + jX_{Tr} = 0.0015 + j0.03\ p.u$$

The harmonics resistance and reactance combination

$$R_s = R_{Tr} = 0.0015\ p.u$$

$$X_h = hX_{Tr} = h * 0.03\ p.u$$

$$R_p = 80X_{Tr} = 80 * 0.03 = 2.4\ p.u$$

The equivalent harmonics impedance for each harmonics order of the transformer is given by equation 5.8

$$Z_{TOT} = R_s + \frac{h^2 X_p^2 R_p}{R_p^2 + h^2 X_{Tr}^2} + \mathrm{j}\frac{hX_{Tr}R_p^2}{R_p^2 + h^2 X_{Tr}^2}\ , h \neq 1$$

The per unit values of resistance and reactance of the equivalent impedance for each harmonic frequency order are calculated and tabulated as follows:

Table 6.4: Per unit harmonics impedance values of T1 for each harmonics order

Frequency order(h)	$R_{T1}(p.u)$	$X_{T1}(p.u)$
h = 5	0.01084	0.15
h = 7	0.0197	0.208
h = 11	0.046	0.324
h = 13	0.0635	0.38

Transformer T2:

The fundamental impedance of the transformer can be calculated as:

$$Z_{p.u} = \frac{Z\%(S_b)}{S_{Tr}} = \frac{0.06(10)}{5} = 0.12p.u$$

$$R_{p.u} = \frac{Z_{p.u}}{\sqrt{\left(\frac{X}{R}\right)^2 + 1}} = \frac{0.12}{\sqrt{(12)^2 + 1}} = 0.00996p.u$$

$$X_{p.u} = R_{p.u}\left(\frac{X}{R}\right) = 0.00996(12) = 0.1196p.u$$

$$Z_{Tr} = R_{Tr} + jX_{Tr} = 0.00996 + j0.1196\,p.u$$

The harmonics resistance and reactance combination

$$R_s = R_{Tr} = 0.00996\,p.u$$

$$X_h = hX_{Tr} = h * 0.1196\,p.u$$

$$R_p = 80X_{Tr} = 80 * 0.1196 = 9.57\,p.u$$

The equivalent harmonics impedance for each harmonics order of the transformer is given by equation 5.8

The per unit values of resistance and reactance of the equivalent impedance for each harmonic frequency order are calculated and tabulated as follows:

Table 6.5: Per unit harmonics impedance values of T2 for each harmonics order

Frequency order(h)	$R_{T1}(p.u)$	$X_{T1}(p.u)$
$h = 5$	0.04716	0.6
$h = 7$	0.08296	0.831
$h = 11$	0.18746	1.3
$h = 13$	0.256	1.515

Passive load:

The passive load will be represented by the model (A) shown in Fig 5.7. In this model, the load is represented by a resistance and a reactance in parallel between the bus and the ground.

$$S_{p.u} = \frac{S_L}{S_b} = \frac{3}{10} = 0.3p.u$$

$$R_{p.u} = \frac{V_{L-L\,p.u}^2}{P_{p.u}} = \frac{(1)^2}{0.3(0.9)} = 3.7037p.u$$

$$X_{p.u} = \frac{V_{L-L\,p.u}^2}{Q_{p.u}} = \frac{(1)^2}{0.3(0.436)} = 7.6472p.u$$

The equivalent harmonics impedance of passive load for each harmonics is given by:

$$Z_{TOT} = \frac{h^2 X_L^2 R_L}{R_L^2 + h^2 X_L^2} + \mathrm{j}\frac{h X_L R_L^2}{R_L^2 + h^2 X_L^2}\ , h \neq 1$$

The per unit values of resistance and reactance for each harmonics frequency order are tabulated as follows:

Table 6.6: Per unit harmonics impedance values of load for each harmonics order

Frequency order(h)	$R_L(p.u)$	$X_L(p.u)$
$h = 5$	3.6693	0.3554
$h = 7$	3.686	0.255
$h = 11$	3.697	0.163
$h = 13$	3.699	0.138

Capacitors:

For capacitor C1:

The fundamental reactance can be calculated as follows:

$$X_{p.u} = -\frac{MVA_b}{MVA_{cap}} = -\frac{10}{0.6} = -16.667p.u$$

The harmonics impedance of the capacitor is given as:

$$X_h = \frac{X_{50Hz}}{h}$$

Hence, the per unit values of reactance for each harmonics frequency order are as follows:

Table 6.7: Per unit harmonics impedance values of C1 for each harmonics order

Frequency order(h)	$X_{C1}(p.u)$
$h = 5$	-3.333
$h = 7$	-2.381
$h = 11$	-1.515
$h = 13$	-1.282

For capacitor C2:

The fundamental reactance can be calculated as follows:

$$X_{p.u} = -\frac{MVA_b}{MVA_{cap}} = -\frac{10}{3.6} = -2.778p.u$$

The harmonics impedance of the capacitor is given as:

$$X_h = \frac{X_{50Hz}}{h}$$

Hence, the per unit values of reactance for each harmonics frequency order is are as follows:

Table 6.8: Per unit harmonics impedance values of C2 for each harmonics order

Frequency order(h)	$X_{C1}(p.u)$
$h = 5$	-0.556
$h = 7$	-0.4
$h = 11$	-0.253
$h = 13$	-0.214

Induction motor:

The locked rotor impedance Z_{LR} is taken in the harmonics flow analysis.

- First step is to calculate the locked rotor impedance at new base values

$$S_{M-inp} = \frac{P_{out}}{P.F * \eta} = \frac{2000HP(0.746)}{0.9266 * 0.9394} = 1714.06kVA$$

$$X_{p.u} = \frac{X''S_b}{S_{M-inp}} = \frac{0.15257(10)}{1.71406} = 0.9p.u$$

$$R_{p.u} = \frac{X''}{(\frac{X}{R})} = \frac{0.9}{30.8} = 0.03p.u$$

- Second step is to adjust the resistance and reactance with frequency change using equations 5.15 and 5.16

Hence, the per unit values of resistance and reactance for each harmonics frequency order as follows($\propto = 1$, is taken):

Table 6.9: Per unit harmonics impedance values of IM for each harmonics order

Frequency order(h)	$R_M(p.u)$	$X_M(p.u)$
$h = 5$	0.15	4.5
$h = 7$	0.21	6. 3
$h = 11$	0.33	9.9
$h = 13$	0.4	11.7

The harmonics per unit impedance diagram of the whole network is shown in Fig 6.3

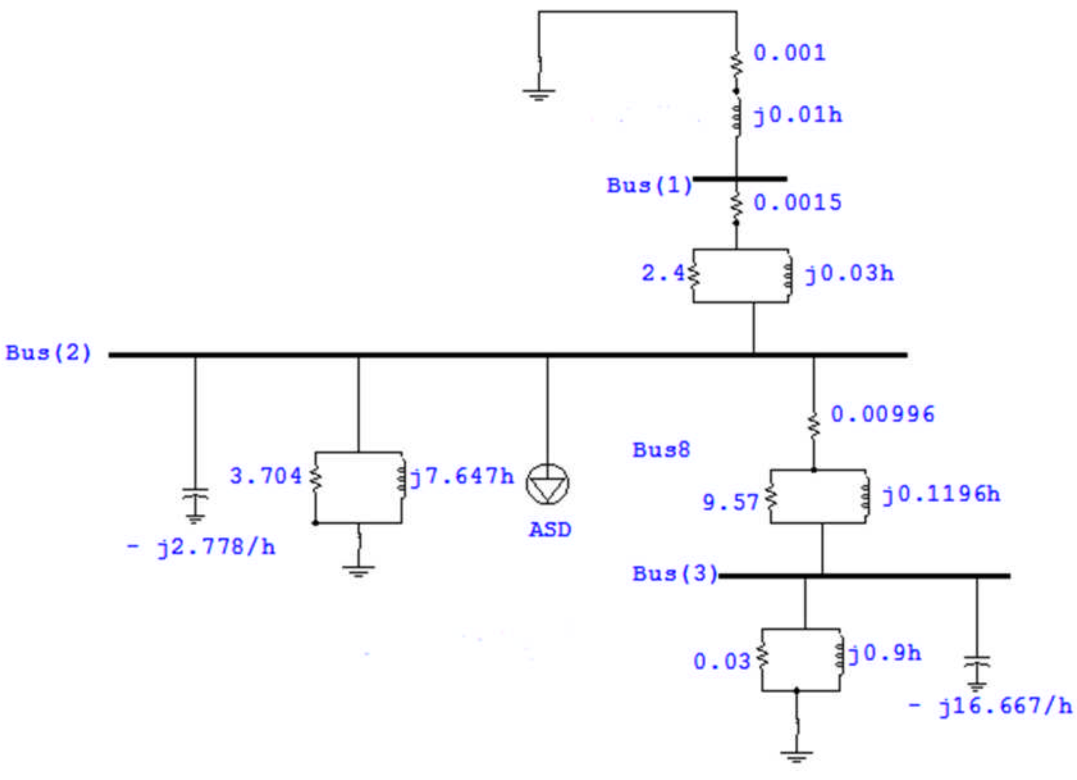


Fig 6.3: The harmonics per unit impedance diagram of the whole network

6.4 Harmonics modeling of nonlinear load (harmonics source)

The harmonics source (nonlinear load) is represented by an ideal current source that injects a different current value for each harmonics order. This hypothesis becomes more accurate whenever the values of voltage distortion are small. References mention that in cases of voltage distortion (THD_v) that exceeds 10%, this hypothesis gives less accurate results[9]. Actually, the distortion on the current is more severe than voltages. This makes the nonlinear load representation as a current source often is true and accurate.

In the network that was adopted, the nonlinear load was a 6-pulse converter drive which is used to control an induction motor. This type of nonlinear load generates harmonics characteristics based on the number of pulses and determined by:

$$h = Pn \pm 1$$

Where: *h*: harmonics order, *P*: pulse number, *n*: integer number.

for 6-pulse converter, harmonics orders (5,7,11,13,17,19….) will appear. Because the amplitude of the harmonics decreases inversely by increasing the harmonics order following this pattern:

$$I_h = \frac{1}{h} I_1$$

the analysis will be limited to (5,7,11,13) only.

Harmonics current data of nonlinear load as a percentage of fundamental current for considered harmonics orders are

Table 6.10: 6-pulse converter current as a percentage value of fundamental current for each harmonics order

h	1	5	7	11	13
$\frac{I_h}{I_1}$ (%)	100	20	14.3	9.1	7.7

Hence, we find the per unit values of harmonics current using both fundamental current and base current. As an example ,the per unit value for harmonics current of 5^{th} order can be calculated as follows:

Base current I_b=524.86A while the fundamental current I_{50Hz}=413.2A. Fifth order harmonics current will be:

$$I_{h=5} = \left(\frac{20\%(413.2)}{524.86}\right) = 0.15745p.u$$

Consequently, the per unit values of harmonics current are

Table 6.11: Per unit value of the 6-pulse converter current for each harmonics order

h	1	5	7	11	13
$current(p.u)$	0.78726	0.15745	0.11258	0.071640	0.06062

6.5 Calculation of harmonics distortion

In harmonics analysis, the only current source which is exists in the network is the nonlinear load (harmonics source) and the grid itself does not produce currents into the network. Hence, the number of current sources is equal to the number of harmonics sources in the network.

There is a current associated with each harmonics frequency emitted by the current source. Thus, it is necessary to apply superposition technique to find the value of the distortion for each harmonics current.

The method of calculation of bus voltages is accomplished by solving the following linear equation:

$$[\, I_h \,] = [\, Y_h \,]\,[\, V_h \,]\,, h \neq 1 \qquad (6.1)$$

Where $[Y_h\ ]$ is the bus admittance matrix of the system for the harmonics order of interest. This linear equation can be written in details like the following

$$\begin{bmatrix} I_{h,bus1} \\ I_{h,bus2} \\ \vdots \\ I_{h,busn} \end{bmatrix} = \begin{bmatrix} Y_{h(1,1)} & Y_{h(1,2)} & \cdots & Y_{h(1,n)} \\ Y_{h(2,1)} & Y_{h(2,2)} & & Y_{h(2,n)} \\ & \vdots & \vdots & \vdots \\ Y_{h(n,1)} & Y_{h(n,2)} & \cdots & Y_{h(n,n)} \end{bmatrix} \begin{bmatrix} V_{hbus1} \\ V_{hbus2} \\ \vdots \\ V_{hbusn} \end{bmatrix}$$

Here, the admittance matrix and current vector will be formed for every harmonic order separately. Also, it is formed according to the network configuration (topology).

This calculation method avoids iteration process which is a tedious. Also, it can be used in the presence of more than one harmonics source.

According to Fig 6.3, current vector will be as

$$\begin{bmatrix} 0 \\ I_h \\ 0 \end{bmatrix}$$

And admittance matrix as:

$$\begin{bmatrix} (\frac{1}{Z_{h(g)}} + \frac{1}{Z_{h(T1)}}) & -\frac{1}{Z_{h(T1)}} & 0 \\ -\frac{1}{Z_{h(T1)}} & (\frac{1}{Z_{h(T1)}} + \frac{1}{Z_{h(T2)}} + \frac{1}{Z_{h(L)}} + \frac{1}{Z_{h(C2)}}) & -\frac{1}{Z_{h(T2)}} \\ 0 & -\frac{1}{Z_{h(T2)}} & (\frac{1}{Z_{h(T2)}} + \frac{1}{Z_{h(M)}} + \frac{1}{Z_{h(C1)}}) \end{bmatrix}$$

Our goal is to calculate the harmonics voltages of the buses, so equation 6.1 has to be rearranged to the following form:

$$[\ V_h\ ] = [\ Z_h\ ][\ I_h\ ] \qquad (6.2)$$

$$[\, Z_h \,] = [\, Y_h^{-1} \,] \tag{6.3}$$

Once the harmonics voltages are calculated, the corresponding time-domain voltages can be obtained by applying superposition to convert harmonics voltages values to time -domain for each bus as follows:

$$V_{bus}(t) = \sum_{h=1}^{k} V_{h,bus} \sin\left(hw_1 t + \delta_{h,bus}\right) \tag{6.4}$$

Where k is the highest harmonics order of interest . δ_h is the phase angle of h^{th} harmonics order at the bus considered.

For h=5 , the per unit admittance matrix [Z_5]=

$$\begin{bmatrix} \frac{1}{0.001+j0.05}+\frac{1}{0.0108+j0.15} & \frac{-1}{0.0108+j0.15} & 0 \\ \frac{-1}{0.0108+j0.15} & \frac{1}{0.0108+j0.15}+\frac{1}{0.047+j0.6}+\frac{1}{3.67+j0.355}+\frac{1}{-j0.556} & \frac{-1}{0.047+j0.6} \\ 0 & \frac{-1}{0.047+j0.6} & \frac{1}{0.047+j0.6}+\frac{1}{0.15+j4.5}+\frac{1}{-j3.33} \end{bmatrix}^{-1}$$

The per unit Current vector [I_5] =

$$\begin{bmatrix} 0 \\ 0.15745 \\ 0 \end{bmatrix}$$

Solving

$$[\, V_5 \,] = [\, Z_5 \,][\, I_5 \,]$$

yields to bus voltages at fifth order frequency. Calculation is done by using MAT LAB software and the per unit bus voltages associated to h=5 are:

$$\begin{bmatrix} V_{5,bus1} \\ V_{5,bus2} \\ V_{5,bus3} \end{bmatrix} = \begin{bmatrix} 1.23\% \\ 4.93\% \\ 5.17\% \end{bmatrix}$$

Per unit values can be converted to actual voltages (kV_{LL}) by multiplying by base values

$$\begin{bmatrix} V_{5,bus1} \\ V_{5,bus2} \\ V_{5,bus3} \end{bmatrix} = \begin{bmatrix} 1.23\% * 66kV \\ 4.93\% * 11kV \\ 5.17\% * 4.16kV \end{bmatrix} = \begin{bmatrix} 0.811kV \\ 0.542kV \\ 0.215kV \end{bmatrix}$$

For $h=7$, the per unit impedance matrix [Z_7]=

$$\begin{bmatrix} \frac{1}{0.001+j0.07}+\frac{1}{0.0197+j0.208} & \frac{-1}{0.0197+j0.208} & 0 \\ \frac{-1}{0.0197+j0.208} & \frac{1}{0.0197+j0.208}+\frac{1}{0.083+j0.83}+\frac{1}{3.686+j0.255}+\frac{1}{-j0.4} & \frac{-1}{0.083+j0.83} \\ 0 & \frac{-1}{0.083+j0.83} & \frac{1}{0.083+j0.83}+\frac{1}{0.21+j6.3}+\frac{1}{-j2.38} \end{bmatrix}^{-1}$$

The per unit Current vector [I_7] =

$$\begin{bmatrix} 0 \\ 0.11258 \\ 0 \end{bmatrix}$$

Solving

$$[\ V_7\ ] = [\ Z_7\ ][\ I_7\ ]$$

yields to bus voltages at fifth order frequency. Calculation is done by using MAT LAB software and the per unit bus voltages associated to h=7 are:

$$\begin{bmatrix} V_{7,bus1} \\ V_{7,bus2} \\ V_{7,bus3} \end{bmatrix} = \begin{bmatrix} 3.06\% \\ 12.2\% \\ 15.57\% \end{bmatrix}$$

Per unit values can be converted to actual voltages (kV_{LL}) by multiplying by base values

$$\begin{bmatrix} V_{7,bus1} \\ V_{7,bus2} \\ V_{7,bus3} \end{bmatrix} = \begin{bmatrix} 3.06\% * 66kV \\ 12.2\% * 11kV \\ 15.57\% * 4.16kV \end{bmatrix} = \begin{bmatrix} 2.02kV \\ 1.342kV \\ 0.648kV \end{bmatrix}$$

For $h=11$, the per unit impedance matrix [Z_{11}]=

$$\begin{bmatrix} \frac{1}{0.001+j0.11}+\frac{1}{0.046+j0.324} & \frac{-1}{0.046+j0.324} & 0 \\ \frac{-1}{0.046+j0.324} & \frac{1}{0.046+j0.324}+\frac{1}{0.187+j1.3}+\frac{1}{3.7+j0.163}+\frac{1}{-j0.253} & \frac{-1}{0.187+j1.3} \\ 0 & \frac{-1}{0.187+j1.3} & \frac{1}{0.187+j1.3}+\frac{1}{0.33+j9.9}+\frac{1}{-j1.52} \end{bmatrix}^{-1}$$

The per unit Current vector [I_{11}] =

$$\begin{bmatrix} 0 \\ 0.07164 \\ 0 \end{bmatrix}$$

Solving

$$[\,V_{11}\,] = [\,Z_{11}\,][\,I_{11}\,]$$

yields to bus voltages at fifth order frequency. Calculation is done by using MAT LAB software and the per unit bus voltages associated to h=11 are:

From MATLAB results, the per unit bus voltages associated to $h=11$ are:

$$\begin{bmatrix} V_{11,bus1} \\ V_{11,bus2} \\ V_{11,bus3} \end{bmatrix} = \begin{bmatrix} 0.5\% \\ 1.98\% \\ 6.62\% \end{bmatrix}$$

Per unit values can be converted to actual voltages (kV_{LL}) by multiplying by base values

$$\begin{bmatrix} V_{11,bus1} \\ V_{11,bus2} \\ V_{11,bus3} \end{bmatrix} = \begin{bmatrix} 0.5\% * 66kV \\ 1.98\% * 11kV \\ 6.62\% * 4.16kV \end{bmatrix} = \begin{bmatrix} 0.33kV \\ 0.218kV \\ 0.275kV \end{bmatrix}$$

For $h=13$, the per unit impedance matrix [Z_{13}]=

$$\begin{bmatrix} \frac{1}{0.001+j0.13}+\frac{1}{0.0635+j0.38} & \frac{-1}{0.0635+j0.38} & 0 \\ \frac{-1}{0.0635+j0.38} & \frac{1}{0.0635+j0.38}+\frac{1}{0.256+j1.52}+\frac{1}{3.8+j0.138}+\frac{1}{-j0.214} & \frac{-1}{0.256+j1.52} \\ 0 & \frac{-1}{0.256+j1.52} & \frac{1}{0.256+j1.52}+\frac{1}{0.4+j11.7}+\frac{1}{-j1.28} \end{bmatrix}^{-1}$$

The per unit Current vector [I_{13}] =

$$\begin{bmatrix} 0 \\ 0.06062 \\ 0 \end{bmatrix}$$

Solving

$$[\, V_{13}\,] = [\, Z_{13}\,][\, I_{13}\,]$$

yields to bus voltages at fifth order frequency. Calculation is done by using MAT LAB software and the per unit bus voltages associated to h=13 are:

From MATLAB results, the per unit bus voltages associated to $h=13$ are:

$$\begin{bmatrix} V_{13,bus1} \\ V_{13,bus2} \\ V_{13,bus3} \end{bmatrix} = \begin{bmatrix} 0.35\% \\ 1.38\% \\ 7.29\% \end{bmatrix}$$

Per unit values can be converted to actual voltages (kV_{LL}) by multiplying by base values

$$\begin{bmatrix} V_{13,bus1} \\ V_{13,bus2} \\ V_{13,bus3} \end{bmatrix} = \begin{bmatrix} 0.35\% * 66kV \\ 1.38\% * 11kV \\ 7.29\% * 4.16kV \end{bmatrix} = \begin{bmatrix} 0.231kV \\ 0.152kV \\ 0.303kV \end{bmatrix}$$

From the bus voltages all other values such as current distortion(THD_i), voltage distortion(THD_v), feeder harmonics currents and losses can be calculated. Here, for each bus, the voltage distortion (THD_v) and V_{RMS} are calculated. Also the time-domain voltage is created.

Bus#1:

$$V_{RMS} = \sqrt{66^2 + 0.811^2 + 2.02^2 + 0.33^2 + 0.231^2} = 66.037\text{kV}$$

$$THD_v = \frac{\sqrt{0.811^2 + 2.02^2 + 0.33^2 + 0.231^2}}{66} = 3.354\%$$

$$v_{bus\#1} = 66\sin(w_1 t) + 0.811\sin(5w_1 t + 81.92^\circ) + 2.02\sin(7w_1 t + 56.07^\circ) + 0.33\sin(11w_1 t - 64.82^\circ) + 0.231\sin(13w_1 t - 16.42^\circ)$$

Bus#2:

$$V_{RMS} = \sqrt{10.9^2 + 0.542^2 + 1.342^2 + 0.218^2 + 0.152^2} = 10.998\text{kV}$$

$$THD_v = \frac{\sqrt{0.542^2 + 1.342^2 + 0.218^2 + 0.152^2}}{10.9} = 13.5\%$$

$$v_{bus\#2} = 10.934\sin(w_1 t) + 0.542\sin(5w_1 t + 79.66^\circ) + 1.342\sin(7w_1 t + 52.62^\circ) + 0.218\sin(11w_1 t - 70.49^\circ) + 0.152\sin(13w_1 t - 23.16^\circ)$$

Bus#3:

$$V_{RMS} = \sqrt{4.125^2 + 0.215^2 + 0.648^2 + 0.275^2 + 0.303^2} = 4.200\text{kV}$$

$$THD_v = \frac{\sqrt{0.215^2 + 0.648^2 + 0.275^2 + 0.303^2}}{4.125} = 19.3\%$$

$$v_{bus\#3} = 4.125\sin(w_1t) + 0.215\sin(5w_1t + 79.18^{\circ}) + 0.648\sin(7w_1t + 50.68^{\circ}) + 0.275\sin(11w_1t - 91.89^{\circ}) + 0.303\sin(13w_1t - 128.99^{\circ})$$

6.6 Software simulation of harmonics analysis

As an attempt to validate the results obtained from the harmonics analysis calculations, we will compare them with the results of the same network given by ETAP 12.6 software. The one-line diagram of the network will be drawn in order to exploit ETAP 12.6 capabilities in harmonics analysis.

Next, it is required to enter data related to the harmonics source which includes amplitude and phase angle of each harmonics order, this data is called harmonics spectrum. The harmonics source which is entered to the network at bus #2 is a 6-pulse converter which has frequencies of harmonics order (5f ,7f ,11f, 13f ,17f ,19f ,23f ,25f…..). Due to the fact that harmonics amplitude decreases with the increase in harmonics order, a harmonics source which has only (5f ,7f ,11f ,13f) harmonics order will be accepted. This applies to calculations that have been done and which are limited to (5f ,7f ,11f ,13f).

In the program library, there are several harmonics sources with different specifications to choose from, including a 6-pulse converter of course.

Also, the program has the possibility to insert a harmonics source with any wanted data spectrum. A source with desired harmonics spectrum has been entered into the program library named An-Najah Univ.

When adding the harmonics source to the program library, it is determined as a current source. Also, the current amplitude and phase angle of each harmonics order is added in a separate step.

After adding the harmonics source with wanted data, and executing the program , an output report which includes these harmonics indices of buses ($\%THD_v$, $\%IHD_v$) is obtained in a tabulated form. Results related to the analysis of the entered network are as shown in Fig 6.4:

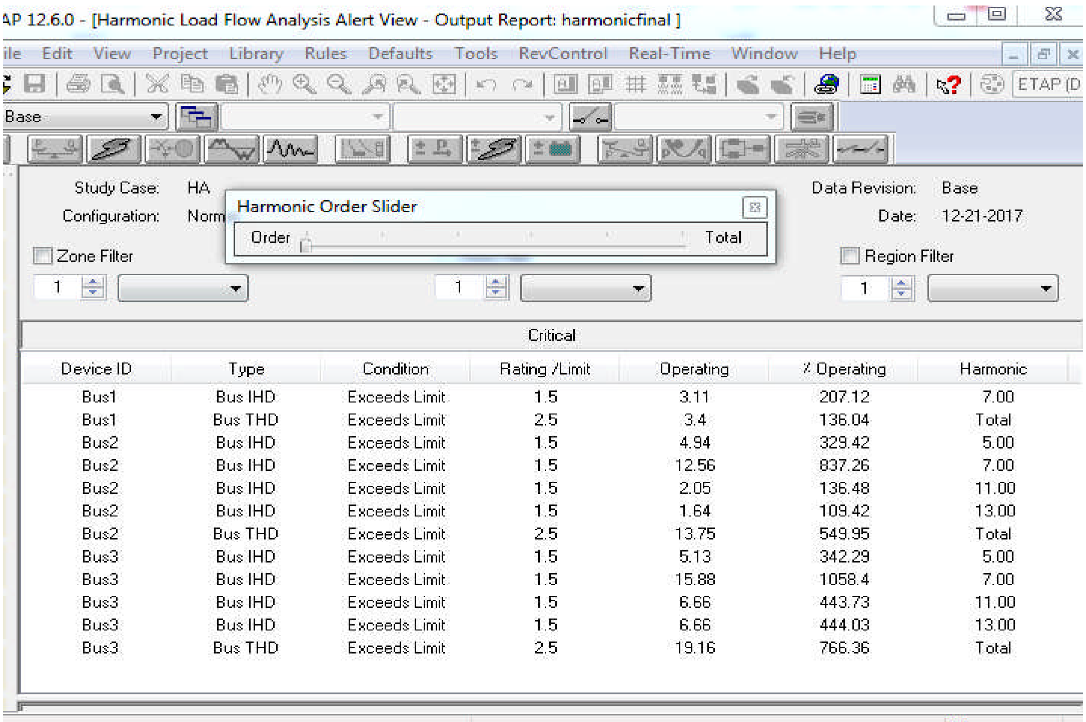


Fig 6.4: Output report of harmonics load flow analysis

As seen, the THD_v results of simulation of each bus are shown in Table 6.12:

Table 6.12: Total harmonics distortion value of the buses

Bus number	$\%THD_v$
Bus#1	3.4%
Bus#2	13.75%
Bus#3	19.16%

Also, the bus voltages for each harmonics order are obtained in the following Fig 6.5,6.6,6.7 and 6.8

For 5th harmonics order:

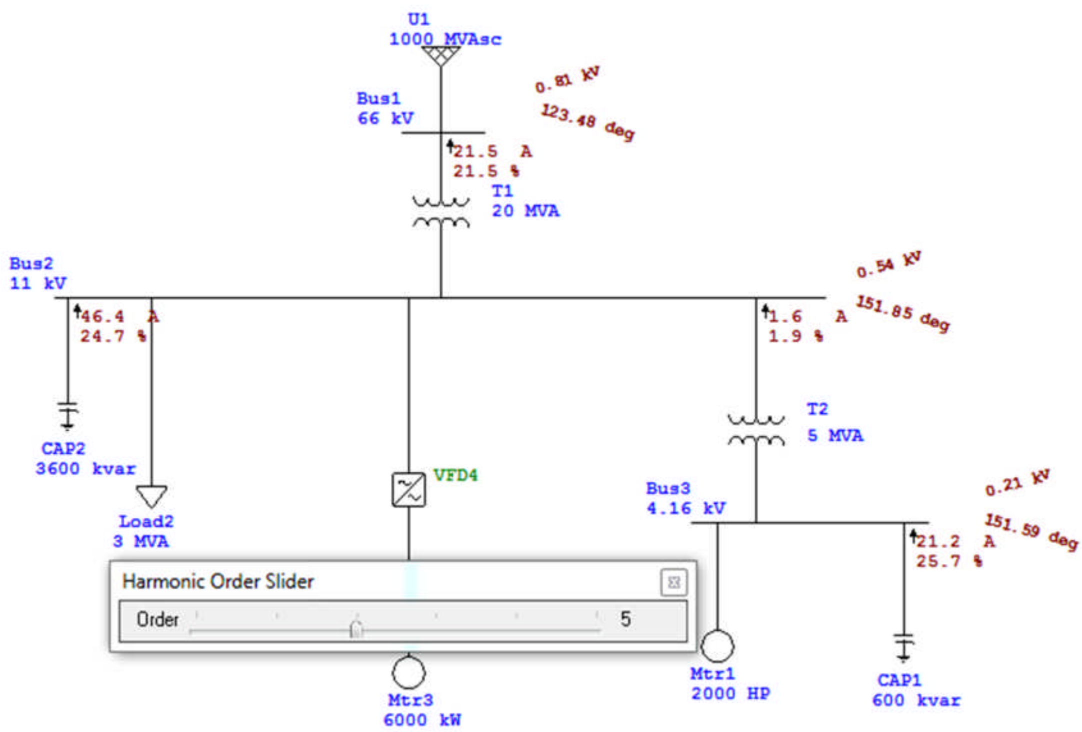


Fig 6.5: Bus voltages of **5**th harmonics order

Table 6.13: Voltage values of the buses for 5th **harmonics order**

Bus number	Bus voltage(kV)
Bus#1	0.81kV
Bus#2	0.54kV
Bus#3	0.21kV

For 7th harmonics order:

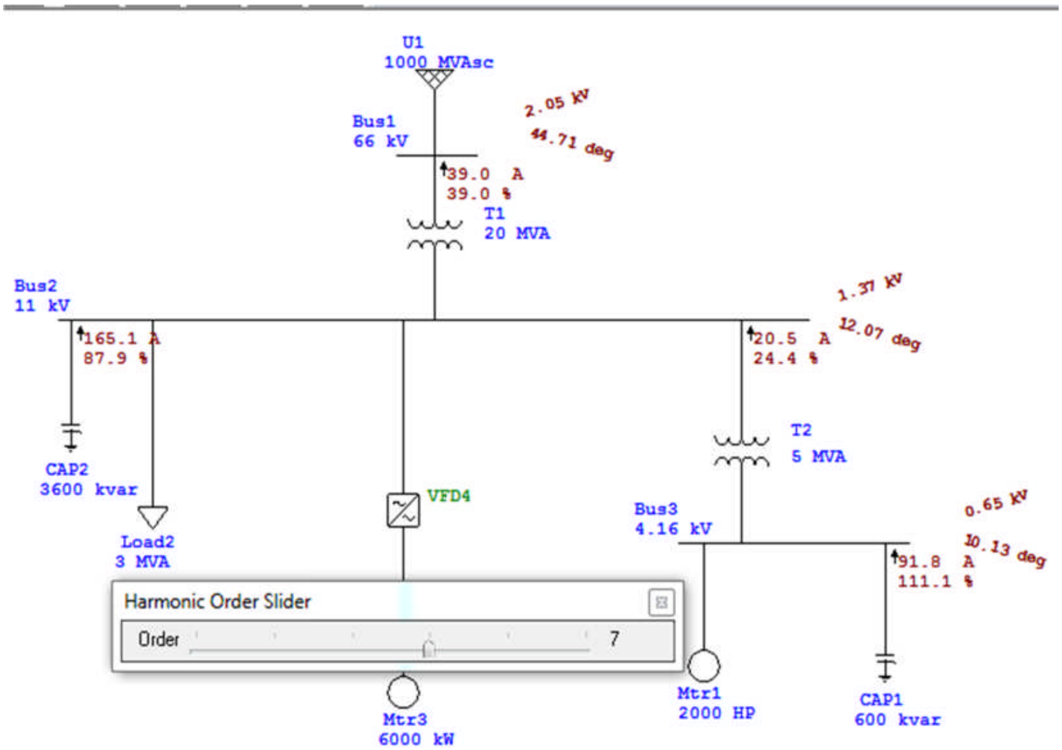


Fig 6.6: Bus voltages of 7^{th} harmonics order

Table 6.14: Voltage values of the buses for 7^{th} harmonics order

Bus number	Bus voltage(kV)
Bus#1	2.05kV
Bus#2	1.37kV
Bus#3	0.651kV

For 11^{th} harmonics order:

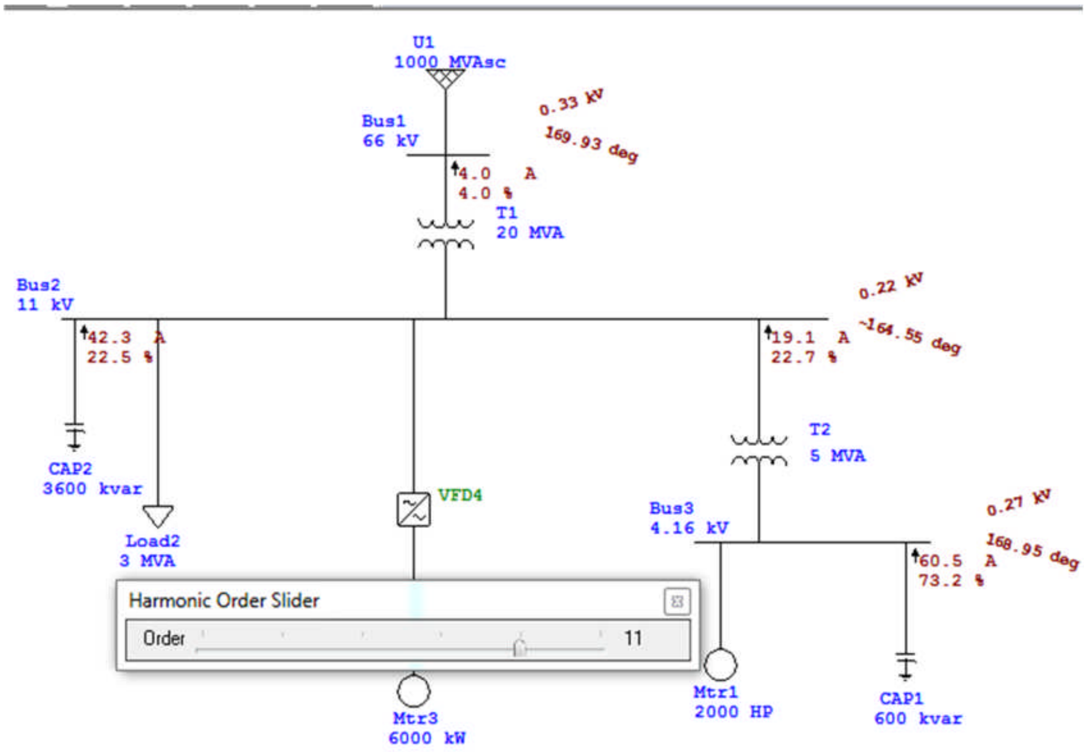


Fig 6.7: Bus voltages of 11^{th} harmonics order

Table 6.15: Voltage values of the buses for 11^{th} harmonics order

Bus number	Bus voltage(kV)
Bus#1	0.33kV
Bus#2	0.22kV
Bus#3	0.27kV

For 13^{th} harmonics order:

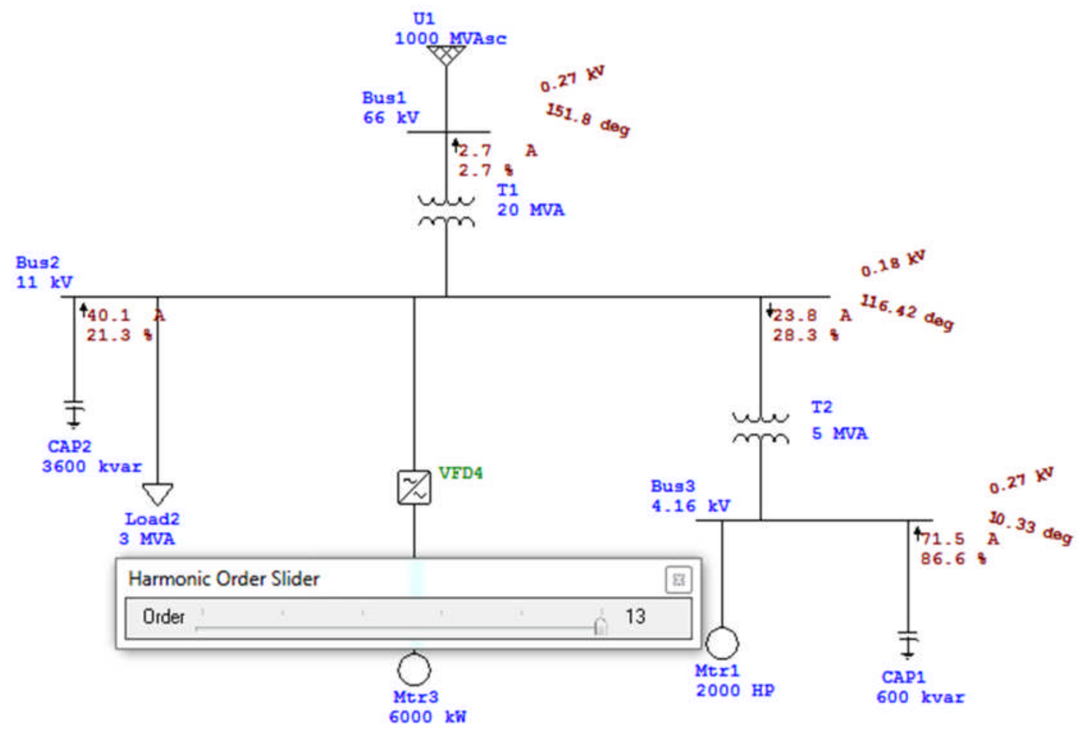


Fig 6.8: Bus voltages of $\mathbf{13^{th}}$ harmonics order

Table 6.16: Voltage values of the buses for $\mathbf{13^{th}}$ harmonics order

Bus number	Bus voltage(kV)
Bus#1	0.27kV
Bus#2	0.18kV
Bus#3	0.27kV

The simulated waves with their spectrum for each bus were taken from all buses as shown in Fig 6.9,6.10, and 6.11:

Bus#1:

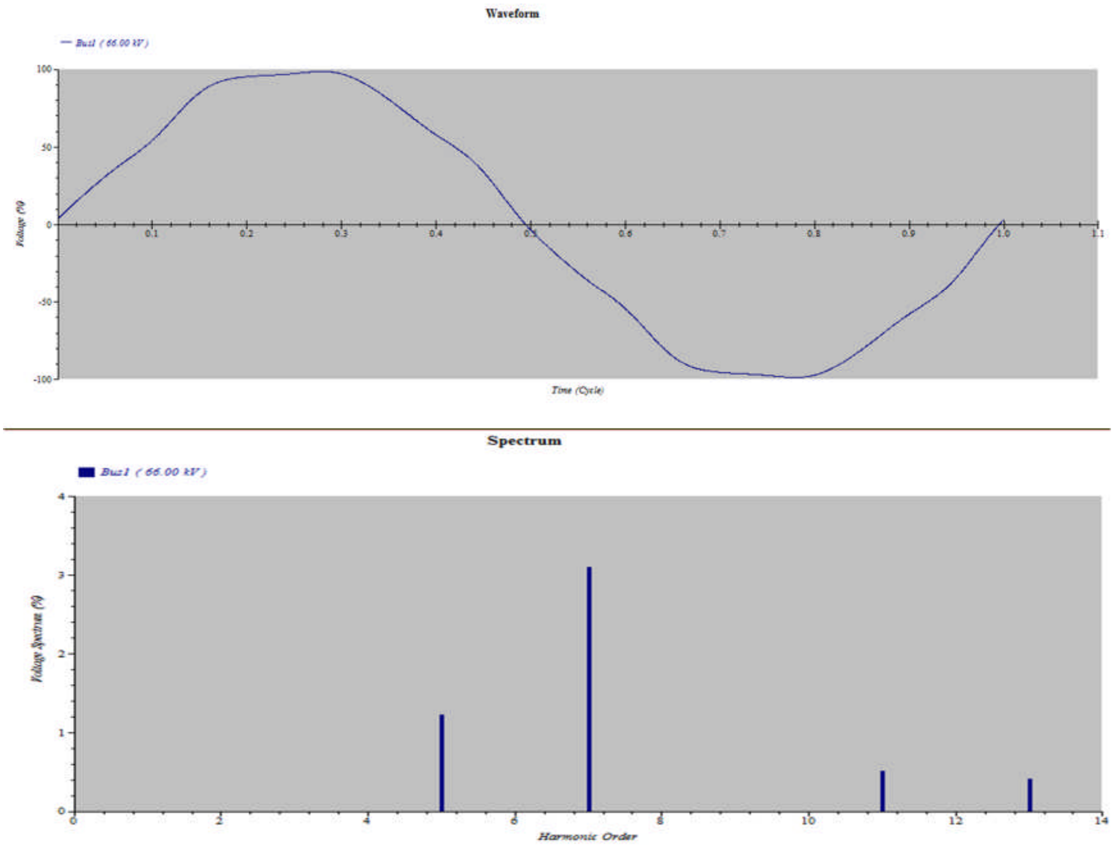


Fig 6.9: Voltage wave and spectrum of bus#1

bus#2:

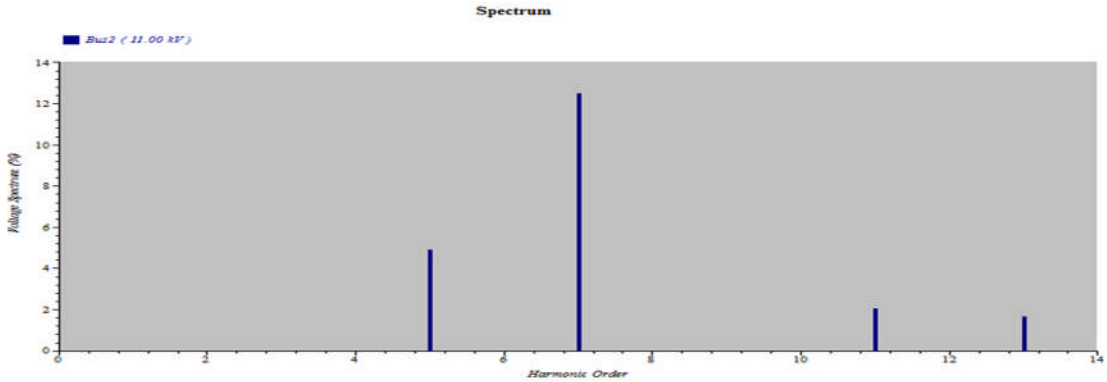


Fig 6.10: Voltage wave and spectrum of bus#2

bus#3:

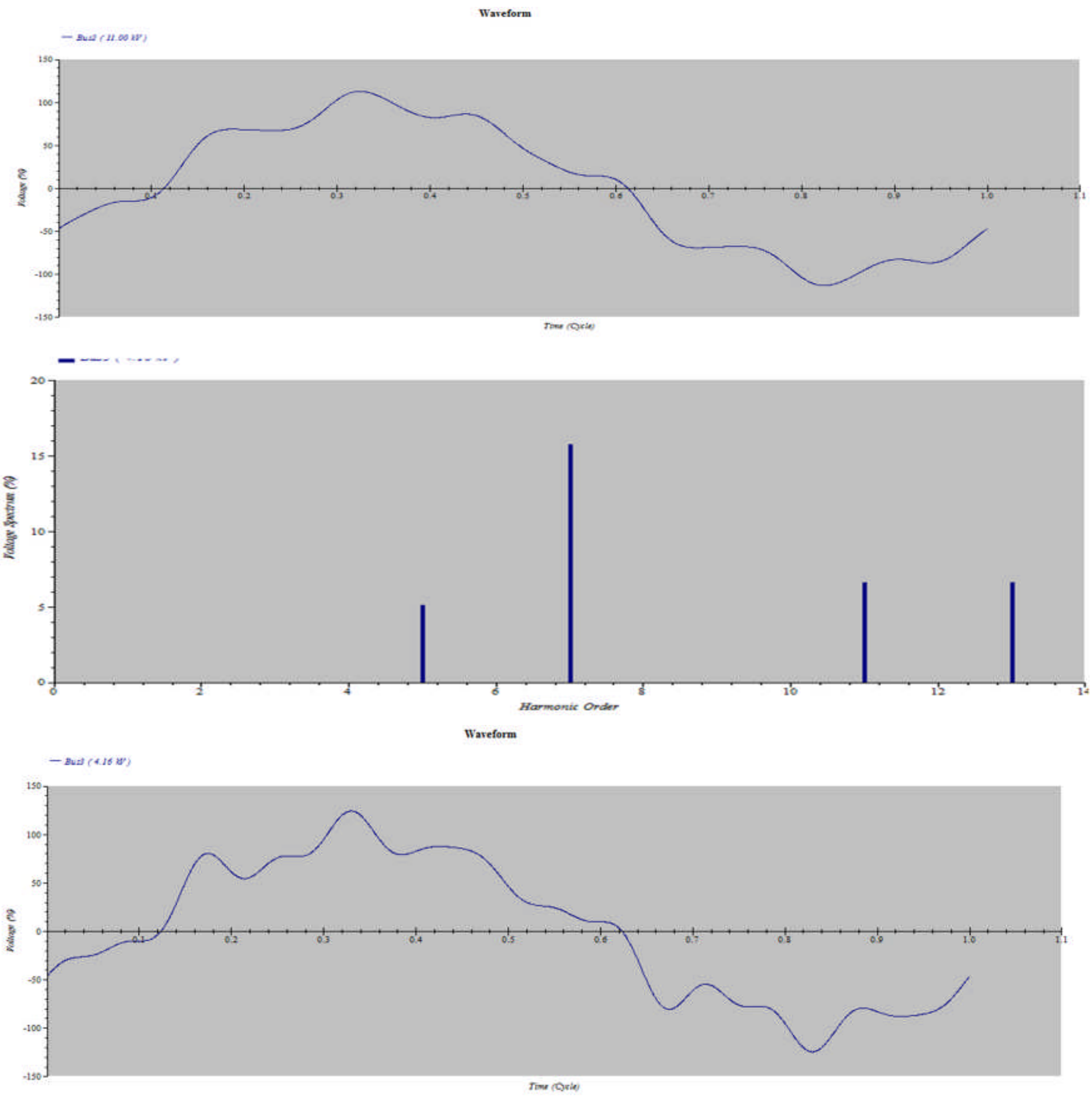


Fig 6.11: Voltage wave and spectrum of bus#3

According to the simulation results, the values of the total voltage of the buses - which are the resultant of the fundamental and the harmonics- were as shown in Fig 6.12:

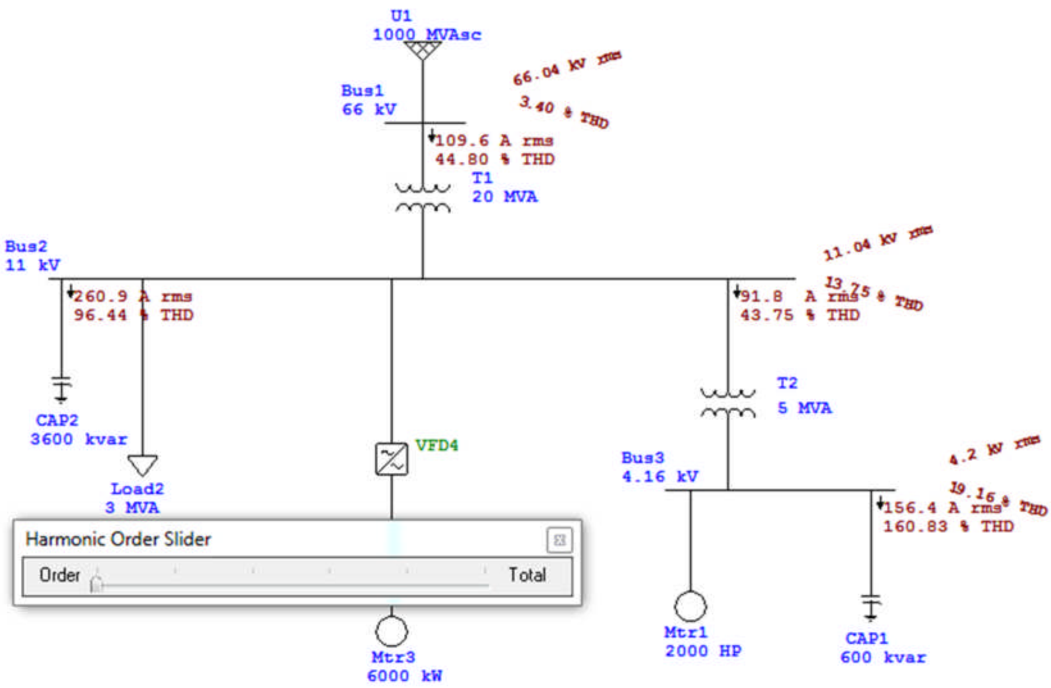


Fig 6.12: Total voltage value of buses

6.7 Comparison between the results

Table 6.17 and Fig 6.13 summarize the results obtained from calculations and simulations. It is found that there is an almost exact match between the calculated results and simulated results. This reveals that the adopted method for modeling and calculation of harmonics analysis is accurate and applicable.

Table 6.17: Total harmonics distortion results comparison

Bus number	$\%THD_v$	
	calculated	simulated
Bus#1	3.354%	3.4%
Bus#2	13.5%	13.75%
Bus#3	19.3%	19.16%

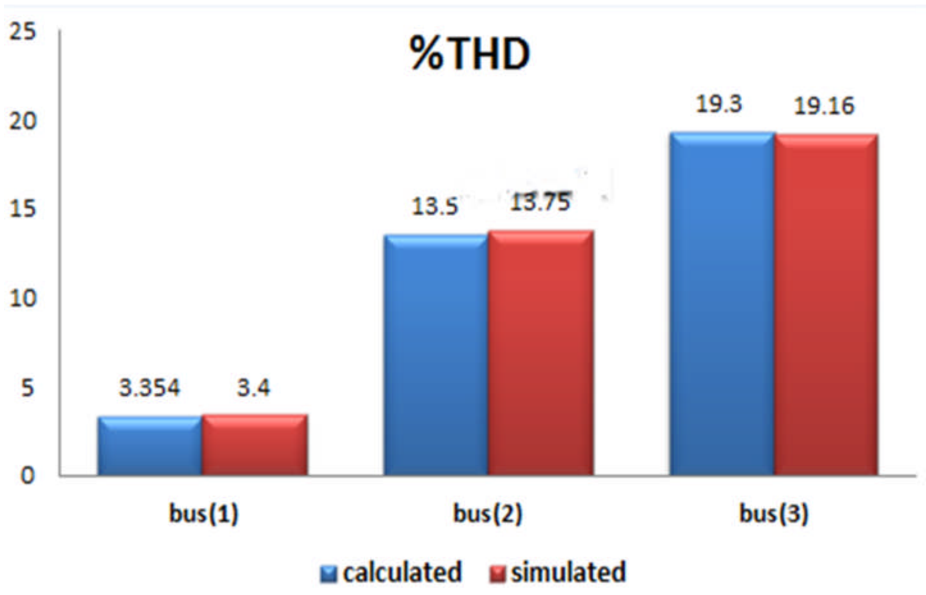


Fig 6.13: Total harmonics distortion of voltage comparison

The calculated results are clearly close to the results of ETAP 12.6.

It is also important to note that the distortion of the buses (2 and 3) exceeds 5%, which is the limitation of IEEE Standard 519- 1992.

As for the voltage values of the buses, the values were very close to each other. Table 6.16 shows the comparison

Table 6.18: Voltage values results comparison

Bus number	Harmonics order	Voltage of the bus(kV)	
		calculated	**simulated**
Bus#1	*h=5*	0.811	0.81
	h=7	2.02	2.05
	h=11	0.33	0.33
	h=13	0.231	0.27
	V_{RMS}	66.037	66.04
Bus#2	*h=5*	0.542	0.54
	h=7	1.342	1.37
	h=11	0.218	0.22
	h=13	0.152	0.18
	V_{RMS}	10.998	11.04
Bus#3	*h=5*	0.215	0.21
	h=7	0.648	0.65
	h=11	0.275	0.27
	h=13	0.303	0.27
	V_{RMS}	4.2	4.2

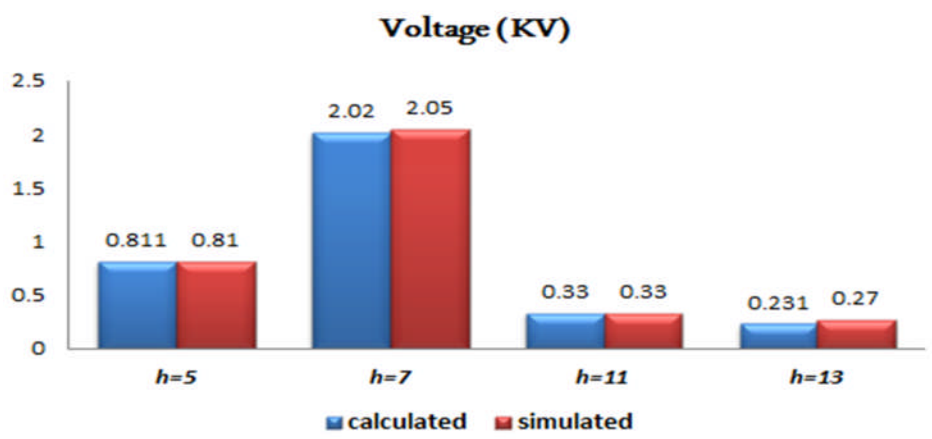


Fig 6.14: Voltage of bus (1) comparison for each harmonics order

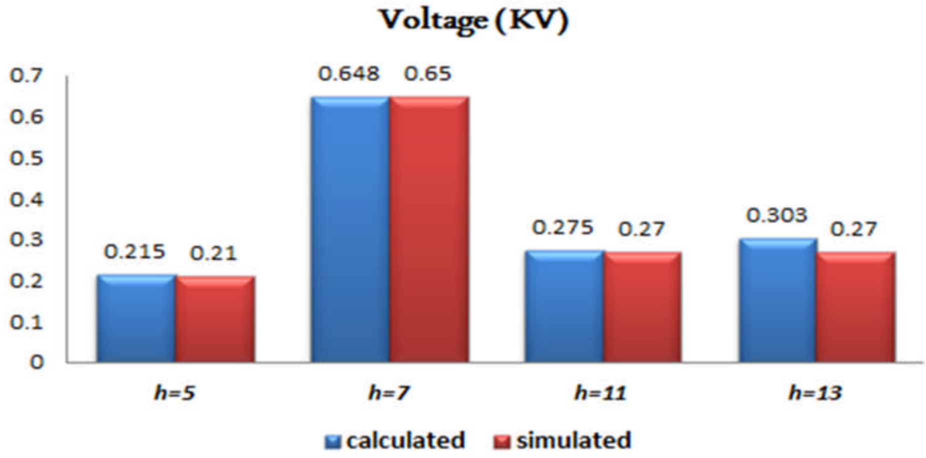


Fig 6.15: Voltage of bus(2) comparison for each harmonics order

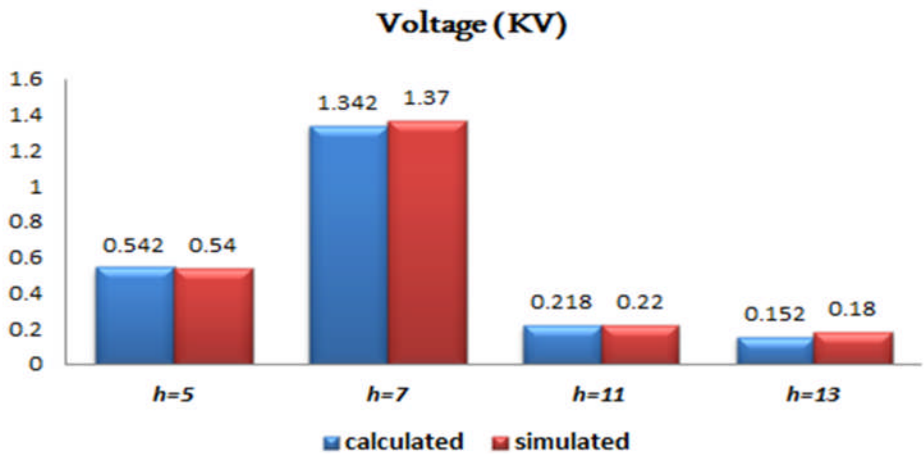


Fig 6.16: Voltage of bus(3) comparison for each harmonics order

6.8 Calculation of efficiency

In this section, the efficiency of some selected network elements and the whole network efficiency in the presence of harmonics will be calculated taking into account the power flow direction. For comparison purposes, the efficiency of the fundamental frequency without harmonics will be calculated.

At the beginning, the points at which the power will be calculated have to be selected as in Fig 6.17. No capacitor-related points were selected because the power associated with them is not real.

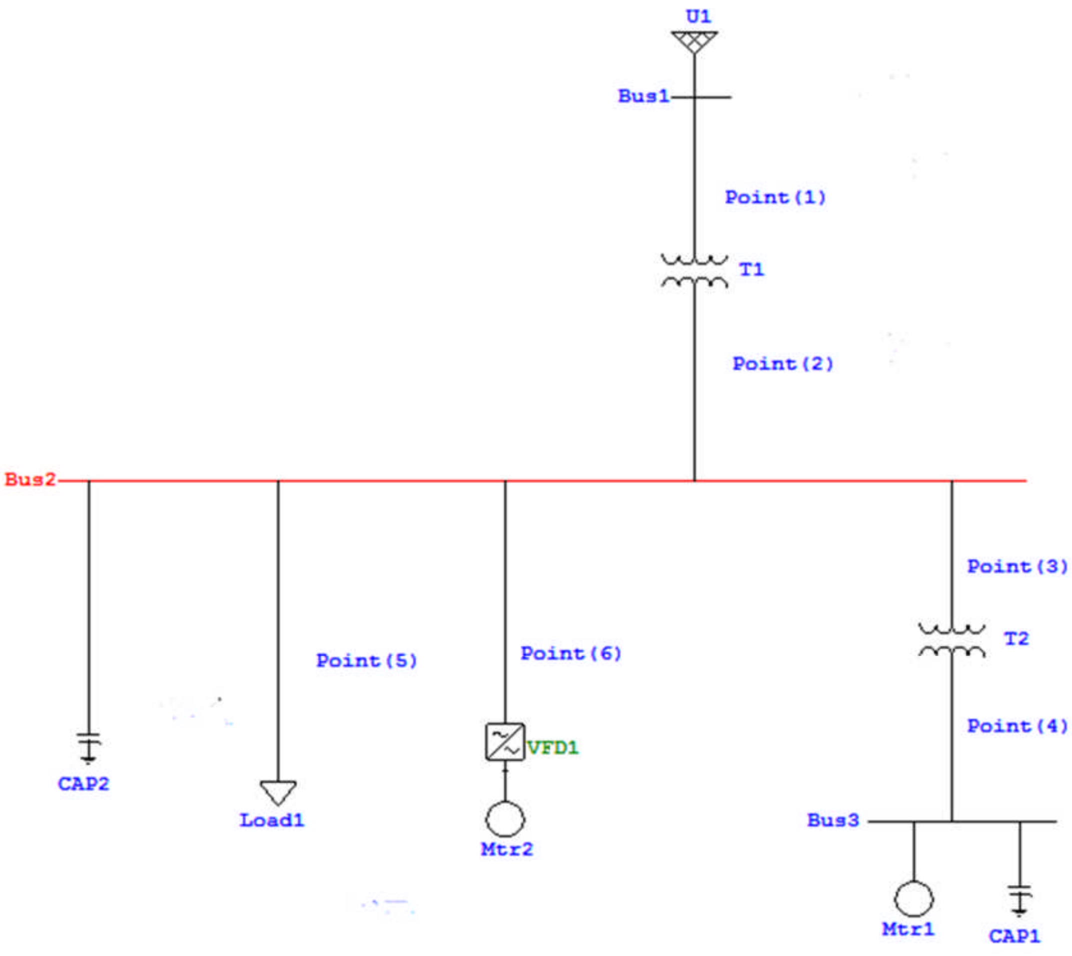


Fig 6.17: Selected points for power flow study

Power values which are needed for efficiency calculation can be calculated from the voltage and current values. Previously, the voltage values were found for each harmonics order. Current values can then be calculated using the voltage and impedance values at each harmonics order. Using the ohm's law, the current values of each harmonics order were calculated and presented in Tables 6.19,6.20 and 6.21.

Table 6.19: Per unit values of current which flows from bus(1) to bus(2)

Harmonics order	$V_{at\ bus(1)}$	$V_{at\ bus(2)}$	Z_{T1}	$I_{bus(1)\rightarrow bue(2)}$
h=5	$0.0123\angle 1.494$	$0.0493\angle 1.389$	0.01084+j0.15	$0.24612\angle 3.02$
h=7	$0.0306\angle 0.987$	$0.122\angle 0.927$	0.0197+j0.208	$0.43781\angle 2.57$
h=11	$0.005\angle -1.13$	$-1.23\angle 0.0198$	0.046+j0.324	$0.04532\angle 0.45$
h=13	$0.0035\angle -0.28$	$0.0138\angle -0.4$	0.0635+j0.38	$0.02681\angle 1.3$

Table 6.20: Per unit values of current which flows from bus(2) to bus(3)

Harmonics order	$V_{at\ bus(2)}$	$V_{at\ bus(3)}$	Z_{T2}	$I_{bus(2)\rightarrow bue(3)}$
h=5	$0.0493\angle 1.389$	$0.0517\angle 1.381$	0.04716+j0.6	$0.00404\angle 2.87$
h=7	$0.122\angle 0.927$	$0.1557\angle 0.894$	0.08296+j0.83	$0.04072\angle 2.44$
h=11	$0.0198\angle -1.2$	$0.0662\angle -1.6$	0.18746+j1.3	$0.037\angle -0.04$
h=13	$0.0138\angle -0.4$	$0.0729\angle -2.25$	0.256+j1.515	$0.0506\angle -0.7$

Table 6.21: Per unit values of current which flows in the passive load

Harmonics order	$V_{at\ bus(2)}$	Z_L	I_L
h=5	$0.0493\angle 1.39$	3.6693+j0.3554	$0.01337\angle 1.3$
h=7	$0.122\angle 0.927$	3.686+j0.255	$0.03302\angle 0.858$
h=11	$0.0198\angle -1.23$	3.697+j0.163	$0.00535\angle -1.274$
h=13	$0.0138\angle -0.404$	3.699+j0.138	$0.00373\angle -0.441$

Power values can now be calculated at the selected points. Initially the power at fundamental frequency will be found. For the fundamental frequency, power values can be obtained from the load flow study in ETAP 12.6. The results were as in the following Fig 6.18

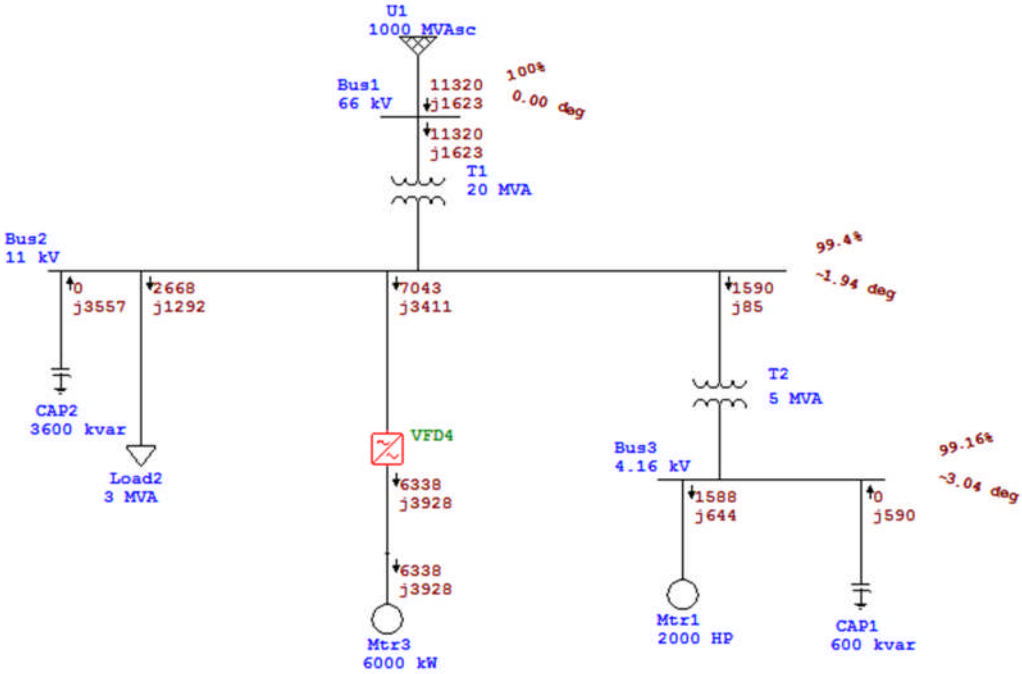


Fig 6.18: Fundamental power flow result in load flow study

From the results of the load flow study, the power values at the selected points are found and shown in Table 6.22. According to point (2), the power is found by summing the power in the three branches connected to it.

Table 6.22: Real power values of load flow at the selected points

Selected point	P_1 **(kW)**
Point(1)	11320
Point(2)	11301
Point(3)	1590
Point(4)	1588
Point(5)	2668
Point(6)	7043

Using the relationship $P_h = V_h I_h \cos(\theta_{v,h} - \theta_{i,h})$the power values associated with harmonics are calculated at each point. The results were shown in Table 6.23.

Table 6.23: Real power values for different harmonics at the selected points

Test point	P_5(kW)	P_7(kW)	P_{11}(kW)	P_{13}(kW)
Point(1)	-0.61153	-1.64828	-0.022668	-0.014735
Point(2)	-7.21575	-38.6391	-0.9753	-0.49173
Point(3)	0.17861	2.85971	2.70862	6.7227
Point(4)	0.17128	1.57195	0.18983	0.02201
Point(5)	6.56491	40.1891	1.05826	0.5144
Point(6)	13.981	82.463	4.7451	7.69177

As shown in Table 6.21, the power associated with harmonics at points (1 and 2) is negative. This is due to the fact that the current flow at the fundamental frequency shall be from the grid to all loads including non-linear loads. But the situation becomes completely different at the harmonics frequencies where the direction of the current flow will reverse to be from the non-linear load to all parts of the network [8]. see Fig 6.19.

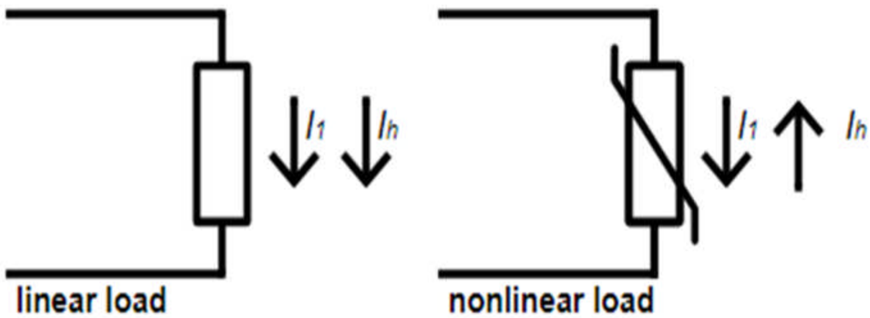


Fig 6.19: Current flow direction of linear and non-linear load

Now, two individual elements are selected for efficiency calculations, they are transformers T1and T2; also the whole network efficiency at fundamental frequency (without harmonics sharing) will be calculated.

T1:

$$\zeta = \frac{P_{1,at\ point(2)}}{P_{1,at\ point(1)}} 100\% = \frac{11301}{11320} 100\% = 99.83\%$$

T2:

$$\zeta = \frac{P_{1,at\ point(4)}}{P_{1,at\ point(3)}} 100\% = \frac{1588}{1590} 100\% = 99.87\%$$

The whole network:

$$\zeta = \frac{P_{1,out}}{P_{1,in}} 100\% = \frac{10160}{11320} 100\% = 89.75\%$$

Where from load flow study:

- $P_{1,in} = 11320kW.$
- $P_{1,out} = P_{1,6-pulse} + P_{1,IM} + P_{1,L}$

$= \left(P_{1,at\ point(6)} * \zeta_{ASD}{}^{(1)} * \zeta_{IM}\right) + \left(P_{1,at\ point(4)} * \zeta_{IM}\right) + P_{1,at\ point(5)}$

$= 7043 * (0.9 * 0.9466) + (1588 * 0.9394) + 2668 = 10160$kW.

On the other hand, the efficiency of the individual elements and the whole network efficiency in the presence of harmonics can be calculated as follows:

T1:

The flow of the fundamental power in T1 is from the grid to the rest of the network elements (point(1) → point(2)). But the flow of the harmonics power is from the nonlinear load to the grid (point(2) → point(1)).

$$\zeta = \frac{P_{T,at\ point(2)}}{P_{T,at\ point(1)}} 100\%$$

$\bullet\ At\ point(2)\!: P_T = P_1 + P_5 + P_7 + P_{11} + P_{13}$

$= 11301 - 7.216\ -\ 38.64 - 0.975\ -\ 0.492 = 11253.677kW.$

$\bullet\ At\ point(1)\!: P_T = P_1 + P_5 + P_7 + P_{11} + P_{13}$

$= 11320 - 0.612\ -\ 1.648 - 0.023\ -\ 0.0147 = 11317.7kW.$

$$\zeta = \frac{11253.677}{11317.7} 100\% = 99.43\%$$

(1) This value is the same as the drive efficiency which was entered in the load flow analysis

T2:

The flow of the fundamental power in T2 is from the grid to the rest of the network elements (point(3) → point(4)). Also the flow of the harmonics power is from the nonlinear load to the rest of network (point(3) → point(4)).

$$\zeta = \frac{P_{T,at\ point(4)}}{P_{T,at\ point(3)}} 100\%$$

$\bullet\ At\ point(4)\!: P_T = P_1 + P_5 + P_7 + P_{11} + P_{13}$

$= 1588 + 0.171 +\ 1.572 + 0.19 +\ 0.022 = 1589.955kW.$

$\bullet\ At\ point(3)\!: P_T = P_1 + P_5 + P_7 + P_{11} + P_{13}$

$= 1590 + 0.179 +\ 2.86 + 2.708 +\ 6.723 = 1602.47kW.$

$$\zeta = \frac{1589.955}{1602.47} 100\% = 99.22\%$$

The whole network:

$$\zeta = \frac{P_{T,out}}{P_{T,in}} 100\%$$

Where:

- $P_{T,in} = P_{T,at\ point(1)}$

$$= P_{1,at\ point(1)} + P_{5,at\ point(1)} + P_{7,at\ point(1)} + P_{11,at\ point(1)} + P_{13,at\ point(1)}$$
$$= 11320 - 0.61153 - 1.64828 - 0.022668 - 0.014735$$
$$= 11317.7kW.$$

- $P_{T,out} = P_{T,6-pulse} + P_{T,IM} + P_{T,L}$=

5907.45+1493.6+2716.25=10117.3kW(these values are shown below)

$$P_{T,6-pulse} = \left(P_{1,at\ point(6)} - P_{5,at\ point(6)} - P_{7,at\ point(6)} - P_{11,at\ point(6)} - P_{13,at\ point(6)}\right) * \zeta_{ASD} * \zeta_{IM}$$
$$= (7043 - 13.98 - 82.46 - 4.75 - 7.7) * 0.9 * 0.9466$$
$$= 5907.45kW$$

$$P_{T,IM} = \left(P_{1,at\ point(4)} + P_{5,at\ point(4)} + P_{7,at\ point(4)} + P_{11,at\ point(4)} + P_{13,at\ point(4)}\right) * \zeta_{IM}$$
$$= (1588 + 0.17 + 1.57 + 0.19 + 0.02) * 0.9394$$
$$= 1493.6kW$$

$$P_{T,L} = \left(P_{1,at\ point(5)} - P_{5,at\ point(5)} - P_{7,at\ point(5)} - P_{11,at\ point(5)} - P_{13,at\ point(5)}\right) = (2668 + 6.56 + 40.12 + 1.06 + 0.51)$$
$$= 2716.25kW$$

$$\zeta = \frac{10117.3}{11317.7} 100\% = 89.39\%$$

Table 6.24 compares between the efficiency values at the fundamental frequency and with harmonics for T1, T2, and the whole network. It is clear that harmonics decrease the efficiency with harmonics and this decrease is because of the losses associated with harmonics

Table 6.24: Efficiency values results comparison

	Efficiency value	
	Without harmonics	With harmonics
T1	99.83%	99.43%
T2	99.87%	99.22%
The whole network	89.75%	89.39%

Chapter Seven

Harmonics Mitigation Techniques

7.1 Introduction

The production of harmonics by nonlinear loads is essential to their work and cannot be prevented. But there are ways to prevent these generated harmonics from crossing into the rest of the system.

Some ways are classified as preventive, aiming to reduce harmonics before they are injected into the power system like phase shift transformer. Other ways are classified as remedial, aiming to reduce harmonics which are existing in the power system like passive filters.

There are variety of techniques that can be used to get rid of the harmonics in the network feeding the consumer or to reduce their impact, the most important are listed below.

7.2 Phase shift transformer

One of the new and distinctive ways to reduce the effect of harmonics in the network is to let those harmonics cancel each other. The idea of this method is that each harmonics order frequency has a value and angle of its own. If we can combine the harmonics in a way that their vector sum is equal to zero (as in three phase balanced systems), we prevent harmonics from crossing to the rest of the network.

In this method, we make a shift for one of harmonic sources by 180 degrees compared to the other harmonics sources and then merge the waves of the two sources together. As a result, harmonics cancel each other at the primary side of the transformer before entering to the rest of the network. The fact that harmonics eliminate each other is proven in AppendixB.

Two transformers are required , One of them is $\Delta - \Delta\ (or\ Y - Y)$ and the other is $\Delta - Y\ (or\ Y - \Delta)$. Or one transformer with two secondary windings can be used. Nonlinear loads are equally divided into secondary windings in both cases.

In this way, harmonics of order 5 and 7 are disposed of. They are the harmonics that cause the most distortion in power systems. The concept of this method is illustrated in Fig 7.1. Of course , since the transformers Δ windings have no neutral line, the third harmonics will not return to the grid. It will remain in the transformer.

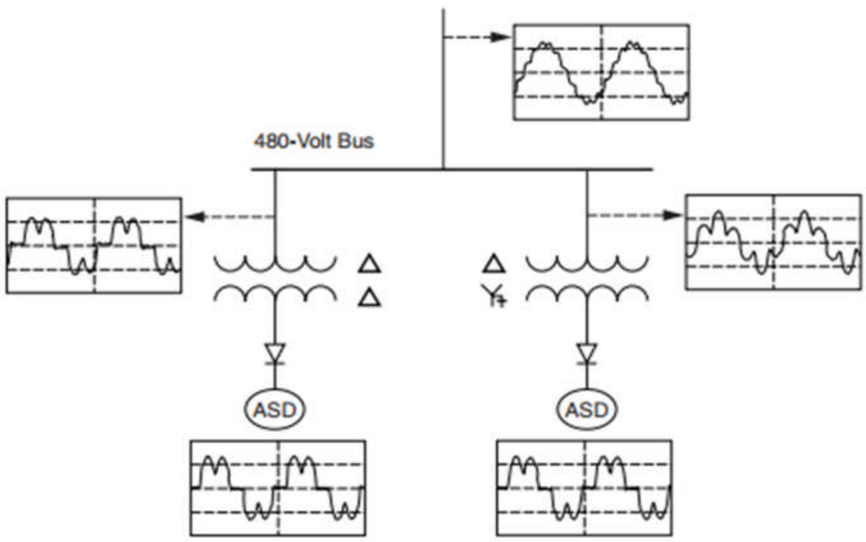


Fig 7.1: A schematic of harmonics mitigation by the phase shift transformer [8]

Each harmonics order current need a special phase shift to be eliminated. Table 7.1 summarizes phase shift required to eliminate different harmonics orders

Table 7.1: The phase shift required to eliminate different harmonics orders

Phase shift in two outputs	Eliminated harmonics order
15°	11,13
30°	5,7
60°	3

For example, consider fifth order harmonics. Each half cycle in this harmonics occupies $= \frac{180^{\circ}}{5} = 36^{\circ}$. Hence, if a phase shift equals 30° is done to one harmonics and to Leave the second without phase shift , the result is that the two harmonics cancel each other.

To prove the effectiveness of this method in the elimination of certain harmonics. The same network will be studied by adding another nonlinear load of the same type. The type of harmonics spectrum emitted from the nonlinear loads has been changed from the type previously created (An-Najah Uni) to the type (IEEE) which already existed in the program library. Two simulations are taken for the modified network in Fig 7.2. In the first simulation, both transformers $\Delta - \mathrm{Y}$ are connected, while in the second simulation, one of the transformer $\Delta - Y$ is connected (i.e.30°phase shift) and the other $\Delta - \Delta$ is connected (i.e. no phase shift).

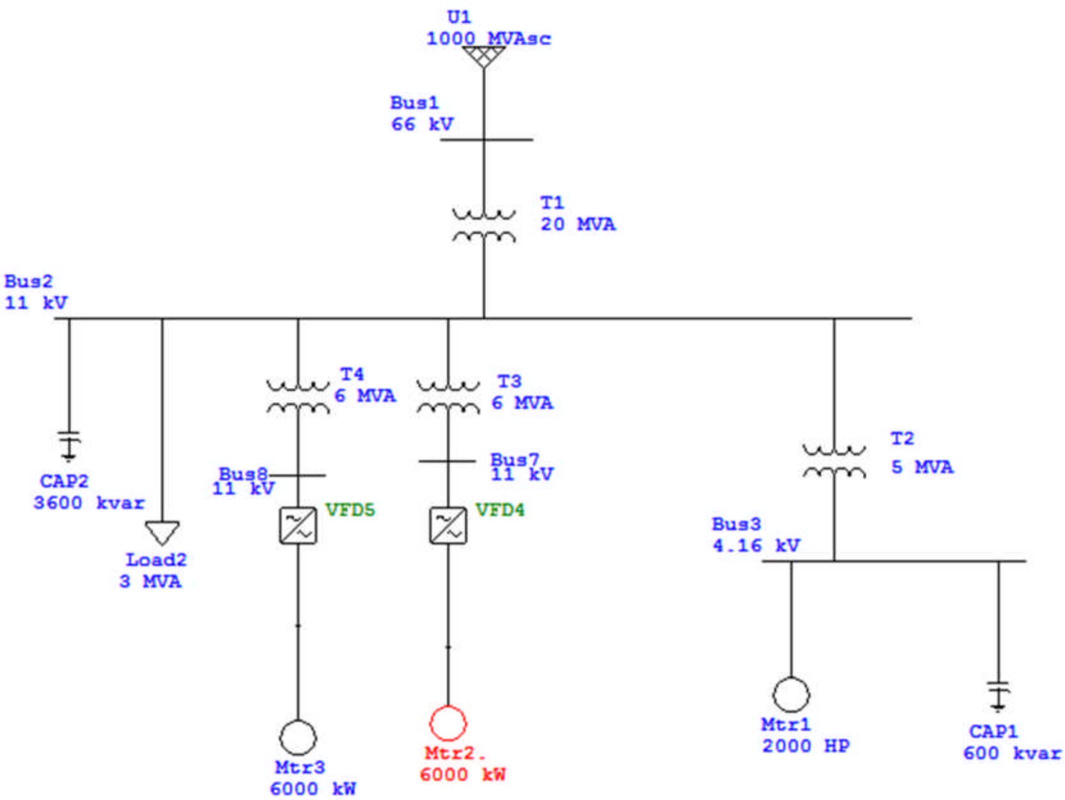
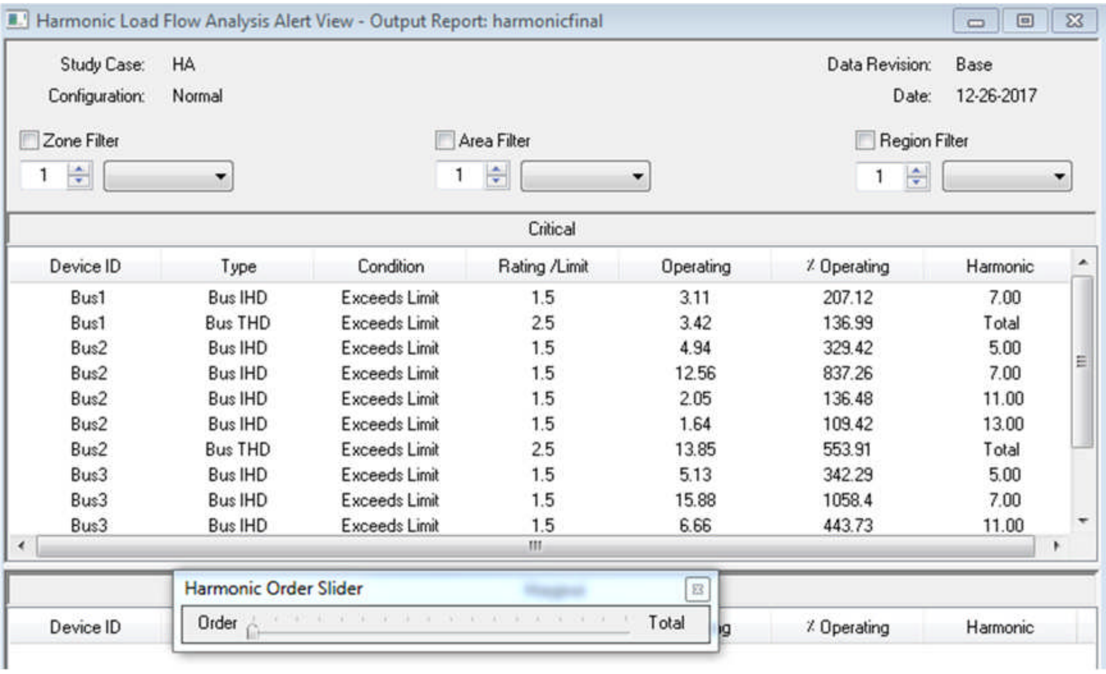


Fig 7.2: Schematic diagram of the modified network with two nonlinear loads

7.2.1 Results and simulation

The simulated results of voltage waveform as taken from bus#2 were as follows:

- First case in which both transformers $\Delta - Y$ are connected i.e. without phase shift case. The voltage distortion ($\%THD_v$ and $\%IHD_v$), voltage waveform shape and harmonics spectrum were as in the Fig 7.3,7.4 and 7.5 respectively



Harmonic Load Flow Analysis Alert View - Output Report: harmonicfinal

Study Case: HA
Configuration: Normal
Data Revision: Base
Date: 12-26-2017

Zone Filter 1 | Area Filter 1 | Region Filter 1

Critical

Device ID	Type	Condition	Rating /Limit	Operating	% Operating	Harmonic
Bus1	Bus IHD	Exceeds Limit	1.5	3.11	207.12	7.00
Bus1	Bus THD	Exceeds Limit	2.5	3.42	136.99	Total
Bus2	Bus IHD	Exceeds Limit	1.5	4.94	329.42	5.00
Bus2	Bus IHD	Exceeds Limit	1.5	12.56	837.26	7.00
Bus2	Bus IHD	Exceeds Limit	1.5	2.05	136.48	11.00
Bus2	Bus IHD	Exceeds Limit	1.5	1.64	109.42	13.00
Bus2	Bus THD	Exceeds Limit	2.5	13.85	553.91	Total
Bus3	Bus IHD	Exceeds Limit	1.5	5.13	342.29	5.00
Bus3	Bus IHD	Exceeds Limit	1.5	15.88	1058.4	7.00
Bus3	Bus IHD	Exceeds Limit	1.5	6.66	443.73	11.00

Harmonic Order Slider
Order Total

Device ID | % Operating | Harmonic

Fig 7.3: Output report of no phase shift case

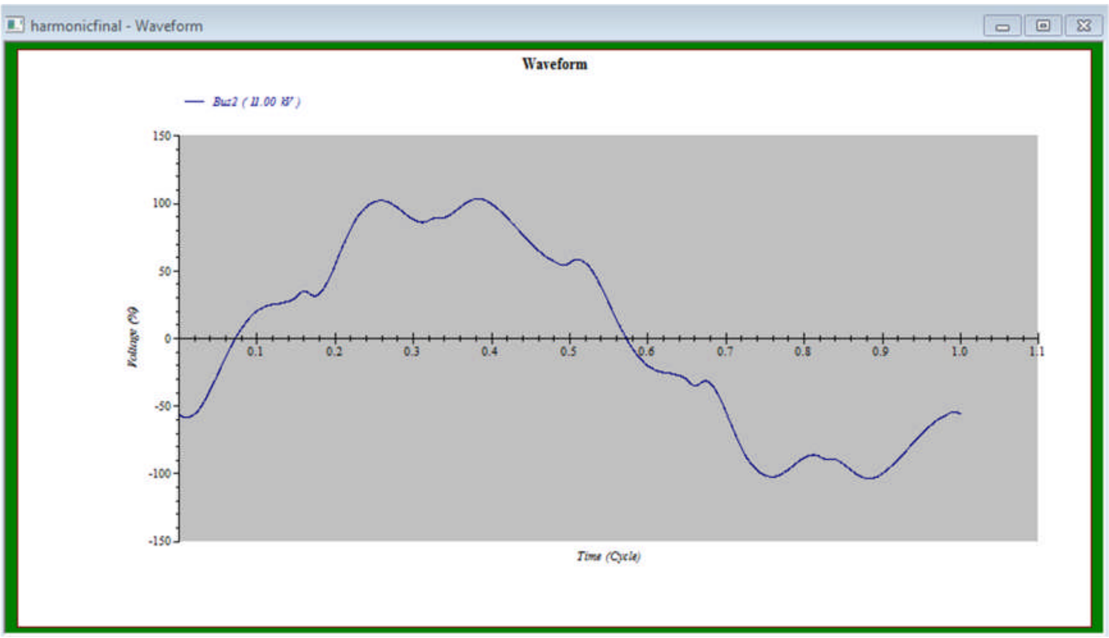


Fig 7.4: Voltage shape of bus#2 for the first case

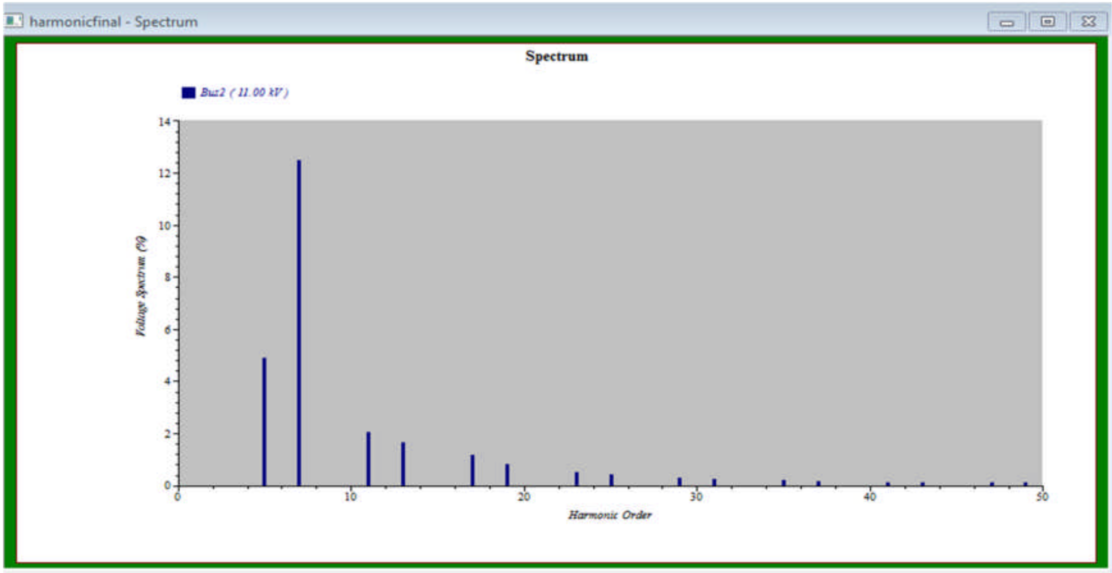
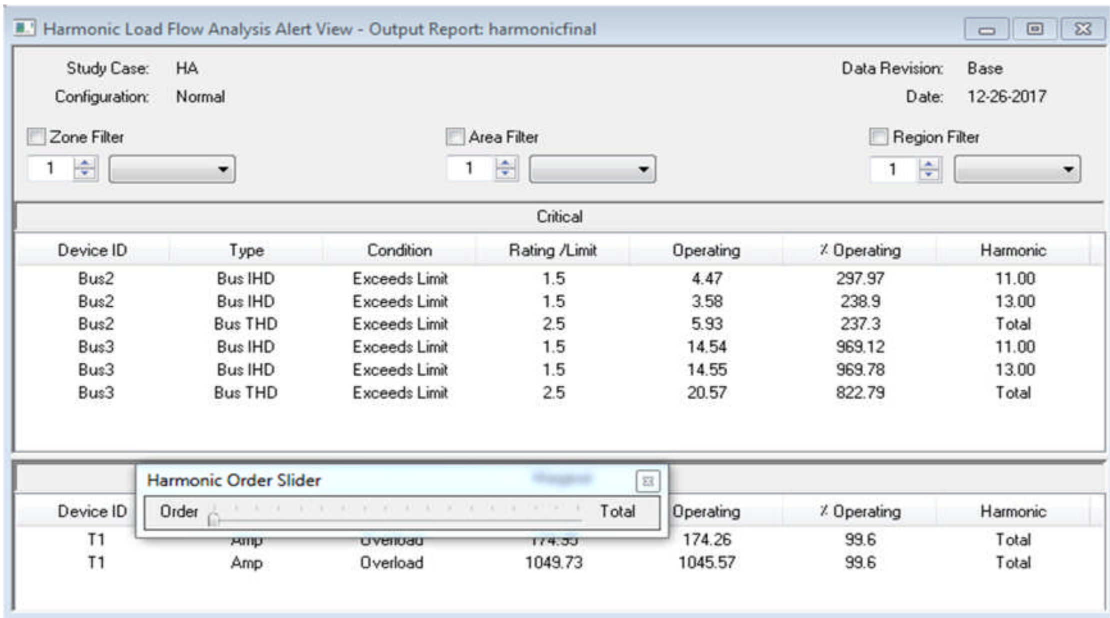


Fig 7.5: Harmonics spectrum of bus#2 for the first case

- Second case in which one transformer $\Delta - Y$ is connected and the other $\Delta - \Delta$ is connected i.e. with phase shift $= 30^{\circ}$ case. The voltage distortion $(\%THD_v \; and \; \%IHD_v)$, voltage waveform shape and harmonics spectrum were as shown in the Fig 7.6,7.7 and 7.8 respectively


Harmonic Load Flow Analysis Alert View - Output Report: harmonicfinal

Study Case: HA
Configuration: Normal
Data Revision: Base
Date: 12-26-2017

Zone Filter 1 | Area Filter 1 | Region Filter 1

Critical

Device ID	Type	Condition	Rating /Limit	Operating	% Operating	Harmonic
Bus2	Bus IHD	Exceeds Limit	1.5	4.47	297.97	11.00
Bus2	Bus IHD	Exceeds Limit	1.5	3.58	238.9	13.00
Bus2	Bus THD	Exceeds Limit	2.5	5.93	237.3	Total
Bus3	Bus IHD	Exceeds Limit	1.5	14.54	969.12	11.00
Bus3	Bus IHD	Exceeds Limit	1.5	14.55	969.78	13.00
Bus3	Bus THD	Exceeds Limit	2.5	20.57	822.79	Total

Harmonic Order Slider: Order / Total

Device ID				Operating	% Operating	Harmonic
T1				174.26	99.6	Total
T1	Amp	Overload	1049.73	1045.57	99.6	Total

Fig 7.6: Output report for the second case

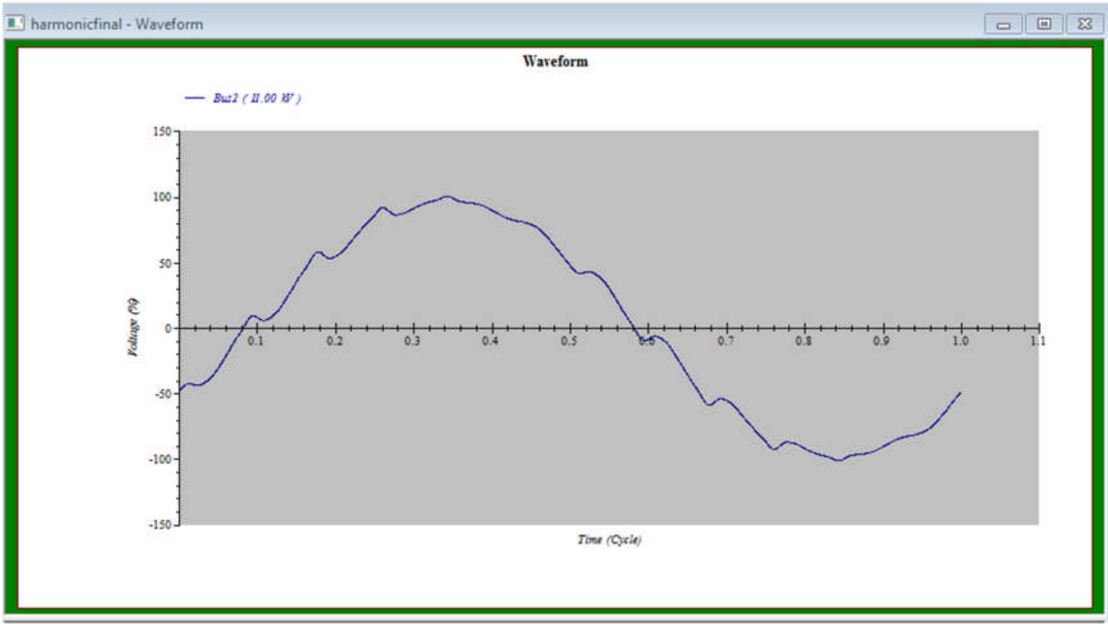


Fig 7.7: Voltage shape of bus#2 for the second case

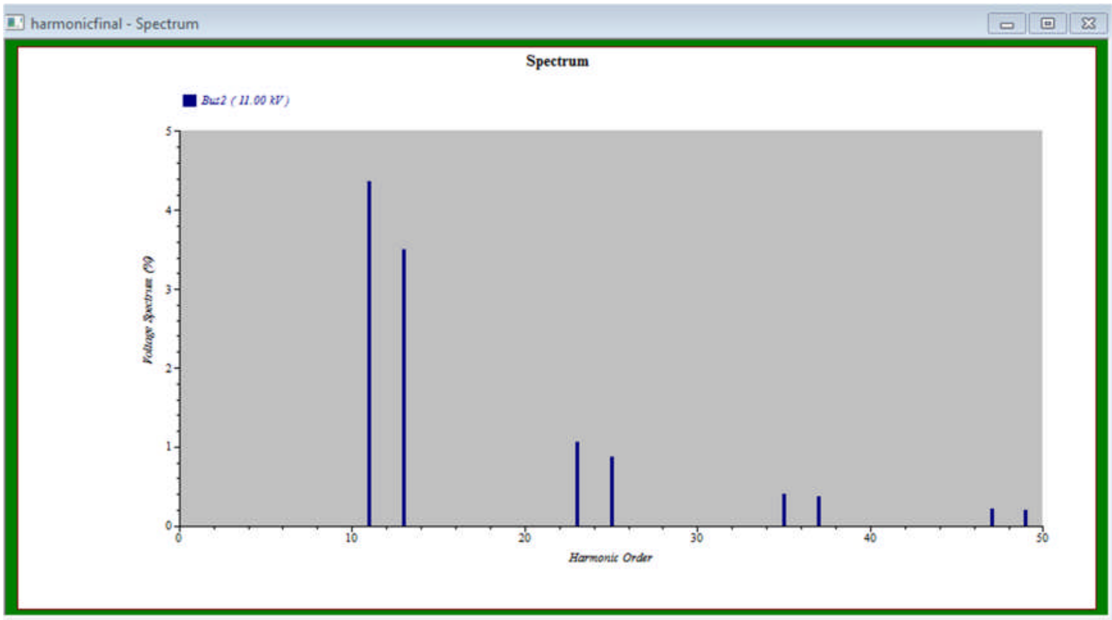


Fig 7.8: Harmonics spectrum of bus#2 for the second case

From the simulated results; the following observations are very clear:

- The phase shift by transformer led to the elimination of the fifth and seventh harmonics as seen in Fig 7.8. Also, other harmonics (*h*=17,19…….) were eliminated as shown in the same Fig.

- The amount of distortion on the voltage wave with phase shift (Fig7.7) is less as it has become closer to the sinusoidal wave despite the presence of some other harmonics.
- THD_v value - which represents the amount of distortion- was decreased significantly. THD_v values were as follows:

Table 7.2: Comparison of the voltage distortion values

$\%THD_v$	
Without phase shift	With phase shift =30°
13.85%	5.93%

The simulated current waveforms of the two separate nonlinear loads after phase shift and their resultant current waveform are as shown in Fig 7.9,7.10,7.11and 7.12. Fig 7.9 and 7.10 show the current wave shape and harmonic spectrum of the two nonlinear loads respectively. The wave of the $\Delta - Y$ transformer was shifted by 30° . Fig 7.11 and 7.12 show the current wave and harmonic spectrum at bus#2 which are resulted from the summing of the two nonlinear loads waves. It is clear that the resultant current wave is closer to the sinusoidal shape than the wave for each nonlinear load.

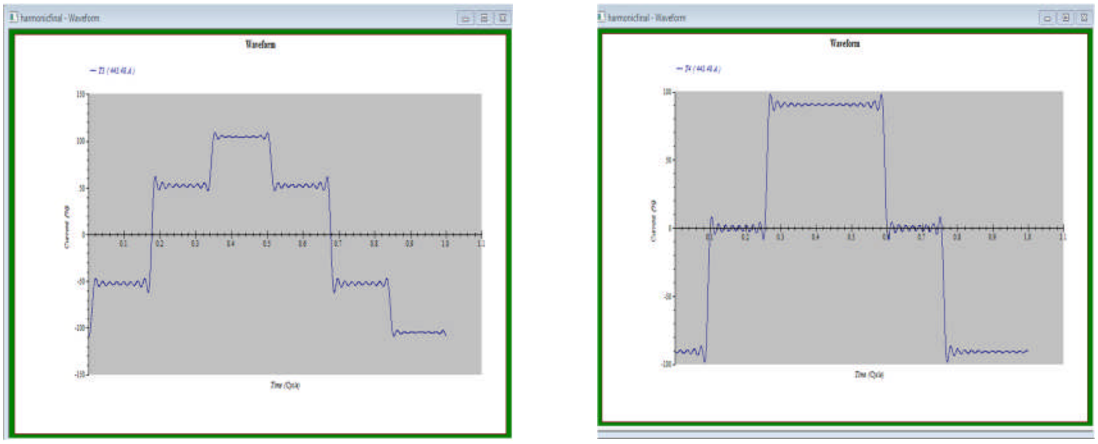


Fig 7.9: Current shape of the two nonlinear load

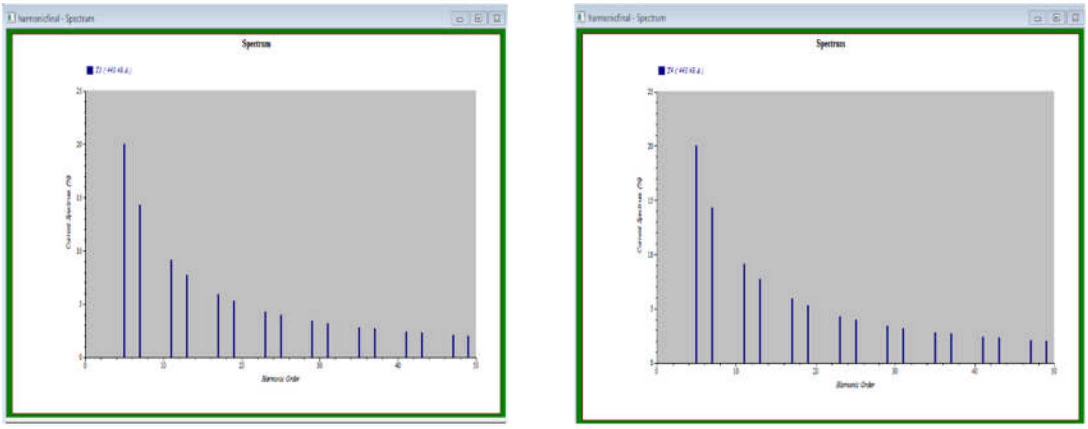


Fig 7.10: Current harmonics spectrum of the two nonlinear load

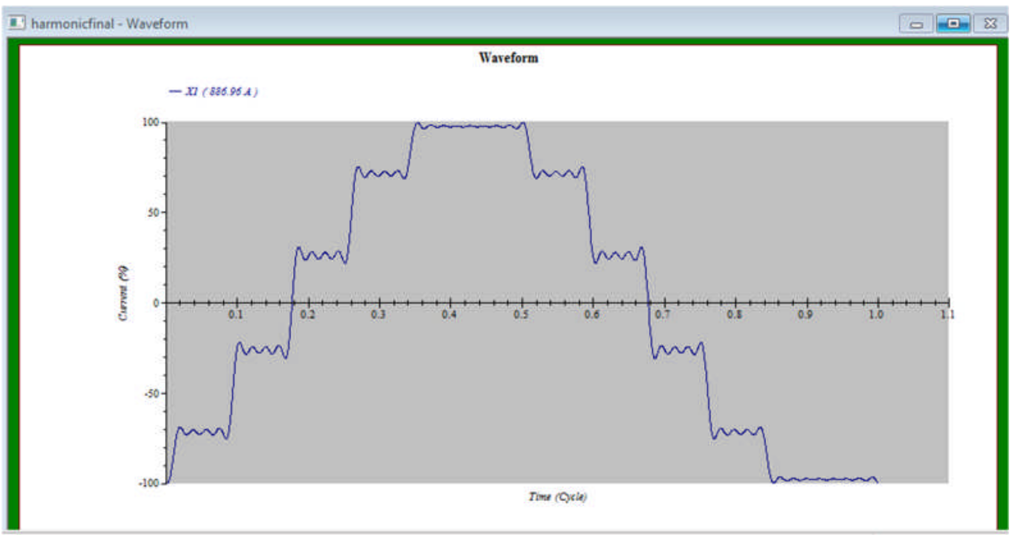


Fig 7.11: Current shape of the resultant of the two nonlinear loads

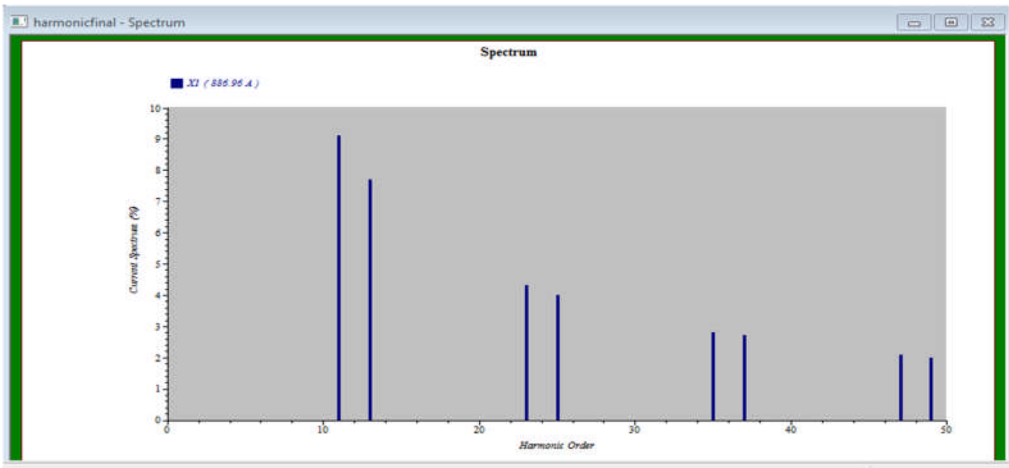


Fig 7.12: Current harmonics spectrum of the resultant of the two nonlinear loads

7.3 Passive filter

Passive fillers are a cheap and simple tool compared to other procedures used to eliminate certain network harmonics. This type of filter consists of passive elements and its principle of operation based on the resonance phenomenon. This type of filter comes in many sizes, shapes, and the most widespread and applied type is the single tuned filter " notch filter", which consists of inductance, capacitance and sometimes resistance. This filter is tuned to get a resonance between the capacitor and the inductor at a certain frequency. Thus, the filter presents a very low impedance path for the targeted harmonics current and therefore the harmonics current flows in the filter instead of crossing to the rest of the system.

In case there are several harmonics orders to be disposed of; more than one filter should be used, each one dedicated to a certain harmonics order. This filter type is connected in parallel with the non-linear load. This type is used a lot to get rid of fifth and seventh harmonics which are the most harmful harmonics in power systems.

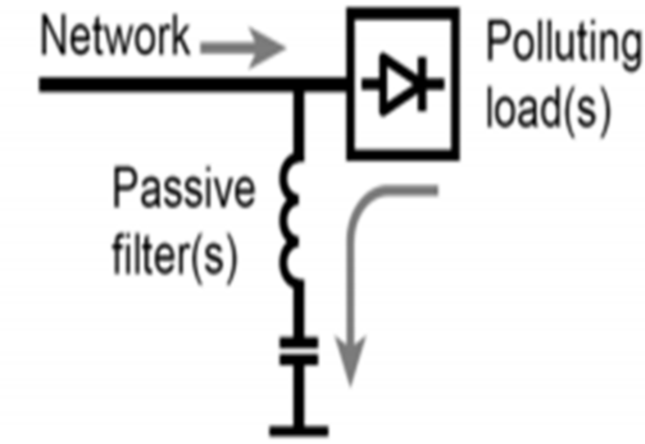


Fig 7.13: The operation mechanism of the passive filter

The filter is usually tuned at a frequency slightly lower than the frequency of harmonics to be filtered out for the following reasons [10]:

- With the factors of increasing temperature and aging, the capacitance of the filter decreases and hence the tuned frequency increases, so adjusting the filter to a lower frequency value than targeted frequency is required.
- This filter forms a parallel resonance with the inductance of the network at a frequency lower than the targeted harmonics frequency. As shown in Fig 7.13. Network changes can shift the parallel resonance frequency into the tuned frequency. This is destructive to the network.
- Tuning the filter at the harmonics frequency exactly leads to huge current that passes through the filter. This requires a large size filter.

Typical values for tuning this filter are: 4.7^{th} (for 5^{th}), 6.7^{th}(for7^{th}), 10.5^{th}(for11^{th}).These values offer sufficient filtering and avoid the above risk.

The filter is placed in the system starting from the lowest harmonics frequency to be filtered out. For example, if we want to tune the filter to get rid of the seventh harmonics, there are fears that the parallel resonance associated to the filter applies to the least harmonics frequency which may be the fifth. Because of this, before installing the filter of seventh harmonics there must be a filter that has been tuned at fifth harmonics.

In addition to filtering harmonics, this filter will provide the power system with the reactive power (called effective kVAR) needed for power factor correction. and thus improving voltage level in case of heavy loads. Power factor capacitors are often converted to a filter by adding a suitable reactor.

Despite all the advantages of this type of filters, it has some disadvantages which are:

- The harmonics for which the filter is designed, do not disappear totally from the system. Instead, harmonics flow between the nonlinear load and the filter itself (less path than before). Hence, the need to adjust the neutral conductor and other necessary procedures is still required.
- It does not absorb harmonics other than those that it is tuned at.
- As mentioned earlier, this filter as it is constructed from LC circuit, forms a parallel resonance with the system inductance at a frequency lower than the tuned frequency. This amplifies harmonics lower than tuned ones.

- The filter is designed according to the existed network. For any change in the network such as adding a new motor, the filter should be replaced.

7.3.1 Passive filter design procedure

Initially, the required power to improve the power factor is determined. This power is called an effective kVAR(Q_{eff}). This effective kVAR is derived from LC combination (filter bank). For this goal we can follow IEE std 1036-1992 to get a multiplying factor for each load kilowatts as

$$Q_{eff} = (multiplying\ factor)(kW) \quad (7.1)$$

In our network, capacitors are installed for power factor correction at each bus. The 3600 kVAR capacitor will be exploited as a filter. Hence the effective kVAR value (Q_{eff}) =3600 kVAR.

Then , the effective reactance (X_{eff}) can be calculated from effective kVAR as follows:

$$X_{eff} = \frac{V_{LL}^2}{Q_{eff}} \quad (7.2)$$

$$X_{eff} = \frac{11kV^2}{3.6MVAR} = 33.61\Omega$$

The tuned frequency is selected which is approximately 5% below the wanted harmonics frequency. In our case, it is wanted to filter out the fifth harmonics component. Hence, choosing h=4.7 in tuning the filter will be fine. From X_{eff} and h values, the capacitive reactance (X_C) and inductive reactance (X_L) of the filter are calculated using the following formulas

Capacitive reactance [8]:

$$X_C = \frac{h^2}{h^2 - 1} X_{eff} \tag{7.3}$$

$$X_C = \frac{4.7^2}{4.7^2 - 1} 33.61 = 35.2\Omega$$

Inductive reactance [8]:

$$X_L = \frac{X_C}{h^2} \tag{7.4}$$

$$X_L = \frac{35.2}{4.7^2} = 1.6\Omega$$

The final step is to determine the filter component ratings. First the ratings of the capacitor are determined which include voltage and kVAR. The rated voltage is determined from the following formula [3]:

$$V_r = \sum_{h=1}^{\infty} I_h X_h \tag{7.5}$$

Fundamental current is calculated as follows:

$$I_1 = \frac{V_\emptyset}{(X_C - X_L)} \tag{7.6}$$

$$I_1 = \frac{6.35kV}{(35.2 - 1.6)} = 189A$$

For our network, the harmonics currents were as shown in Table 7.3 (see Appendix C)

Table 7.3: Current value of the passive filter associated to each harmonics order

Harmonics order	Associated harmonics current(A)
h=5	60.15
h=7	22.04
h=11	17.06
h=13	4.88

Applying equation 7.5 gives us

$$V_r = 189\left(\frac{35.2}{1}\right) + 60.15\left(\frac{35.2}{5}\right) + 22.04\left(\frac{35.2}{7}\right) + 17.06\left(\frac{35.2}{11}\right) + 4.88\left(\frac{35.2}{13}\right)$$

$$V_r = 6652.8 + 423.456 + 110.83 + 54.6 + 13.21 = 7.2549kV$$

As seen here the required rated voltage for the capacitor is 7.2549 kV which is more than the line voltage (V_{LL}=6.351kV) of bus#2 to which the filter is connected. The reason behind that is that the harmonics currents will increase the voltage to a value larger than the rated bus value. Also, the reactor of the filter will develop a voltage which rises the voltage across the capacitor.

The kVAR rated value calculated from the found rated voltage is:

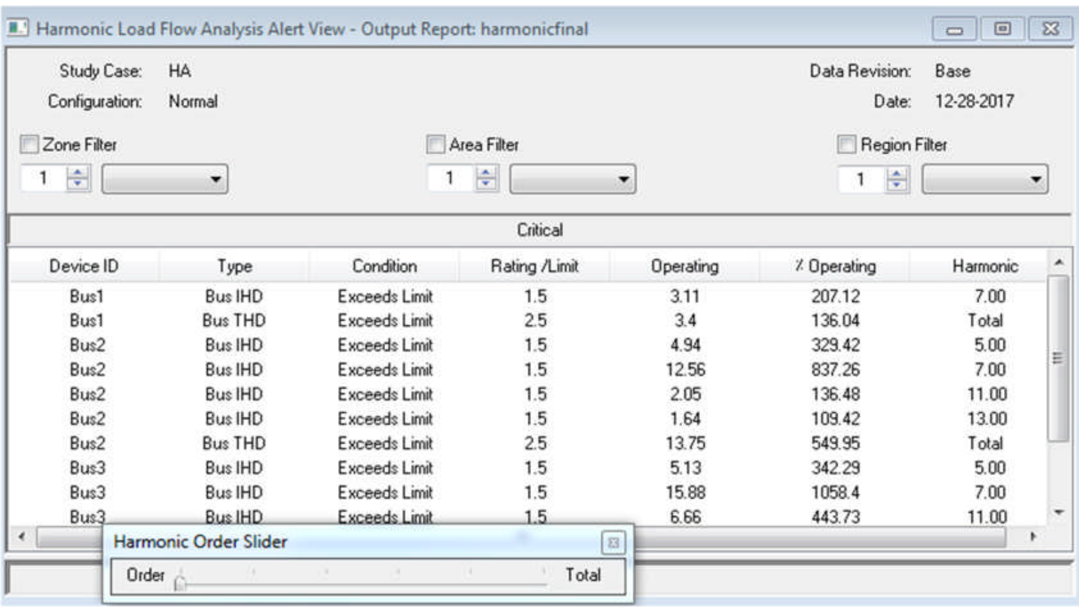
$$Q_r = \frac{V_{LL,r}^2}{X_C} = \frac{157.9MV}{35.2} = 4.4858MVAR$$

Which is greater than the effective kVAR (Q_{eff}) needed for power factor correction. This is true, since the calculated rated voltage of the capacitor is greater than the nominal voltage of the bus to which the filter is connected.

7.3.2 Results and simulation

For comparison purpose and to observe the effect of adding the filter in reducing the harmonics which exist in the network, the network was analyzed first without adding a filter and then the same network was analyzed after adding a filter with the same values previously calculated in section 7.3.1.

First, the simulated results which are taken from bus#2 of the original network were as in the following Fig 7.14,7.15,7.16 and 7.17. These values include the voltage distortion ($\%THD_v$ and $\%IHD_v$), voltage waveform shape , harmonics spectrum and impedance magnitude as in Fig 7.14,7.15,7.16 and 7.17 respectively.



Device ID	Type	Condition	Rating /Limit	Operating	% Operating	Harmonic
Bus1	Bus IHD	Exceeds Limit	1.5	3.11	207.12	7.00
Bus1	Bus THD	Exceeds Limit	2.5	3.4	136.04	Total
Bus2	Bus IHD	Exceeds Limit	1.5	4.94	329.42	5.00
Bus2	Bus IHD	Exceeds Limit	1.5	12.56	837.26	7.00
Bus2	Bus IHD	Exceeds Limit	1.5	2.05	136.48	11.00
Bus2	Bus IHD	Exceeds Limit	1.5	1.64	109.42	13.00
Bus2	Bus THD	Exceeds Limit	2.5	13.75	549.95	Total
Bus3	Bus IHD	Exceeds Limit	1.5	5.13	342.29	5.00
Bus3	Bus IHD	Exceeds Limit	1.5	15.88	1058.4	7.00
Bus3	Bus IHD	Exceeds Limit	1.5	6.66	443.73	11.00

Fig 7.14: Output report of the original network

Fig 7.15: Voltage shape of bus#2 of the original network

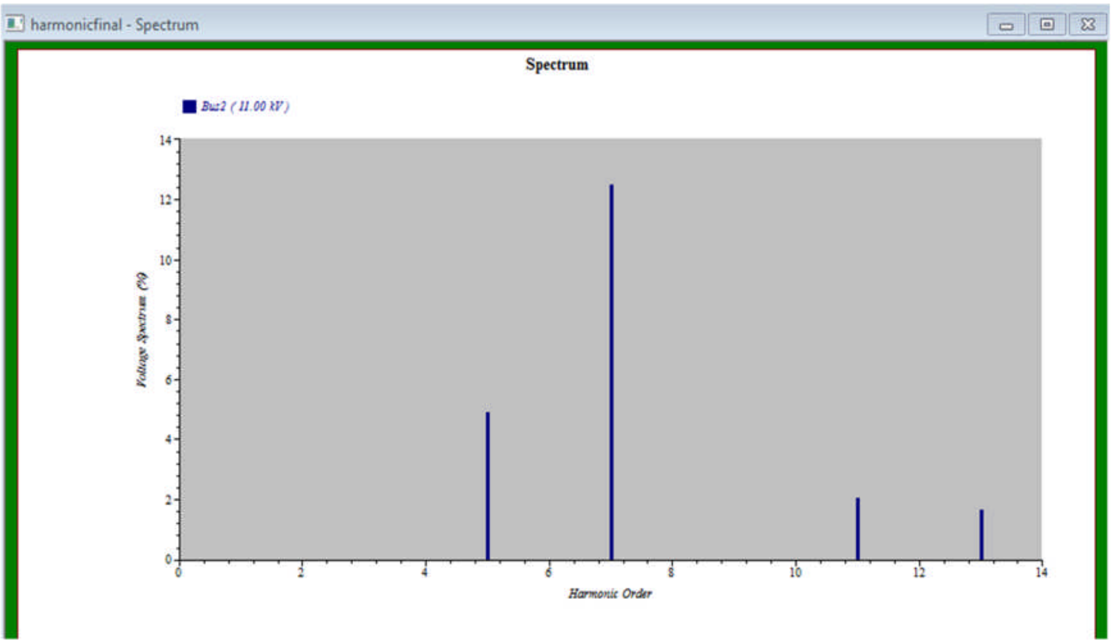


Fig 7.16: Harmonics spectrum of bus#2 of the original network

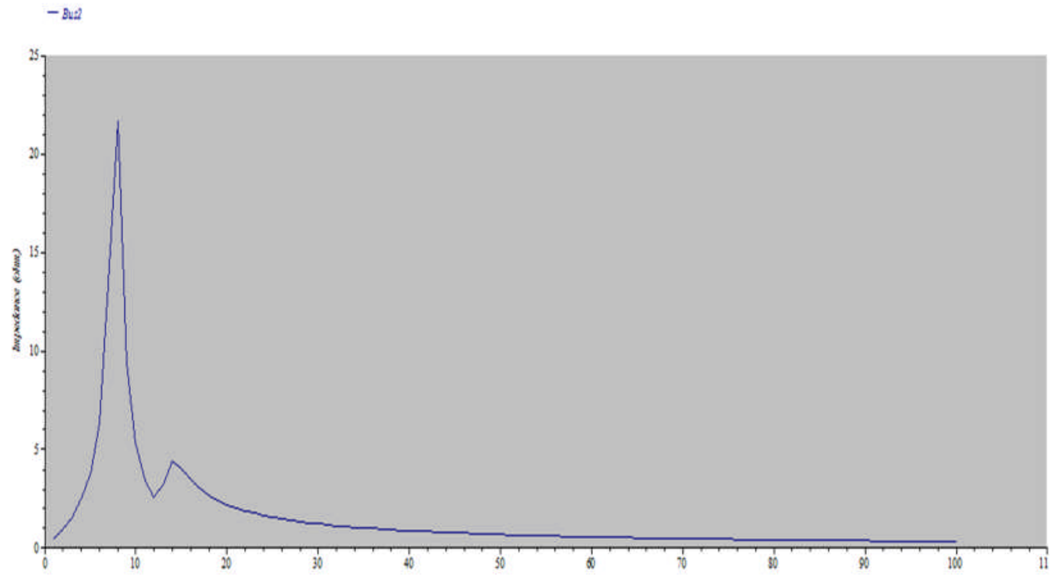


Fig 7.17: Impedance magnitude of the original network

After adding the filter as shown in Fig 7.18, the previous values were as shown in Fig 7.19,7.20.7.21 and 7.22.

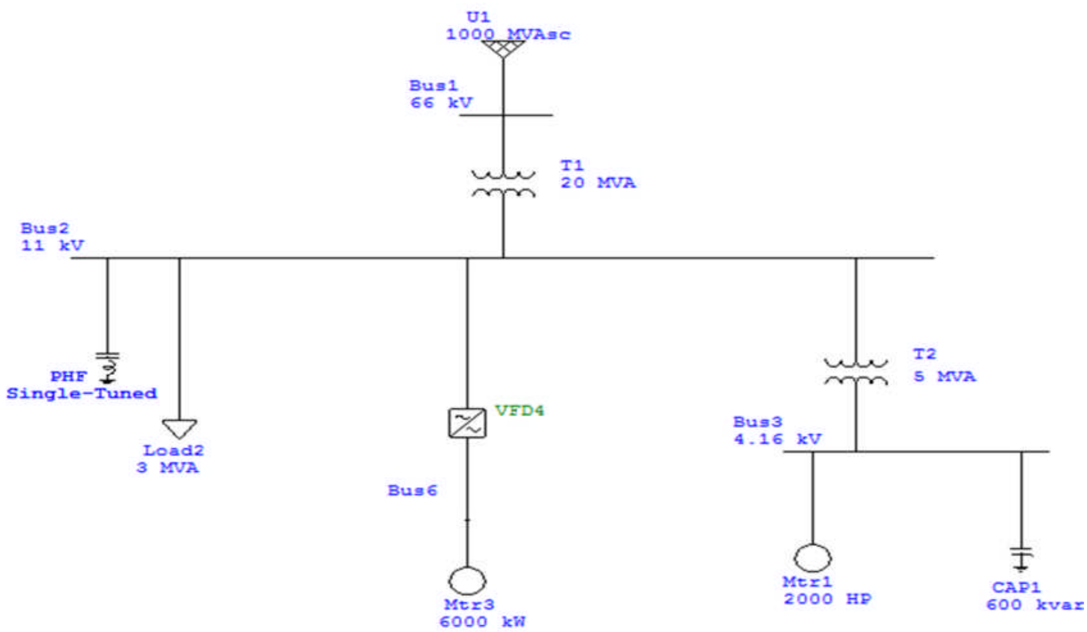
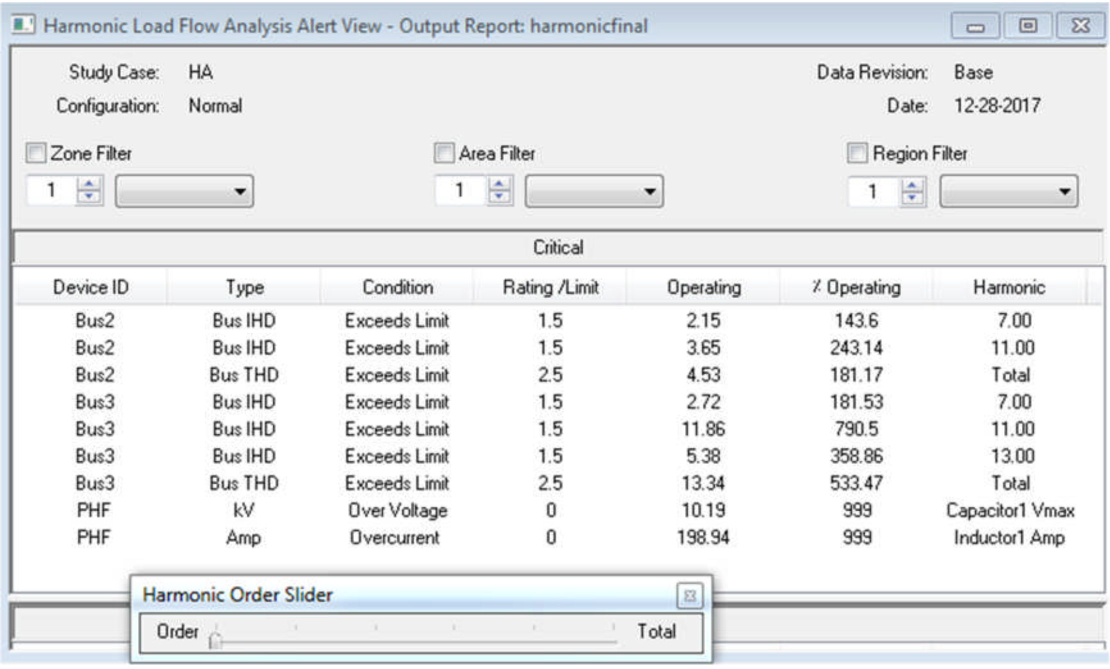


Fig 7.18: The network after adding the suitable passive filter



Harmonic Load Flow Analysis Alert View - Output Report: harmonicfinal

Study Case: HA — Configuration: Normal — Data Revision: Base — Date: 12-28-2017

Critical

Device ID	Type	Condition	Rating /Limit	Operating	% Operating	Harmonic
Bus2	Bus IHD	Exceeds Limit	1.5	2.15	143.6	7.00
Bus2	Bus IHD	Exceeds Limit	1.5	3.65	243.14	11.00
Bus2	Bus THD	Exceeds Limit	2.5	4.53	181.17	Total
Bus3	Bus IHD	Exceeds Limit	1.5	2.72	181.53	7.00
Bus3	Bus IHD	Exceeds Limit	1.5	11.86	790.5	11.00
Bus3	Bus IHD	Exceeds Limit	1.5	5.38	358.86	13.00
Bus3	Bus THD	Exceeds Limit	2.5	13.34	533.47	Total
PHF	kV	Over Voltage	0	10.19	999	Capacitor1 Vmax
PHF	Amp	Overcurrent	0	198.94	999	Inductor1 Amp

Harmonic Order Slider — Order — Total

Fig 7.19: Output report of the network after adding a passive filter

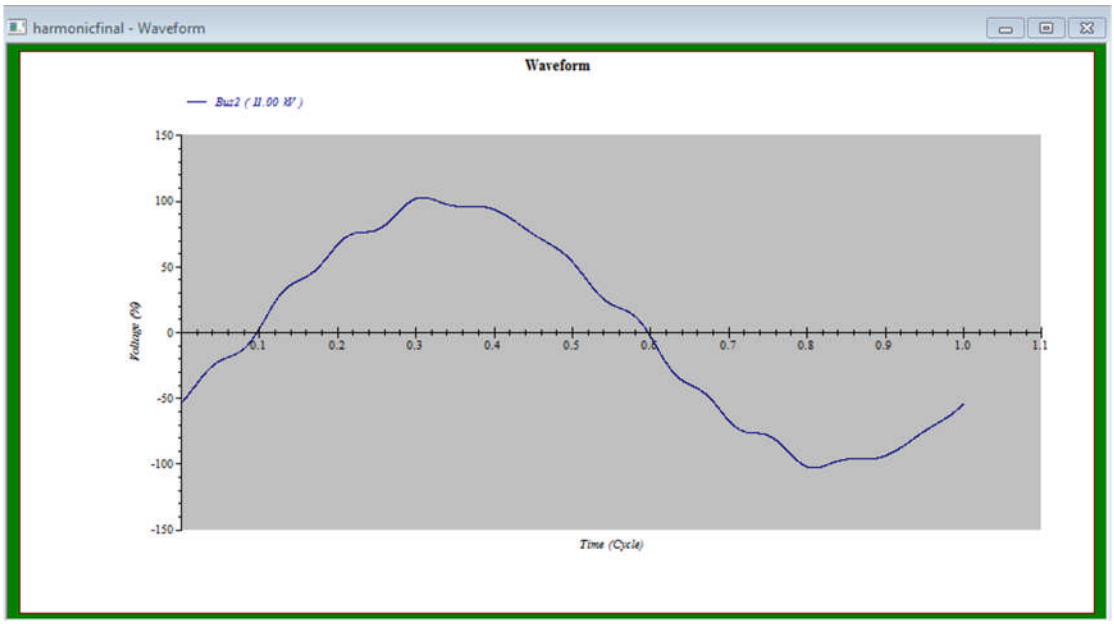


Fig 7.20: Voltage shape of bus#2 of the network after adding a passive filter

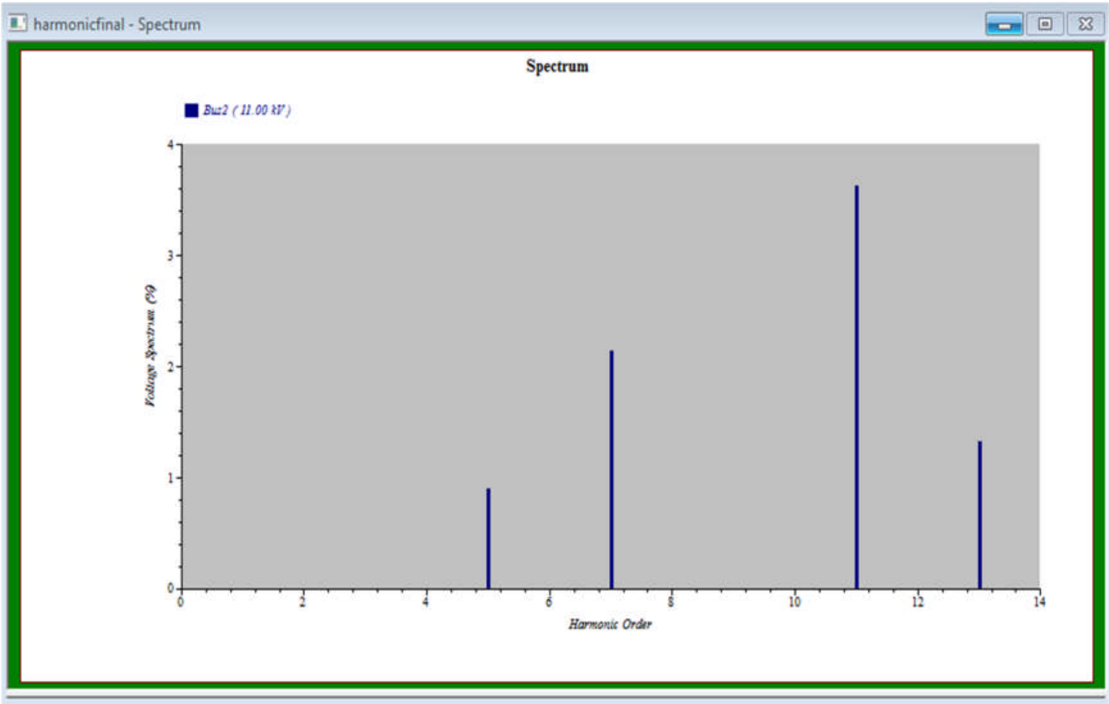


Fig 7.21: Harmonics spectrum of bus#2 of the network after adding a passive filter

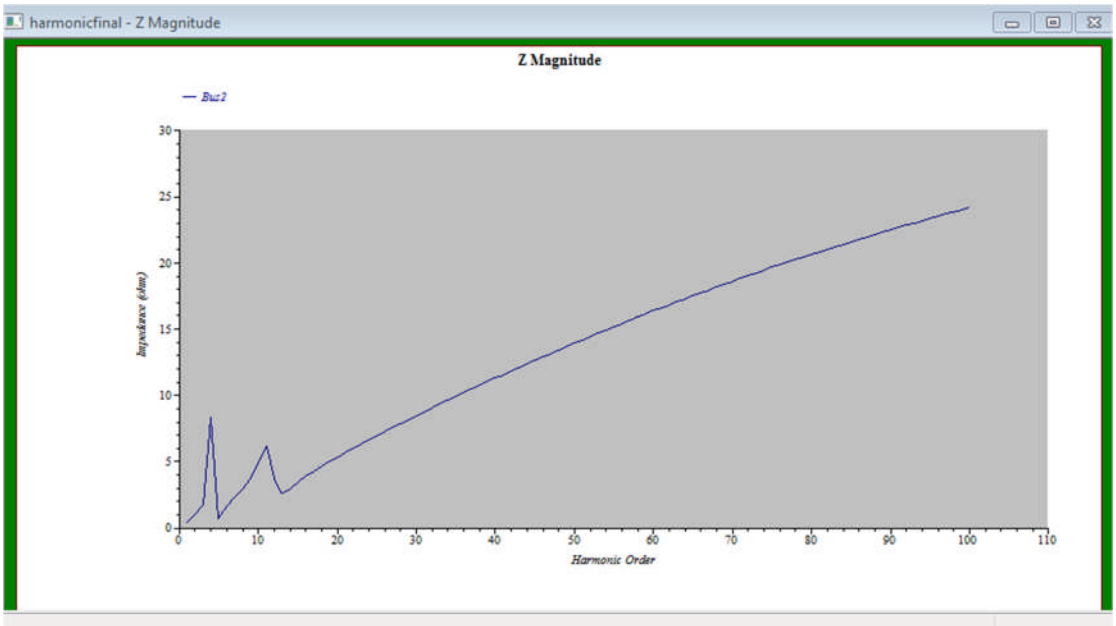


Fig 7.22: Impedance magnitude of the network after adding a passive filter

The following points about the effect of adding the filter can be observed:

- Adding the filter leads to reducing the distortion values especially for the fifth harmonics. This is clear from absence of the fifth harmonics from output report of harmonics analysis because its distortion value ($\%IHD_v$) becomes less than the limit value.
- The wave shape of bus#2 became purer and less distorted. This means that the wave contains less harmonics than before.
- The impedance value at the tuned frequency order (h=*4.7)* is very low. This is because at tuned frequency a series resonance occurs. This is preceded by a parallel resonance at a lower frequency due to the interface of the filter with the grid inductance.

7.4 In-line reactor placement

An easy and effective way to reduce the generated harmonics is simply to install a reactor in the line of the nonlinear load. It is known that the current in a reactor is slowly changing due to the induced voltage between the reactor terminals which resists the change of current. As a result, charging the dc bus capacitor becomes slower and then pulling the current becomes over a longer time. This leads to reducing the harmonics amplitude.

A standard range reactor values includes 2%, 3%, 5% and 7.5%. Where 3% is a typical value which may reduce distortion up to 40%-80% [8].

The most convenient nonlinear loads to apply this procedure are AC drives. The reactor can be placed in the AC side or DC link according to drive type.

The lower the size of the drive compared to supply transformer, the better the reduction of distortion would be.

Generally, drives larger than 10hp contain a built-in dc link reactor(chock) to minimize current distortion as much as possible. Smaller sizes(< 10 hp) do not contain chock. Thus, in case of installing many drives, adding in-line reactor should be performed. This method could not be used in this study.

7.5 Detuning

Power factor capacitor banks can interact with the network inductance at one of the harmonics frequencies and may cause resonance. This, in turn, causes amplification of harmonics. There are destructive effects of network elements due to the mentioned scenario if it occurs.

In order to prevent such a scenario, a well-calculated reactor is used in series with capacitor banks so that resonance occurs at a frequency below the lowest frequency of the system's harmonics. i.e. the harmonics current spectrum range falls outside the resonance frequency. This reactor called detuning reactor.

Usually, the detuning reactor selected as its reactance is 5.7 %, 7% or 14% of the reactance of the capacitor. This ratio called tuning factor (P).

The tuning ratio can be calculated as:

$$P = \frac{X_L}{X_C} = \left(2\pi f_{sy}\right)^2 (LC) = \left(2\pi\sqrt{LC}\right)^2 f_{sy}^2 \qquad (7.7)$$

Resonance will occur when the reactance of the detuning reactor (X_L) equals the reactance of the capacitor(X_C). For the reactor-capacitor combination, the resulted series resonance frequency is given as:

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{7.8}$$

From equations 7.7and 7.8, we can write

$$f_r = \frac{f_{sy}}{\sqrt{P}} \tag{7.9}$$

We can exploit the detuning process to provide filtering for the third harmonics order. This will be accomplished by choosing a tuning factor of 11%. Here the resonance frequency equal

$$f_r = \frac{50Hz}{\sqrt{0.11}} = 150Hz$$

As seen for 11% tuning factor, a series resonance occurred at the third harmonics order frequency which offer an almost zero path for third harmonics.

Finally, the rated values written on the reactor-capacitor combination are the system voltage at fundamental frequency and reactive power of the combined unit.

By choosing a tuning factor magnitude of 7% and applying equation 7.7, we will get a detuning reactor reactance equal to:

$$X_L = 0.07X_C = 0.07(33.611) = 2.353\Omega$$

The shifted resonance frequency will be:

$$f_r = \frac{60Hz}{\sqrt{0.07}} = 226.778Hz$$

Consequently, $h = \frac{226.778}{60}$ =3.78.

Pervious reactor value is inserted to ETAP 12.6 and then a simulation is executed to investigate the nature of impedance frequency response of the network. The simulated response was as shown in Fig 7.23. which reveals that resonance will occur at *h*=3.78? Hence, the harmonics order of circuit resonance now falls outside of harmonics orders (5,7,11,13) which are generated by the nonlinear load which was considered in the study. This mode prevents amplification of harmonics currents to harmful values.

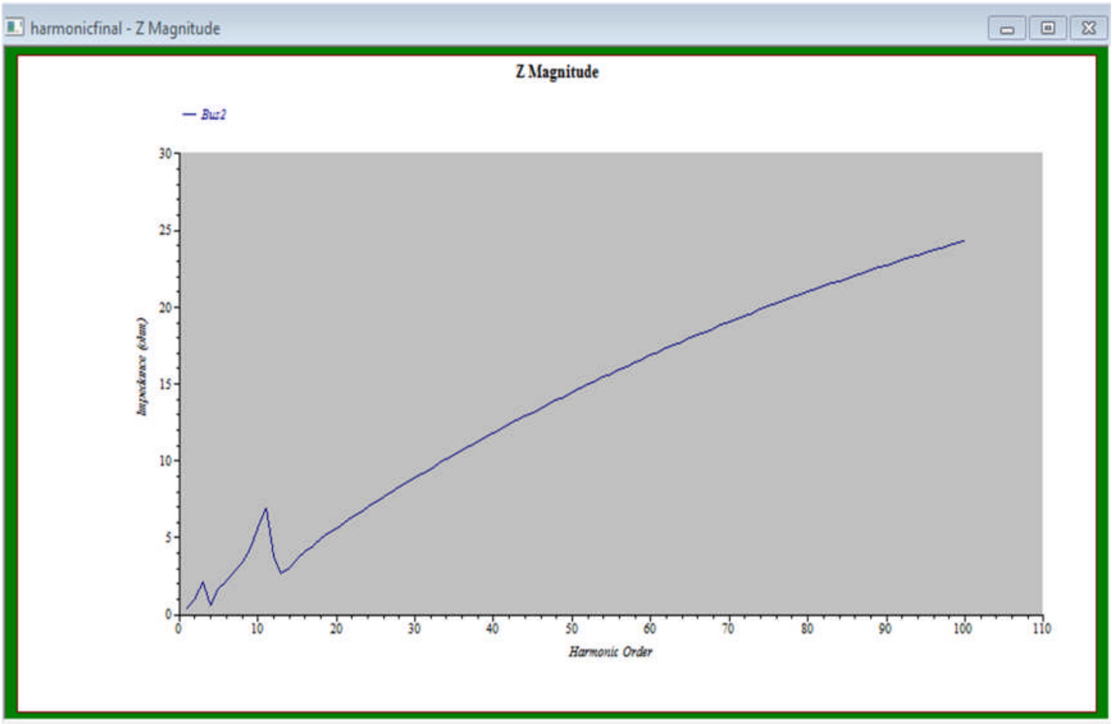


Fig 7.23: Impedance magnitude of the network after adding a detuning reactor

7.6 Basic solutions in distribution system

There are simple measures taken during design to minimize the negative effects of the harmonics problem. These procedures do not cost too much when applied and are remarkably effective.

Separation of linear loads from nonlinear loads so that the position of the non-linear loads to be upstream in the system is an effective design step. Moreover, each of load type can be supplied from a separate bus bar.

Avoiding using three phase circuits to feed a single phase outlet when a single neutral is used to feed the outlets. Rather than, the neutral line can be divided into several neutral lines each of them feeds single outlet.

Using k-factor transformers which are designed with extra steel in their core and their neutral conductors are twice the phase conductors. All of these modifications are made to help the transformer to withstand overheating.

Oversizing cables especially the neutral to withstand heating which is resulted from the pass of third harmonics. Motors also can be chosen with more rated capacity.

Chapter Eight

Conclusions and future work

8.1 Conclusions

No previous study has used a detailed method for analyzing a distorted electric network as a whole by using complete hand calculations. This thesis is mainly intended to provide a direct and efficient method that can be used in the harmonics analysis of the distribution networks. Thus, understanding how nonlinear loads effect on power quality. This understanding is achieved through calculations of the distortions and calculations of the electrical quantities with the presence of harmonics in the network. The first step was to choose the most accurate model of each network element and then to study how to represent the sources of harmonics. The latter step was to perform the calculations based on the network admittance matrix. The calculations were carried out by hand as well as by using ETAP 12.6 software.

It was found that the method adopted in the study has a very high accuracy with the real results. This was proved by comparing the results of hand calculations with simulation results and both results were equal to a very large degree.

The traditional formula for calculating the efficiency is suitable only for sinusoidal networks and is not suitable for non- sinusoidal networks. The present study fills a gap in the literature by developing a formula for calculating the efficiency in non-sinusoidal networks, i.e., under distorted conditions.

Finally, the procedures for the mitigation of harmonics were examined and the effectiveness of these procedures was determined through simulation. These procedures were found to be effective in treating the harmonics problem. In this study, harmonics were taken into consideration in determining the filter rated values as an important contribution to the field of harmonics analysis.

8.2 Future work

- To develop a method that can be used to analyze the cases of unbalances in the distribution networks and this will lead to an extension to symmetrical components analysis.
- Conducting the analysis in the presence of more than one non-linear load and this, in turn, will pay attention to the shifting harmonics spectrum angles because of the possibility of interference of current waves with each other leading to summation or subtraction.
- To achieve better components modeling than what is adopted in this thesis in order to obtain more accurate calculations (if any).

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Appendices

Appendix A

Matlab Coding for Harmonics Voltages Calculation

```
clc;clear;
t=1;l=2;m=3;c=4;g=5;ol=6;gl=7;
zdata=input('please enter impedance values zdata= ');
h=input('please enter the harmonics order h=');
i=input('please enter the harmonics current vector i=');
sp=zdata(:,1);
fp=zdata(:,2);
r=zdata(:,3);
x=zdata(:,4);
type=zdata(:,5);
nbr=length(zdata(:,1));
nbus=max(max(sp),max(fp));%number of buses
z=zeros(length(type),1);

for k=1:length(type); %modeling of components impedances to be based
on frequency
    if type(k)==c
        z(k)=(r(k)+j*x(k))/h;
    elseif type(k)==t
        rp=80*x(k);
        z(k)=r(k)+((h^2)*rp*(x(k)^2))/((rp^2)+(h^2)*(x(k)^2)) +
j*((h*x(k)*(rp^2))/((rp^2)+(h^2)*(x(k)^2)));
    elseif type(k)==m
        z(k)=h*r(k)+j*h*x(k);
    elseif type(k)==l
        z(k)=((h^2)*r(k)*(x(k)^2))/((r(k)^2)+(h^2)*(x(k)^2)) +
j*((h*x(k)*(r(k)^2))/((r(k)^2)+(h^2)*(x(k)^2)));
    elseif type(k)==g
        z(k)=r(k)+j*h*x(k);
    elseif type==ol
        z(k)=r(k)*((1+0.646*(h^2))/(192+0.518*(h^2)))+h*x(k);
    elseif type==gl
        r(k)*(0.187+0.532*(h^0.5))+h*x(k);

    end
end
y=ones(nbr,1)./z; %branch admittance vector
Y=zeros(nbus,nbus); %initial Y to zero value
for k=1:nbr; %formation of off diagonal elements of admittance matrix
    if sp(k)>0 & fp(k)>0
        Y(sp(k),fp(k))=Y(sp(k),fp(k))-y(k);
        Y(fp(k),sp(k))=Y(sp(k),fp(k));
    end
end
for n=1:nbus %formation of diagonal elements of admittance matrix
    for k=1:nbr
        if sp(k)==n | fp(k)==n
            Y(n,n)=Y(n,n)+y(k);
```

```
        else, end
    end
end
znew=inv(Y);
v=znew*i;
rho=abs(v);
theta=angle(v);
result=[rho,theta]
bar(rho)
xlabel('the number of the bus');
ylabel('voltage (per unit)');
title(['voltage of buses at harmonics order = ',num2str(h)]);
```

Appendix B

Phase Shift for Harmonics Cancelation ($\Delta/\Delta\ \boldsymbol{to}\ \Delta/ \boldsymbol{Y\ Connection}$)

First, considering Δ connected secondary to write the line current associated with. For example, harmonics order 5,7,11,13 will be considered. Fundamental current in phase A

$$I_a = I_1 \sin(wt)$$

Due to nonlinear load, the harmonics current wave in phase A will be

$$I_a = I_1 \sin(wt) + I_5 \sin(5wt) + I_7 \sin(7wt) + I_{11} \sin(11wt) + I_{13} \sin(13wt).$$

This Δ secondary line current will be the same in Δ primary line. Assuming 1:1 winding ratio between both winding for simplicity.

Now, moving to Y connected secondary. It is known that in $\Delta - Y\ or\ Y - \Delta$ transformer, the high voltage side positive sequence quantities lead the low voltage side quantities by $+30^{\circ}$.While negative sequence quantities lag by -30° . Hence, the fundamental current in phase A

$$I_a = I_1 \sin(wt - 30°)$$

Due to nonlinear loads, the harmonics current wave in phase A will be

$$I_a = I_1 \sin(\mathrm{wt} - 30^{\circ}) + I_5 \sin(5wt - 150^{\circ}) + I_7 \sin(7wt - 210^{\circ}) + I_{11} \sin(11wt - 330^{\circ}) + I_{13} \sin(13wt - 390^{\circ}).$$

This secondary line current will be shifted by $+30^{\circ} or -30^{\circ}$ depending on the sequence of each harmonics order . The primary line current becomes

$$I_a = I_1 \sin(\mathrm{wt} - 30^{\circ} + 30^{\circ}) + I_5 \sin(5wt - 150^{\circ} - 30^{\circ})$$
$$+ I_7 \sin(7wt - 210^{\circ} + 30^{\circ}) + I_{11} \sin(11wt - 330^{\circ} - 30^{\circ})$$
$$+ I_{13} \sin(13wt - 390^{\circ} + 30^{\circ}).$$

$$I_a = I_1 \sin(\mathrm{wt}) + I_5 \sin(5wt - 180^{\circ}) + I_7 \sin(7wt - 180^{\circ})$$
$$+ I_{11} \sin(11wt - 360^{\circ}) + I_{13} \sin(13wt - 360^{\circ}).$$

When both currents are added in the primary line, the total primary current

$$I_A = 2I_1 \sin(wt) + 2I_{11} \sin(11wt) + 2I_{13} \sin(13wt)$$

As seen the harmonics order 5 and 7 had been vanished in the line primary current. The new harmonics order pattern will be as follows:

$$h = 12p \mp 1$$

Appendix C

Filter Harmonics Currents Calculation

The aim is to represent the circuit so that the impedance which is seen by the harmonics source is the filter impedance in parallel with the equivalent impedance of all the elements of the network at the same point (PCC) as in Fig C.1. This representation is required at the frequency of each harmonics order. Then the current division rule is applied to obtain the harmonics current values in the filter.

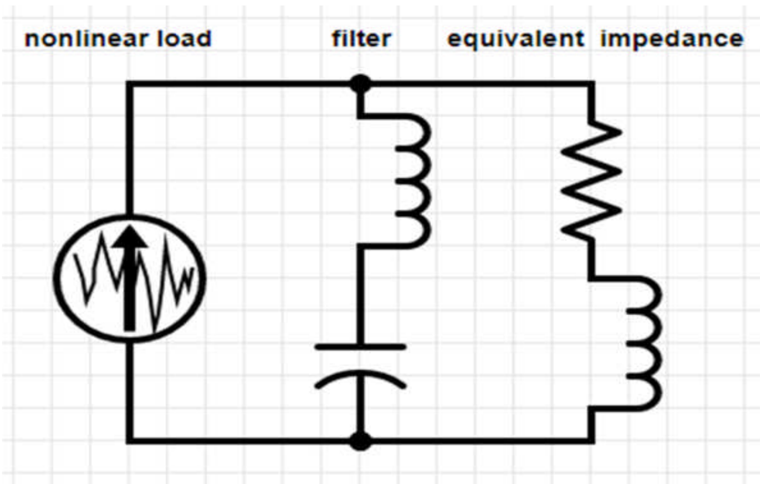

Fig C.1: Simple circuit representation for harmonics currents estimation of the filter

The impedances of the network are assembled at the (PCC) as follows:

The resultant impedance of the induction motor (IM) with the capacitor (C1) in parallel are shown in Table C.1

Table C.1: Equivalent impedance estimation of (IM,C1)

Harmonics order	Z(IM,C1)
h=5	0.85635-j11.14582
h=7	0.06756-j3.7108
h=11	0.0098-j1.7723
h=13	0.0054-j1.4307

Adding the previous results to the transformer (T2) impedance in series

Table C.2: Equivalent impedance estimation of (IM,C1,T2)

Harmonics order	Z(IM,C1,T2)
h=5	0.9035-j10.546
h=7	0.1505-j2.88
h=11	0.19725-j0.4723
h=13	0.26140-j0.0843

The resultant of the previous value Z (IM,C1,T2) is calculated with the passive load (L) impedance in parallel to get new impedances shown in Table C.3

Table C.3: Equivalent impedance estimation of (IM,C1,T2,L)

Harmonics order	Z(IM,C1,T2,L)
h=5	3.3935-j0.83
h=7	1.5375-j1.7213
h=11	0.24-j0.421
h=13	0.2454-j0.074

The resultant impedances of grid (G) and transformer (T1) is in series are shown in Table C.4

Table C.4: Equivalent impedance estimation of (G, T1)

Harmonics order	Z(G, T1)
h=5	0.01184-j10.2
h=7	0.0207-j0.278
h=11	0.047-j0.434
h=13	0.0645-j0.51

Finally, the resultant impedances of Z(G,T1) and Z(IM,C1,T2,L) are found in parallel in Table C.5

Table C.5: Equivalent impedance estimation of (IM,C1,T2,G,L)

Harmonics order	Z(IM,C1,T2,G,L)
h=5	0.02341-j0.20075
h=7	0.051-j0.3
h=11	0.687-j0.263
h=13	0.158-j0.1214

Now, moving to the filter impedance at each harmonics frequency. Filter impedances Z(f) at a certain frequency = $(X_L - X_C)$. These impedances are shown in Table C.6

Table C.6: Equivalent impedance estimation of the filter

Harmonics order	**Z(f)**
h=5	j0.08
h=7	j0.51
h=11	j1.2
h=13	j1.5

Applying current division rule will give us the harmonics currents values which flow in the filter as shown in Table C.7

Table C.7: Harmonics current estimation of the filter

Harmonics order	**Filter harmonics current(per unit)**
h=5	0.113
h=7	0.0418
h=11	0.0326
h=13	0.00741

Appendix D

Selected Examples of Harmonics Analyzers [12]

There are many devices for measuring and analyzing harmonics. In fact, these devices are considered three phase power quality devices because they carry simultaneous measurements such as energy (kVAh, kWh, kVARh), transients, flicker, harmonics, power factor and voltage sags.

These devices vary in terms of voltage and current ratings values which they deal with safely. The most famous of these devices are:

<u>FLUK 434/435</u>

It measures values rated up to 1000 V_{RMS}, 2000A.

Fig D.1: FLUK 434/435

AEMC 3945

It measures values rated up to 830 V_{RMS} ,6500A

Fig D.2: AEMC 3945

Hioki 3196

It measures values rated up to 600 V_{RMS}, 5000A.

Fig D.3: Hioki 3196

جامعة النجاح الوطنية
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إعداد
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قدمت هذه الأطروحة استكمالاً لمتطلبات الحصول على درجة الماجستير في هندسة القوى الكهربائية، بكلية الدراسات العليا، في جامعة النجاح الوطنية، نابلس، فلسطين.
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الملخص

يمكن وصف شبكات الطاقة بأنها ذات جودة رديئة إذا كانت تحتوي على تشوهات في موجات التيار والفولتية والتي تعرف بالتوافقيات. التوافقيات تعني أن موجة التيار المتناوب (AC) تحتوي على ترددات من مضاعفات التردد الأساسي.

في الماضي، كان هذا التشويه ناتجًا عن عناصر الشبكة نفسها، مثل المحولات، عندما تدخل منطقة التشبع في فترات ارتفاع الطلب على الطاقة. المولدات نفسها تنتج موجات بدرجة تشويش طفيفة لأن توزيع التدفق المغناطيسي في الغالب ليس مثاليا. ولكن في الوقت الحاضر، فإن السبب الرئيسي لهذه المشكلة هو انتشار الأحمال غير الخطية، وخاصة أجهزة الكترونيات القدرة في الاستخدام المنزلي والتجاري. العديد من الأجهزة الصغيرة المنتشرة عبر الشبكة بأكملها تشارك في التشويه.

أصبح التشوه الناتج عن التوافقيات أمراً هاماً للغاية في مجال دراسات جودة القدرة بسبب الآثار السلبية للتشويه على المعدات وما يصاحبه من ظواهر خطرة مثل الرنين.

لفهم مشكلة التوافقيات، يجب إجراء تحليل دقيق للشبكة في ظل وجود مصادر التوافقيات. الهدف الرئيسي من هذا التحليل هو إيجاد قيم التشويش المختلفة ومقارنتها بالقيم المعيارية التي تحددها المواصفات. أيضا هذه الدراسات تمكننا من دراسة فعالية الإجراءات المختلفة المتبعة في القضاء على التوافقيات والتحكم في تدفقها.

في هذه الأطروحة، تم تطوير نموذج ممانعة النطاق الترددي لشبكة توزيع وتم إجراء تحليل لحساب قيم التشويه المطلوبة. وقد رافق كل هذا محاكاة عن طريق البرامج لنفس الشبكة لمقارنة دقة النتائج.