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Conference Paper

Harmonics Reduction in a Wind Energy Conversion System with a Permanent Magnet Synchronous Generator

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Abstract: This paper 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 5^{th}, 7^{th}, 11^{th}, and 13^{th}, and high pass filters which are responsible to filter higher harmonics such as 24^{th}. 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 11^{th} and 13^{th}) 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.

Keywords: Wind, Turbine, Power, Harmonics, Filter

1. Introduction

The achievement of wind energy has grown in recently years [1]. According to the Global Wind Energy Council (GWEC), the capacity of installed wind energy has grown up to 19% in 2012 to 282 GW. The total installed wind capacity in the world by the end of 2012 is 44.711 GW [2].

With the remarkable progress to the use of wind power, the wind energy conversion system has been installed in many countries. However, the generated power from the wind is variable due to the variations in wind speed. Wind turbine concepts are divided into four types: first, fixed – speed wind turbine, secondly, variable speed wind turbine with variable rotor resistance, the third is a variable speed wind turbine with partial – scale power converter, and lastly, variable speed wind turbine with full – scale power converter. In fixed speed turbine, the generator used is mostly a Squirrel Cage Induction Generator (SCIG) and it is connected straightway to the grid through a transformer. The second configuration is connected to an Optislip Induction Generator (OSIG). One advantage of this type is no need of slip – rings due to the control system in the rotor windings. Thirdly, the most common generator used with this type is a Doubly – Fed Induction Generator (DFIG). Lastly, it is a variable speed wind turbine concept with full – scale power converter. There are two possible generators that could be used in this configuration. They are Permanent Magnet Synchronous Generator (PMSG) and (SCIG) [3].

Power electronic is an important part in wind turbine systems [4]. It uses to integrate the variable speed wind power generation to improve the efficiency and performance to the system. The disadvantages of using power electronics are increasing the cost and power losses. Moreover, they produce harmonics in WECS, such as rising electrical losses and the low quality of the output power [5]. The active filters could be a choice to reduce those harmonics as well as passive filters. But, in this study, we will use active filters. In this type of filters, based on the output signals the essential high pass filter is connected to the lines to decrease the harmonics in the system.

1.1. Harmonics in Wind Turbine Systems

A typical wind energy conversion system consists of five main components which are wind turbine, the PMS generator, rectifier, inverter, and the grid represented as a three phase load, as shown in figure 1.

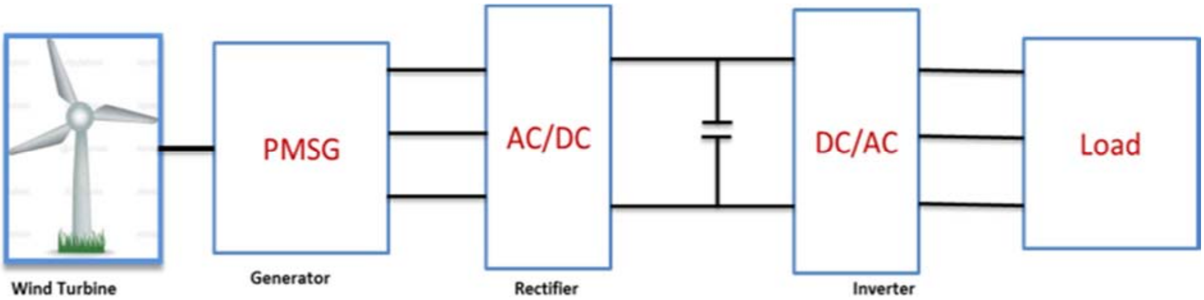


Figure 1. *Wind Energy Conversion System.*

Harmonics lead to cause harm to electrical system components. The sources of harmonics are primary the substantial increase of non – linear loads, for example, power electronics circuits. In addition, there are other sources, such as generators, transformers, motors, and switching power supply.

To verify the harmonics content of the PMSG, Fast Fourier Transform (FFT) is used as well as determining the Total Harmonics Distortion (THD). FFT could be determined by using a tool in Simulink / Matlab, and the THD is found either mathematically or by using Matlab, as follows:

$$THD = \frac{\sqrt{I_3^2 + I_5^2 + I_7^2 + \cdots \ldots . I_n^2}}{I_1}$$

Where:

I_1 = fundamental harmonic.
I_3, I_5, I_7 = odd harmonics.
I_n = nth harmonics.

1.2. The Proposed Model

The main parts of the model are the wind turbine, the PMSG, AC/AC converter, and three phase resistive load, as shown in figure 2.

The purpose of this paper is to reduce the current and voltage harmonics in a WECS, in which the PMSG is driven by a fixed pitch wind turbine connected with a rectifier, inverter, and the HPF. The HPF is an active filter which is used to filter high order harmonics and works at a wide range of frequency.

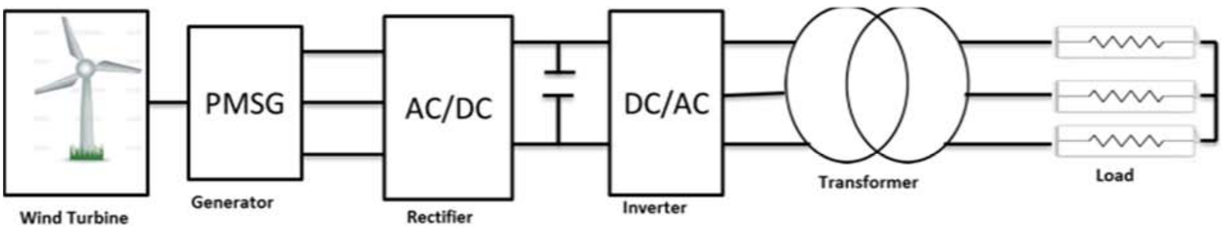


Figure 2. *The Proposed Model.*

This section will focus on the WT model, the generator, and their characteristics.

1.2.1. The WT Model

The characteristics of a wind turbine can be known by the relation between the power coefficient Cp and the Tip - Speed Ratio (TSR).

Figure 3 illustrates a wind turbine model. It can be designed by using Matlab from the following equations:

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

Where
ρ = the air density.
A= the swept area.
V = the wind velocity.
Cp = the power coefficient.

Cp depends on the tip speed ratio and blade pitch angle, and can be expressed by the following equation:

$$C_p(\beta, \lambda) = 0.258\left(\frac{100}{\lambda_i} - 0.4\beta - 2.164\right) * e^{\left(\frac{-15.21}{\lambda_i}\right) + 0.0057\lambda}$$

Where λ is the tip speed ratio (m/sec), which is a function of wind and rotor speeds:

$$\lambda = \frac{\omega R}{V}$$

ω = the rotational speed.
β = the blade pitch angle.
λ_i can be calculated by the following equation:

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

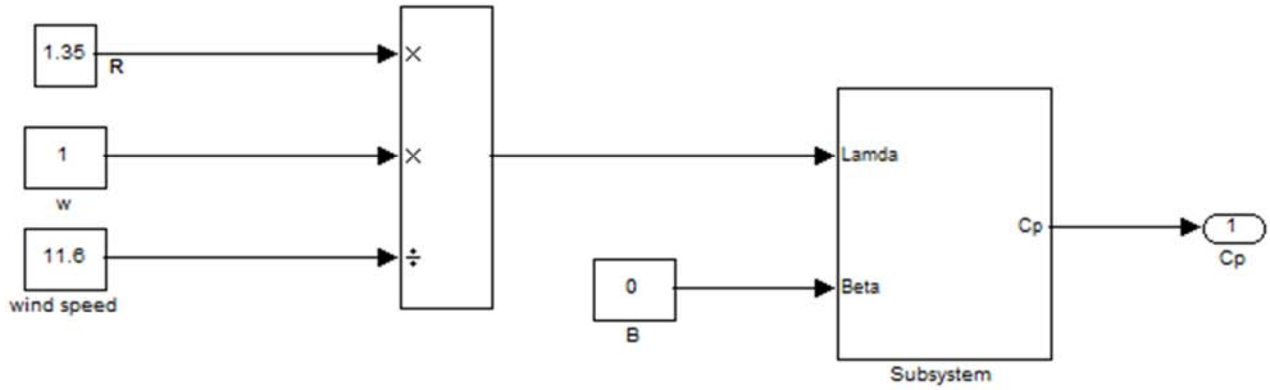


Figure 3. *Wind Turbine Model.*

If the TSR is less than 3, the wake effect reduces the maximum rotor power efficiency. The relation between the power coefficient and the TSR is shown in figure 4. As we can see from the figure, the maximum value of power coefficient is 0.47, while the maximum power coefficient, regardless of the configurations, is 0.593 as the German physicist Albert Betz concluded.

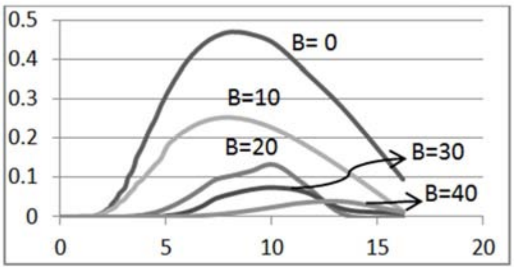


Figure 4. *Power Coefficient Curves for a Wind Turbine.*

1.2.2. The PMSG 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 [6]

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

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

Where:
d, q denotes the physical quantities obtained from abc synchronous.
R_a: The armature resistance.
ω_e: The electrical rotating speed.
λ_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

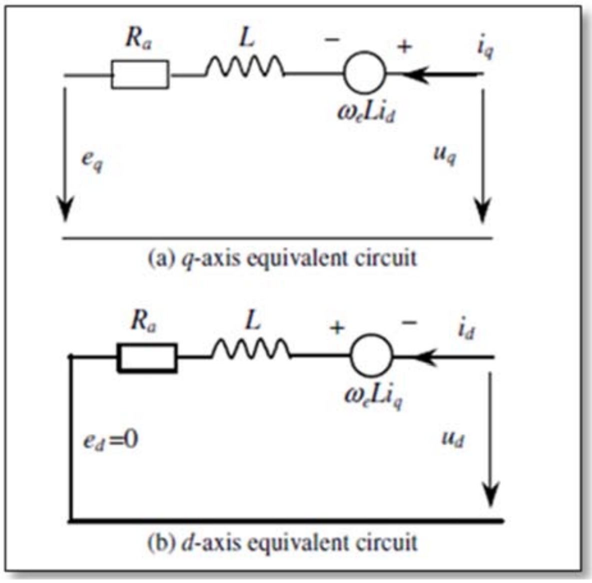


Figure 5. *Equivalent Circuit of PMSG in the Synchronous Frame. [6].*

2. Modeling and Simulating a Wind Energy Conversion System

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 [7]. Furthermore, the model is tested at a wind speed of 8 m/sec to evaluate which one is optimal for operation. We will study the system performance at three levels of wind speeds and compare the generator output voltage and current waveforms in three cases. Figure 6 shows the distributed generation based on a stand-alone wind energy conversion system (WECS) including PMSG is simulated, with the model. 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).

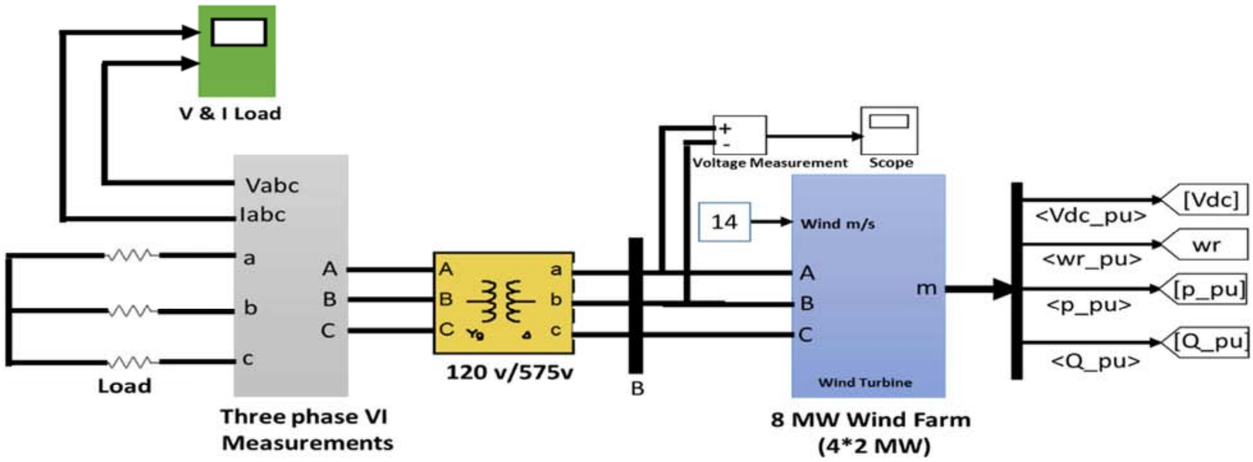


Figure 6. *The Simulated Model.*

We used two different AC/DC/AC converter which are diode rectifier and thyristor rectifier. 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.

2.1. 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:

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

2.2. 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 stages of harmonic filters to connect to the generator. The first stage 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 7. 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 [8].

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

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:

1. One capacitor bank.
2. One high-pass filter tuned to the 24th harmonic order.
3. One double-tuned filter of the 11/13th harmonics orders.
4. 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 case 3).

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).

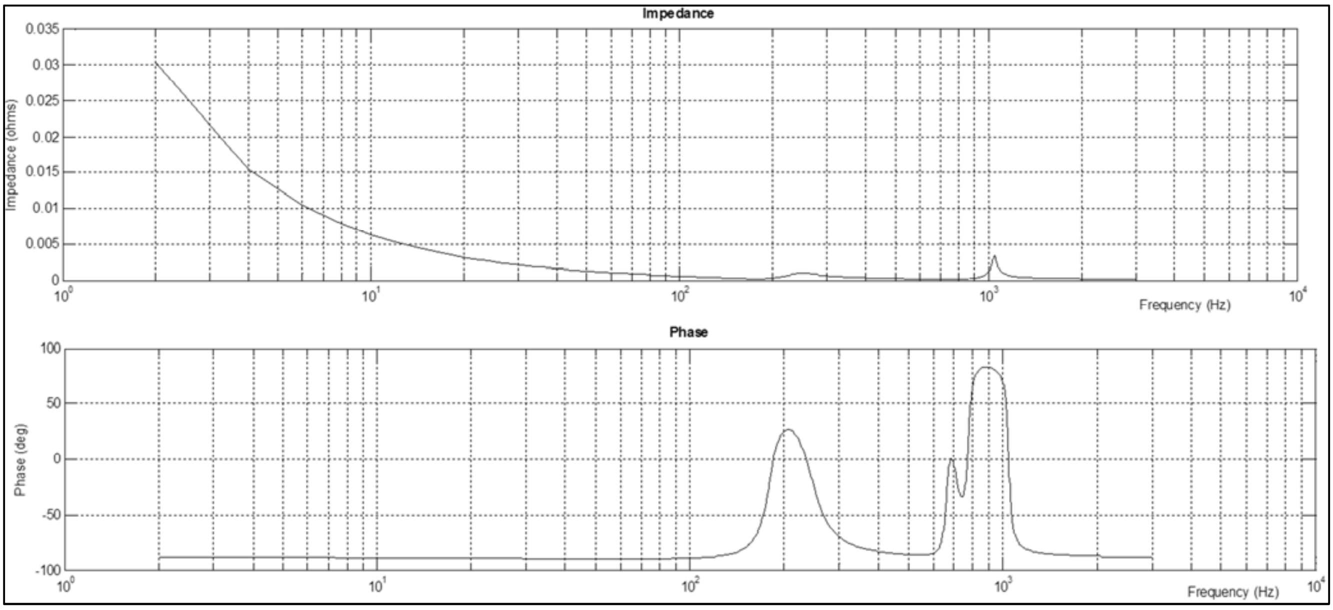


Figure 7. *Frequency-Domain Response.*

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

Table 1. *The parameters of the used filters.*

1. Double –tuned filter.

Reactive power (Mvar)	133.22
Tuning frequencies (Hz)	[11*60 13*60]
n	11, 13
The quality factor $Q = \frac{X_c}{nR}$	1

2. Double –tuned filter.

Reactive power (Mvar)	133.22
Tuning frequencies (Hz)	[24*60]
n	24
The quality factor $Q = \frac{X_c}{nR}$	8

3. C- type high pass filter.

Reactive power (Mvar)	133.22
Tuning frequencies (Hz)	[3*60]
n	3
The quality factor $Q = \frac{X_c}{nR}$	5

4. Single – tuned filter.

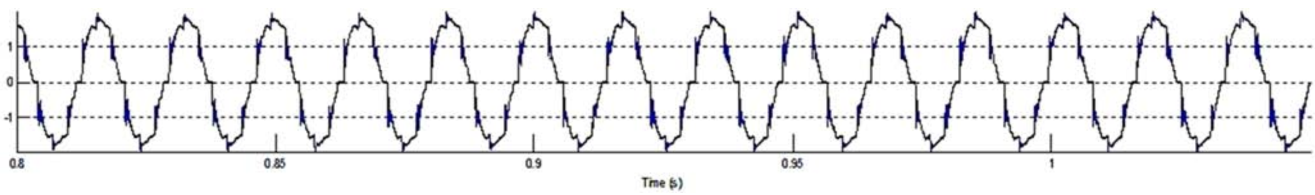
Reactive power (Mvar)	133.22
Tuning frequencies (Hz)	[5*60]
n	5
The quality factor $Q = \frac{X_c}{nR}$	2

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 phase 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.

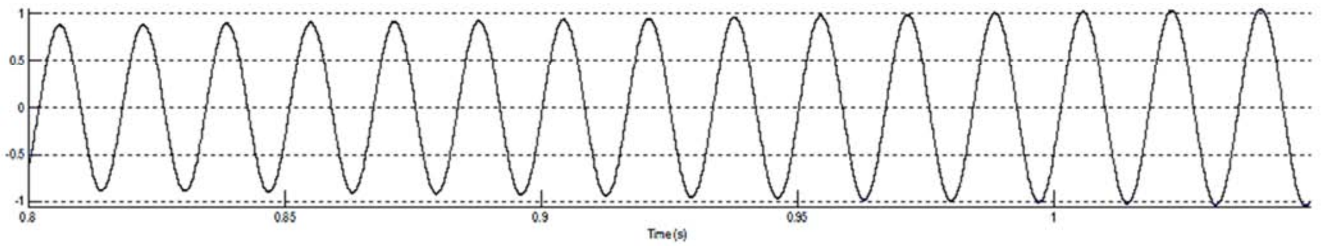
3. The Generator Voltage and Current Outputs

3.1. Using Diode Rectifier Converter

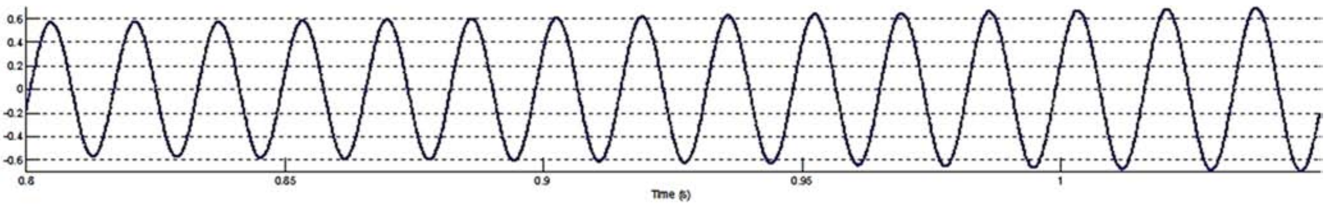
Figure 8-a shows the distorted generator voltage output due to AC/DC diode rectifier. It appears as if there are many harmonics passing through the generator. After deploying the filters, the voltage harmonics are considered a sine wave form. Figure 8-b illustrates the improved generator voltage output due to AC/DC diode rectifier. The simulated THD for the improved voltage waveform decreased from 4.17% to 0.79%. Figure 8-c illustrates the improved generator voltage output after placing two stages of filters. The total harmonic distortion of the sine wave voltage signal reduced from 0.79% to 0.52%.



a. case 1.



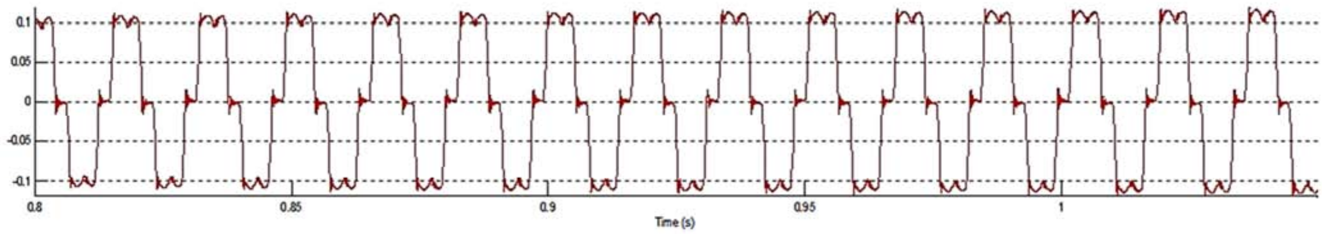
b. case 2.



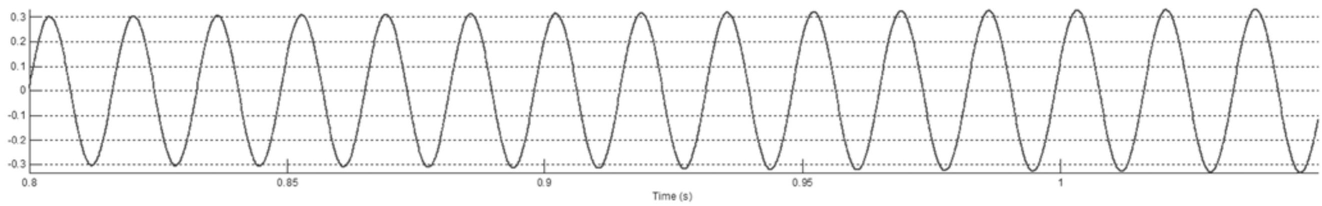
c. case 3.

Figure 8. *The Generator Voltage Output for the Three Cases Using Diode Rectifier.*

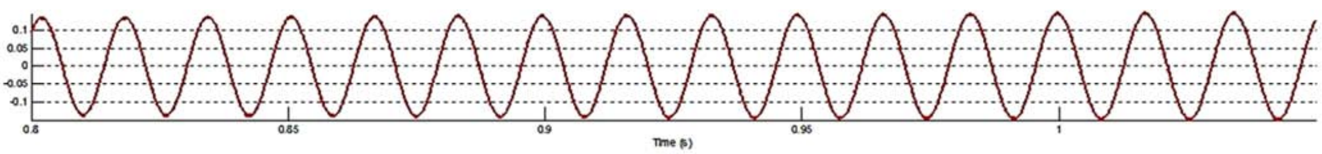
Figure 9-a shows the distorted generator current output. It appears as if there are many harmonics passing through the generator. After placing the filters, the current harmonics are considered a sine wave form. Figure 9-b illustrates the improved generator voltage output due to AC/DC diode rectifier. The simulated THD for the improved voltage waveform decreased from 7.55% to 0.75%. Figure 9-c illustrates the improved generator voltage output after placing two stages of filters. The total harmonic distortion of the sine wave voltage signal reduced from 0.75% to 0.5%.



a. case 1.



b. case 2.



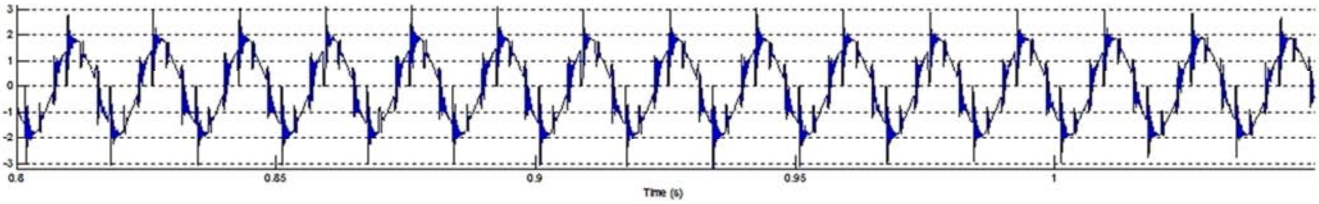
c. case 3.

Figure 9. *The Generator Current Output for the Three Cases Using Diode Rectifier.*

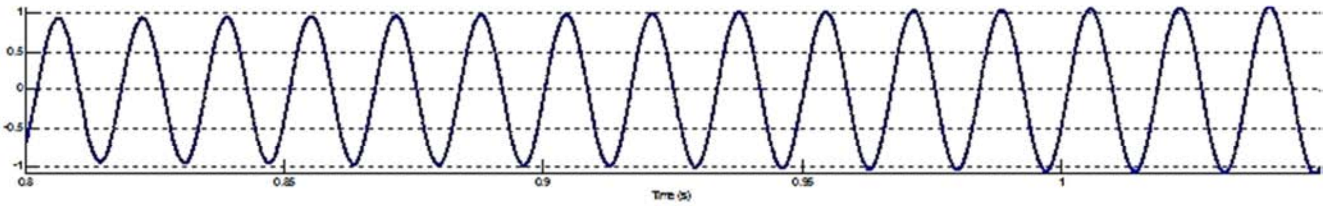
3.2. Using Thyristor Rectifier Converter

Figure 10-a illustrates the distorted generator phase A voltage output due to AC/DC thyristor rectifier. As shown in the figure, it is slightly distorted. Based on this distorted signal, there appear to be much harmonic contents passing through the generator. Figure 10-b shows the improved generator phase A voltage output after placing three phase filters, As we can see from the figure, it is significantly developed. The simulated THD for the improved voltage waveform decreased from 11.16% to 0.63%. We get improvements in THVD for this method comparing with using diode rectifier in this case.

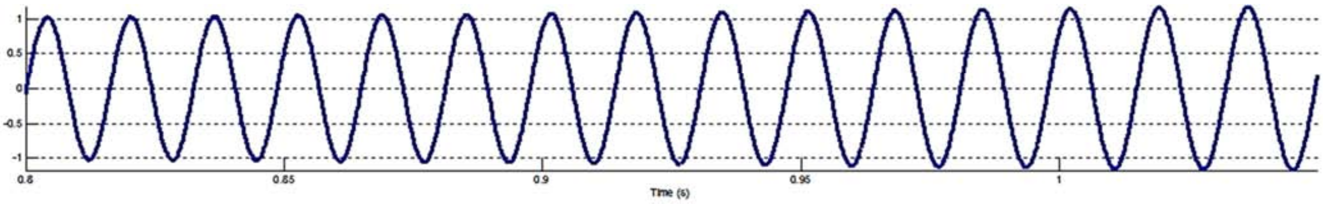
Figure 10-c illustrates the improved generator phase A voltage output after placing another stage of three phase filters. It is significantly developed. The simulated THD for the improved voltage waveform decreased from 0.63% to 0.62%. We get better results in both THVD for this method comparing with the second one.



a. case 1.



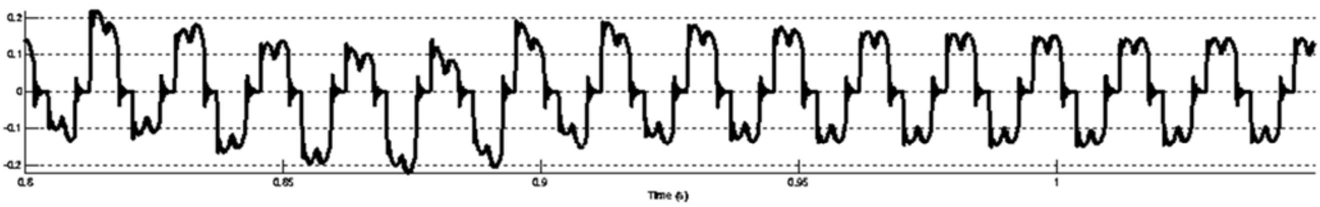
b. case 2.



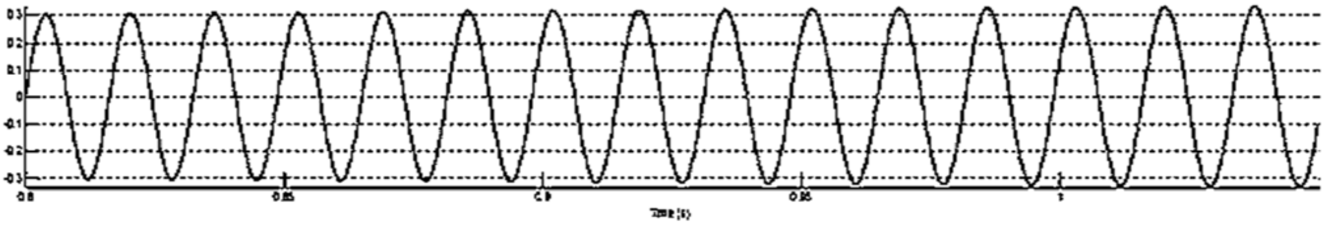
c. case 3.

Figure 10. *The Generator Voltage Output for the Three Cases Using Thyristor Rectifier.*

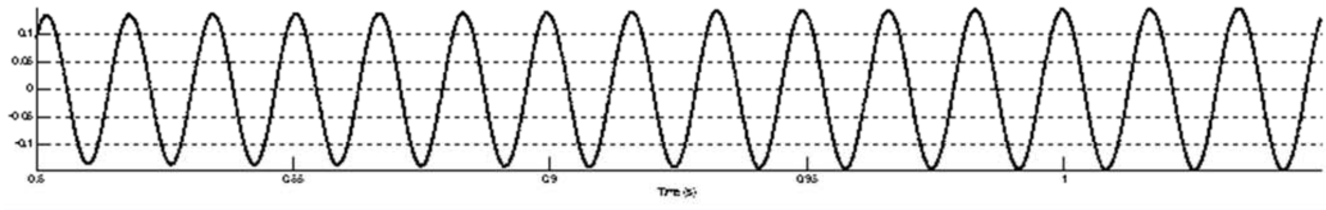
Figure 11-a illustrates the distorted generator phase A current output due to AC/DC thyristor rectifier. As shown in the figure, it is slightly distorted. Based on this distorted signal, there appear to be much harmonic contents passing through the generator. Figure 11-b shows the improved generator phase A current output after placing three phase filters, As we can see from the figure, it is significantly developed. The simulated THD for the improved current waveform decreased from 23.85% to 0.69%. We get improvements in THID for this method comparing with using diode rectifier in this case. Figure 11-c illustrates the improved generator phase A current output after placing another stage of three phase filters. It is significantly developed. The simulated THD for the improved current waveform decreased from 0.69% to 0.53%. We get better results in THID for this method comparing with the second one.



a. case 1.



b. case 2.



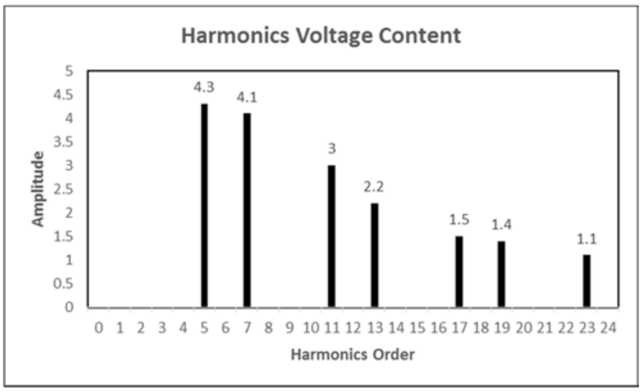
c. case 3.

Figure 11. *The Generator Current Output for the Three Cases Using Thyristor Rectifier.*

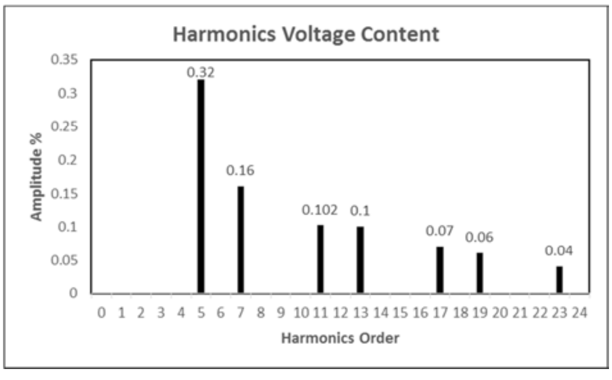
4. Harmonics Contents of the Generator Voltage and Current

4.1. Using Diode Rectifier

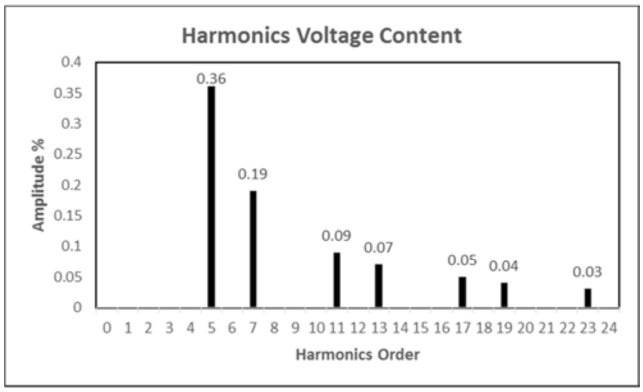
To find the harmonics, the Fast Fourier Transform is applied to these signals by using a Matlab function of FFT to calculate the order harmonics and the THD. The amplitudes of the 5th and 7th harmonics are 4.3% and 4.1% of the fundamental component, respectively. We can observe from the figures that the harmonic orders of the 5th, 7th, 11th, and 13th are significant. The total harmonic distortion obtained for the output voltage is THD=4.17%. Therefore, we attempt to lower these percentages by using a three-phase harmonic filter. After we place one stage of filters, we got better THD which is 0.79%. And 0.52% when we use two stages of filters. Harmonics voltage content of the three cases is shown in Figure 12.



a. case 1.



b. case 2.

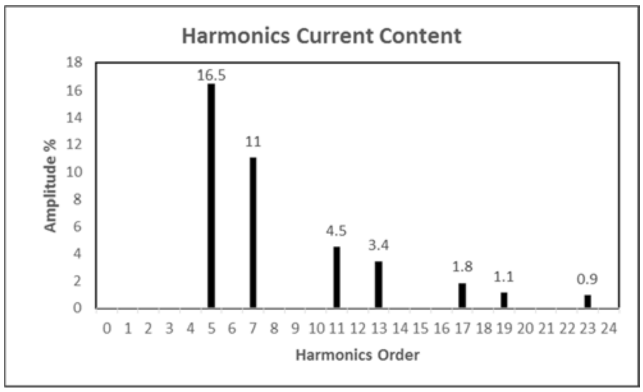


c. case 3.

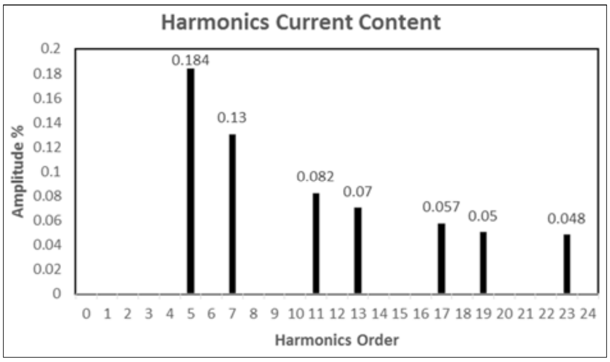
Figure 12. *Harmonics Content of the Generator Output Voltage When Using Diode Converter.*

We find the harmonics by using the Fast Fourier Transform function to current signals to calculate the order harmonics and the THD. The amplitudes of the 5th and 7th harmonics are 16.5% and 11% of the fundamental component, respectively. We can observe from the figures that the harmonic orders of the 5th, 7th, 11th, and13th are significant. The total harmonic distortion obtained for the output current is THD=7.55%. Therefore, we try to decrease these percentages by using a three-phase harmonic filter. After we place one stage of filters, we got better THD which is 0.75%. And 0.50% when we use two stages of filters.

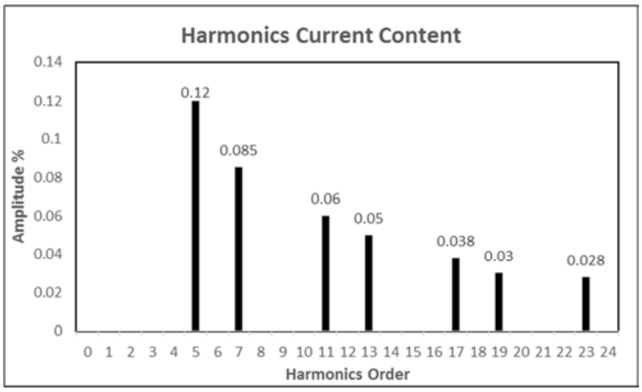
Harmonics current content of the three cases is shown in Figure 13.



a. case 1.



b. case 2.

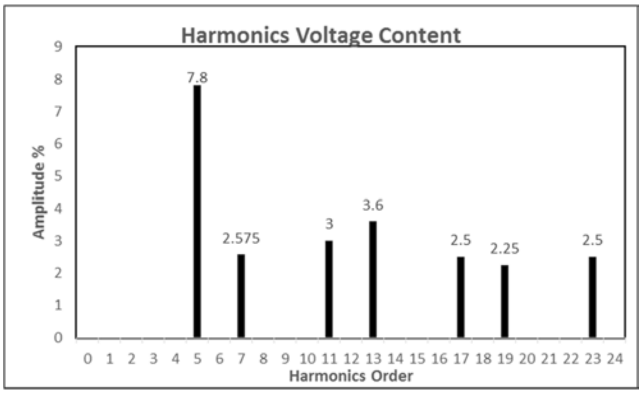


c. case 3.

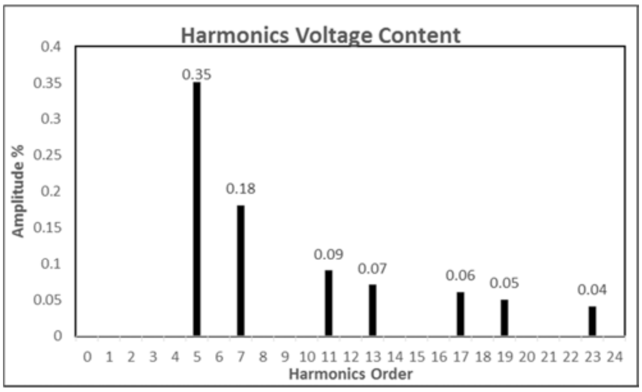
Figure 13. *Harmonics Content of the Generator Output Current When Using Diode Converter.*

4.2. Using Thyristor Rectifier

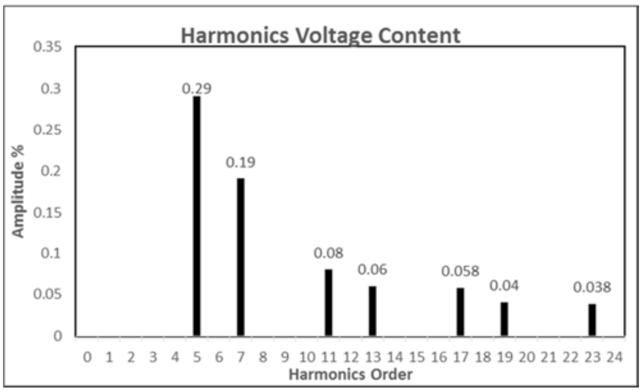
In order to find the harmonics, we apply the Fast Fourier Transform to voltage signals to calculate the order harmonics and the THD. The amplitudes of the 5th and 7th harmonics are 7.5% and 2.5% of the fundamental component, respectively. We can observe from the figures that the harmonic orders of the 5th, 7th, 11th, and13th are bigger than the first converter's results. The total harmonic distortion obtained for the output voltage is THD=11.16%. Therefore, we attempt to lower these percentages by using a three-phase harmonic filter. After we place one stage of filters, we got better THD which is 0.63%. And 0.62% when we use two stages of filters. Harmonics voltage content of the three cases is shown in Figure 14.



a. case 1.



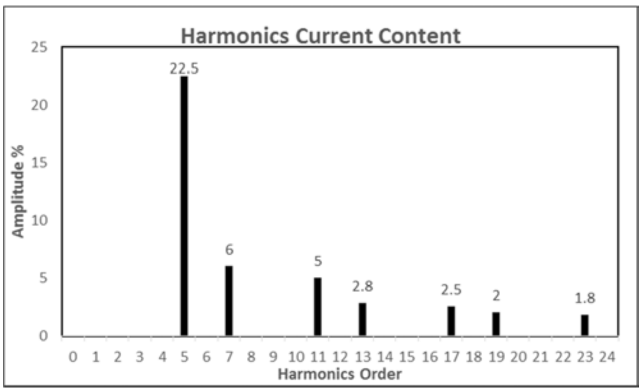
b. case 2.



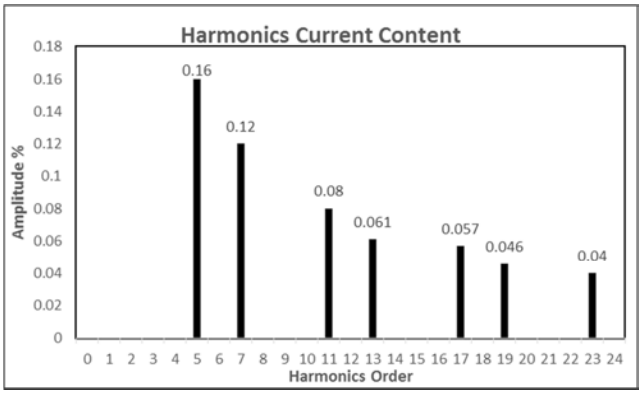
c. case 3.

Figure 14. *Harmonics Content of the Generator Output Voltage When Using Thyristor Converter.*

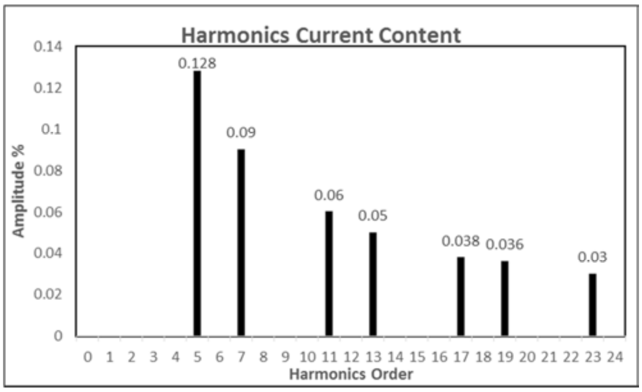
We should apply the Fast Fourier Transform function to current signals to calculate the order harmonics and the THD. The amplitudes of the 5th and 7th harmonics are 22.5% and 6% of the fundamental component, respectively. We can observe from the figures that the harmonic orders of the 5th, 7th, 11th, and13th are significant. The to42tal harmonic distortion obtained for the output current is THD=23.85%. Therefore, we try to reduce these percentages by using a three-phase harmonic filter. After we place one stage of filters, we got better THD which is 0.69%. And 0.53% when we use two stages of filters. Harmonics current content of the three cases is shown in Figure 15.



a. case 1.



b. case 2.



c. case 3.

Figure 15. *Harmonics Content of the Generator Output Current When Using Thyristor Converter.*

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.

Table 2. *Total Voltage and Current Harmonics Distortions in the Wind Turbine Generator for the Three Cases.*

Wind speed m/s	THVD%		THID%	
	Diode	Thyristor	Diode	Thyristor
case 1				
8	4.17	11.16	7.55	23.85
case 2				
8	0.79	0.63	0.75	0.69
case 3				
8	0.52	0.62	0.5	0.53

6. 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 avoid distortions, three-phase harmonic filters were used to connect with the synchronous generator. 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 5^{th}. 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 two stages of filters, the THVD and THID are 0.5% and 0.53%, respectively. These optimal results were obtained at a wind speed of 8 m/s with using thyristor converter, whereas for the diode rectifier, the THD was found to be 0.52% and 0.62%, respectively.

Nomenclature

WECS	Wind Energy Conversion System.
PMSG	Permanent Magnet Synchronous Generator.
PWM	Pulse Width Modulation.
IGBT	Insulated Gate Bipolar Transistors.
AC	Alternative Current.
DC	Direct Current.
HPF	High – Pass Filters.
THD	Total Harmonics Distortion.
FFT	Fast Fourier Transform.
DFIG	Doubly – Fed Induction Generator.
GWEC	Global Wind energy Council.
GW	GigaWatts.
SCIG	Squirrel Cage Induction Generator.
OSIG	Optislip Induction Generator.
TSR	Tip – Speed Ratio.
Cp	Power Coefficient.
WT	Wind Turbine.

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Biographies

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