# HARMONICS ANALYSIS OF A WIND ENERGY CONVERSION SYSTEM WITH A PERMANENT MAGNET SYNCHRONOUS GENERATOR

by

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## Dedication

I would like to dedicate this work to my beloved parents.

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# Abstract

Global energy demands are growing daily, with renewable energy options such as wind power emerging as attractive alternatives to fossil fuels. This thesis is mainly doing simulation using Matlab to filter harmonics which are found in a Permanent Magnet Synchronous Generator (PMSG) Wind Energy Conversion System (WECS) connected to a three-phase load through a full converter (AC/DC/AC). Harmonics are caused by the converter system. To reduce these harmonics, an effective filter is needed. There are two types of filters that are usually used, active and passive filters. Among the types of passive filters are band pass which block lower harmonics orders such as 5th, 7th, 11th, and 13th, and high pass filters which are responsible to filter higher harmonics such as 24th. So, we use two stages of harmonic filtering. The first stage includes a c- type high pass filter (for lower orders), a double – tuned filter (for 11th and 13th ) and high pass filter (for higher orders). Secondly, this stage includes a single – tuned filter instead of C- type filter with keeping the other filters. We applied Fast Fourier Transform (FFT) to determine the harmonics and purposes. In this thesis, we investigate and analyse the level of harmonic content of two AC/DC converters working at different wind speeds. Our findings indicate significant improvements in Total Harmonic Distortion (THD) with best results in the second method.

## List of Abbreviations and Symbols Used

$\rho$: air density ( Kg/$m^3$)

A: swept area

v: wind speed (m/s)

$C_p$: power coefficient

$\beta$ : blade pitch angle

λ: tip speed ratio (m/sec)

$\omega$: rotational speed

$R_a$: armature resistance

$\omega_e$: electrical rotating speed

$\lambda_0$: permanent magnetic flux

$L_d$ & $L_q$: summation of the inductors of the generator

$u_d$ & $u_q$: components of the output voltage of the power converter

$a_n$& $b_n$: Fourier Coefficients of $n^{th}$ harmonics components

$a_0$ : DC component

$X_l$: inductor reactance at the fundamental frequency

N: harmonic order

R: resistance of the filter

L: reactance of the filter

C: capacitor of the filter

$X_c$: capacitor reactance at the fundamental frequency

$f_1$ : fundamental frequency

$Q_c$: reactive power

P: active power losses

V: line-to-line voltage of the generator

$\omega_1$ & $\omega_2$: two tuning frequencies

Q: quality factor

PMSG: Permanent Magnet Synchronous Generator

WECS: Wind Energy Conversion System

AC: Alternative Current

DC: Direct Current

FFT: Fast Fourier Transform

HPF: High Pass Filter

BPF: Band-Pass Filter

THD: Total Harmonic Distortion

AWEA: American Wind Energy Association

GW: Giga-Watt

MW: Mega-Watt

HAWT: Horizontal-Axis Wind Turbine

VAWT: Vertical-Axis Wind Turbine

MPPC: Maximum Power Point Controller

MPFC: Maximum Power Flow Controller

PTF: Passive Trap Filter

PFC: Power Factor Corrector

TSR: Tip Speed Ratio

CSNLs: Current-Source Nonlinear Loads

VSNLs: Voltage-Source Nonlinear Loads

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First of all, I must thank Allah (God) for helping me to complete this research work. Over the past three years I have received support and encouragement from a great number of individuals. First, I would like to express my sincere gratitude to my advisor **Dr. Mohammed ElHawary** for the continuous support of my MASC courses study and research, for his patience, motivation, enthusiasm, and immense knowledge. His guidance helped me in all the time of research and writing of this thesis. Secondly, I would also like to thank my supervisory committee **Dr. William Philips** and **Dr. Jason Gu** for their encouragement, guidance, insightful comments and advice.

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# Chapter 1 Introduction

## 1.1 Background and motivation

Renewable energy has become an important energy source With wind power becoming increasingly important in developed countries. For example, in the United States, the American Wind Energy Association (AWEA) announced that the U.S. wind energy usage in 2012 exceeded 50 gigawatts [1].

An increasing number of countries are using wind power for everyday needs such as pumping water, providing electricity, and grinding corn. People prefer wind power as an alternative energy source because it requires no fuel and generates no greenhouse gas emissions. As of 2010, there were 656,000 small wind turbines around the world, up from 521,000 in 2009 and 450,000 in 2008 [2]. As of the end of June 2012, the installed wind capacity was approximately 254 GW in annual energy production [2].

Figure 1-1 shows the total cumulative installed capacity of wind generation as of 2012. Noteworthy is that the installed capacity has increased every year.

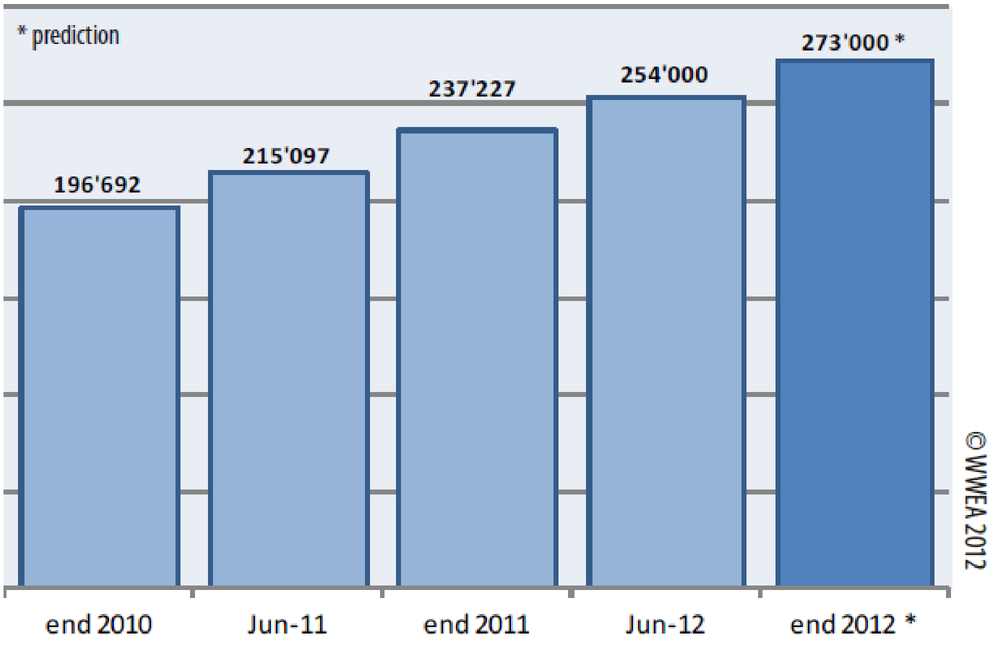


Figure 1-1Total Cumulative Installed Capacity as of the End of 2012 [2].

Figure 1-2 illustrates the small wind turbine installed capacity world market forecast for 2020. According to the figure, China is responsible for roughly 25% of the total installed capacity, accounting for 67,774 MW, followed by the U.S., with 49,802 MW.

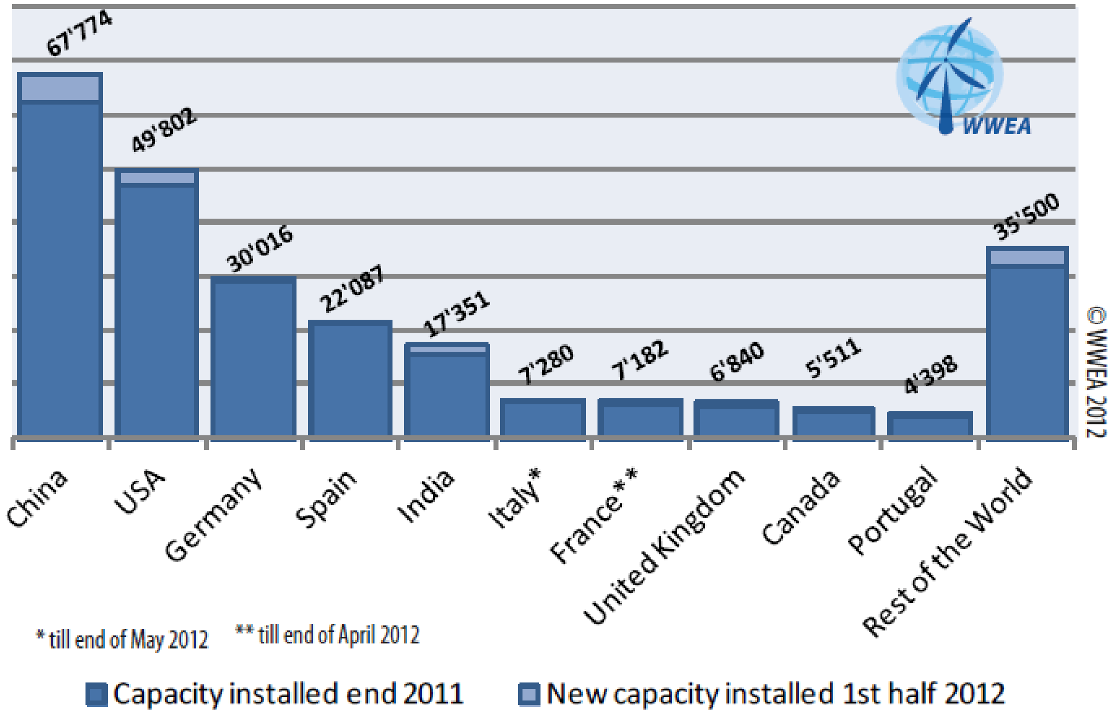


Figure 1-2 Total Installed Capacity Worldwide 2011-2012 (MW) [2].

The motivation for this thesis is the annual growth in energy consumption and environmental impacts, which makes wind an attractive alternative for efficient and clean energy. Wind-electric systems can provide electricity in remote off-grid sites and in towns connected to three-phase loads. The wind turbine converter represents a source of harmonics in an electric power system. The harmonics are worth considering because they cause high heating in the generator and throughout the system. Hence, finding a technique to reduce or eliminate these harmonics is both necessary and attractive.

## 1.2 Types of wind turbines

Wind turbines are classified into two types, based on the movement of the axis of rotation in relation to the wind direction, as shown in [3].

1. Horizontal axis.
2. Vertical axis.

(a) (b)

Figure 1-3 (a) Horizontal-axis wind turbine (b) Vertical-axis wind turbine [3].

### 1.2.1 Horizontal-Axis Wind Turbine (HAWT)

At present, most installed wind turbines use Horizontal-Axis Wind Turbines (HAWT). A HAWT is a wind turbine whose rotor's rotation axis is parallel to the ground and to the wind direction, as shown in Figure 1-3-a[4-7].

The advantages of a HAWT are:

a. The blade pitch can be varied.
b. It has high efficiency.
c. It can produce power at low cut-in wind speeds.

The disadvantages are:

a. It is difficult to construct.
b. For large-size HAWTs, moving the equipment is difficult.
c. It needs extra yaw control to adjust the blades to wind direction.

### 1.2.2 Vertical-Axis Wind Turbine (VAWT):

A Vertical-Axis Wind Turbine (VAWT) can capture wind from any direction and at low wind speeds. There are two types of VAWTs: the Darrieus and Savonius types, as shown in Figure 1-3-b [7-9]

The advantages of a VAWT are:

a. All equipment is at ground-level, so it is easy to maintain and operate the system.
b. It does not need a heavy tower structure.
c. It has lower start-up speeds than a HAWT.

The disadvantages are:

a. VAWTs have longer blade-lengths than HAWTs.
b. Most vertical axis wind turbines generate 50% of a HAWT's efficiency.
c. VAWTs have a low rotor height and thus a lower rotor wind speed.

## 1.3 Thesis objectives and contribution

Wind Energy Conversion Systems (WECSs) have been steadily gaining the world's attention as a means of generating energy, due to increasing demands for power and environmental issues related to the use of fossil fuels. Wind turbine generators are an important part of WECS. The Permanent Magnet Synchronous Generator (PMSG) is currently used in low-power wind turbine applications.

Harmonics are considered as a main problem for wind turbine systems. Therefore, the thesis objective is to investigate, and try to reduce these harmonics by designing three-phase passive filter, connected in parallel with the generator. The harmonics reduction is beneficial to the system for two reasons: first, harmonics elimination decreases power losses in the overall system so there will be less heat on it; and second, power quality can be improved by reducing the Total Harmonics Distortion (THD).

The main contributions of this thesis are as follows:

- Simulating a stand-alone wind energy conversion system with PMSG connected through a full convertor to a three-phase load.
- Adding three-phase passive filters to the stator portion of the generator.
- Showing how the filters will perform at different wind speeds.
- Improving the output current and voltage of the wind turbine generator with two different AC/DC converters.

## 1.4 Problem statement

The PMSG current and voltage waveforms deviate from an idealsine wave. They are mainly distorted due to non – linear loading effects from the AC/DC converter. Therefore, a filter is installed between the generator and three phase rectifier. It will filter the harmonics produced by the system itself such as injected by the converter.

## 1.5 Organization of thesis:

This work is organized into five chapters. The present chapter introduces the theme and purposes of the thesis, followed by a literature review in Chapter 2. The Wind Energy Conversion Systems are reviewed in Chapter 3, and Chapter 4 presents the harmonics analysis. The mmethodology is provided in Chapter 5, where the WECS is simulated using Simulink/Matlab environment. Results and discussions are presented in Chapter 6, including conclusions and suggestions for future work.

# Chapter 2 Literature review

## 2.1 Introduction

Each Wind Energy Conversion System (WECS) includes either an induction or a synchronous generator within its structure. The permanent magnet synchronous generator is considered the best choice for wind turbines due to the simplicity of its generating mechanism and good power density. Moreover, and based on previous research, harmonic production in wind turbine systems has increased. Harmonics filtering techniques generally are classified as either passive or active. Passive filtering is the most common method used in harmonic distortion control and is divided into single-tuned and band-pass filters. In general, passive filters operate work within a limited frequency range, while active filters can operate in a wide frequency range [10].

The literature review is divided into two sections: wind turbine systems and harmonic mitigations in wind power system.

## 2.2 Wind turbine systems

Collier and Heldwein proposed a model for a micro wind energy system, in which the turbine is connected to a permanent magnet synchronous generator and a power rectifier. In consideration of this model, we present the following three sections: first, the dynamic model of a wind turbine with three blades, where the turbine is connected via a PMSG and three-phase rectifier to the grid; secondly, a proposed design of the Wind Energy Conversion System (WECS) based on the relationship between the steady state torque and speed characteristics of the wind turbine, PMSG, and the rectifier; and thirdly, an analysis of operational points in steady state in the three areas of operation [11].

Arifujjaman presented a mathematical model and control strategy for a PMSG-based small wind turbine connected to the grid. The author described two methods of controllers to ensure variable speed operation and increase the annual energy capture. The two methods are Maximum Power Point Controller (MPPC) and Maximum Power Flow Controller (MPFC). He concluded that the dependence on system variables can be reduced by his control strategy[12].

The efficiency of three small commercial wind turbines was analyzed by Rodrigo, et al, [13]. In their paper, the performance of the three turbines was compared with another turbine using turbine speed control. They found that performance of each turbine could be improved depending on the technology used.

## 2.3 Harmonics mitigation in wind power systems.

There are many techniques which can be used to reduce harmonics in wind power systems. We can summarize them as follows:

Tsai and Tan [14] presented a technique to eliminate current harmonics for a PMSG wind energy conversion system. In their paper, they used a variable frequency active power filter to reduce harmonic power losses. The proposed variable frequency active power contains a variable frequency synchronizer and phase-locked-loop (PLL) voltage source- current controlled inverter (VS-CCI). The variable frequency synchronizer consists of a 2nd order low pass filter and a PLL. The PLL is used to lock on to the phase input signal and frequency thus providing a current reference signal to the current controlled inverter. Simulations were conducted to examine the performance of the filter within the WECS and models were tested at two different wind speeds (5 m/s, 8 m/s and 11 m/s). They concluded from their findings that the active power filter offers the best approach to use at different wind speeds to eliminate current harmonics in the PMSG wind turbine system. The wind speed of 8 m/s is the optimum speed as THD is the lowest obtained. The performance of the system can be seen in Table 2-1

Table 2-1 Total current harmonics distortions in the PMSG wind turbine generator.[14]

| Wind speed | Frequency | THDi Without VF-APF | THDi With VF-APF |
|---|---|---|---|
| 5 m/s | ≈20Hz | 35.5% | 4.9% |
| 8 m/s | ≈32Hz | 21.0% | 0.6% |
| 11 m/s | ≈45Hz | 16.0% | .6% |

Three different methods of harmonics mitigation of PMSG wind turbines were proposed by Reis, Tan and Islam. They are harmonic trap filters, a single-switch three-phase boost rectifier, and a three-phase boost-type PWM rectifier. The Passive Trap Filter (PTF) is related to the idea of harmonic elimination, as this kind of filter specializes in reducing the 5th and 7th harmonics order. Because wind speed varies in a real-life WECS and changes the generator voltage and frequency output, including a number of trap filters is crucial. A single-switch three-phase boost rectifier is a suitable option for implementing the input rectifier. This converter has many advantages, including a lower THD in the input current and easy manageability. The disadvantages of this scheme are that it needs an extra input capacitor for certain operations of the converter, and there are more power losses in the components [15].

The final approach is a three-phase boost-type PWM rectifier (AC-DC converter). This can work as a Power Factor Corrector (PFC) with a low THD at any operation point. The main advantage of this converter is its capability of bi-directional power flow, while its main disadvantage is that it needs six transistors.

Table 2-2 Current and voltage harmonics distortions in the PMSG wind turbine.

| Method 1<br>12 m/s | | Method 2<br>12 m/s | | Method 3<br>Any operation point | |
|---|---|---|---|---|---|
| TVHD | TIHD | TVHD | TIHD | TVHD | TIHD |
| 9.2 % | 2.25 % | 6.56 % | 3.28 % | - | 0.06 % |

In [16], a shunt active filter is used to improve power quality. Here, a new procedure was proposed by three researchers who presented a filter technique to reduce current harmonics in Wind Energy Conversion System (WECS). The WECS includes a PMSG, in addition to a wind turbine, a power electronics converter, and a grid. The filter is connected parallel with the stator part of the generator.

Hong et al. proposed a harmonic mitigation technique in a wind turbine-driven variable speed permanent magnet synchronous generator [17]. The technique (which is implemented in this work) utilizes passive filters, and the AC/DC/AC converter. A harmonic trap filter, is used for harmonic reduction of the PMSG output waveform. In order to investigate the harmonic trap filter best tuned frequency for the WECS, the Harmonic Trap Filter (HTF) was tuned to target at average wind speed (7m/s) and maximum wind speed (11m/s). A six-pulse rectifier is used to convert AC voltage to DC voltage. The filter performance of the two types of rectifiers considered in their paper (thyristor and diode) is examined. comparison between these two converters in terms of their total harmonic distortion level. It can be deduced that the thyristor rectifier control contributes higher distortion as compared to the rectifier as shown in Table 2-3.

Table 2-3 Current and voltage harmonics distortions in the PMSG wind turbine using two different converters.

| Average wind speed | Rectifier | | Thyristor | |
|---|---|---|---|---|
| 7 m/sec | Without filter | With filter | Without filter | With filter |
| TVHD | 16.28% | 5.94 % | 32.18 % | - |
| TIHD | 23.36% | 6.75 % | 30.01% | - |

## 2.4 Summary

This chapter presented various techniques for eliminating or reducing harmonics in WECs. As mentioned, the most popular filters for decreasing harmonics are active filters. The objective in using active filters is to reduce the Total Harmonics Distortion (THD) of the output voltage and current of the generator, thereby decreasing power losses in the system.

# Chapter 3 Wind turbine conversion systems

## 3.1 Introduction

As illustrated in Figure 3-1, a typical wind energy conversion system consists of four major components: the turbine, a generator, a power electronics controller, connected to the grid.

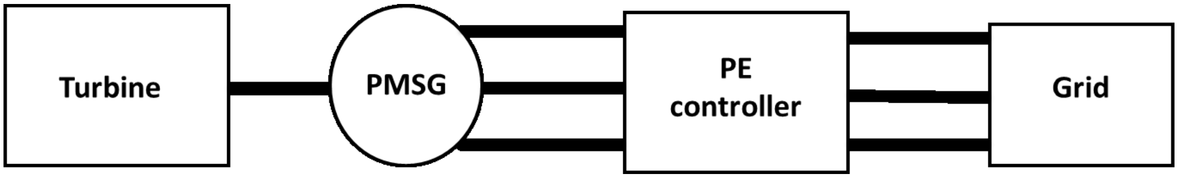


Figure 3-1 Generic model of a wind energy conversion system.

This chapter presents the details of a WECS, first providing an example of a wind turbine model and then showing the performance of the turbine. The generator model is briefly described, followed by a description of the converter system used in this model. Lastly, the represented equivalent of the grid is addressed.

## 3.2 Wind turbine model

The wind turbine converts the energy of the air (kinetic power) into useful energy in the form of electricity. This energy depends on the wind speed and other variables , such as the friction factor and power losses. A model of a wind turbine can be built simply using the following well-known equation [18]:

$$P_m = \frac{1}{2}\rho A V^3 C_p(\lambda, \beta) \qquad \text{3-1}$$

This equation shows the mechanical power extracted from the wind turbine.

where:

$\rho$ is the air density ( Kg/m$^3$).

A is the swept area.

V is the wind speed (m/s).

$C_p$ is the power coefficient.

$C_p$ depends on the Tip Speed Ratio (TSR) and blade pitch angle $\beta$.

It can also be briefly expressed by the following more detailed equation [19]:

$$C_p(\lambda,\beta) = 0.258\left(\frac{100}{\lambda_i} - 0.4\beta - 2.164\right) * e^{\left(\frac{-15.21}{\lambda_i}\right)+0..0057\lambda} \tag{3-2}$$

$C_p$ is defined (approximately) by using numerical calculations [19], where λ is the tip speed ratio (m/sec), which is a function of wind and rotor speeds, shown as follows:

$$\lambda = \frac{\omega R}{V} \tag{3-3}$$

$\omega$ is the rotational speed and $\lambda_i$ can be calculated as follows:

$$\lambda_i = \left[\frac{1}{\lambda + 0.008\beta} - 0.035\right]^{-1} \tag{3-4}$$

The maximum power coefficient, regardless of configuration, is 0.593, as the German physicist Albert Betz concluded [20]. Wind speed and energy decrease after passing rotor blades; therefore, in wind farms, the close proximity of turbines may have an effect on their performance.

### 3.3 The performance of wind turbines

The performance of any wind turbine is modeled by the relationship between the power coefficient Cp and TSR. This relationship is found by using the above equations on Simulink / Matlab. Below, an example of a wind turbine model has been designed and analyzed [21]. The wind turbine specifications are shown in Appendix 7. Figure 3-2 shows a generic model of wind turbines.

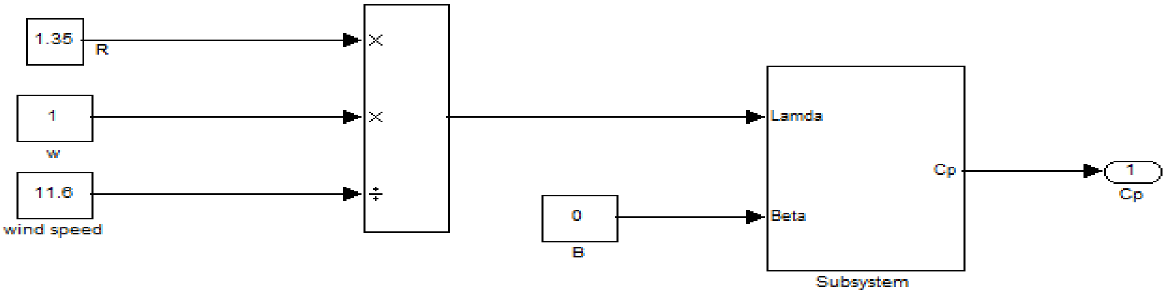


Figure 3-2 Wind turbine model.

If the tip speed ratio (TSR) is less than 3, the wake effect further reduces the maximum rotor power efficiency [6]. The can be calculated from the above equation. In our example, the maximum value of the power coefficient is 0.47 when the pitch angle is set to zero, as shown in Figure 3-2. The relationship between the TSR and the power coefficient is shown in Figure 3-3.

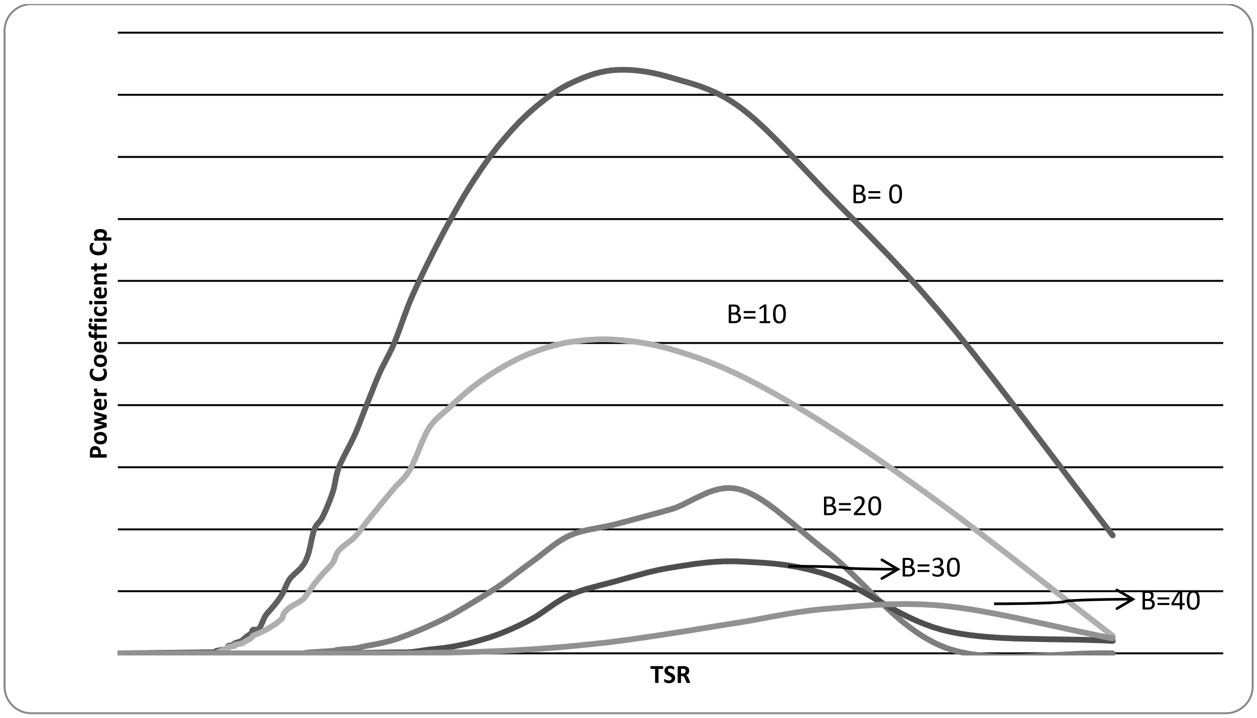


Figure 3-3 Cp vs TSR characteristics.

### 3.4 The generator model

The type of generator used in this thesis is a Permanent Magnet Synchronous Generator (PMSG). The PMSG contains two parts: the stator and the rotor. The stator part is also called the electrical portion, while the rotor part is known as the mechanical portion. The stator is connected to a three-phase load through an AC / AC converter and transformer. This type of the rotor is salient-pole.

The PMSG model is determined from the dq reference frame. The dq frame is two-phase synchronous, derived from a three-phase frame (abc). The dq reference frame of the PMSG model is given in the following equations [22]:

$$\frac{di_d}{dt} = -\frac{R_a}{L_d} i_d + \omega_e \frac{L_q}{L_d} i_q + \frac{1}{L_d} u_d \tag{3-5}$$

$$\frac{di_q}{dt} = -\frac{R_a}{L_q} i_q - \omega_e \left( \frac{L_d}{L_q} i_d + \frac{1}{L_q} \lambda_0 \right) + \frac{1}{L_q} u_q \tag{3-6}$$

where:

d, q denotes the physical quantities obtained from abc synchronous.

$R_a$: the armature resistance.

$\omega_e$: the electrical rotating speed.

$\lambda_0$: the permanent magnetic flux.

$L_d$ & $L_q$: the summation of the inductors of the generator on the d- and q-axis and the transformer's inductance L.

$u_d$ & $u_q$: the components of the output voltage of the power converter. The dq- reference frame circuit is shown in Figure 3-4.

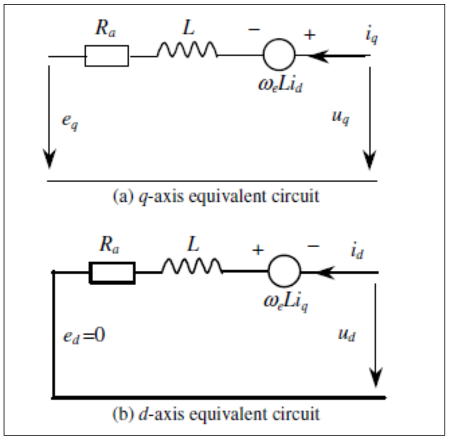


Figure 3-4 Equivalent circuit of PMSG in the synchronous frame [22].

### 3.5 Power electronics converter

Variable speed wind turbine systems use power electronic systems to extract power from generators as well as control frequency and voltage. Since wind turbines run at variable rotational speeds, the electric frequency of the generator varies depending on the wind speed. Therefore, it must be disconnected from the frequency of the grid, which can be done by using a power electronics converter system [23].

In this thesis, the power electronic used is a full converter that is divided into two stages: the AC/DC rectifier and the DC/AC inverter. The AC/DC rectifier, which will be discussed in the next subsection, is represented as a diode bridge. Another technique used to convert AC to DC is called a thyristor rectifier.

This section provides a brief description of a diode rectifier and its sub-types and also gives a brief description of thyristor rectifiers. A rectifier converts three-phase voltage into direct continuous voltage. A general block diagram of a rectifier is shown in Figure 3-5 [24].

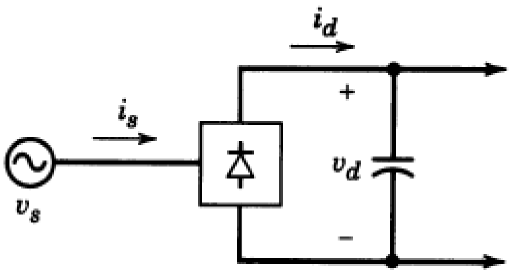


Figure 3-5 Block diagram of a rectifier [24].

The input power in most power electronic applications is provided by a voltage source in the form of 50- or 60-Hz converted to DC voltage and then transformed to another DC voltage level [24]. A control system for the DC/DC converter is used to maintain the rotor speed at 1 p.u [25].

The three most common types of diode rectifiers are single-phase, three-phase, and poly-phase. Single-phase diode rectifiers have two different forms: single-phase half-wave rectifiers, and single-phase full-wave rectifiers. Three-phase diode rectifiers are suitable only for low-to-medium power applications and are generally divided into star rectifiers and bridge rectifiers. The third type of diode rectifier is a poly-phase diode rectifier, of which there are three kinds: a six-phase star rectifier, a six-phase series bridge rectifier, and a six-phase parallel bridge rectifier. The first two of these three common types of rectifiers will be described briefly in the following subsections [26].

## 3.6 Diode Rectifiers

### 3.6.1 Single-phase diode rectifiers

These rectifiers have been commonly used in low-to-medium and medium-to-high power applications. A DC capacitor is connected to the conventional rectifier output, as illustrated in Figure 3-6. However, the input power factor that injects to these rectifiers is poor, allowing a high content of low-order harmonics to enter into the supply current, which can cause a number of problems in the other electrical components [27].

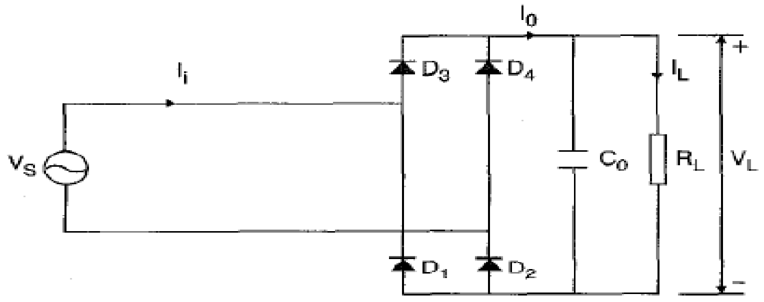


Figure 3-6 Conventional Single-Phase Diode Rectifier topology [27].

The two types of single-phase diode rectifiers are single-phase half-wave rectifiers and single-phase full-wave rectifiers. These filters convert a single AC voltage to DC voltage. The diodes are assumed to be ideal, in that they have zero forward voltage drop and reverse recovery time. In addition, in such cases, it is assumed that the load is purely resistive, such that the load voltage and the load current have similar waveforms [26].

### 3.6.2 Three-phase diode rectifiers

Three-phase diode rectifiers are used in power output that is higher than 15 kW. These rectifiers are divided into two types: star rectifiers and bridge rectifiers. For the sake of simplicity, the diodes and the transformers are considered to be ideal, in that the diodes have zero forward voltage drop and reverse current, and the transformers possess no resistance and no leakage inductance. Moreover, it is assumed that the load is purely resistive, such that the load voltage and the load current have similar waveforms [26].

One type of three-phase diode rectifier, shown in Figure 3-7, is a three-phase bridge rectifier.

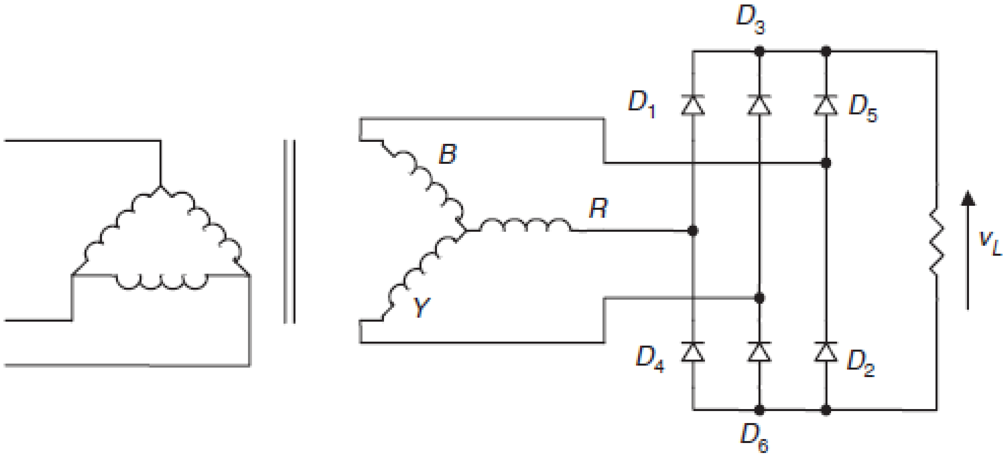


Figure 3-7 Three-phase bridge rectifier [26].

### 3.7 Thyristor rectifiers

Three-phase thyristor rectifiers have a wide range of applications, from small rectifiers to large High Voltage Direct Current (HVDC) transmission systems [28]. Thyristor rectifiers are also called SCR (Silicon Controlled Rectifiers). An SCR module is used to control and change AC to DC current and can be used like a mechanical switch (i.e., either on or off). When a current/voltage pulse is applied to the gate of a SCR, it will be 'switched' on and begin to conduct. The SCR will continue to conduct even when the gate current is completely removed. The SCR will turn off once the load current drops below zero [29].

### 3.8 Grid model

The grid model consists of a three-phase load. The three-phase load may be resistive, inductive, capacitive, or a mixture of the three types. In this thesis, a three-phase resistive load is fed from a wind turbine generator.

# Chapter 4 Harmonics analysis in power systems

## 4.1 Introduction

Although power systems are designed to run at frequencies of 50 or 60 Hz, certain components produce currents and voltages with frequencies that are different from the 50 or 60 Hz fundamental frequency. These higher frequencies are considered electrical pollution known as power system harmonics [30].

The most common harmonic sources are nonlinear and discontinuous loads, which are generally represented in power electronic converters such as diodes, thyristors, and switching power suppliers. There are two types of harmonics sources: Current-Source Nonlinear Loads (CSNLs) and Voltage-Source Nonlinear Loads (VSNLs). Thyristor converters cause harmonic current distortion, while diode converters are considered a source of harmonic voltage [31].

## 4.2 Harmonics fundamentals

Mathematically, harmonics describe a voltage or current (or both) waveform distortion. The term ‘harmonic’ denotes a component of a waveform that occurs at an integer multiple of the fundamental frequency, as mentioned above. Fourier theory states that any periodic waveform can be defined in terms of adding together sinusoidal waveforms that are integer multiples (or harmonics) of the fundamental frequency [32]. The Fourier series can be expressed as follows [33]:

$$f(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} (a_n \cos n\omega_0 t + b_n \sin n\omega_0 t) \tag{4-1}$$

where $\omega_0 = \frac{2\pi}{T_0}$ and the coefficients of the series are given as:

$$a_0 = \frac{2}{T_0} \int_{-T_0/2}^{T_0/2} f(t) dt \tag{4-2}$$

$$a_n = \frac{2}{T_0} \int_{-T_0/2}^{T_0/2} f(t) \cos n\omega_0 t \, dt \tag{4-3}$$

$$b_n = \frac{2}{T_0}\int_{-T_0/2}^{T_0/2} f(t)\sin n\omega_0 t\, dt \qquad \text{4-4}$$

$a_n$& $b_n$ are called the Fourier Coefficients of n$^{th}$ harmonics components and the coefficient $a_0$ is referred to as the DC component.

We can decompose 4-1 into many terms, as follows:

$$f(t) = \frac{a_0}{2} + (a_1 \cos \omega_0 t + b_1 \sin \omega_0 t) + (a_2 \cos 2\omega_0 t + b_2 \sin 2\omega_0 t) + \cdots.. \qquad \text{4-5}$$

The term $(a_1 \cos \omega_0 t + +b_1 \sin \omega_0 t)$ is known as the fundamental.

The term $(a_2 \cos 2\omega_0 t + b_2 \sin 2\omega_0 t)$ is called the second harmonic.

The term $(a_3 \cos 3\omega_0 t + b_3 \sin 3\omega_0 t)$ is called the third harmonic, and so on.

### 4.3 Harmonic number (n)

Harmonic number (n) denotes individual frequency elements that include a complex waveform. For example, n = 3 refers to the third harmonic component with a frequency equal to three times the fundamental frequency. If the fundamental frequency is 60 Hz, then the third harmonic frequency is 3 × 60, or 180 Hz. The harmonic number 4 is a component with a frequency of 240 Hz. The main aspect to keep in mind when dealing with harmonics is to deal with its numbers rather than its frequencies, for the following two reasons.

The fundamental frequency differs from one country to another. For example, the fundamental frequency in Canada is 60 Hz, whereas in Europe, Africa and many Asian countries, it is 50 Hz. Moreover, some applications employ other frequencies. For instance, 400 Hz is a common frequency in the aerospace industry, while some AC systems for electric traction use 25 Hz as the fundamental frequency. The inverter part of an AC adjustable speed drive can operate at any frequency between zero and its full-rated maximum frequency, and the fundamental frequency then becomes the frequency at which the motor is operating. The use of harmonic numbers easily allows us to know how we express harmonics. The second reason for using harmonic numbers is the simplification realized in performing mathematical operations involving harmonics [34].

### 4.4 Odd and even order harmonics

Odd and even harmonics are implied to odd numbers (e.g., 3, 5, 7, 9, 11) and even numbers (e.g., 2, 4, 6, 8, 10), respectively. The fundamental frequency component of a signal is referred by a harmonic number of 1, whereas the DC component is assigned to 0. The DC component is the net difference between the positive and negative halves of one complete waveform cycle [34].

### 4.5 Harmonics sources

Much of harmonics come from power electronic devices. Using these devices to control power apparatuses and systems has given rise to concerns about waveform distortion. A power electronic converter can be viewed as a matrix of static switches that provide a flexible interconnection between input and output nodes of an electrical power system. The most common power electronic aid is the single-phase rectifier, used to power most modern office and domestic appliances. Although the individual ratings are typically small, their combined effect can be an important source of waveform distortion [35]. Harmonic sources can be given as follows:

- Converters.
- Devices which include semi-conductor elements.
- Generators.
- Motors.
- Transformers.
- Lightening equipment working by gas discharge principle.
- Photovoltaic systems.
- Computers.
- Electronic ballasts.
- Uninterruptable power supplies.
- Switching power supplies.
- Welding machines.
- Control circuits.
- Frequency converters.
- Static Var compensators.
- Arc furnaces.
- HVDC transmission systems.
- Electrical Communication systems.

### 4.6 Harmonic Measurements

This section briefly introduces some of most common measurements that are important to a power system. Concerns about power system measurements are anticipated when collecting relevant data to assist in utility planning and operation. Issues may arise in a number of characteristics key to the high quality of transmission and distribution of electric energy. For instance, over the course of a day, loads vary in value in response to different demand patterns. Consequently, utilities switch capacitor banks on and off to keep the voltage profile within acceptable limits. Another example of measurements is related to protection system, which follows pre-built settings that allow protective devices to open as a response to large currents identified as faults [36].

Measuring harmonics in a power system is considered a major challenge, but the problem of harmonic source locations can be worse. The unfiltered higher-frequency components of current at harmonic-producing components can produce communication interference, high heating problems, false protective device tripping, and instability conditions on voltage regulation systems in synchronous generators [36].

As an example, the expected output waveforms of a generator are sinusoidal, but due to nonlinear loads in systems the waveforms will be distorted. Measuring waveform distortion provides some objectives to the electric grid. These objectives can be summarized as follows [36]:

- To verify that the order and magnitude of harmonic currents at the substation and at remote locations where customer harmonic sources may be affecting neighbouring installations.
- To compare the obtained parameters with recommended limits or planning levels.
- To find the resultant waveform distortion expressed in the form of spectral analysis.

Parameters, such as real, reactive, and total power energy, can be found using two quantities: voltage and current. Any measurements of harmonics would thus have to consider these quantities. As mentioned earlier in this chapter, distorted voltage and current waveforms can be expressed as a Fourier series.

## 4.7 Total Harmonic Distortion (THD)

THD is defined as the summation of all harmonics orders of current or voltage compared to the fundamental frequency component. A perfect sinusoidal waveform is 100%, and the fundamental frequency of the system is 50 or 60 Hz. Harmonic distortion is caused by the introduction of waveforms at frequencies in multiplies of the fundamental. For example, the 5th harmonic is five times the fundamental frequency (250 or 300 Hz). Total harmonic distortion is a measurement of the sum value of the waveform that is distorted and can be expressed as follows [37]:

$$THD = \frac{\sqrt{{V_2}^2 + {V_3}^2 + {V_4}^2 + \cdots {V_n}^2}}{V_1} * 100 \tag{4-6}$$

## 4.8 Harmonic filters

Passive filters are used more frequently than active filters. There are three main types of passive filters: single-tuned, double-tuned, and high-pass**.** [36]. Figure 4-1 illustrates the different types of passive filters. The C-type is a specific type of high-pass filter.

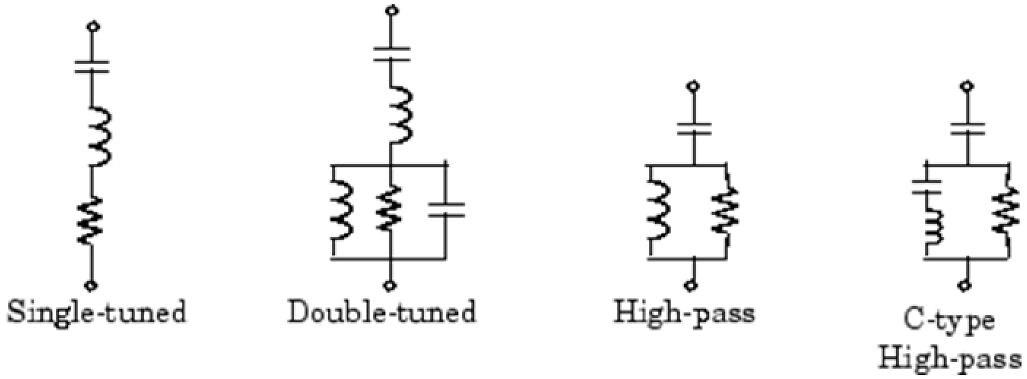


Figure 4-1 Different types of passive filters [38].

Three-phase harmonic filters are built of RLC elements. The resistance, inductance, and capacitance values are determined from the filter type and from the following parameters [38]:

- Reactive power at nominal voltage

- Tuning frequencies
- Quality factor. (The quality factor is a measure of the sharpness of the tuning frequency, determined by the resistance value.)

### 4.8.1 Single-tuned filters

Single-tuned filters present very low impedance at the tuning frequency, through which all currents of that particular frequency will be changed. Thus, passive filter designs must take into account expected growth in harmonic current sources or load reconfigurations because such a filter can be exposed to overloading, which can then rapidly develop into extreme overheating and thermal breakdown. Passive filters provide permanent reactive compensation to a degree dictated by the volt-ampere size and voltage of the extra capacitor bank used with them [36].

Single-tuned filters are the simplest filter type. The following equations provide practical formulae for computing their reactive power, $Q_c$, and active power losses, P. The quality factor, Q, of the filter is the quality factor of the reactance at the tuning frequency and can be expressed as [38]:

$$Q = \frac{nX_l}{R} = \frac{X_c}{nR} \tag{4-7}$$

where

$X_l$ is the inductor reactance at the fundamental frequency, n is the harmonic order, R is the resistance of the filter, and $X_c$ is the capacitor reactance at the fundamental frequency.

The tuned harmonic order is given in Equation 4-8:

$$n = \frac{f_n}{f_1} = \sqrt{X_c/X_l} \tag{4-8}$$

where $f_1$ is the fundamental frequency.

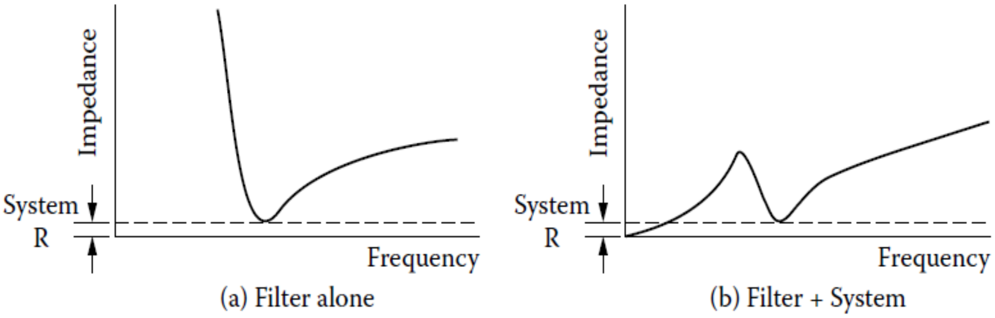
The reactive power, $Q_c$, is calculated as follows:

$$Q_c = \frac{V^2}{X_c} * \frac{n^2}{n^2 - 1} \qquad 4\text{-}9$$

where V represents the line-to-line voltage of the generator. The active power at the fundamental frequency is represented as follows:

$$P = \frac{Q_c}{Q} * \frac{n}{n^2 - 1} \qquad 4\text{-}10$$

The impedance-frequency relationship of this filter is illustrated in Figure 4-2, showing that the system impedance must be greater than the filter impedance at the tuning frequency. In low-voltage systems in which ratio X/R is small, an individual filter may suffice to provide the required reduction. A resistive component with a theoretical zero resistance would make the filter absorb the entire harmonic current of frequency equal to the tuning frequency of the filter. Sometimes a series resistive component is included to control the maximum current allowed through the filter [36].



(a) Filter alone

(b) Filter + System

Figure 4-2 Frequency response of a single-tuned harmonic filter [33].

### 4.8.2 Double-tuned filters

The conventional double-tuned filter has two resonance circuits. The first circuit contains a reactor and capacitor, connected in a series. In addition to having a reactor and a capacitor, the second circuit is resistant but connects in parallel, as shown in Figure 4-1. Figure 4-3 illustrates the structure and frequency impedance characteristic curve of a traditional double-tuned filter [39].

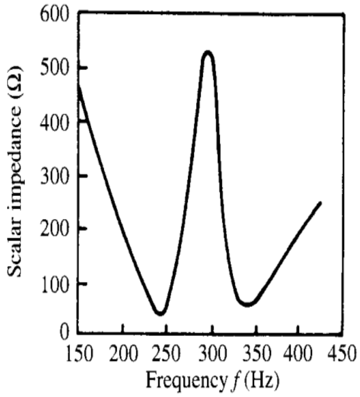


Figure 4-3 Impedance vs frequency response curve [32].

If $\omega_1$ and $\omega_2$are the two tuning frequencies, both the series circuit and the parallel circuit are tuned to approximately the mean geometric frequency, which is given in Equation 4-11:

$$f_m = \sqrt{f_1 f_2} \tag{4-11}$$

The quality factor, Q, of the double-tuned filter is calculated as the quality factor of the parallel L, R elements at the mean frequency, $f_m$

$$Q = \frac{R}{L.2\pi.f_m} \tag{4-12}$$

### 4.8.3 High-pass filter

A high-pass filter is similar to a single-tuned filter, but the L and R elements are connected in parallel instead of in a series. This connection results in a wide-band filter whose impedance at high frequencies is limited by the resistance, R [38]. Moreover, the quality factor of the high-pass filter is the quality factor of the parallel RL circuit at the tuning frequency:

$$Q = \frac{R}{L * 2\pi * f_n} \tag{4-13}$$

A C-type high-pass filter is a special type of high-pass filter, whose inductance, L, is changed to a series LC circuit, tuned at the fundamental frequency. This type of high-pass filter is used to reduce lower harmonic orders (e.g., 3rd and 5th) in the system.

As a type of band-pass filter, high-pass filters are easily identified by their small impedance value above the corner frequency. The impedance-frequency response of a high-band pass filter is illustrated in Figure 4-4.

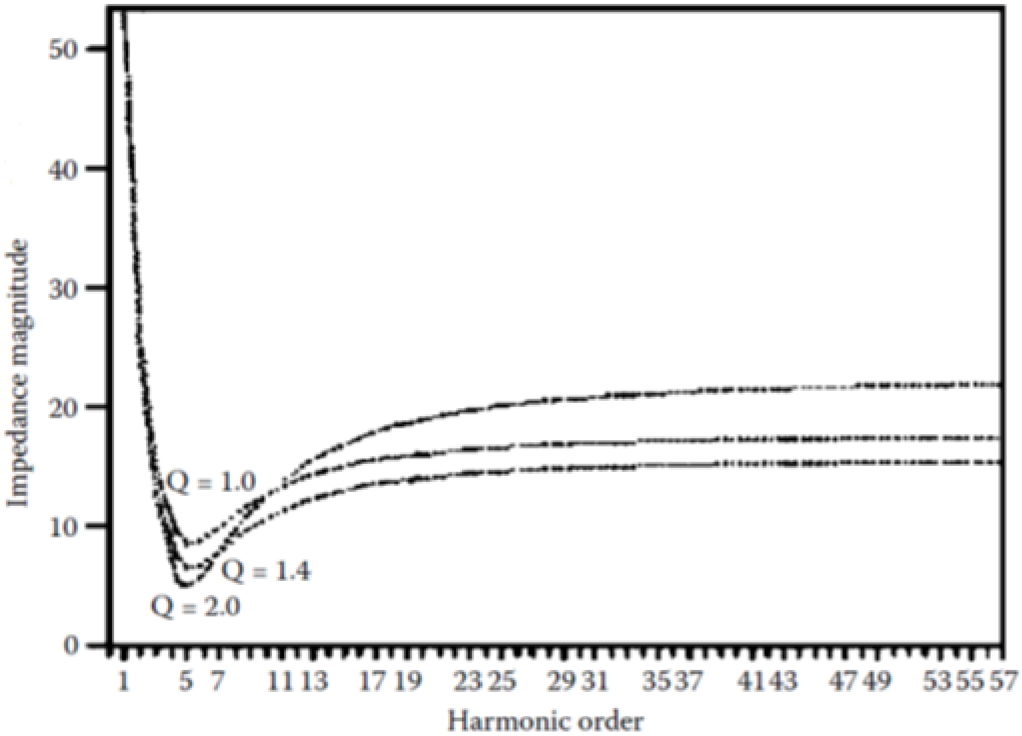


Figure 4-4 Response of a high-pass filter to different Qs [33].

As we can see from figure 4-4, the resistance, R, is decreased when the quality factor increases. At all Q values, resistance will be small. For instance, when Q is equal to 1, the resistance would be around 10 ohms.

# Chapter 5 Modeling and simulating a wind energy conversion system

## 5.1 Introduction

In Chapters 3 and 4, we discussed the wind energy conversion system along with the PMS generator and harmonics. In this chapter, we consider the problem of improving the power quality of an electric system by connecting a passive filter in parallel with the generator to reduce harmonics in the WECS. The entire model is simulated and studied by using the wind turbine toolbox in Matlab [40]. Furthermore, the model is tested at a wind speed of 8 m/sec.

## 5.2 The simulated model

In this section, distributed generation based on a stand-alone wind energy conversion system (WECS) including PMSG is simulated, with the model shown in Figure 5-1. This is an 8 MW wind turbine connected to a PMSG through an AC/DC/AC converter and 575/100 V transformer to a three-phase resistive load (300 Ω).

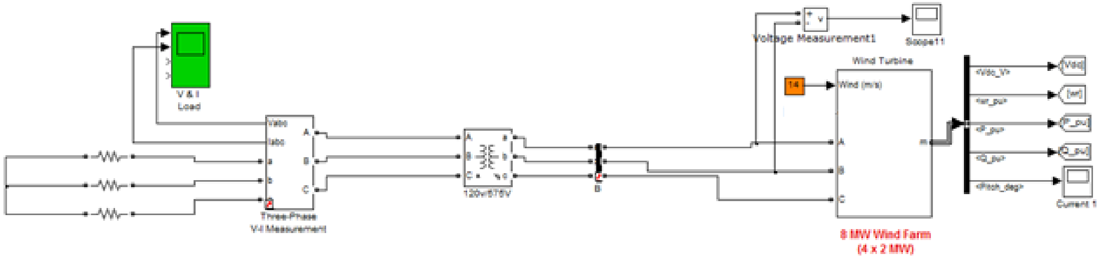


Figure 5-1 The simulated model.

The wind farm consists of 8 MW turbines connected to the generator. The stator part of the generator (called the armature) is directly linked to a diode rectifier, the DC/DC boost IGBT, and the DC/AC inverter, as shown in Figure 5-2. The rotor is a salient-pole type and is used as the field.

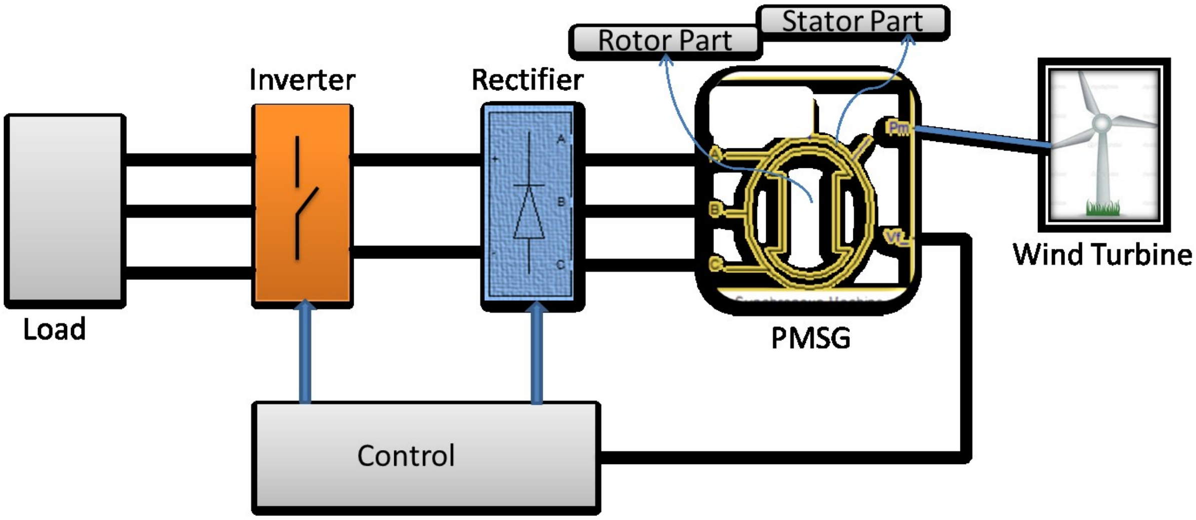


Figure 5-2 Wind turbine connected to the PMSG.

## 5.3 Diode rectifier configuration

To investigate the harmonic distortion level, the first stage of WECS was considered. The first stage of the converter is a three-phase diode rectifier, as shown in Figure 5-3. The diode rectifier block implements a bridge of selected power electronic devices, and Series RC snubber circuits are connected in parallel with each switching device. The universal bridge has three arms, each of which consists of either one or two power switches connected in a bridge configuration. The type of power switch and converter configuration can be selected from the dialog box of rectifier.

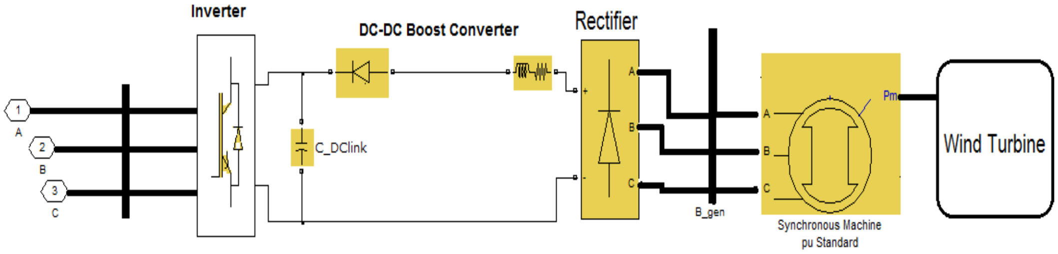


Figure 5-3 Rectifier converter configuration.

## 5.4 Thyristor rectifier configuration

Another stage of the converter is a three-phase thyristor rectifier. A configuration of this type is shown in Figure 5-4. The difference between this type of rectifier and the previous one is the presence of a firing angle. This angle can be determined by using a PI controller at the converter's output, as illustrated in [41], or by changing the angle with different values, as was done in [38]. In this thesis, we assume that the firing angle is set at 40.

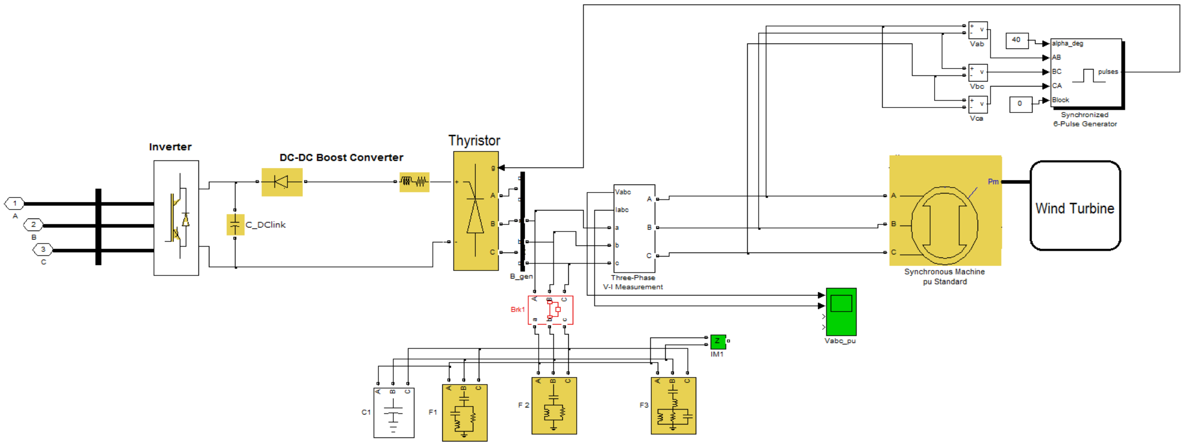


Figure 5-4 Thyristor rectifier configuration.

## 5.5 The approach

All power systems contain harmonics in their components due to the presence of nonlinear loads. In the model, which has been simulated in a normal situation, we find that there are harmonics in the generator through the output voltage and current waves. The harmonics orders found in this system are mostly 3rd, 5th, 7th, 11th, and 24th. So, we try to improve the Total Harmonic Distortion (THD) by adding a three-phase filter in parallel with the generator side through a circuit breaker. Here, we consider two types of these filters, as follows [38]:

1. Band-pass filters

Band-pass filters are divided into two types (single-tuned and double-tuned), based on their number of frequencies. These filters are used to remove lowest-order harmonics, from the 5th to the 13th.

2. High-pass filter

High-pass filters are used to filter high-order harmonics and cover a wide range of frequencies. The C-type high-pass filter is a special type of high-pass filter which can be used to deliver reactive power and prevent parallel resonances. This type is designed to remove low order harmonics (e.g., 3rd).

### 5.6 The three-phase harmonic filter

The three-phase harmonic filter is built of RLC elements, with resistance, inductance, and capacitance values determined from the filter type and the following parameters:

- Reactive power at nominal voltage.
- Tuning frequencies.
- Quality factor. (The quality factor is a measure of the sharpness of the tuning frequency, determined by the resistance value.)

Three-phase harmonic filters are shunt elements used to reduce voltage and current distortion and for power factor correction. The resulting distorted currents flowing through the system impedance produce harmonic voltage distortion. Harmonic filters reduce distortion by diverting harmonic currents to low impedance paths. These filters are considered to be capacitive at a fundamental frequency and thus will also produce the reactive power required by the converters [42].

### 5.7 The harmonics filtering method

The harmonics found in this system fluctuate between the 3rd and the 24th. Therefore, our approach is to try two different combinations of harmonic filters to connect to the generator. The first combination contains double-tuned filters, C-type high-pass filters, and high-pass filters (HPF), due to their abilities to work in these frequency ranges. Secondly, three filters are connected in parallel to the generator. They are single – tuned, double – tuned and high – pass filters. We will use those combinations with diode rectifier and thyristor rectifier converters.

Before selecting the filter, the impedance vs. frequency of the harmonics is determined. This is shown in Figure 5-5. As can be seen, the impedance of the three-phase filters at the system frequency (60 Hz) is 0.001 ohms with $(-90^0)$ phase angle. The following equation can be used to compute the total reactive power provided by filters [42].

$$Q_c = \frac{V^2}{X_c}$$

where:

$Q_c$ is the total reactive power of the filters.

V is the phase-to-phase voltage of the generator, equal to 730 volts.

$X_c$ is capacitor reactance at a fundamental frequency (60 Hz)

In order to minimize the total harmonic distortion, we evaluated the best parameters. The filter designed in this thesis consists of the following four components:

- One capacitor bank.
- One high-pass filter tuned to the 24th harmonic order.
- One double-tuned filter of the 11/13th harmonics orders.
- One C-type high-pass filter tuned to the 3rd harmonic order.

Each component provides a negative reactive power, as follows:

$$Q_c = \frac{V^2}{X_c} = \frac{730^2}{0.001} = 532.9\ Mvar$$

Assuming four identical capacitors, each will supply 133.22 Mvar (we will use a Single – tuned filter instead of C- type high pass in method 2).

So, the final setting of filters is

1. One capacitor bank of 133.22 Mvar.
2. One C-type high-pass filter (133.22 Mvar).
3. One double-tuned filter (133.22 Mvar).
4. One high-pass filter (133.22 Mvar).
5. Single – tuned filter (133.22 Mvar).

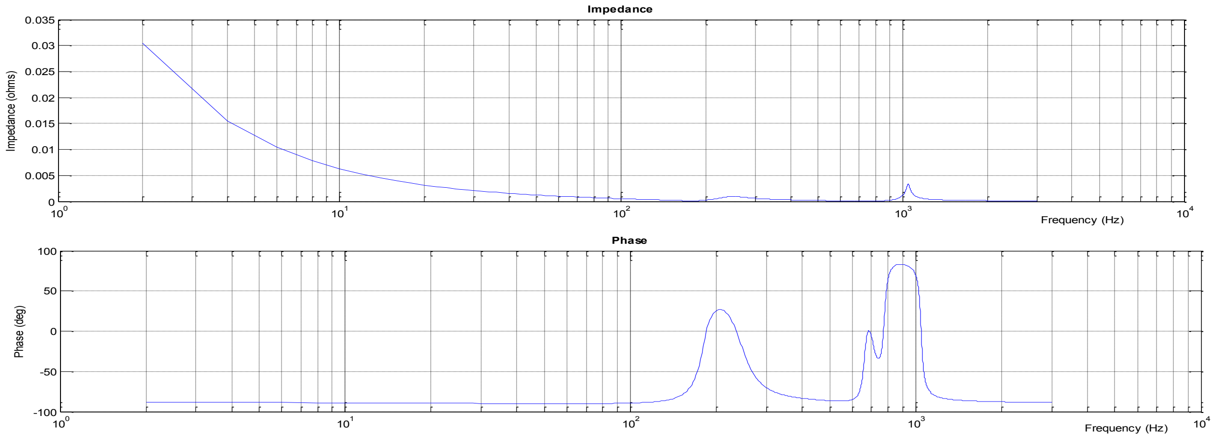


Figure 5-5 Frequency-Domain Response.

Next, we will calculate the parameters of each type of filter used.

1. Double-tuned filter

The tuned frequencies of this filter are 660 and 780 Hz. Figure 2 shows the impedance vs. frequency of a double-tuned filter. At the fundamental frequency of 60 Hz, the impedance is equal to Z = - j 0.004 ohms, which represents the capacitor reactance, Xc. The impedances at the tuned frequencies are given as follows:

$$z = 0.0005 - j0.004\, ohms \;\rightarrow f_1 = 660\, Hz, n = 11$$

$$z = 0.0003 - j0.004\, ohms \;\rightarrow f_2 = 780\, Hz, n = 13$$

where n is the harmonic order.

These impedances represent resistances. Therefore, we could calculate the quality factor Q by using the following equation:

$$Q = \frac{X_c}{nR} = \frac{0.004}{11 * 0.0005} = 0.722 \;\cong 1$$

Or

$$Q = \frac{X_c}{nR} = \frac{0.004}{13 * 0.0003} = 1.025 \;\cong 1$$

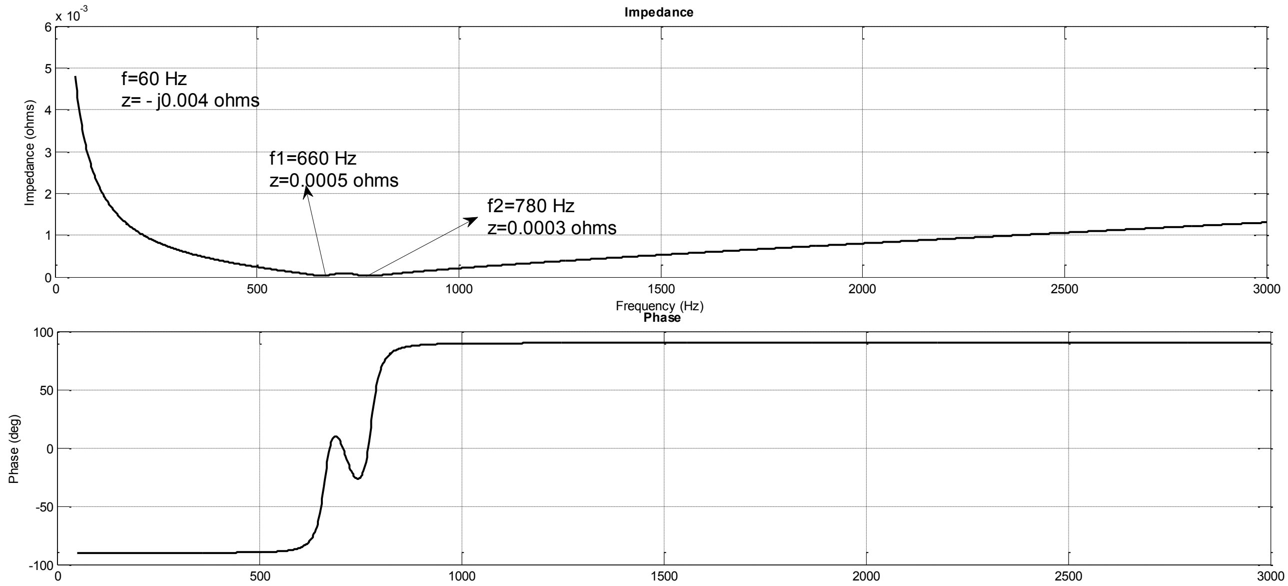


Figure 5-6 The impedance vs. frequency of the double-tuned pass filter.

The parameters of the filter will therefore be as follows:

| | |
|---|---|
| Reactive power (Mvar) | 133.22 |
| Tuning frequencies (Hz) | [11*60 13*60] |
| The quality factor Q | 1 |

2. High-pass filter

The tuned frequency of the high-pass filter is 1440 Hz. Figure 3 shows the impedance vs. frequency of this filter. At the fundamental frequency of 60 Hz, the impedance is equal to Z = - j 0.004 ohms, which represents the capacitor reactance, Xc. The impedance at the tuned frequency is obtained as follows:

$$z = 0.00002 - j0.004\, ohms \ \rightarrow f_1 = 1440\, Hz, n = 24$$

We can thus calculate the quality factor, Q, by using the following equation:

$$Q = \frac{X_c}{nR} = \frac{0.004}{24 * 0.00002} = 8.333 \ \cong 8$$

The parameters of the filter will be as follows:

|  |  |
|---|---|
| Reactive power (Mvar) | 133.22 |
| Tuning frequencies (Hz) | [24*60] |
| The quality factor (Q) | 8 |

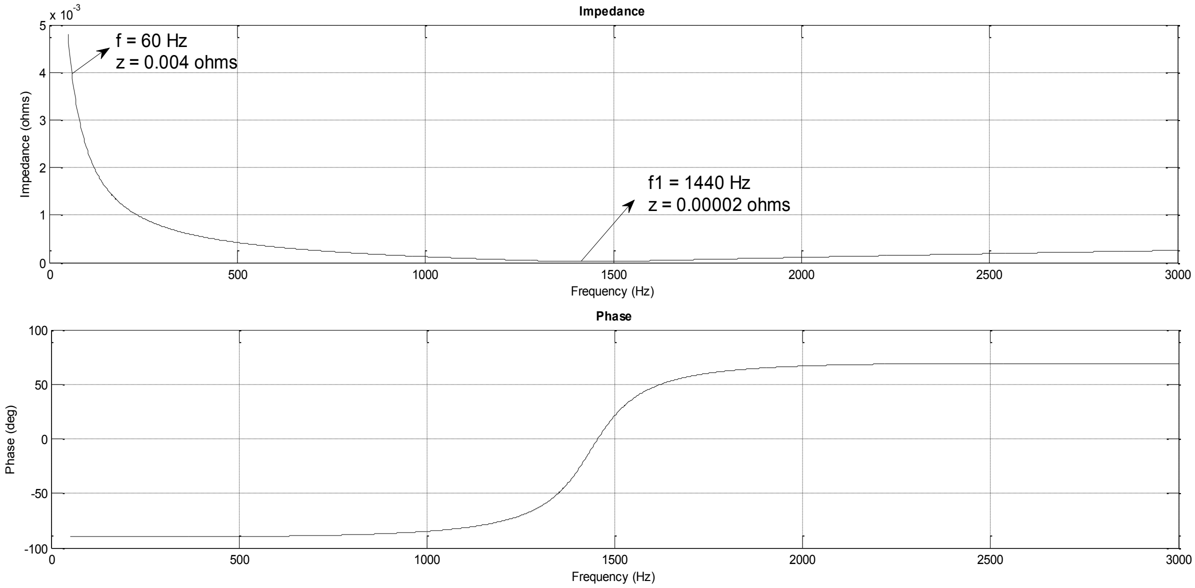


Figure 5-7 Impedance vs. frequency of a high-pass filter.

3. C-type high-pass filter

The tuned frequency of the C-type high-pass filter is selected as 180 Hz. Figure 5-8 shows the impedance vs. frequency of this filter. At the fundamental frequency of 60 Hz, the impedance is equal to Z = - j 0.004 ohms, which represents the capacitor reactance, Xc. The impedance at the tuned frequency is obtained as follows:

$$z = 0.00025 - j0.004\ ohms\ \rightarrow f_1 = 180\ Hz, n = 3$$

This impedance represents resistance. We can therefore calculate the quality factor, Q, by using the following equation:

$$Q = \frac{X_c}{nR} = \frac{0.004}{3 * 0.00025} = 5.333 \cong 5$$

The parameters of the filter will be as follows:

| | |
|---|---|
| Reactive power (Mvar) | 133.22 |
| Tuning frequencies (Hz) | [3*60] |
| The quality factor (Q) | 5 |

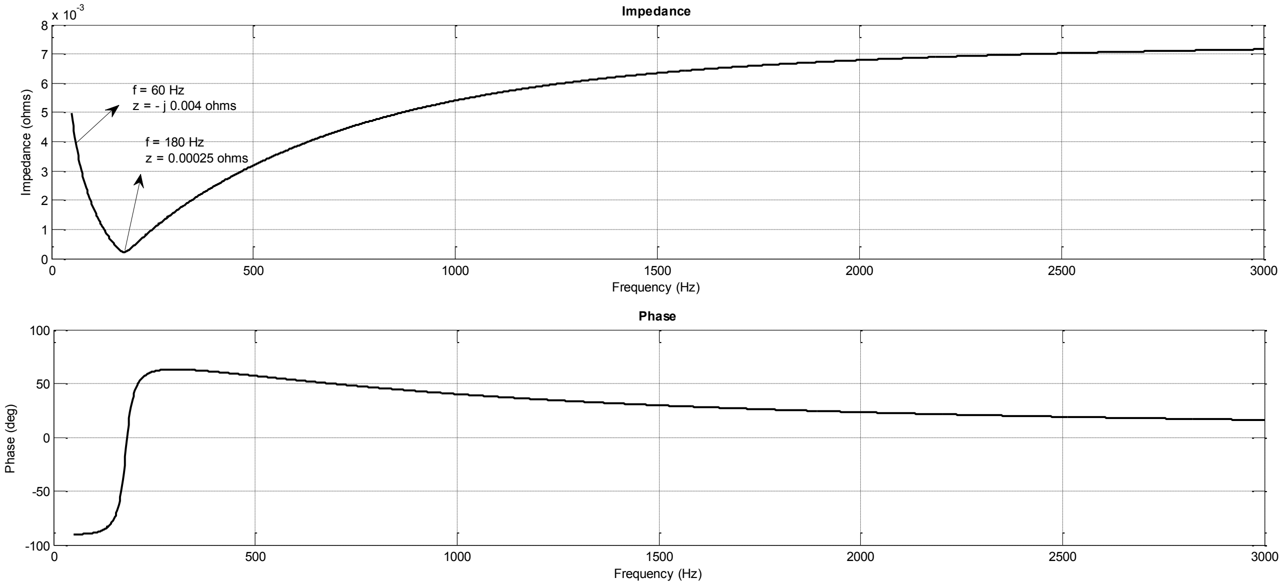


Figure 5-8 Impedance vs. frequency of a C-type high-pass filter.

4. Single – tuned filters

The tuned frequency of single – tuned filter is selected to be 300 Hz. Figure 5-9 shows the impedance vs. frequency of this filter. At the fundamental frequency of 60 Hz, the impedance is equal to Z = - j 0.005 ohms, which represents the capacitor reactance, $X_c$. The impedance at the tuned frequency is obtained as follows:

z=0.0005-j0.005 ohms →f=300 Hz,n=5

$$Q = \frac{X_c}{nR} = \frac{0.005}{5 * 0.0005} = 2$$

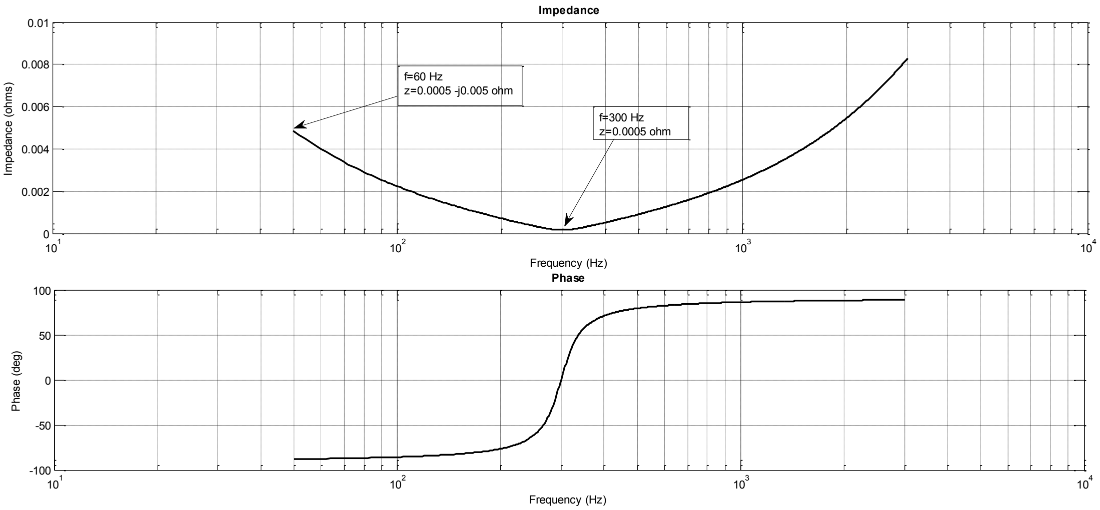


Figure 5-9 Impedance vs. frequency of a single - tuned filter

# Chapter 6 Results and discussions

## 6.1 Introduction

In this chapter, we discuss three cases of harmonics filtering. The first case is to simulate the system without having three phase filters. Secondly, we simulate the system with having one stage of three ohase filters. The third case is to simulate the system with having two stages of three phase filters. The output voltage and current generator signals are presented and analyzed. Results are compared and discussed using two different converters.

## 6.2 Case 1: Harmonics analysis of the model without placing three phase filters

Figure 6-1shows a wind turbine connected to the PMSG, feeding a three-phase resistive load throughout a full converter is studied at wind speed of 8 m/sec. Filters are not connected in this case as the circuit breaker is open. Simulations are conducted to find harmonics in the generator using a three-phase diode rectifier and three-phase thyristor rectifier to convert the variable voltage into a direct voltage. We will find the voltage and current harmonics by implementing Fast Fourier transform tool (FFT) in Matlab.

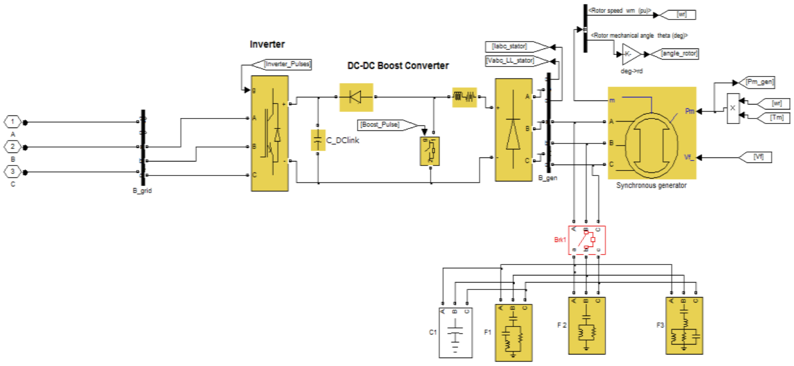


Figure 6-1 Three-phase harmonics filters configuration unconnected to the generator side.

### 6.2.1 Using diode rectifier converter

The operational region of WTG was simulated at wind speed of 8 m/. The output current and voltage waveform from the generator were obtained to find analysis purposes at the operational wind speed.

Figure 6-2 shows the distorted generator voltage output due to AC/DC diode rectifier, while Figure 6-3 shows the distorted generator current output due to harmonics in the overall model (WECS). It appears as if there are many harmonics passing through the generator. To find the harmonics, the Fast Fourier Transform is applied to these signals by using a Matlab function of FFT to calculate the order harmonics and the THD.

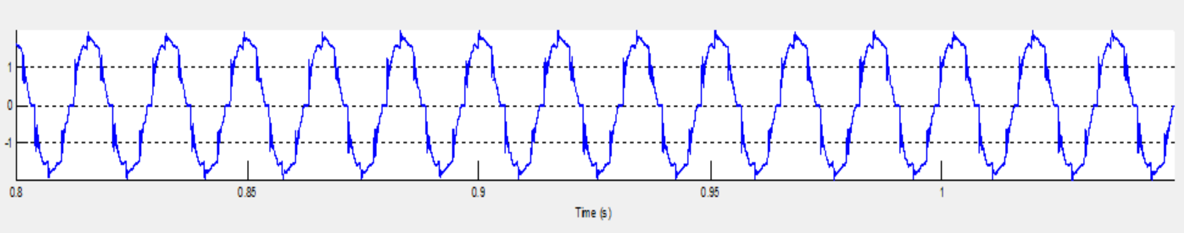


Figure 6-2 Generator voltage output signal when using diode converter(without placing filters)

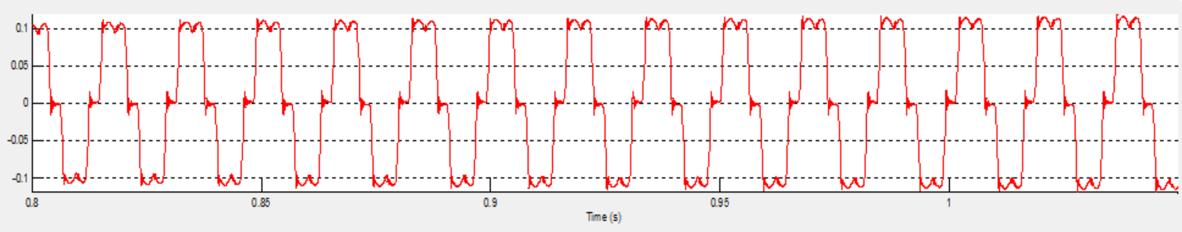


Figure 6-3 Generator current output signal when using diode converter(without placing filters)

Figure 6-4 shows the detailed harmonics content of the generator voltage signal, while Figure 6-5 presents a detailed harmonics content of the generator current signal. The amplitudes of the $5^{th}$ and $7^{th}$ harmonics are 16.5% and 11% of the fundamental component, respectively, which is greater than the allowed limit (10%) set by the IEEE 519 standard [43]. We can observe from the figures that the harmonic orders of the 5th, 7th, 11th, 13th and 17th are significant. The total harmonic distortion obtained for the output voltage and current is THD=4.17 % and 7.55 %, respectively, which is considered high. Therefore, we attempt to lower these percentages by using a three-phase harmonic filter.

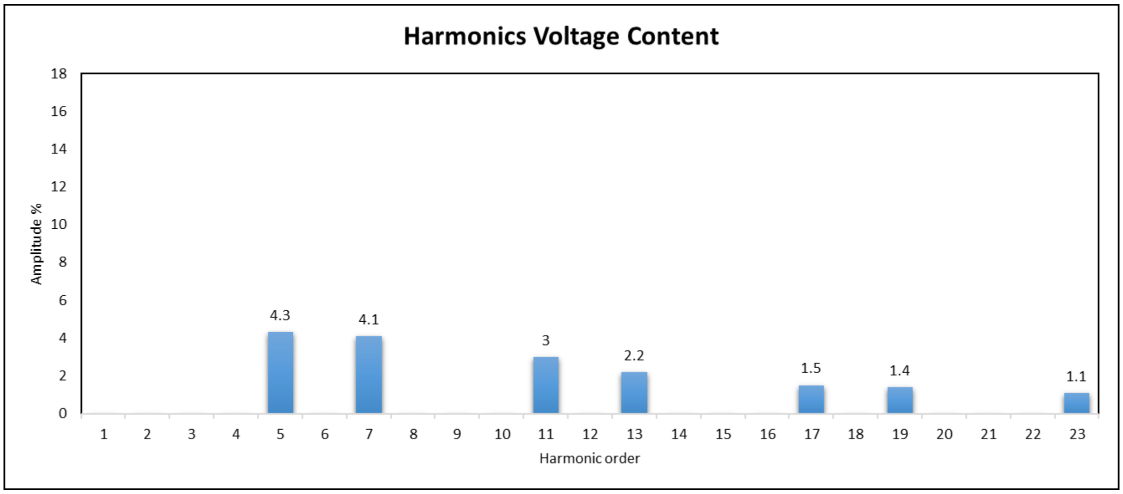


Figure 6-4 Harmonics content of the generator output voltage when using diode converter (without placing filters)

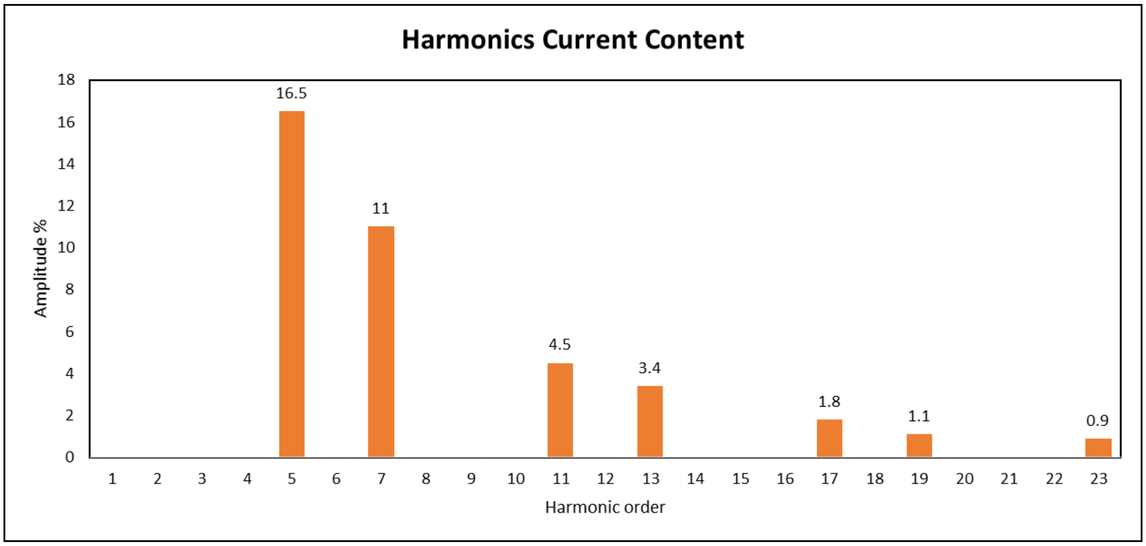


Figure 6-5 Harmonics content of the generator output current when using diode converter (without placing filters)

### 6.2.2 Using thyristor rectifier converter

Figure 6-6 illustrates the distorted generator phase A voltage output due to AC/DC thyristor rectifier, while Figure 6-7 shows the distorted generator phase A current output due to harmonics in the entire model (WECS). As shown in the figures, they are slightly distorted, especially the current waveform. Based on these distorted signals, there appear to be much harmonic contents passing through the generator. Fast Fourier Transform is applied to these signals by using a Matlab function of FFT to calculate the order harmonics and the THD.

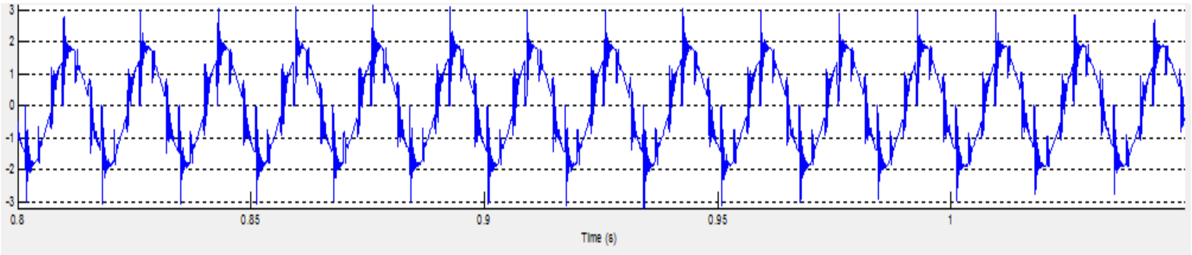


Figure 6-6 Generator voltage output signal when using thyristor converter (without placing filters)

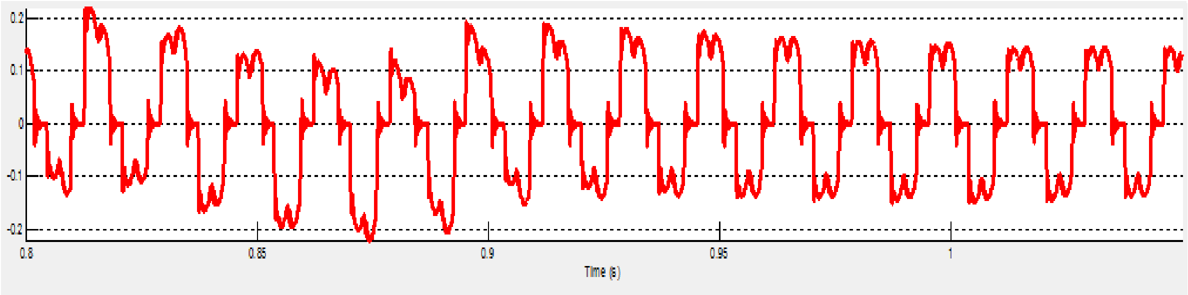


Figure 6-7 Generator current output signal when using thyristor converter(without placing filters)

Figure 6-8 presents a detailed harmonics content of the generator voltage content. The amplitudes of the 5th and 7th voltage harmonics are 7.8 % and 2.6 % of the fundamental component, respectively. Figure 6-9 shows a detailed harmonics content of the generator current output. The amplitudes of the 5th and 7th voltage harmonics are 22.6

% and 6 % of the fundamental component, respectively. In this case, the 5th order is greater than the allowed limit (10%) set by the IEEE 519 standard, while the 7th exceeds the IEEE limit. We can observe from theos figures that the harmonic orders of the 5th, 7th, 11th, 13th and 17th are significant. The obtained total harmonic distortion for the output voltage and current is THD=11.16 % and 23.85 %, respectively, which is considered higher than THVD and THID when the diode is in operation.

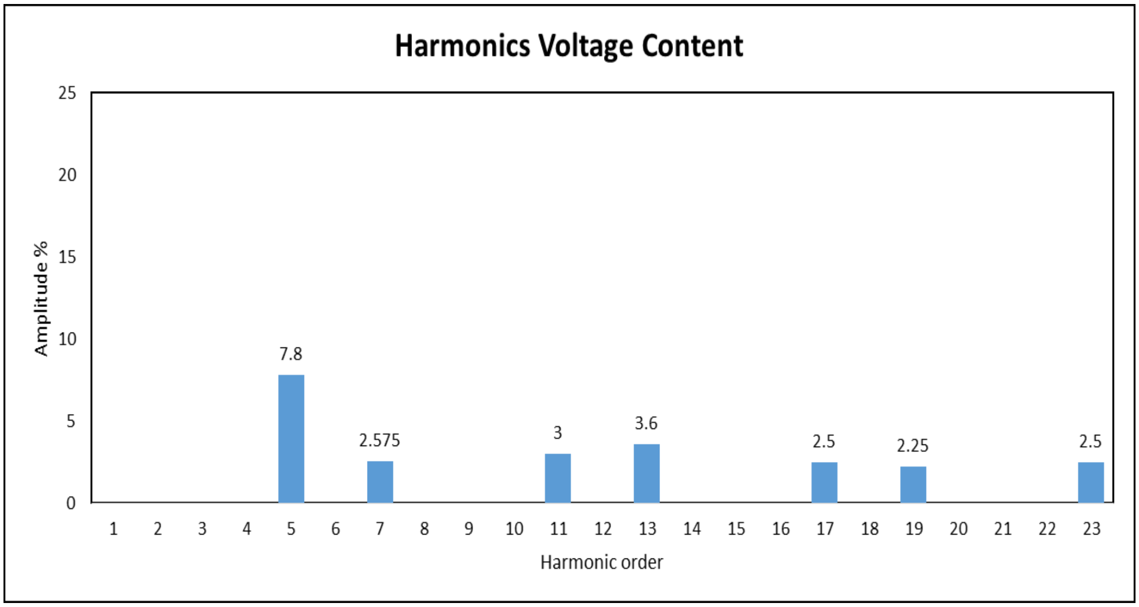


Figure 6-8 Harmonics content of the generator output voltage when using thyristor converter (without placing filters)

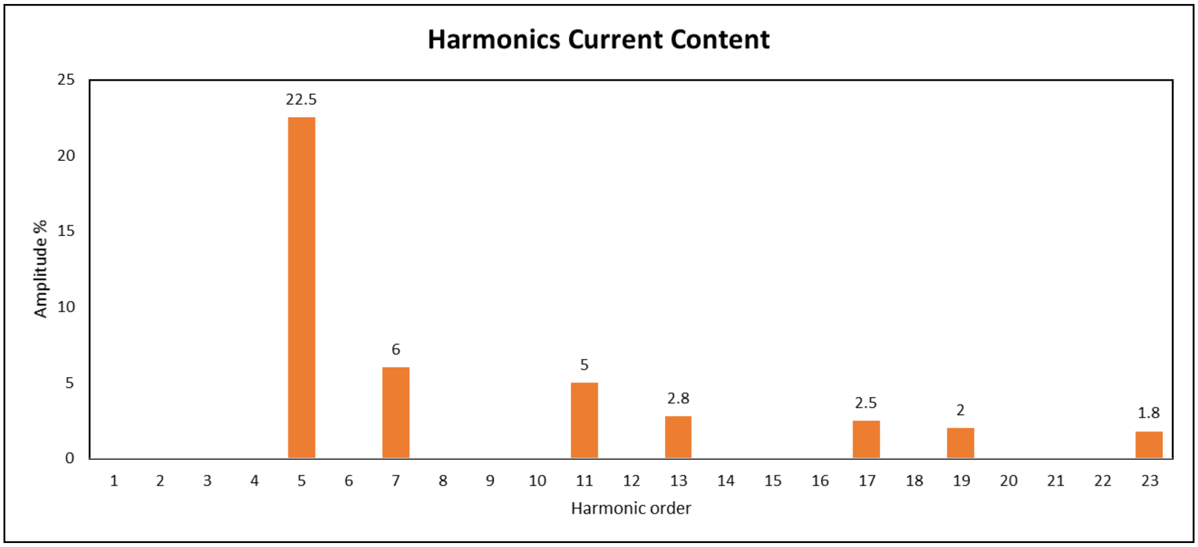


Figure 6-9 Harmonics content of the generator output current when using thyristor converter (without placing filters)

## 6.3 Case 2: Harmonics analysis of the model with having one stage of three phase filters

In this case, the filters are connected as the circuit breaker is closed. Figure 6-10 shows a wind turbine connected to the PMSG, feeding a three-phase resistive load throughout a full converter is studied at wind speed of 8 m/sec. Simulations are conducted to find harmonics in the generator using a three-phase diode rectifier and three-phase thyristor rectifier to convert the variable voltage into a direct voltage. We will find the voltage and current harmonics by implementing Fast Fourier transform tool (FFT) in Matlab.

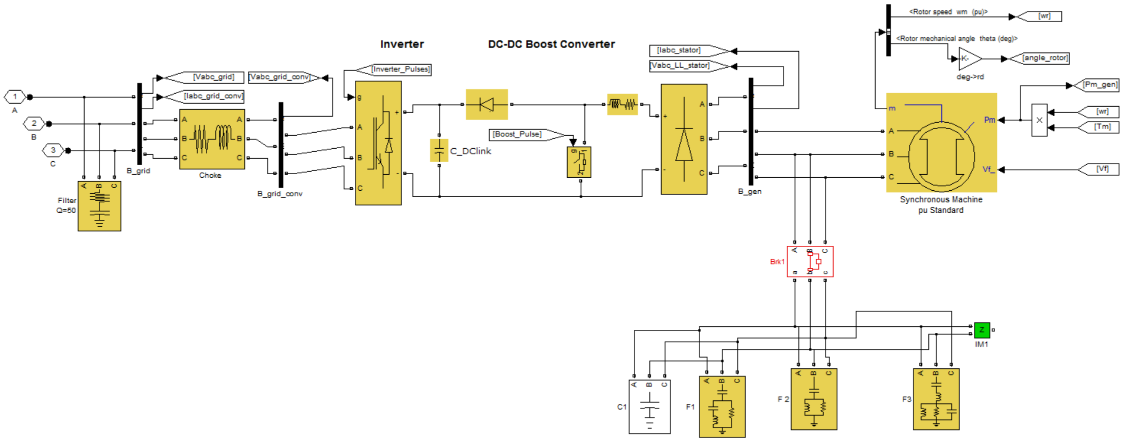


Figure 6-10 Three-phase harmonics filters configuration connected to the generator side.

### 6.3.1 Using diode rectifier converter

After deploying the filters, the voltage and current harmonics are considered a sine wave form. Figure 6-11 illustrates the improved generator voltage output due to AC/DC diode rectifier, while Figure 6-12 shows the improved generator current output due to harmonics in the entire model (WECS).The calculated THD for the improved voltage and current waveforms decreased from 4.17 % to 0.79 % and from 7.55 to 0.75% in raw calculation. We get improvments in both THVD and THID for this method comparing with the first one.

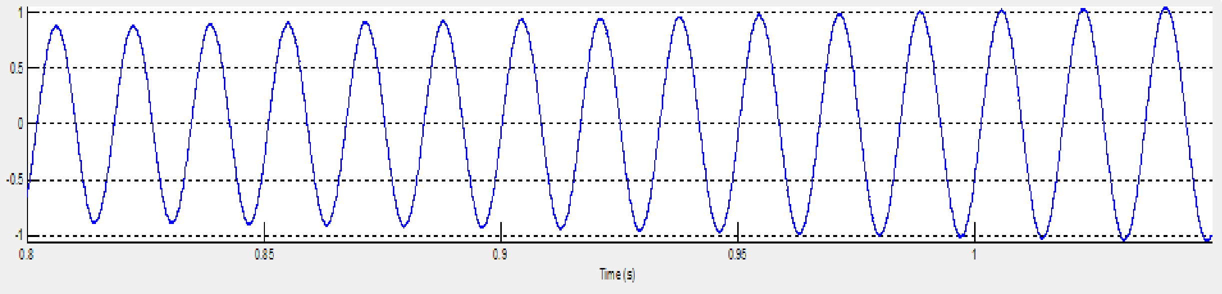


Figure 6-11 Generator voltage output signal when using diode converter(with having one stage of filters)

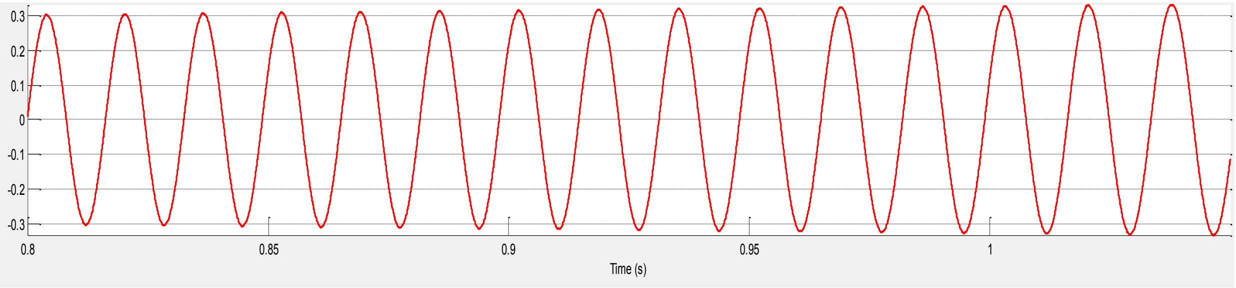


Figure 6-12 Generator current output signal when using diode converter(with having one stage of filters)

Figure 6-13 shows a detailed harmonics content of the generator voltage content with one stage of filters, while Figure 6-14 presents a detailed harmonics content of the generator current output. The amplitudes of the $5^{th}$ and $7^{th}$ current harmonics are decreased from 16.5% to 0.184 % and from 11% to 0.13 % of the fundamental component, respectively.We can observe from theos figures that the harmonic orders of the 5th, 7th, 11th, 13th and 17th are considered low. The obtained total harmonic distortion for the output voltage and current is 0.79 % and 0.75 %, respectively, which is considered not high.

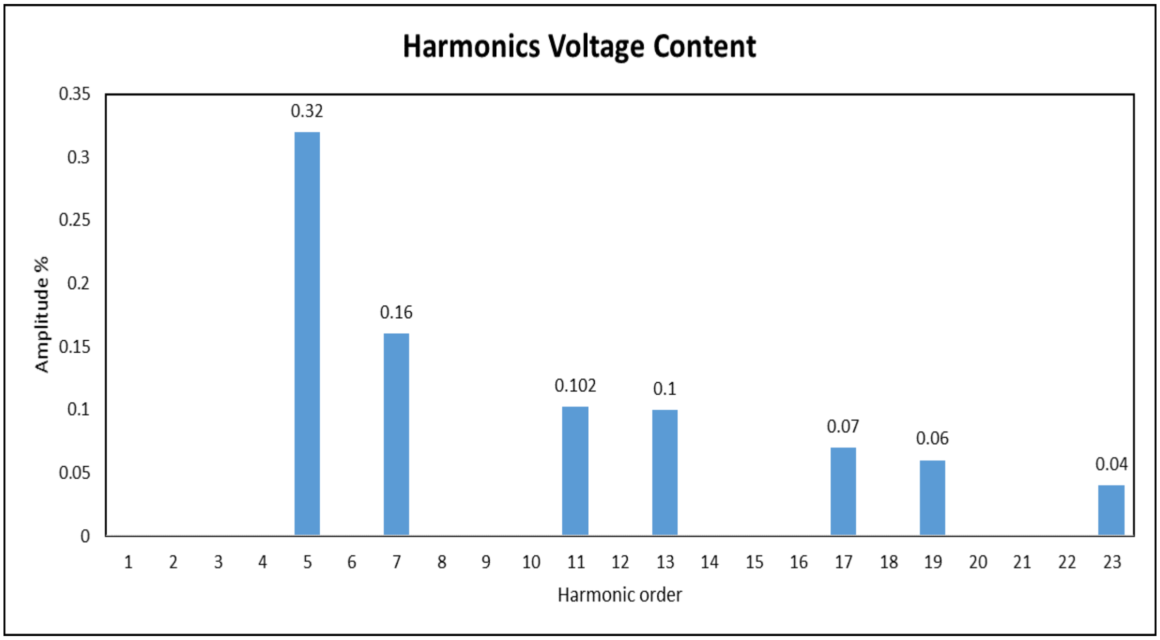


Figure 6-13 Harmonics content of the generator output voltage when using diode converter (with placing one stage of filters)

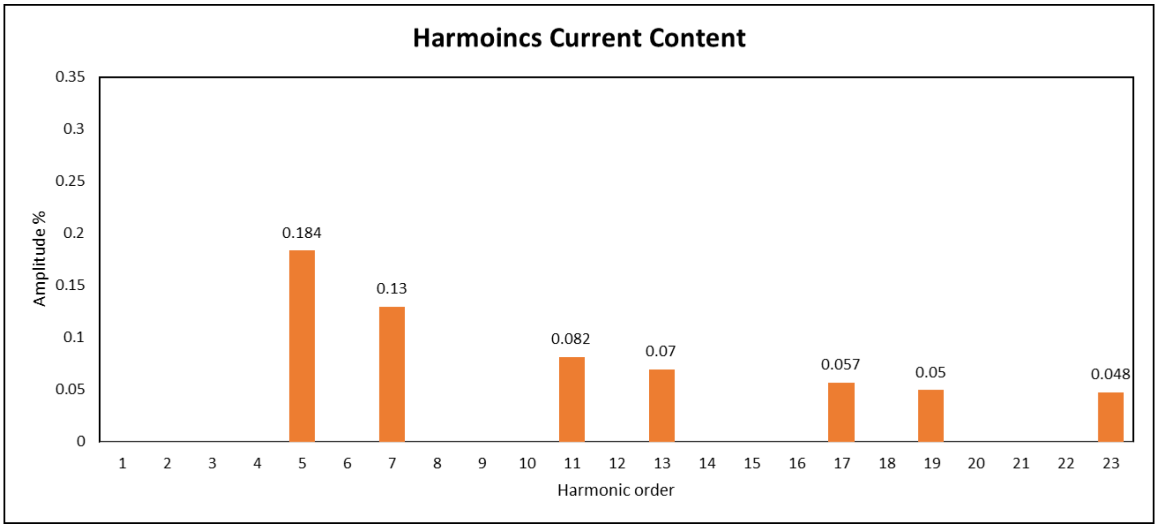


Figure 6-14Harmonics content of the generator output current when using diode converter (with placing one stage of filters)

### 6.3.2 Using thyristor rectifier converter

Figure 6-15 illustrates the improved generator phase A voltage output after placing three phase filters, while Figure 6-16 shows the improved generator phase A current output. As we can see from the figures, they are significantly developed. We apply Fast Fourier Transform to these signals by using a Matlab function of FFT to calculate the order harmonics and the improved THD. The calculated THD for the improved voltage and current waveforms decreased from 11.16 % to 0.63 % and from 23.85 to 0.69 % in raw calculation. We get improvments in both THVD and THID for this method comparing with using diode rectifier in this case.

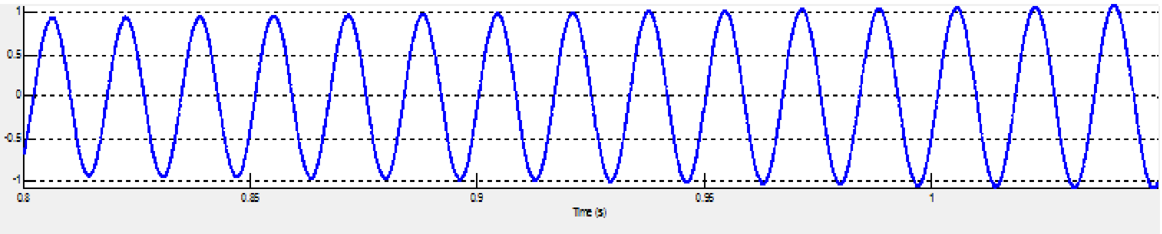


Figure 6-15 Generator voltage output signal when using thyristor converter(with having one stage of filters)

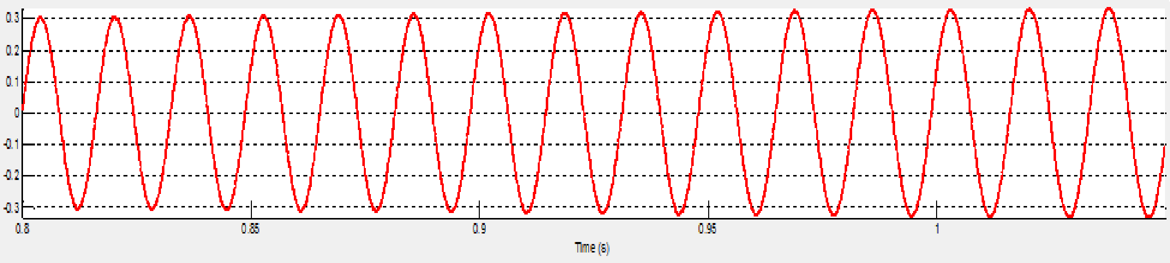


Figure 6-16 Generator current output signal when using thyristor converter(with having one stage of filters)

Figure 6-17 presents a detailed harmonics content of the generator voltage content. The amplitudes of the 5th and 7th voltage harmonics are 0.35 % and 0.18 % of the fundamental component, respectively. Figure 6-18 shows a detailed harmonics content of the generator current output. The amplitudes of the 5th and 7th voltage harmonics are 0.16 % and 0.12 % of the fundamental component, respectively. We can observe from theos figures that the harmonic orders of the 5th, 7th, 11th, 13th and 17th are insignificant. The obtained total harmonic distortion for the output voltage and current is THD=0.63 % and 0.69 %, respectively.

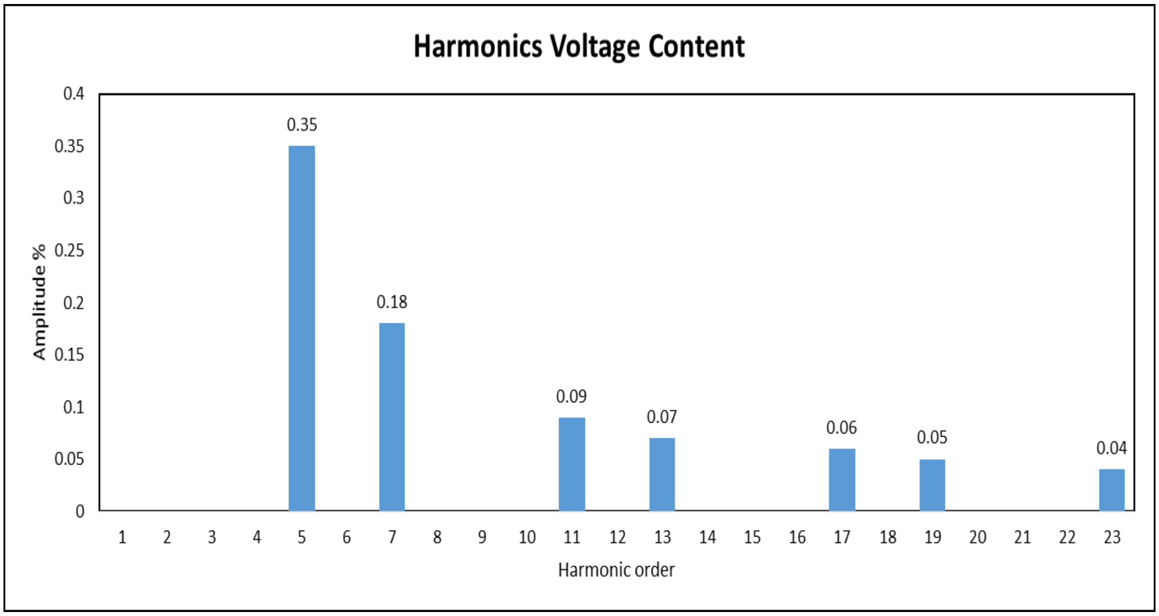


Figure 6-17 Harmonics content of the generator output voltage when using thyristor converter (with placing one stage of filters)

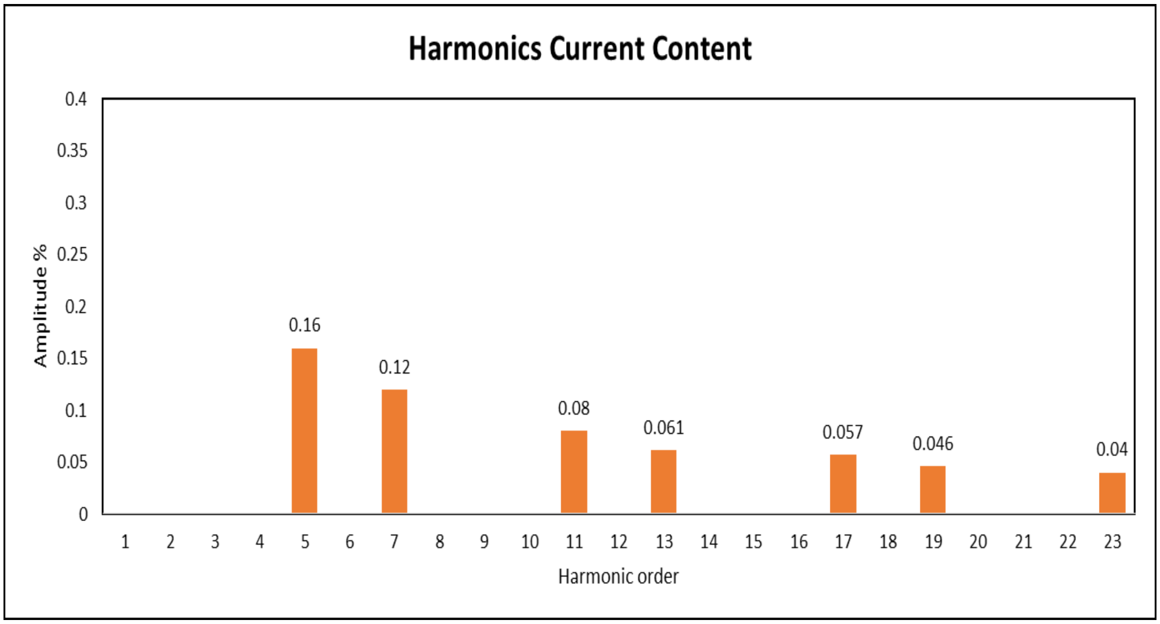


Figure 6-18 Harmonics content of the generator output current when using thyristor converter (with placing one stage of filters)

## 6.4 Case 3: Harmonics analysis of the model with having two stages of three phase filters

In this case, we add another stage of three phase filters. The filters added in this case are single – tuned, double – tuned, and high pass filters. So, we have two stages of filters, which are connected to the generator in order to get better harmonics reduction. Simulations are conducted to find harmonics in the generator using a three-phase diode rectifier and three-phase thyristor rectifier to convert the variable voltage into a direct voltage. We will find the voltage and current harmonics by implementing Fast Fourier transform tool (FFT) in Matlab.

### 6.4.1 Using diode rectifier converter

After connecting another stage of filters, the voltage and current harmonics are considered a sine wave form. The simulated THD for the improved voltage and current waveforms decreased from 0.79 % to 0.52 % and from 0.75 to 0.5% in a raw. We get better results in both THVD and THID for this method comparing with the second one.

Figure 6-19 illustrates the improved generator voltage output after placing two stages of filters, while Figure 6-20 shows the improved generator current output after having two stages of filters. As we can see from the figures, they are single-phase waves of the voltage and current, respectively. We will find the harmonics of these signals by using Fast Fourier Transform.

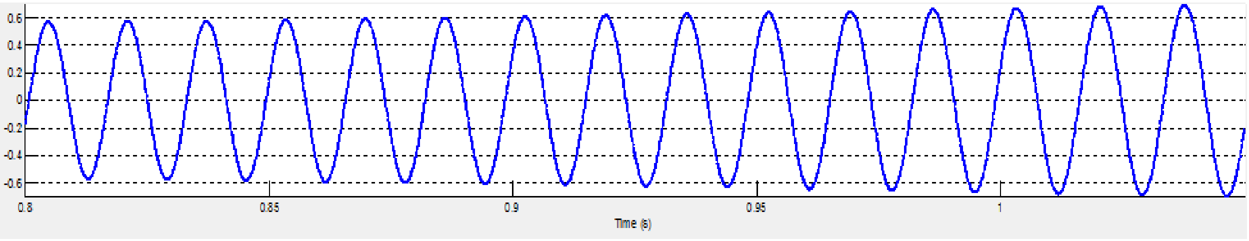


Figure 6-19 Generator voltage output signal when using diode converter(with having two stages of filters)

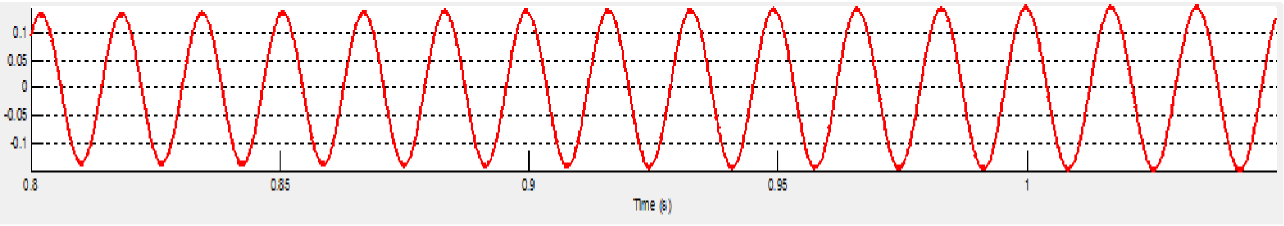


Figure 6-20 Generator current output signal when using diode converter(with having two stages of filters)

Figure 6-21 shows a detailed harmonics content of the generator voltage content with two stages of filters, while Figure 6-22 presents a detailed harmonics content of the generator current output. The amplitudes of the 5th and 7th current harmonics are decreased from 0.184 to 0.12 % and from 0.13 % to 0.085 % of the fundamental component, respectively.We can observe from theos figures that the harmonic orders of the 5th, 7th, 11th, 13th and 17th are considered lower than the second case. The obtained total harmonic distortion for the output voltage and current is 0.52 % and 0.50 %, respectively, which is considered the best between the three cases.

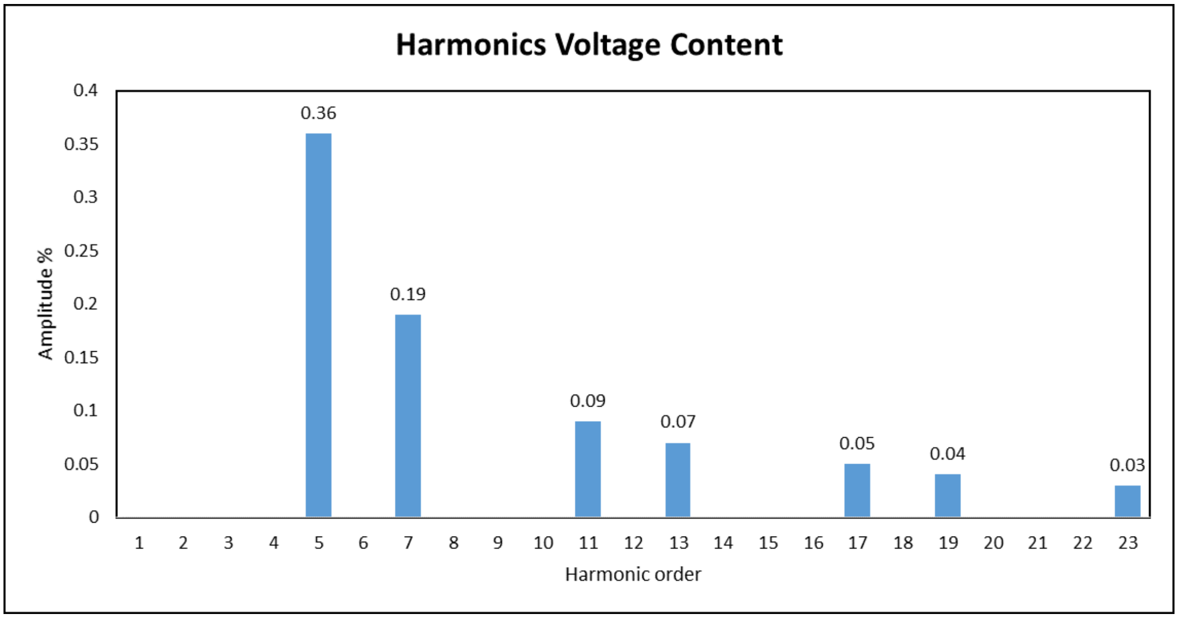


Figure 6-21 Harmonics content of the generator output voltage when using diode converter (with placing two stages of filters)

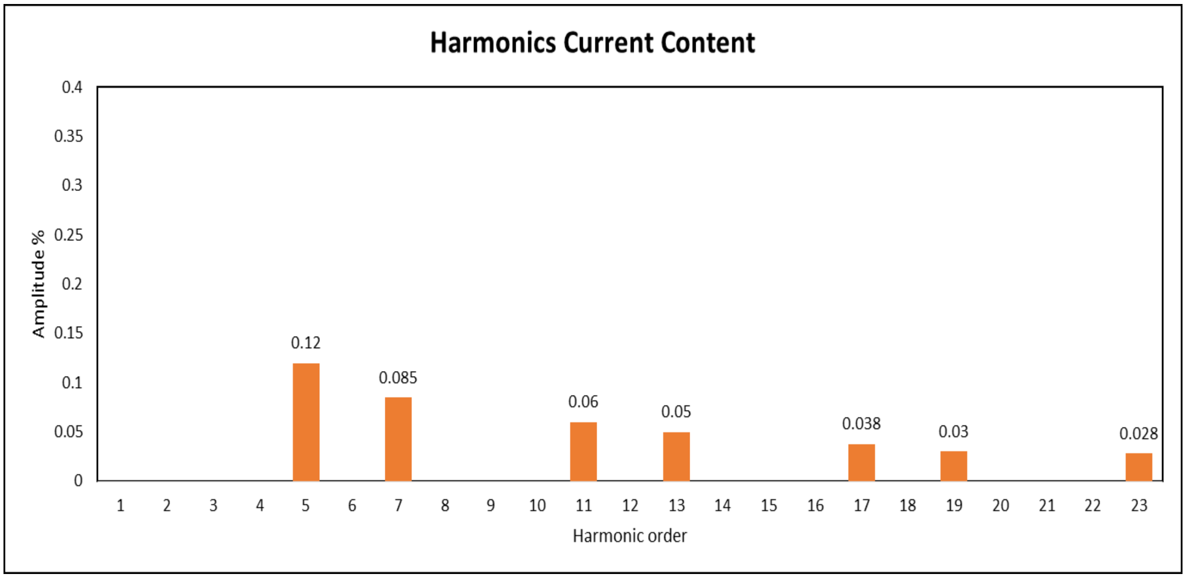


Figure 6-22 Harmonics content of the generator output current when using diode converter (with placing two stages of filters)

### 6.4.2 Using thyristor rectifier converter

Figure 6-23 illustrates the improved generator phase A voltage output after placing three phase filters, while Figure 6-24 shows the improved generator phase A current output. As we can see from the figures, they are significantly developed.. The simulated THD for the improved voltage and current waveforms decreased from 0.63 % to 0.62 % and from 0.69 to 0.53 % , respectively. We get better results in both THVD and THID for this method comparing with the second one.

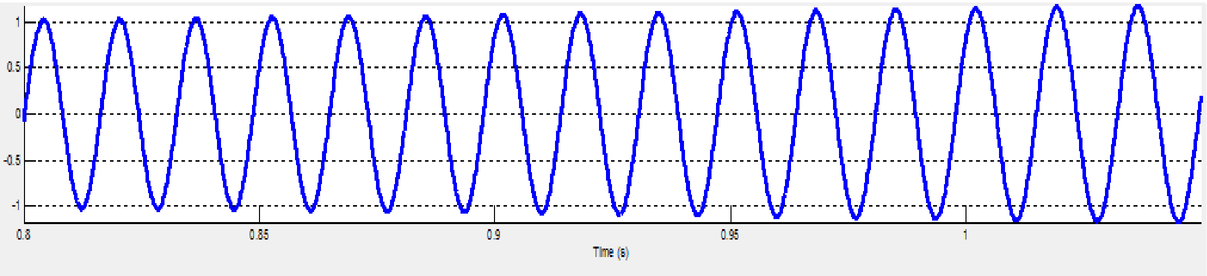


Figure 6-23 Generator voltage output signal when using thyristor converter(with having two stages of filters)

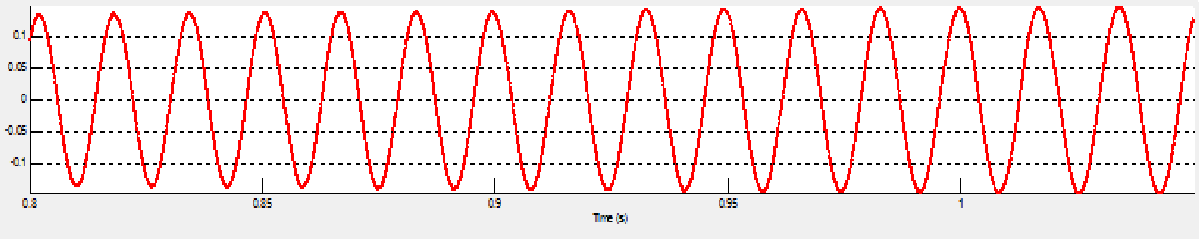


Figure 6-24 Generator current output signal when using thyristor converter(with having two stages of filters)

Figure 6-25 presents a detailed harmonics content of the generator voltage content. Figure 6-26 shows a detailed harmonics content of the generator current output. The amplitudes of the $5^{th}$ and $7^{th}$ voltage harmonics are 0.128 % and 0.09 % of the fundamental component, respectively. We can observe from theos figures that the harmonic orders of the 5th, 7th, 11th, 13th and 17th are very small. The obtained total harmonic distortion for the output voltage and current is THD=0.62 % and 0.53 %, respectively.

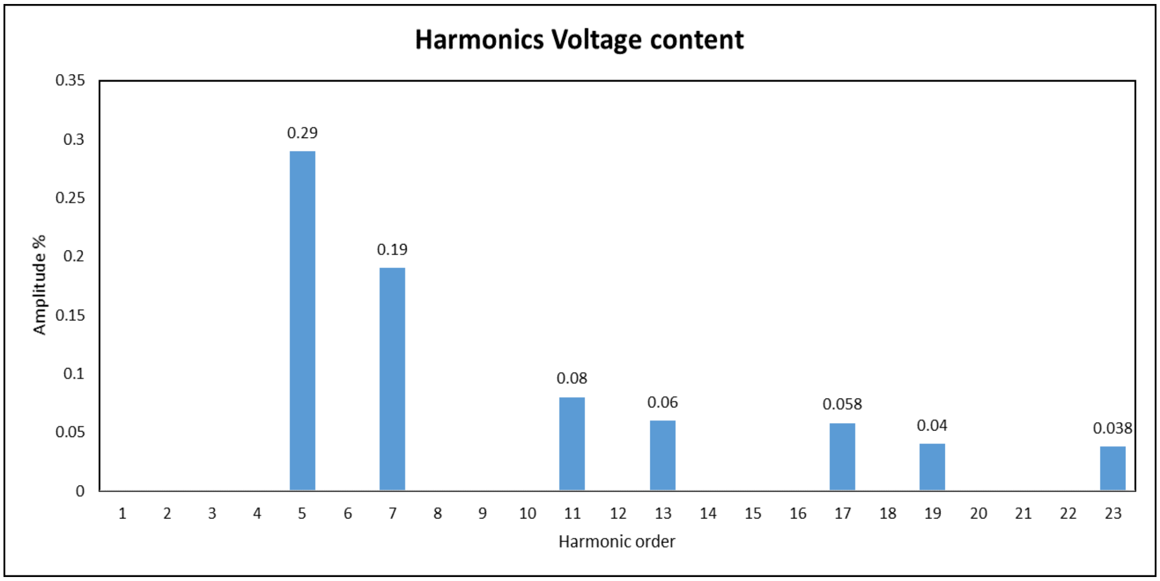


Figure 6-25 Harmonics content of the generator output voltage when using thyristor converter (with placing two stages of filters)

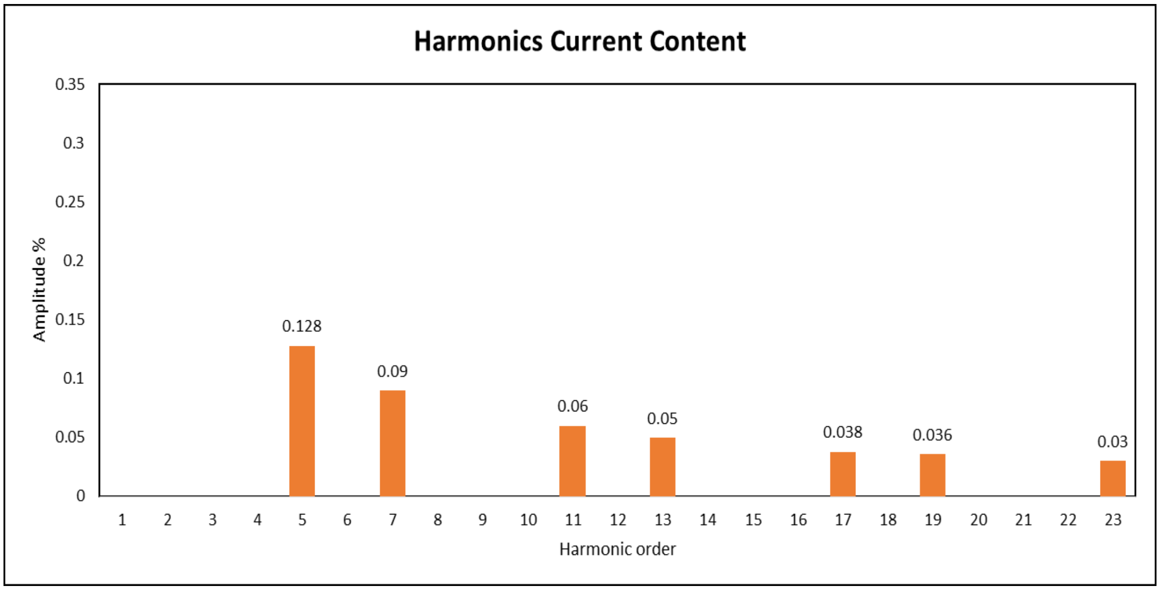


Figure 6-26 Harmonics content of the generator output current when using thyristor converter (with placing two stages of filters)

### 6.5 Discussion of the results

In our investigations, we have carried out three distinct case studies. In one case, the wind energy conversion system with a PMSG was connected to a three-phase load without having harmonics filters, using two different rectifiers. In the second case, the WECS with a PMSG was connected to a three-phase load with harmonics filters on the generator side and with two different rectifiers. The harmonics filters are C- type pass, double-tuned, and high-pass. Thirdly, the WECS with a PMSG was connected to a three-phase load with two stages of harmonics filters on the generator side and with two different rectifiers. The second stage of harmonics filters are single – tuned, double-tuned, and high-pass. We tested the system in wind speed of 8 m/s.

### 6.5.1 Evaluation of  the first case

From Figure 6-2 to Figure 6-9, the FFT analysis demonstrates that the WECS with a PMSG without harmonics filters has high odd harmonics. These odd harmonics are reduced when the filter is connected.

Table 6-1shows the total voltage and current harmonics distortion in the PMSG wind turbine generator. We can note that the total harmonic distortion whether voltage or current is considered high when we use thyristor as converter. The fundamental of output voltage and current equal to 1.508 p.u. and 0.1003 p.u., respectively, when diode rectifier was used. On the other hand, the fundamental of output voltage and current, when thyristor rectifier was used, are obtained as 1.713 p.u. and 0.1468 p.u. in a raw.

Table 6-1Total Voltage and Current Harmonics Distortions in the wind turbine generator (first case).

| Wind speed m/s | THVD % | | THID % | |
|---|---|---|---|---|
| | Diode | Thyristor | Diode % | Thyristor % |
| 8 | 4.17 | 11.16 | 7.55 | 23.85 |

### 6.5.2 Evaluation of the second case

From Figure 6-11 to Figure 6-18, we can say that the FFT analysis determines that the WECS with a PMSG without harmonics filters has high odd harmonics. Therefore, these odd harmonics are reduced when the filter is connected.

Table 6-2 shows the total voltage and current harmonics distortion in the PMSG wind turbine generator, indicating that the filter works over a different range of wind speeds. The fundamental of output voltage and current equal to 0.911 p.u. and 0.304 p.u., respectively, when diode rectifier was used. On the other hand, the fundamental of output voltage and current, when thyristor rectifier was used, are obtained as 0.9565 p.u. and 0.3048 p.u. in a raw.

Table 6-2Total Voltage and Current Harmonics Distortions in the wind turbine generator (second case).

| Wind speed m/s | THVD % | | THID % | |
|---|---|---|---|---|
| | Diode | Thyristor | Diode % | Thyristor % |
| 8 | 0.79 | 0.63 | 0.75 | 0.69 |

### 6.5.3 Evaluation of using the third case

From Figure 6-19 to Figure 6-26, we can say that the FFT analysis determines that the WECS with a PMSG with two stages of harmonics filters has lower odd harmonics. However, we try to reduce these odd harmonics by connecting two stages of filters.

Table 6-3 shows the total voltage and current harmonics distortion in the PMSG wind turbine generator.The fundamental of output voltage and current equal to 0.983 p.u. and 0.1336 p.u., respectively, when diode rectifier was used. On the other hand, the fundamental of output voltage and current, when thyristor rectifier was used, are obtained as 1.034 p.u. and 0.1337 p.u. in a raw.

Table 6-3 Total Voltage and Current Harmonics Distortions in the wind turbine generator(third case).

| Wind speed m/s | THVD % | | THID % | |
|---|---|---|---|---|
| | Diode | Thyristor | Diode % | Thyristor % |

| | | | | |
|---|---|---|---|---|
| 8 | 0.52 | 0.62 | 0.5 | 0.53 |

## 6.6 THD mathematical calculation

In this section, we calculate the total harmonics voltage and current distortions of the generator output. The THD of either voltage or current can be expressed as in Equation 4-6, as follows:

$$THVD = \frac{\sqrt{{V_5}^2+{V_7}^2+{V_{11}}^2+{V_{13}}^2+{V_{17}}^2+{V_{19}}^2+{V_{23}}^2}}{V_1} * 100 \qquad \textbf{6-1}$$

$$THID = \frac{\sqrt{{I_5}^2+{I_7}^2+{I_{11}}^2+{I_{13}}^2+{I_{17}}^2+{I_{19}}^2+{I_{23}}^2}}{I_1} * 100 \qquad \textbf{6-2}$$

From the simulation results, we can find the fundamental components as well as harmonics orders. The calculated THD of the generator voltage and current can be determined by applying the above equations.

Comparisons between calculated THDs and simulated THDs are shown in Table 6-4. The table shows the THD comparison using a diode rectifier at the wind speed as well as the THD comparison using a thyristor rectifier at the same speed.

Table 6-4 Comparisons between the simulated and calculated THD of PMS generator voltage and current using the first method (diode and thyristor rectifiers).

| First case(without filters) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Diode** | | | | | **Thyristor** | | | |
| Velocity (m/sec) | THVD calculated % | THVD simulated% | THID calculated % | THID simulated % | THVD calculated % | THVD simulated% | THID calculated % | THID simulated % |
| **8** | **7.38** | **4.17** | **20.74** | **7.55** | **10.34** | **11.16** | **24.26** | **23.85** |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Error percentage** | **43.5 %** | | **63.6 %** | | **8 %** | | **1.7 %** | |
| **Second case(with placing one stage of filters)** | | | | | | | | |
| **Diode** | | | | | **Thyristor** | | | |
| Velocity (m/sec) | THVD calculated % | THVD simulated% | THID calculated % | THID simulated % | THVD calculated % | THVD simulated % | THID calculated % | THID simulated % |
| **8** | **0.39** | **0.79** | **0.26** | **0.75** | **0.419** | **0.63** | **0.238** | **0.69** |
| **Error percentage** | **102.5 %** | | **188.5 %** | | **50.35 %** | | **190 %** | |
| **Third case(with placing two stages of filters)** | | | | | | | | |
| **Diode** | | | | | **Thyristor** | | | |
| Velocity (m/sec) | THVD calculated % | THVD simulated% | THID calculated % | THID simulated % | THVD calculated % | THVD simulated % | THID calculated % | THID simulated % |
| **8** | **0.42** | **0.52** | **0.40** | **0.50** | **0.37** | **0.62** | **0.185** | **0.53** |
| **Error percentage** | **24 %** | | **25 %** | | **67.5 %** | | **186.5 %** | |

# Chapter 7 Conclusions and future work

## 7.1 Conclusions

The objectives of this work were to simulate a stand-alone wind energy conversion system, to design three-phase harmonic filters, to reduce voltage and current harmonics of a wind turbine PMSG generator, and to calculate the harmonics order and THD by using FFT analysis. To accomplish these objectives, we used two different AC/DC converters at a wide range of wind speeds with two different combinations of filters. All of our objectives were achieved, as will be presented in the following paragraphs.

The main thrust of our work was to simulate a wind turbine energy conversion system with a permanent magnet synchronous generator connected to a three-phase load. At abnormal conditions, the output voltage and current of the generator are distorted due to electronic elements. To avoid distortions, three-phase harmonic filters were used to connect with the synchronous generator. The filters proved effective. From the impressive results, we concluded that the proposed wind energy conversion system with harmonics filters successfully reduces distortions in the generator voltage and current output.

Additionally, we presented performances of two different AC/DC converters and compared the harmonic content of the voltage and current. The AC/DC thyristor rectifier was shown to have higher harmonic content than the diode rectifier. This research discovered that using a three-phase harmonic filter at an average wind speed proved to be the optimal approach in reducing overall harmonic content to an acceptable level. We got best results when we used a combination of Double – tuned, Single – tuned, and High pass filters.single – tuned , double – tuned as presented in 6.3.1.

From the harmonic content of the generator output, whether voltage and current, we found that harmonic amplitude decreases whenever the order of harmonic increases. In either case, the highest harmonic order is the 5th. The obtained THD of both voltage and current, when using three phase thyristor rectifier, were higher than the THD computed when using the diode rectifier either without or with filters.

We can thus deduce that using a three-phase diode rectifier along with three-phase harmonic filters to reduce harmonics in the generator decreases the THD. After using the filters, the THVD and THID are 0.33% and 0.28%, respectively. These optimal results were obtained at a wind speed of 8 m/s, whereas for the thyristor rectifier, the THD was found to be 0.32% and 0.60%, respectively.

### 7.2 Future work

The work accomplished in this thesis can be extended along the following lines:

- Using three-phase passive filters in WECS connected to the grid.
- Using different types of converters with wind energy systems, such as GTO / Diodes, MOSFET / Diodes, Ideal Switches, and so on.
- Investigating other techniques for reducing harmonics, such as a variable frequency active power filter.
- Need to evaluate the worth of improving the power quality versus cost and equipment size.

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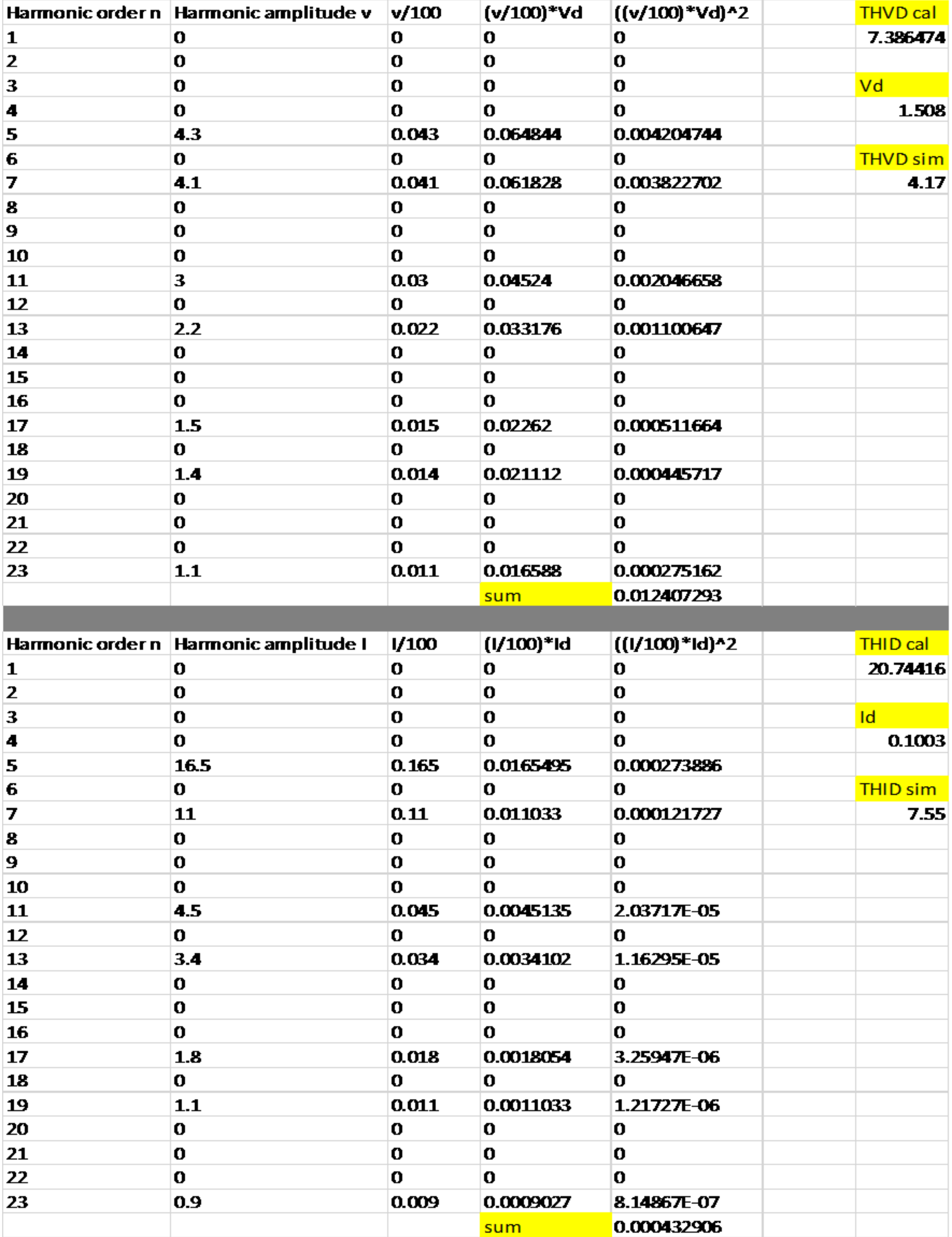
# Appendices

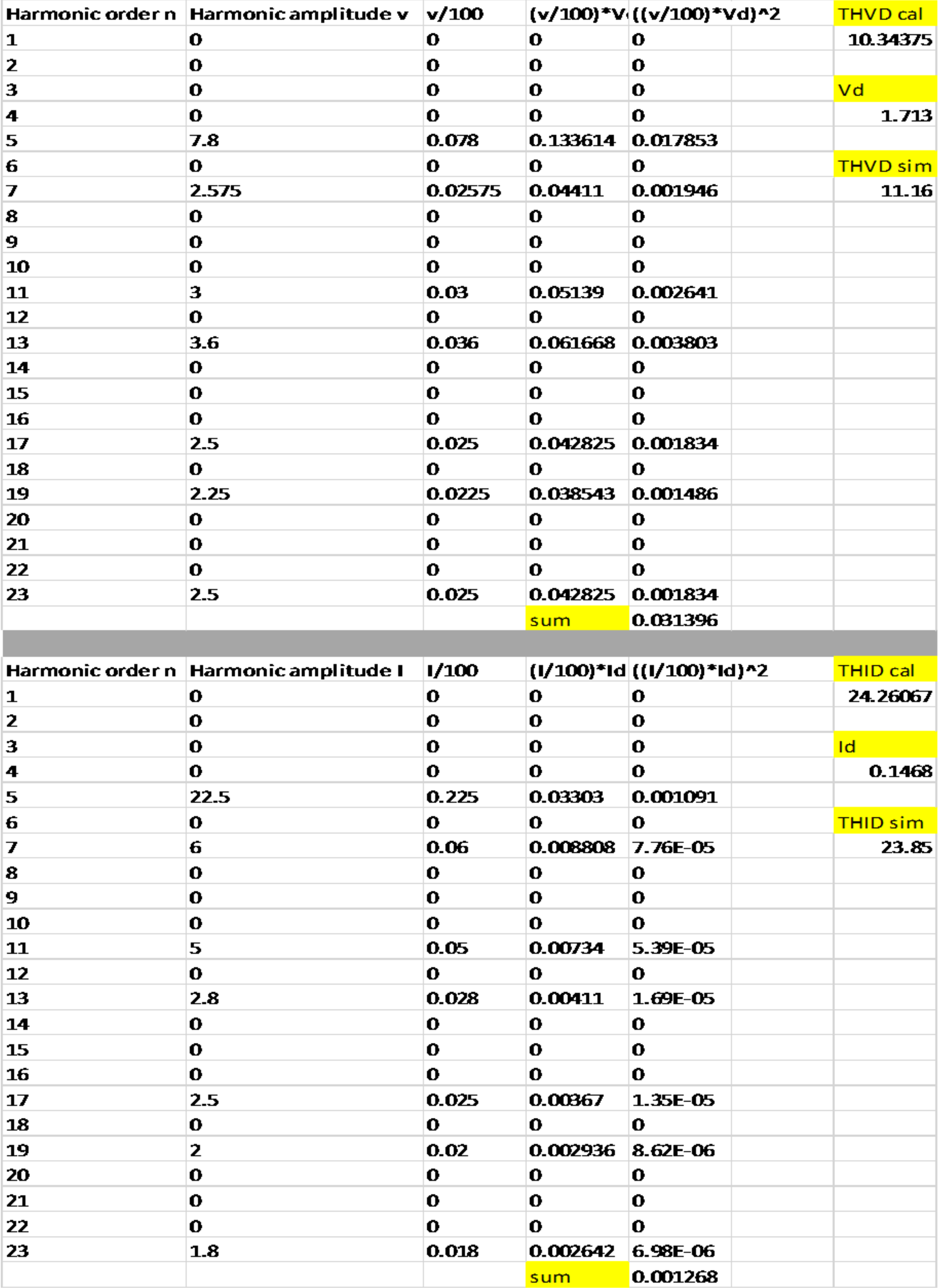
## Appendix 1: **THD calculation using diode rectifiers without having filters.**



| Harmonic order n | Harmonic amplitude v | v/100 | (v/100)*Vd | ((v/100)*Vd)^2 | | THVD cal |
|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | | 7.386474 |
| 2 | 0 | 0 | 0 | 0 | | |
| 3 | 0 | 0 | 0 | 0 | | Vd |
| 4 | 0 | 0 | 0 | 0 | | 1.508 |
| 5 | 4.3 | 0.043 | 0.064844 | 0.004204744 | | |
| 6 | 0 | 0 | 0 | 0 | | THVD sim |
| 7 | 4.1 | 0.041 | 0.061828 | 0.003822702 | | 4.17 |
| 8 | 0 | 0 | 0 | 0 | | |
| 9 | 0 | 0 | 0 | 0 | | |
| 10 | 0 | 0 | 0 | 0 | | |
| 11 | 3 | 0.03 | 0.04524 | 0.002046658 | | |
| 12 | 0 | 0 | 0 | 0 | | |
| 13 | 2.2 | 0.022 | 0.033176 | 0.001100647 | | |
| 14 | 0 | 0 | 0 | 0 | | |
| 15 | 0 | 0 | 0 | 0 | | |
| 16 | 0 | 0 | 0 | 0 | | |
| 17 | 1.5 | 0.015 | 0.02262 | 0.000511664 | | |
| 18 | 0 | 0 | 0 | 0 | | |
| 19 | 1.4 | 0.014 | 0.021112 | 0.000445717 | | |
| 20 | 0 | 0 | 0 | 0 | | |
| 21 | 0 | 0 | 0 | 0 | | |
| 22 | 0 | 0 | 0 | 0 | | |
| 23 | 1.1 | 0.011 | 0.016588 | 0.000275162 | | |
| | | | sum | 0.012407293 | | |

| Harmonic order n | Harmonic amplitude I | I/100 | (I/100)*Id | ((I/100)*Id)^2 | | THID cal |
|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | | 20.74416 |
| 2 | 0 | 0 | 0 | 0 | | |
| 3 | 0 | 0 | 0 | 0 | | Id |
| 4 | 0 | 0 | 0 | 0 | | 0.1003 |
| 5 | 16.5 | 0.165 | 0.0165495 | 0.000273886 | | |
| 6 | 0 | 0 | 0 | 0 | | THID sim |
| 7 | 11 | 0.11 | 0.011033 | 0.000121727 | | 7.55 |
| 8 | 0 | 0 | 0 | 0 | | |
| 9 | 0 | 0 | 0 | 0 | | |
| 10 | 0 | 0 | 0 | 0 | | |
| 11 | 4.5 | 0.045 | 0.0045135 | 2.03717E-05 | | |
| 12 | 0 | 0 | 0 | 0 | | |
| 13 | 3.4 | 0.034 | 0.0034102 | 1.16295E-05 | | |
| 14 | 0 | 0 | 0 | 0 | | |
| 15 | 0 | 0 | 0 | 0 | | |
| 16 | 0 | 0 | 0 | 0 | | |
| 17 | 1.8 | 0.018 | 0.0018054 | 3.25947E-06 | | |
| 18 | 0 | 0 | 0 | 0 | | |
| 19 | 1.1 | 0.011 | 0.0011033 | 1.21727E-06 | | |
| 20 | 0 | 0 | 0 | 0 | | |
| 21 | 0 | 0 | 0 | 0 | | |
| 22 | 0 | 0 | 0 | 0 | | |
| 23 | 0.9 | 0.009 | 0.0009027 | 8.14867E-07 | | |
| | | | sum | 0.000432906 | | |

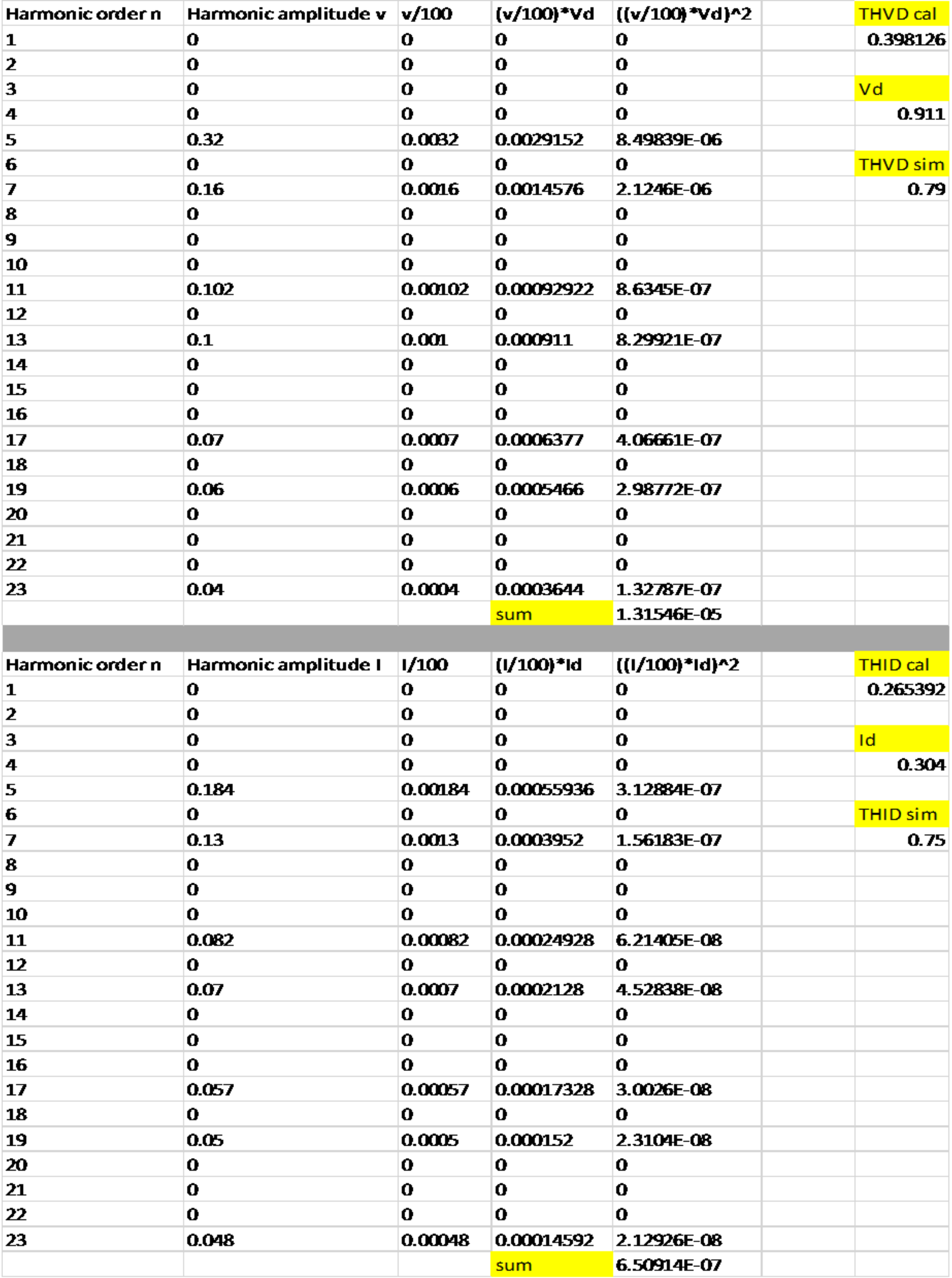
## Appendix 2: **THD calculation using thyristor rectifiers without having filters.**



| Harmonic order n | Harmonic amplitude v | v/100 | (v/100)*V | ((v/100)*Vd)^2 |  | THVD cal |
|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 |  | 10.34375 |
| 2 | 0 | 0 | 0 | 0 |  |  |
| 3 | 0 | 0 | 0 | 0 |  | Vd |
| 4 | 0 | 0 | 0 | 0 |  | 1.713 |
| 5 | 7.8 | 0.078 | 0.133614 | 0.017853 |  |  |
| 6 | 0 | 0 | 0 | 0 |  | THVD sim |
| 7 | 2.575 | 0.02575 | 0.04411 | 0.001946 |  | 11.16 |
| 8 | 0 | 0 | 0 | 0 |  |  |
| 9 | 0 | 0 | 0 | 0 |  |  |
| 10 | 0 | 0 | 0 | 0 |  |  |
| 11 | 3 | 0.03 | 0.05139 | 0.002641 |  |  |
| 12 | 0 | 0 | 0 | 0 |  |  |
| 13 | 3.6 | 0.036 | 0.061668 | 0.003803 |  |  |
| 14 | 0 | 0 | 0 | 0 |  |  |
| 15 | 0 | 0 | 0 | 0 |  |  |
| 16 | 0 | 0 | 0 | 0 |  |  |
| 17 | 2.5 | 0.025 | 0.042825 | 0.001834 |  |  |
| 18 | 0 | 0 | 0 | 0 |  |  |
| 19 | 2.25 | 0.0225 | 0.038543 | 0.001486 |  |  |
| 20 | 0 | 0 | 0 | 0 |  |  |
| 21 | 0 | 0 | 0 | 0 |  |  |
| 22 | 0 | 0 | 0 | 0 |  |  |
| 23 | 2.5 | 0.025 | 0.042825 | 0.001834 |  |  |
|  |  |  | sum | 0.031396 |  |  |

| Harmonic order n | Harmonic amplitude I | I/100 | (I/100)*Id | ((I/100)*Id)^2 |  | THID cal |
|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 |  | 24.26067 |
| 2 | 0 | 0 | 0 | 0 |  |  |
| 3 | 0 | 0 | 0 | 0 |  | Id |
| 4 | 0 | 0 | 0 | 0 |  | 0.1468 |
| 5 | 22.5 | 0.225 | 0.03303 | 0.001091 |  |  |
| 6 | 0 | 0 | 0 | 0 |  | THID sim |
| 7 | 6 | 0.06 | 0.008808 | 7.76E-05 |  | 23.85 |
| 8 | 0 | 0 | 0 | 0 |  |  |
| 9 | 0 | 0 | 0 | 0 |  |  |
| 10 | 0 | 0 | 0 | 0 |  |  |
| 11 | 5 | 0.05 | 0.00734 | 5.39E-05 |  |  |
| 12 | 0 | 0 | 0 | 0 |  |  |
| 13 | 2.8 | 0.028 | 0.00411 | 1.69E-05 |  |  |
| 14 | 0 | 0 | 0 | 0 |  |  |
| 15 | 0 | 0 | 0 | 0 |  |  |
| 16 | 0 | 0 | 0 | 0 |  |  |
| 17 | 2.5 | 0.025 | 0.00367 | 1.35E-05 |  |  |
| 18 | 0 | 0 | 0 | 0 |  |  |
| 19 | 2 | 0.02 | 0.002936 | 8.62E-06 |  |  |
| 20 | 0 | 0 | 0 | 0 |  |  |
| 21 | 0 | 0 | 0 | 0 |  |  |
| 22 | 0 | 0 | 0 | 0 |  |  |
| 23 | 1.8 | 0.018 | 0.002642 | 6.98E-06 |  |  |
|  |  |  | sum | 0.001268 |  |  |

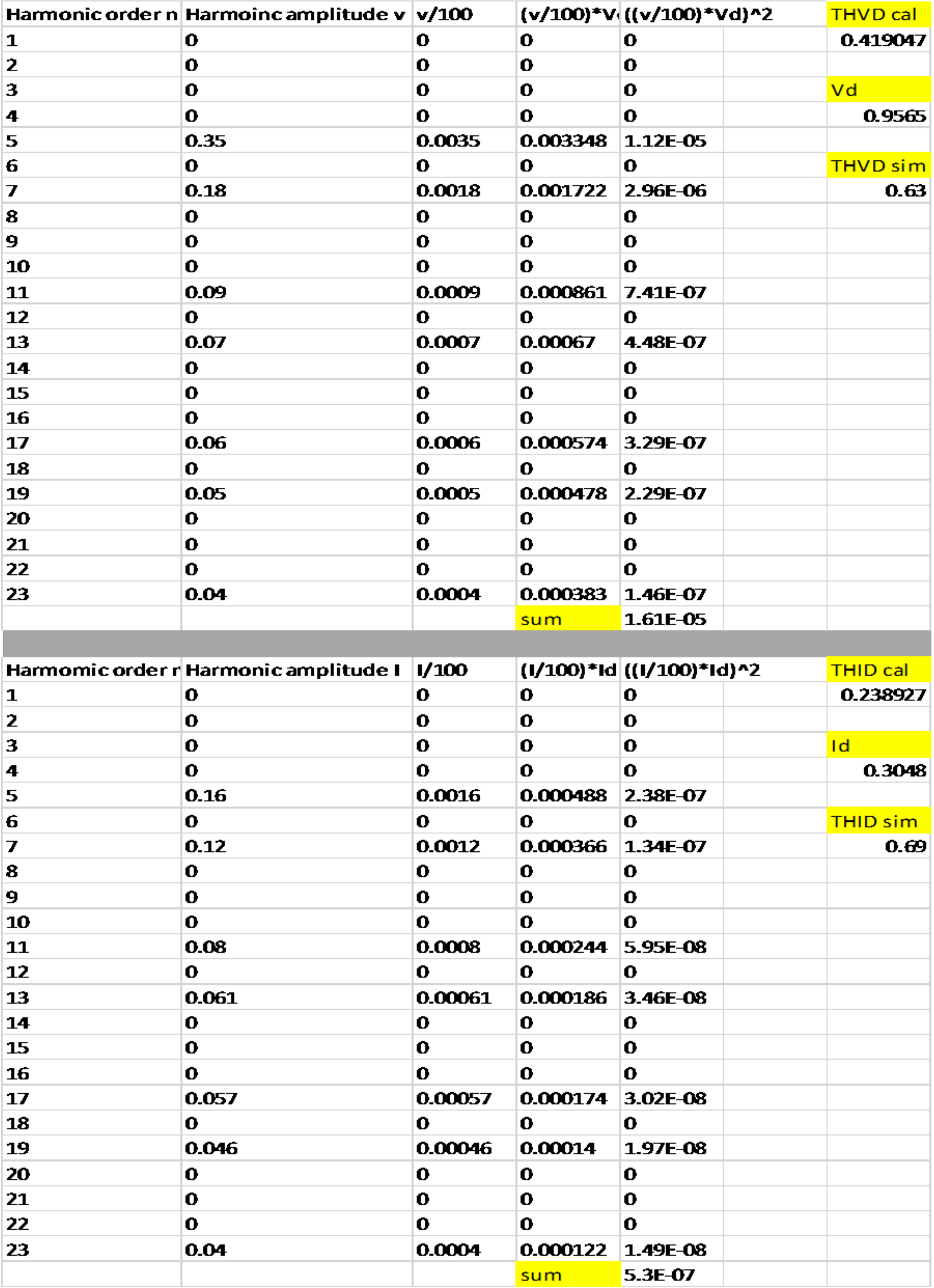
Appendix 3**: THD calculation using diode rectifiers with having one stage of filters.**



| Harmonic order n | Harmonic amplitude v | v/100 | (v/100)*Vd | ((v/100)*Vd)^2 | | THVD cal |
|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | | 0.398126 |
| 2 | 0 | 0 | 0 | 0 | | |
| 3 | 0 | 0 | 0 | 0 | | Vd |
| 4 | 0 | 0 | 0 | 0 | | 0.911 |
| 5 | 0.32 | 0.0032 | 0.0029152 | 8.49839E-06 | | |
| 6 | 0 | 0 | 0 | 0 | | THVD sim |
| 7 | 0.16 | 0.0016 | 0.0014576 | 2.1246E-06 | | 0.79 |
| 8 | 0 | 0 | 0 | 0 | | |
| 9 | 0 | 0 | 0 | 0 | | |
| 10 | 0 | 0 | 0 | 0 | | |
| 11 | 0.102 | 0.00102 | 0.00092922 | 8.6345E-07 | | |
| 12 | 0 | 0 | 0 | 0 | | |
| 13 | 0.1 | 0.001 | 0.000911 | 8.29921E-07 | | |
| 14 | 0 | 0 | 0 | 0 | | |
| 15 | 0 | 0 | 0 | 0 | | |
| 16 | 0 | 0 | 0 | 0 | | |
| 17 | 0.07 | 0.0007 | 0.0006377 | 4.06661E-07 | | |
| 18 | 0 | 0 | 0 | 0 | | |
| 19 | 0.06 | 0.0006 | 0.0005466 | 2.98772E-07 | | |
| 20 | 0 | 0 | 0 | 0 | | |
| 21 | 0 | 0 | 0 | 0 | | |
| 22 | 0 | 0 | 0 | 0 | | |
| 23 | 0.04 | 0.0004 | 0.0003644 | 1.32787E-07 | | |
| | | | sum | 1.31546E-05 | | |

| Harmonic order n | Harmonic amplitude I | I/100 | (I/100)*Id | ((I/100)*Id)^2 | | THID cal |
|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | | 0.265392 |
| 2 | 0 | 0 | 0 | 0 | | |
| 3 | 0 | 0 | 0 | 0 | | Id |
| 4 | 0 | 0 | 0 | 0 | | 0.304 |
| 5 | 0.184 | 0.00184 | 0.00055936 | 3.12884E-07 | | |
| 6 | 0 | 0 | 0 | 0 | | THID sim |
| 7 | 0.13 | 0.0013 | 0.0003952 | 1.56183E-07 | | 0.75 |
| 8 | 0 | 0 | 0 | 0 | | |
| 9 | 0 | 0 | 0 | 0 | | |
| 10 | 0 | 0 | 0 | 0 | | |
| 11 | 0.082 | 0.00082 | 0.00024928 | 6.21405E-08 | | |
| 12 | 0 | 0 | 0 | 0 | | |
| 13 | 0.07 | 0.0007 | 0.0002128 | 4.52838E-08 | | |
| 14 | 0 | 0 | 0 | 0 | | |
| 15 | 0 | 0 | 0 | 0 | | |
| 16 | 0 | 0 | 0 | 0 | | |
| 17 | 0.057 | 0.00057 | 0.00017328 | 3.0026E-08 | | |
| 18 | 0 | 0 | 0 | 0 | | |
| 19 | 0.05 | 0.0005 | 0.000152 | 2.3104E-08 | | |
| 20 | 0 | 0 | 0 | 0 | | |
| 21 | 0 | 0 | 0 | 0 | | |
| 22 | 0 | 0 | 0 | 0 | | |
| 23 | 0.048 | 0.00048 | 0.00014592 | 2.12926E-08 | | |
| | | | sum | 6.50914E-07 | | |

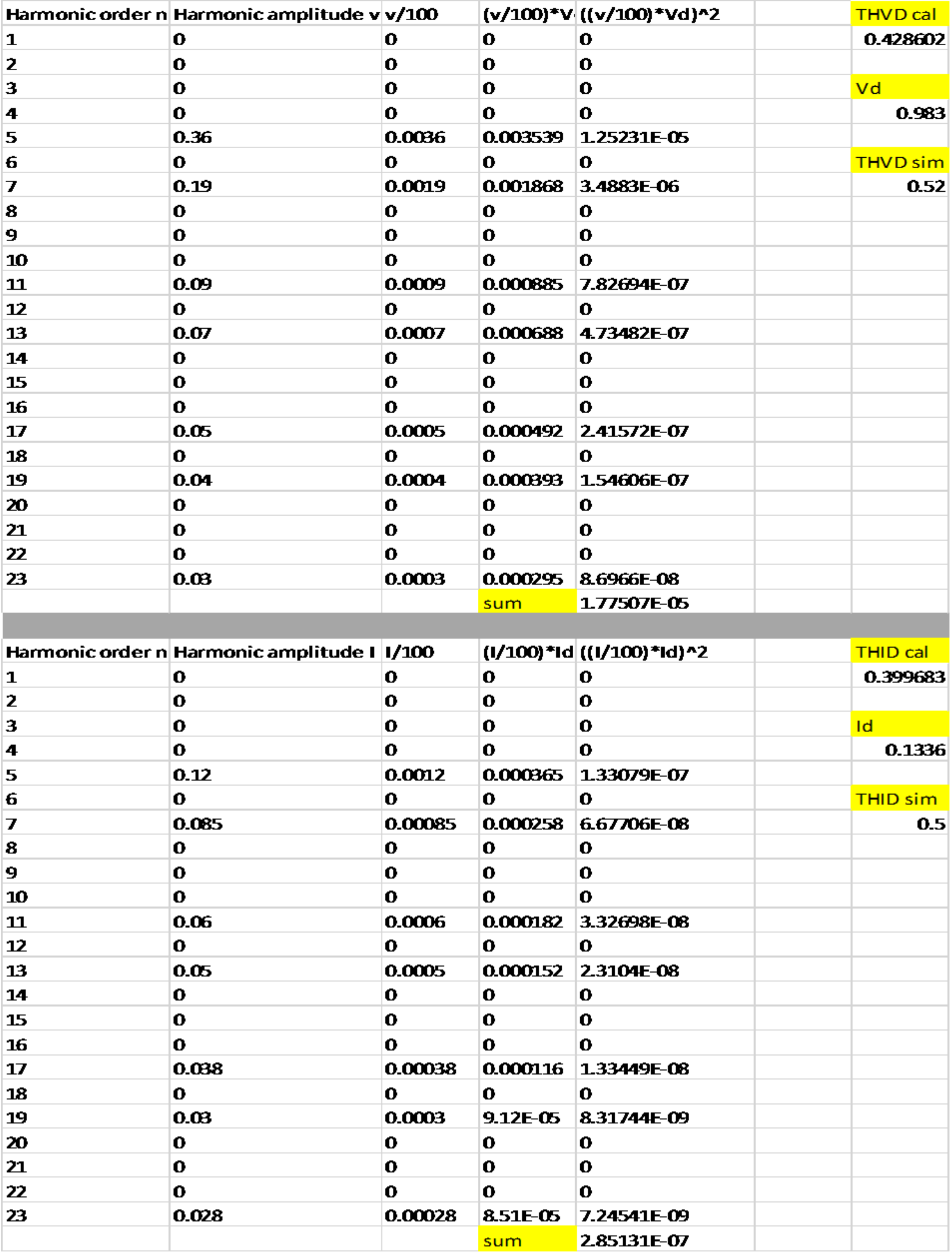
## Appendix 4: THD calculation using thyristor rectifiers with having one stage of filters.



| Harmonic order n | Harmoinc amplitude v | v/100 | (v/100)*V | ((v/100)*Vd)^2 | | THVD cal |
|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | | 0.419047 |
| 2 | 0 | 0 | 0 | 0 | | |
| 3 | 0 | 0 | 0 | 0 | | Vd |
| 4 | 0 | 0 | 0 | 0 | | 0.9565 |
| 5 | 0.35 | 0.0035 | 0.003348 | 1.12E-05 | | |
| 6 | 0 | 0 | 0 | 0 | | THVD sim |
| 7 | 0.18 | 0.0018 | 0.001722 | 2.96E-06 | | 0.63 |
| 8 | 0 | 0 | 0 | 0 | | |
| 9 | 0 | 0 | 0 | 0 | | |
| 10 | 0 | 0 | 0 | 0 | | |
| 11 | 0.09 | 0.0009 | 0.000861 | 7.41E-07 | | |
| 12 | 0 | 0 | 0 | 0 | | |
| 13 | 0.07 | 0.0007 | 0.00067 | 4.48E-07 | | |
| 14 | 0 | 0 | 0 | 0 | | |
| 15 | 0 | 0 | 0 | 0 | | |
| 16 | 0 | 0 | 0 | 0 | | |
| 17 | 0.06 | 0.0006 | 0.000574 | 3.29E-07 | | |
| 18 | 0 | 0 | 0 | 0 | | |
| 19 | 0.05 | 0.0005 | 0.000478 | 2.29E-07 | | |
| 20 | 0 | 0 | 0 | 0 | | |
| 21 | 0 | 0 | 0 | 0 | | |
| 22 | 0 | 0 | 0 | 0 | | |
| 23 | 0.04 | 0.0004 | 0.000383 | 1.46E-07 | | |
| | | | sum | 1.61E-05 | | |

| Harmomic order r | Harmonic amplitude I | I/100 | (I/100)*Id | ((I/100)*Id)^2 | | THID cal |
|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | | 0.238927 |
| 2 | 0 | 0 | 0 | 0 | | |
| 3 | 0 | 0 | 0 | 0 | | Id |
| 4 | 0 | 0 | 0 | 0 | | 0.3048 |
| 5 | 0.16 | 0.0016 | 0.000488 | 2.38E-07 | | |
| 6 | 0 | 0 | 0 | 0 | | THID sim |
| 7 | 0.12 | 0.0012 | 0.000366 | 1.34E-07 | | 0.69 |
| 8 | 0 | 0 | 0 | 0 | | |
| 9 | 0 | 0 | 0 | 0 | | |
| 10 | 0 | 0 | 0 | 0 | | |
| 11 | 0.08 | 0.0008 | 0.000244 | 5.95E-08 | | |
| 12 | 0 | 0 | 0 | 0 | | |
| 13 | 0.061 | 0.00061 | 0.000186 | 3.46E-08 | | |
| 14 | 0 | 0 | 0 | 0 | | |
| 15 | 0 | 0 | 0 | 0 | | |
| 16 | 0 | 0 | 0 | 0 | | |
| 17 | 0.057 | 0.00057 | 0.000174 | 3.02E-08 | | |
| 18 | 0 | 0 | 0 | 0 | | |
| 19 | 0.046 | 0.00046 | 0.00014 | 1.97E-08 | | |
| 20 | 0 | 0 | 0 | 0 | | |
| 21 | 0 | 0 | 0 | 0 | | |
| 22 | 0 | 0 | 0 | 0 | | |
| 23 | 0.04 | 0.0004 | 0.000122 | 1.49E-08 | | |
| | | | sum | 5.3E-07 | | |

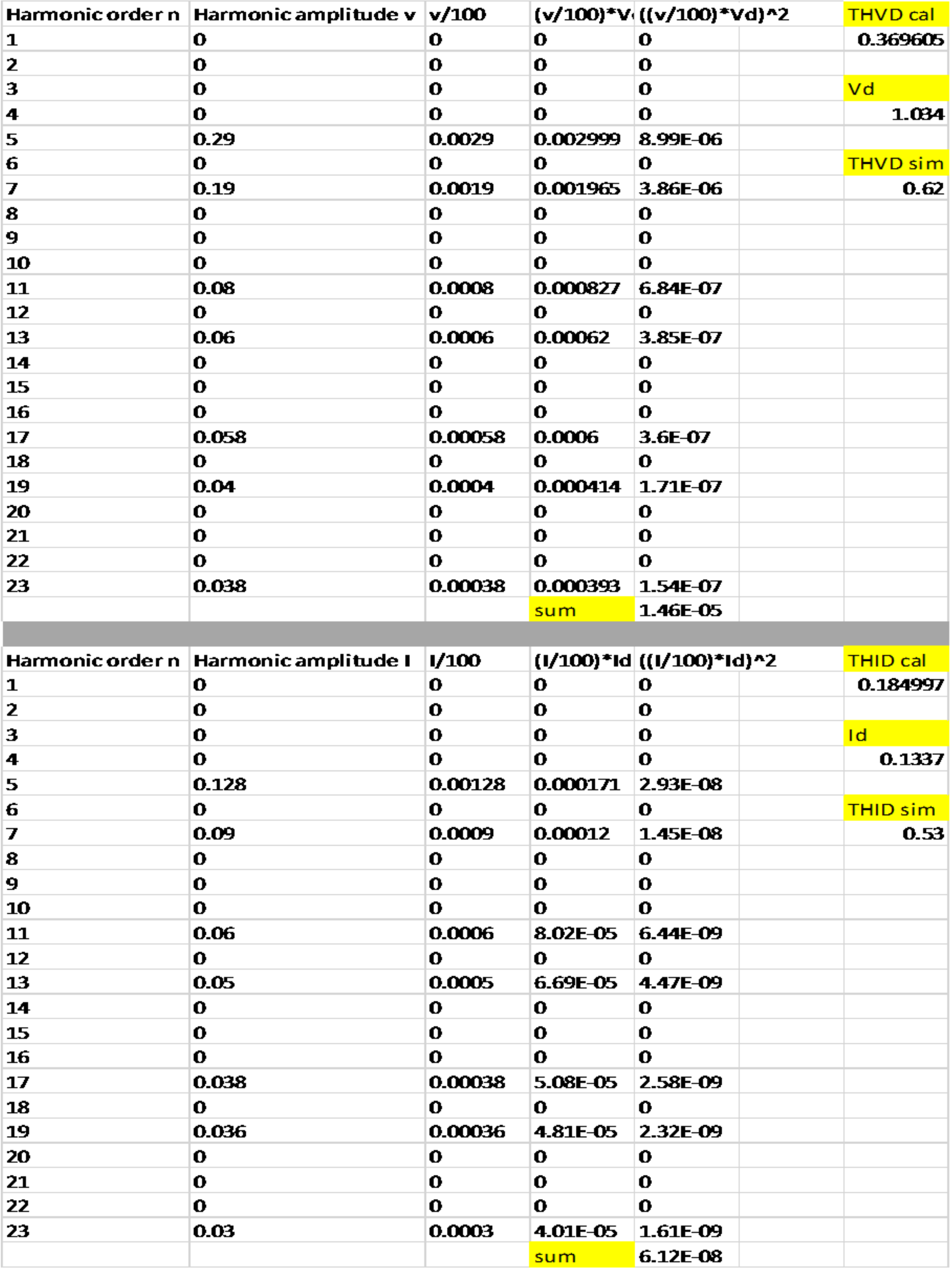
## Appendix 5: THD calculation using diode rectifiers with having two stages of filters.



| Harmonic order n | Harmonic amplitude v | v/100 | (v/100)*V | ((v/100)*Vd)^2 | | THVD cal |
|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | | 0.428602 |
| 2 | 0 | 0 | 0 | 0 | | |
| 3 | 0 | 0 | 0 | 0 | | Vd |
| 4 | 0 | 0 | 0 | 0 | | 0.983 |
| 5 | 0.36 | 0.0036 | 0.003539 | 1.25231E-05 | | |
| 6 | 0 | 0 | 0 | 0 | | THVD sim |
| 7 | 0.19 | 0.0019 | 0.001868 | 3.4883E-06 | | 0.52 |
| 8 | 0 | 0 | 0 | 0 | | |
| 9 | 0 | 0 | 0 | 0 | | |
| 10 | 0 | 0 | 0 | 0 | | |
| 11 | 0.09 | 0.0009 | 0.000885 | 7.82694E-07 | | |
| 12 | 0 | 0 | 0 | 0 | | |
| 13 | 0.07 | 0.0007 | 0.000688 | 4.73482E-07 | | |
| 14 | 0 | 0 | 0 | 0 | | |
| 15 | 0 | 0 | 0 | 0 | | |
| 16 | 0 | 0 | 0 | 0 | | |
| 17 | 0.05 | 0.0005 | 0.000492 | 2.41572E-07 | | |
| 18 | 0 | 0 | 0 | 0 | | |
| 19 | 0.04 | 0.0004 | 0.000393 | 1.54606E-07 | | |
| 20 | 0 | 0 | 0 | 0 | | |
| 21 | 0 | 0 | 0 | 0 | | |
| 22 | 0 | 0 | 0 | 0 | | |
| 23 | 0.03 | 0.0003 | 0.000295 | 8.6966E-08 | | |
| | | | sum | 1.77507E-05 | | |

| Harmonic order n | Harmonic amplitude I | I/100 | (I/100)*Id | ((I/100)*Id)^2 | | THID cal |
|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | | 0.399683 |
| 2 | 0 | 0 | 0 | 0 | | |
| 3 | 0 | 0 | 0 | 0 | | Id |
| 4 | 0 | 0 | 0 | 0 | | 0.1336 |
| 5 | 0.12 | 0.0012 | 0.000365 | 1.33079E-07 | | |
| 6 | 0 | 0 | 0 | 0 | | THID sim |
| 7 | 0.085 | 0.00085 | 0.000258 | 6.67706E-08 | | 0.5 |
| 8 | 0 | 0 | 0 | 0 | | |
| 9 | 0 | 0 | 0 | 0 | | |
| 10 | 0 | 0 | 0 | 0 | | |
| 11 | 0.06 | 0.0006 | 0.000182 | 3.32698E-08 | | |
| 12 | 0 | 0 | 0 | 0 | | |
| 13 | 0.05 | 0.0005 | 0.000152 | 2.3104E-08 | | |
| 14 | 0 | 0 | 0 | 0 | | |
| 15 | 0 | 0 | 0 | 0 | | |
| 16 | 0 | 0 | 0 | 0 | | |
| 17 | 0.038 | 0.00038 | 0.000116 | 1.33449E-08 | | |
| 18 | 0 | 0 | 0 | 0 | | |
| 19 | 0.03 | 0.0003 | 9.12E-05 | 8.31744E-09 | | |
| 20 | 0 | 0 | 0 | 0 | | |
| 21 | 0 | 0 | 0 | 0 | | |
| 22 | 0 | 0 | 0 | 0 | | |
| 23 | 0.028 | 0.00028 | 8.51E-05 | 7.24541E-09 | | |
| | | | sum | 2.85131E-07 | | |

## Appendix 6: THD calculation using thyristor rectifiers with having one stage of filters.



| Harmonic order n | Harmonic amplitude v | v/100 | (v/100)*V | ((v/100)*Vd)^2 | | THVD cal |
|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | | 0.369605 |
| 2 | 0 | 0 | 0 | 0 | | |
| 3 | 0 | 0 | 0 | 0 | | Vd |
| 4 | 0 | 0 | 0 | 0 | | 1.034 |
| 5 | 0.29 | 0.0029 | 0.002999 | 8.99E-06 | | |
| 6 | 0 | 0 | 0 | 0 | | THVD sim |
| 7 | 0.19 | 0.0019 | 0.001965 | 3.86E-06 | | 0.62 |
| 8 | 0 | 0 | 0 | 0 | | |
| 9 | 0 | 0 | 0 | 0 | | |
| 10 | 0 | 0 | 0 | 0 | | |
| 11 | 0.08 | 0.0008 | 0.000827 | 6.84E-07 | | |
| 12 | 0 | 0 | 0 | 0 | | |
| 13 | 0.06 | 0.0006 | 0.00062 | 3.85E-07 | | |
| 14 | 0 | 0 | 0 | 0 | | |
| 15 | 0 | 0 | 0 | 0 | | |
| 16 | 0 | 0 | 0 | 0 | | |
| 17 | 0.058 | 0.00058 | 0.0006 | 3.6E-07 | | |
| 18 | 0 | 0 | 0 | 0 | | |
| 19 | 0.04 | 0.0004 | 0.000414 | 1.71E-07 | | |
| 20 | 0 | 0 | 0 | 0 | | |
| 21 | 0 | 0 | 0 | 0 | | |
| 22 | 0 | 0 | 0 | 0 | | |
| 23 | 0.038 | 0.00038 | 0.000393 | 1.54E-07 | | |
| | | | sum | 1.46E-05 | | |

| Harmonic order n | Harmonic amplitude I | I/100 | (I/100)*Id | ((I/100)*Id)^2 | | THID cal |
|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | | 0.184997 |
| 2 | 0 | 0 | 0 | 0 | | |
| 3 | 0 | 0 | 0 | 0 | | Id |
| 4 | 0 | 0 | 0 | 0 | | 0.1337 |
| 5 | 0.128 | 0.00128 | 0.000171 | 2.93E-08 | | |
| 6 | 0 | 0 | 0 | 0 | | THID sim |
| 7 | 0.09 | 0.0009 | 0.00012 | 1.45E-08 | | 0.53 |
| 8 | 0 | 0 | 0 | 0 | | |
| 9 | 0 | 0 | 0 | 0 | | |
| 10 | 0 | 0 | 0 | 0 | | |
| 11 | 0.06 | 0.0006 | 8.02E-05 | 6.44E-09 | | |
| 12 | 0 | 0 | 0 | 0 | | |
| 13 | 0.05 | 0.0005 | 6.69E-05 | 4.47E-09 | | |
| 14 | 0 | 0 | 0 | 0 | | |
| 15 | 0 | 0 | 0 | 0 | | |
| 16 | 0 | 0 | 0 | 0 | | |
| 17 | 0.038 | 0.00038 | 5.08E-05 | 2.58E-09 | | |
| 18 | 0 | 0 | 0 | 0 | | |
| 19 | 0.036 | 0.00036 | 4.81E-05 | 2.32E-09 | | |
| 20 | 0 | 0 | 0 | 0 | | |
| 21 | 0 | 0 | 0 | 0 | | |
| 22 | 0 | 0 | 0 | 0 | | |
| 23 | 0.03 | 0.0003 | 4.01E-05 | 1.61E-09 | | |
| | | | sum | 6.12E-08 | | |

## Appendix 7: An example of a small wind turbine.

| | | |
|---|---|---|
| General Configuration | Model | Whisper 200 |
| | Rotation Axis | Horizontal |
| | Orientation | Up Wind |
| | Rotation Direction | Clockwise looking upwind |
| | Number of Blades | 3 |
| | Material of blades | Polypropylene/Carbon Reinforced |
| | Material of blade extenders & rotor shaft material | SS 304 |
| | Rotor Diameter | 2.72 M |
| | Body/housing | Cast Aluminum & MS duly marine coated as per ASTM B - 117 |
| | Mount | 2.5 inches |
| | Weight | 30 kg |
| | Certification | ISO 9001-2008, CE, IEC 61400 |
| Performance | Peak Electrical power (watts) | 1000 watts peak (as per IEC 61400 test cert) |
| | 1 min max average power output | 700 watts average (as per IEC 61400 test cert) |
| | Rated/Voltage | LV model 24volts/36volts/48volts DC HV model 120volts/240volts DC |
| | Rated wind speed | 11.6 m/s to 13 m/s |

| | | |
|---|---|---|
| | Startup/Cut in wind speed | 3.1 m/s |
| | Cut out wind speed | 16 to 18 m/s |
| | Survival wind speed | 55 m/s |
| Rotor | Swept area | 5.8 meter square |
| | Rotational speed | 1200 rpm |
| | Blade pitch | Fixed |
| | Direction of rotation | Clockwise |
| | Over speed control | Side furling & dump load |
| Yaw System | Wind direction sensor | By tail fin & tail boom |
| | Yaw control | Free/Passive yaw |