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Harmonic Reduction of a Synchronous Generator in a Wind Energy System

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Abstract

Among the various sources of renewable energy, wind power is one of the fastest growing and most promising sources of electricity in the world, and it is considered as a free energy source. In spite of that, harmonics are regarded as a problem faced by wind system due to its power electronic converters. In general, it is very impotant to provide electricity with less harmonically polluted voltage, so in this paper, the design of a tuned filter that can reduce the total harmonic distortion of a synchronous generator (SG) in wind energy system is proposed. The simulation results show that the proposed design eliminates a 7th harmonic effectively, and the waveform output of voltage and current are in low total harmonic distortion (THD). The proposed design improves the power quality, in addition to the improving of the other factors, resulting in reduced loss of power and enhanced performance under abnormal conditions.

Keywords: wind energy; harmonic reduction; synchronous generator; total harmonic distortion
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1. Introduction

The demand for energy in the growing society has created a concern in the last decades, especially that the conventional sources of energy are exhaustible rapidly. Therefore, the need has arisen to find alternative sources of energy which must be characterized by several features, such as sustainably and friendly to the environment. Wind energy can be considered as one of the solutions to this problem. Compared with the induction generator, SG has a clear advantage as it does not need a gearbox and a reactive magnetizing current [1]. SG is considered to be one type of variable speed wind turbine generator system. A permanent magnet synchronous generator (PMSG) can be used to create a magnetic field in the SG or used with a traditional field winding. Then, a power electronic converter AC-DC-AC connects the stator to the power grid, and a DC link is supplied energy from the generator output and then inverted to the grid as an ac energy [2].

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One of the main problems with modern variable-speed wind turbines is harmonic. For this reason, harmonics measurements are required by relevant standards. A wave that has a frequency that is a whole number multiple of the fundamental frequency is called harmonic. Some harmonics are even frequencies, for example, 2f, 4f, 6f ... etc. and some are odd harmonics such as 3f, 5f, 7f ... etc. The signal is considered as a perfect sin wave if its energy is at the fundamental frequency. Today, there are many sources for harmonics, load harmonic content differs according to the load type, and each load responds according to the harmonics. Harmonics can cause voltage waveform distortion, which is a biggest problem, since it may lead to a number of defects such as overheating in the transformer, failure of power motors, fuse damage and dysfunction of control system of devices. Furthermore, harmonics may cause mal-operation of the exciting protection system, which in turn can lead to healthy system interruption and make the entire system unstable, unless an extra means for harmonic filtering or blocking is provided and especially for numerical relays [3, 4].

Different applications require high power and quality signal with low harmonics. Therefore, a lot of pervious works conducted on reducing harmonic and enhancing wind system output. Lata and Tiwari [5] used a harmonic filter for wind energy conversation system (WECS) that involved doubly fed induction generator (DFIG) and featured an efficient power electronic interface with harmonic filters to reduce the total harmonic distortion (THD) and improve power quality. Gidwani *et al.* [6] studied the use of an unconventional power electronic interface (UPEI) to reduce the total harmonic distortion (THD) and enhance power quality during disturbances, and hence the models used in the study included a pitch-angled controlled wind turbine model, a DFIG model, a power system model and an UPEI that had controlled converters and was able to increase the effectiveness of the utilization of wind energy. Schwanz *et al.* [7] studied the use of active harmonic filters placed at different locations inside a wind power plant, and the results for current and voltage harmonic distortion were compared and discussed in order to determine the most suitable location for placing active harmonic filters within a wind power plant. This study did not deal with a certain type of wind system. In addition to the above work, Wang and Lu [8] used a C-type filter for a wind or solar power plant harmonic mitigation, and the results showed that a C-type filter reduced harmonics and eliminated natural oscillation frequency, reducing THD and increasing the stability of the power system. Finally, Silva *et al.* [9] studied the use of a grid-side converter (GSC) as an active filter for harmonic filtering through the power control of a permanent magnet synchronous generator (PMSG). Referring to all above studies, passive filters and active filters can be used, and each type has advantages and disadvantages. Passive filters are considered to be cheaper and more practical to use, and smaller in size. So, in this research, we deal with the optimization of passive filters, particularly a single-tuned filter for a wind power plant of the synchronous generator type. The main objective is to analyze harmonics that are present in a wind power system, design passive filters to eliminate or control harmonic distortions, and optimize the filter for various parameters. A harmonic filter has been applied to the output of a wind farm synchronous generator (WFSG) using MATLAB/Simulink environment, and the results show the effectiveness of the experimental system in reducing the THD.

2. Materials and Methods

2.1 Harmonic filters and their effects

Voltage distortion in power systems can be decreased by using three-phase harmonic filters, which can be reflected on the power factor correction. The design of the harmonic filters are capacitive behavior at fundamental frequency, therefore, they produce reactive power. All filter types consist of RLC elements. The value of these elements are determined depending on the filter type and the parameters below:

- Nominal voltage reactive power
- Frequencies of tuning
- Quality factor

The measure of the sharpness for the tuning frequency is called quality factor and is determined by the value of resistance. Until 1980, all loads were considered to be linear except in some applications, like factories, but most items of electrical equipment these day, such as UPS, battery chargers printers, and PCs, have nonlinear loads and create harmonics. In such equipment, the fundamental waveforms and the distorted one have a relationship between them, and can be found by dividing the square root of the sum of the squares of all harmonics produced by an individual load, on the fundamental 50 or 60 Hz waveform value [10]. As explained in the Fast Fourier Transform method, this theorem calculates the (THD) included in nonlinear current or voltage waveforms. When THD is unacceptable, many troubles in sensitive equipment and loads occur. Placing a harmonic filter, which is a low impedance device, in parallel near a harmonics source will reduce the harmonic distortion as it draws harmonic current from harmonic sources in the system and consumes it as heat. Due to the fact that these filters do not have any active component such as transistors or do not need an external source of power, they are called passive filters [11].

2.2 Mathematical analysis for a single-tuned filter

The single-tuned filter is one of the simplest filter, and an optimal design means minimizing the cost of the filters and reduces the total harmonic distortion of currents and voltages. Figure 1 shows a single-tuned filter. The quality and size of the filter can be considered as a main notion in the design of the filter, and the reactive power which is supplied at fundamental frequency, determines the filter size. The filter shows a capacitive characteristics at a frequency that has a value less than tuning frequency.

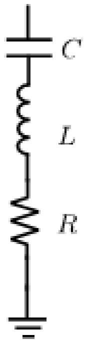

Figure 1. Single-tuned filter

According to the following equations, the tuning of a single-tuned filter can be achieved to mitigate any harmonic order [12]. The order of tuning harmonic frequency (n) can be calculated from:

$$n = \frac{f_r}{f_1} \tag{1}$$

where $f1$ is a fundamental frequency and fr is the resonance or tuning frequency. The frequency, which causes the LC circuit to resonate is giving by:

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

where L is inductance of the filter in henry and C is the capacitance of the filter in farad. For any frequency not equal to the resonance frequency, the filter shows high impedance while it shows a low impedance for the resonance frequency. By applying the equation below, it is possible to calculate filter fundamental and harmonic reactive power:

$$Q_f = C\ \omega_f\ V_L^2\ (1 - \frac{1}{n^2}) \tag{3}$$

where ω_f is the fundamental value of the angular frequency and measured in (rad/sec), and the reactive power is Qf. C is the capacitance in farad (F) and V_L represents the fundamental value of the line voltage where filter is located and n represents the harmonic order.

For given Qf and using equation (3), the value of C can be computed by:

$$C = \frac{n^2}{n^2+1}\ \frac{Q_f}{\omega_f V_L^2} \tag{4}$$

The maximum value of the frequency deviation must be taken in account in the determining of the tuning frequency in addition to the system characteristics if it is inductive or capacitive. In most cases, tuning frequency is made less than harmonic frequency due to the inductive characteristics of the power system, so the trouble of resonance does not happen. The design cannot control two operators such as system frequency deviation and impedance of the network. The two factors are considered to be in bad conditions. The maximum (ϕm) phase angle and (δm) frequency deviation are utilized in the design of the filter.

$$f_r = f_n + \Delta f = f_n + \delta_m f_n \tag{5}$$

Where, fr and fn are the tuning and harmonic frequency, respectively. δ_m is maximum frequency deviation. The optimum (L) is calculated from equation (2). For minimum value of harmonic voltage, the optimum quality factor Q_{opt} of a filter in resonant case for worst condition is given by:

$$Q_{opt} = \frac{1+\cos(\phi_m)}{2\delta_m \sin(\phi_m)} \tag{6}$$

And the optimum value of (R) can be computed by:

$$R = \frac{X_0}{Q_{opt}} = \frac{1}{Q_{opt}}\sqrt{\frac{L}{C}} \tag{7}$$

where X_o is the resonant reactance of the filter. Normally, higher Q_{opt} is considered for loss reduction. The optimal operation of the frequency band for the filter decides the filter quality (Q), which is the representation for the filter tuning sharpness. Best harmonic suppression, in addition to harmonic voltage and power losses reduction, can be achieved by a high quality factor which may lead to an increment in the resonance problem between system and filter [13, 14]. The total harmonic distortion block is used in this simulation to measure the total harmonic distortion (THD) of a periodic distorted signal. The signal can be a measured voltage or current. The. THD is defined as the root mean square (RMS) value of the total harmonics of the signal, divided by the RMS value of its fundamental signal, and then multiplied by 100 % as shown in the following equation:

$$\mathrm{THD} = \frac{\sqrt{I_2^2+I_3^2+\cdots I_n^2}}{I_1} \times \quad 100 \tag{8}$$

where I_n is the rms value of the harmonic current wave and I_1 is the rms value of the fundamental current, same equation can be used for voltage signal.

3. Results and Discussion

The proposed filter design has been validated and optimized via experimental tests using test system as shown in Figure 2. All the system components have been simulated in MATLAB/Simulink platform using simulink library blocks as shown in Figure 3. Hence, the system contains a wind farm of 10 MW power output, which consist of five units, each one of 2MW, 575V. The wind farm has been simulated using a MATLAB wind farm block (PMSG), and the wind block configuration parameters are listed in Table 1.

The wind farm block in the simulation as shown in Figure 2 provides measurement for its internal quantities and contains the main parts of the wind system, which are the wind turbine that is synchronous generator type in addition to the 3 stage of conversion. The first stage is through a 3ph diode rectifier which consists of power diodes connected in a bridge configuration that convert the AC generator output to DC in order to make it controllable. The next step is the DC/DC IGBT-based PWM boost converter which steps up the DC output to higher level and passes it to the DC/AC IGBT-based PWM converter, which converts it to the controllable AC output and passes it on to the grid. This design of the system with three stage of conversion is to extract maximum power for a given wind speed. Moreover, these converters are embedded in one block, i.e. “a wind farm block”, and Figure 4 shows the internal content of the block as modeled in the simulink library, which is available as a ready to use unit, so there are limited number of parameters for the user to modify, as in Table 1. The synchronous generator type of wind turbine has the advantage of increasing the output efficiency during low wind speed and reducing the turbine stresses during high wind speed, so it is the most implemented type in wind turbine. The wind farm output power is delivered to the power grid through a 30km transmission feeder of pi configuration with the aid of two step-up transformers, a 575V/ 25kV star/delta and a 25/120 kV delta/star from both sides of wind farm and grid. The earth point that forms the transmission feeder has been provided through a zigzag transformer as shown in Figure 3, and Table 2 provides all the configuration parameters for the previously mentioned equipment, since the transformer's impedances are the same for primary and secondary sides. The filter connection state can be controlled by the circuit breaker.

Two test cases were performed on the system; the first case was done without the filter to analyze the system components and to find out the harmonics content of both voltage and current waveforms which were injected into the system from the wind farm. With the aid of Powergui tool in Matlab/Simulink, as seen in Figure 5, the FFT analysis was performed on voltage and current waveforms at bus 575V to get their harmonic spectrums and THDs and the results are shown in Figures 6 and 7. The first order is the fundamental one and represents the fundamental wave itself.

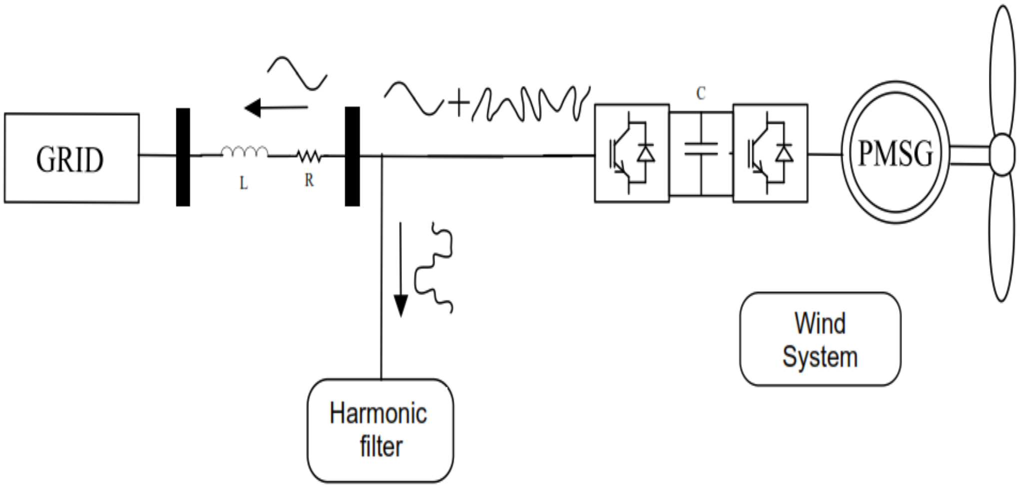

Figure 2. Test system general structure

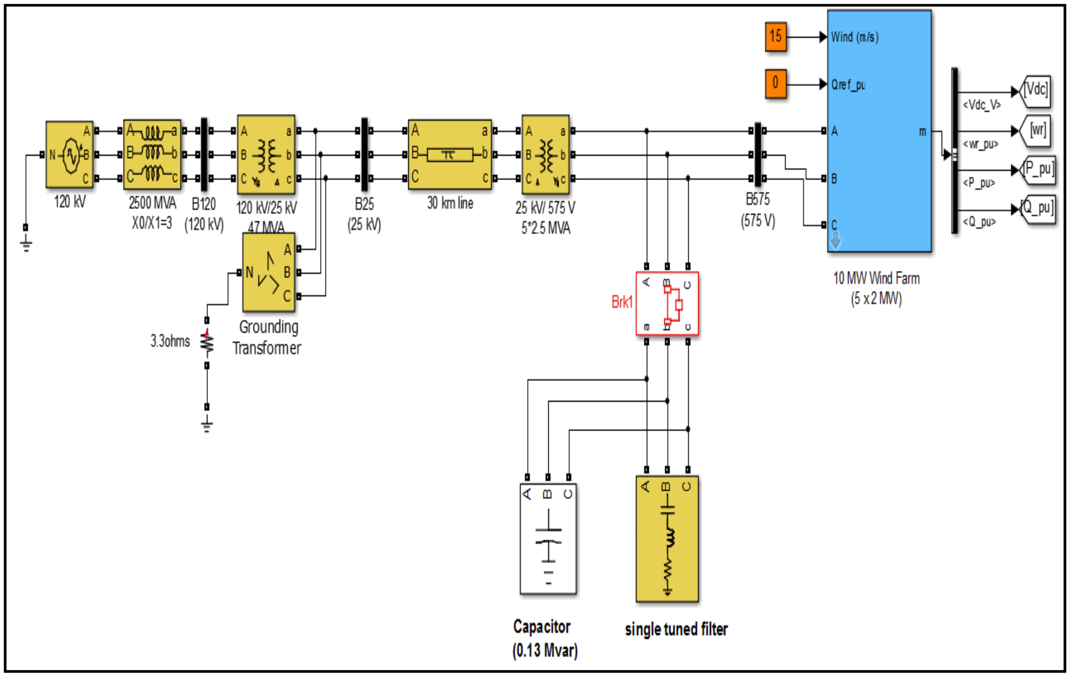

Figure 3. Matlab/Simulink model for the test system with harmonic filter representation

Table 1. Wind farm parameters

Name	Value
Nom. Power VA	10
L-L volt. V	575
Freq. Hz	60
"Controller Parameter"	
Dc bus volt. Reg. gain	1.1, 27.5
Grid-side con. var Reg. gain	0.05
Grid-side con. Volt. Reg. gain	2
Grid-side con. Ct. reg. gains	1, 50
Speed reg. gains	5, 1
Boost inductor Ct. reg. gains	0.025, 100
Pitch controller gain	15
Pitch compensation gains	1.5, 6
"Converter Parameter"	
Grid-side conv. AC Volt. V	575
Grid-side conv. AC Ct. pu	1.1
DC bus Volt. And Capc. V, F	1100, 90000e-6
Boost Conv. Induc. H, Ω	0.0012, 5e-3

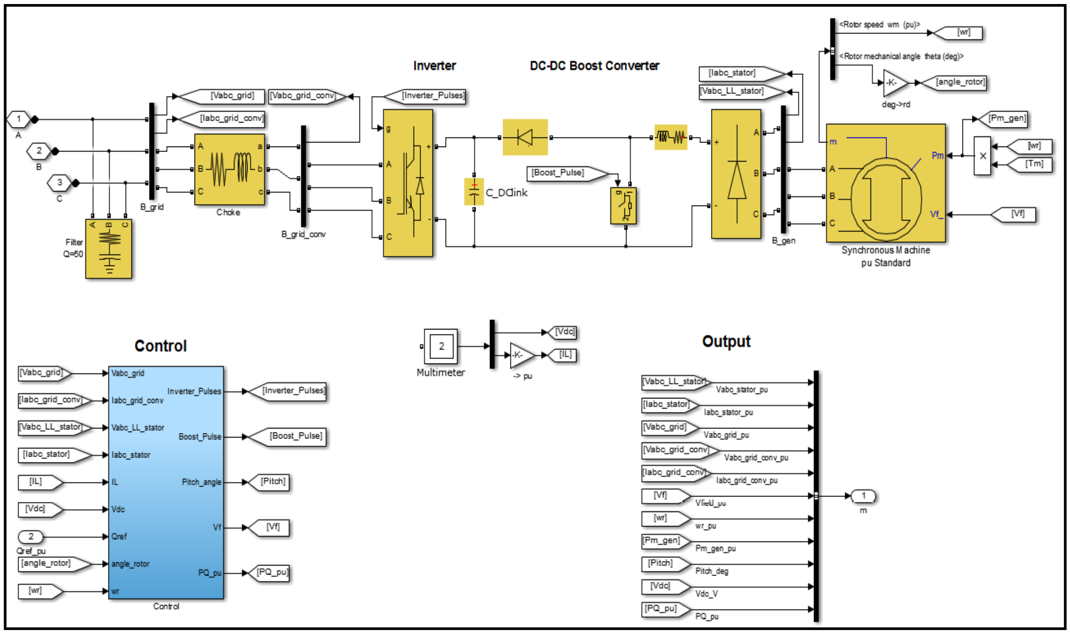

Figure 4. Under mask view for the wind farm block

Table 2. Parameters for equipment at 60 Hz

Equipment	R1	Ro	L1	Lo	C1	Co
Feeder 30 km	0.1153Ω/km	0.413Ω/km	1.05e-3H/km	3.32e-3H/km	11.33e-9F/km	5.01e-9F/km
575V/ 25kV Tr.	8.33e-4pu	----	0.025pu	----	-----	-----
25/120 kV Tr.	0.0026pu	----	0.08pu	----	----	----

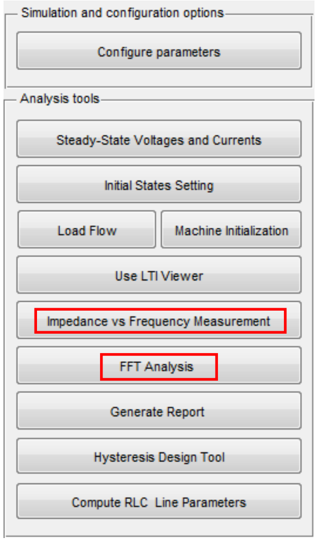

Figure 5. Powergui tools for FFT analysis

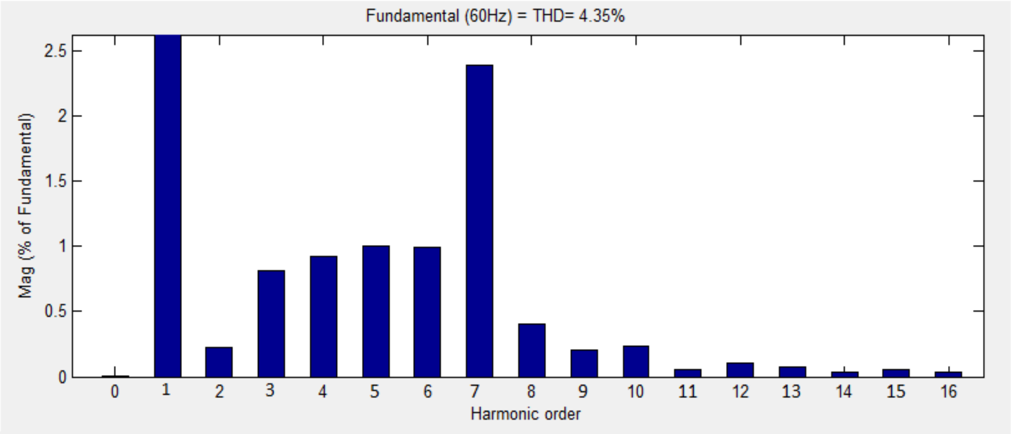

Figure 6. Spectral diagram of AC voltage without filter

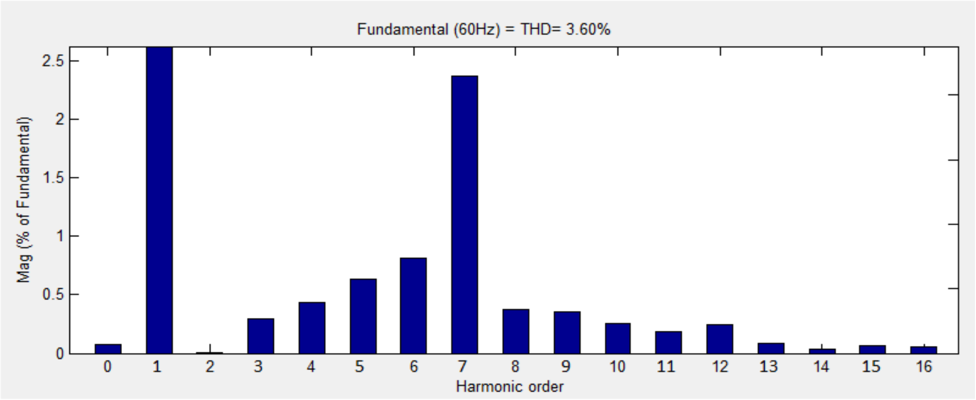

Figure 7. Spectral diagram of AC current without filter

On the other hand, a comparison of the harmonics reveals that the 7th order harmonic is dominant on the spectrum, and its value is shown as a percentage of the fundamental value.

According to the first test, the harmonic filter was designed and optimized using previously presented mathematical analysis equations in order to reduce the effect of the 7th order harmonic. Hence, Figure 8 shows the designed filter impedance vs frequency characteristic and Table 3 includes the parameters used for the filter. The second test case was performed with the filter present in the system to investigate to which extent that the 7th order harmonic could be reduced by the filter, which is assumed to supply 0.8 MVar under normal conditions.

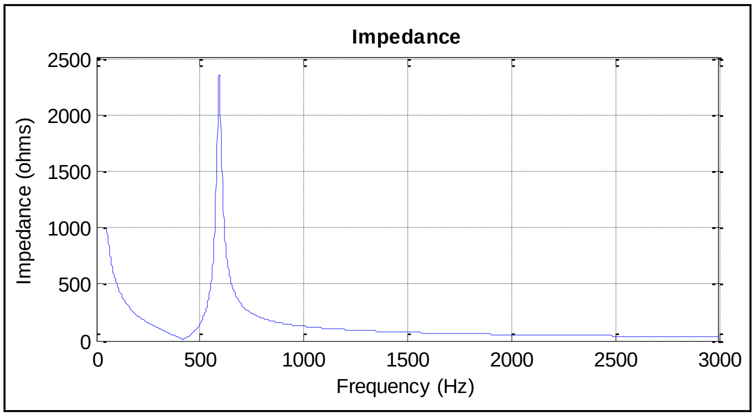

Figure 8. Filter impedance vs frequency characteristic

Table 3. Values of the designed filter

Parameter	Value
C(µf)	6289
L(mH)	0.0229
R(Ω)	0.03
Q	20

Figures 9 and 10 show the FFT analysis for voltage and current waveforms respectively with filter connected to the system. It is clear that all harmonic components fall approximately in the same negligible range. Figure 11 shows a comparison between voltages with and without filter. From the above results, the role of the filter can be noted in reducing harmonic and make voltage smoother.

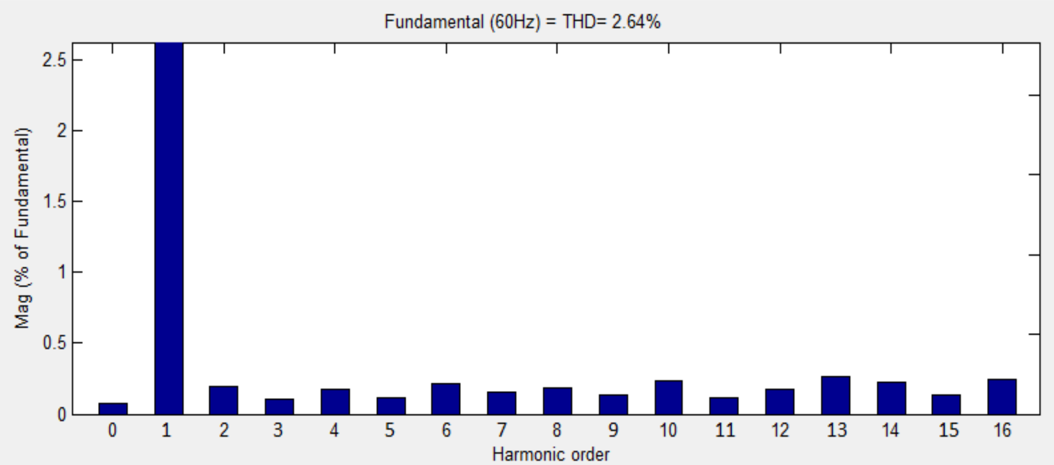

Figure 9. Spectral diagram of AC voltage with filter

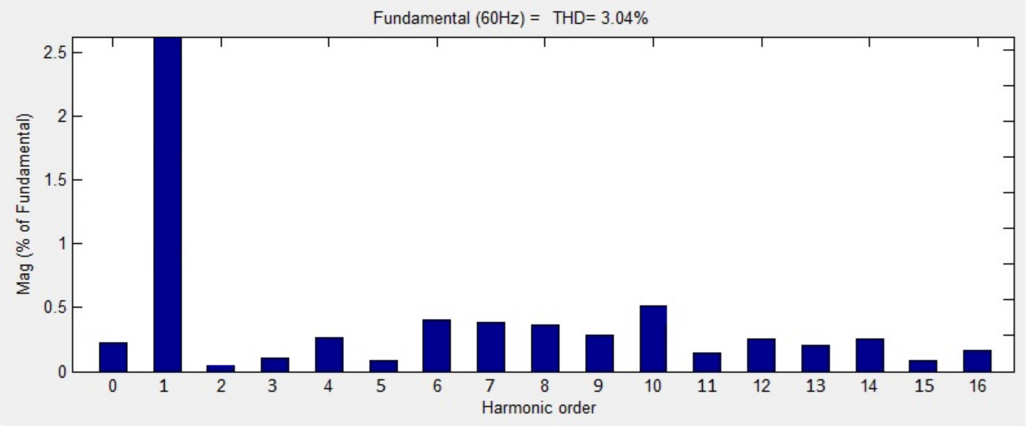

Figure 10. Spectral diagram of AC current with filter

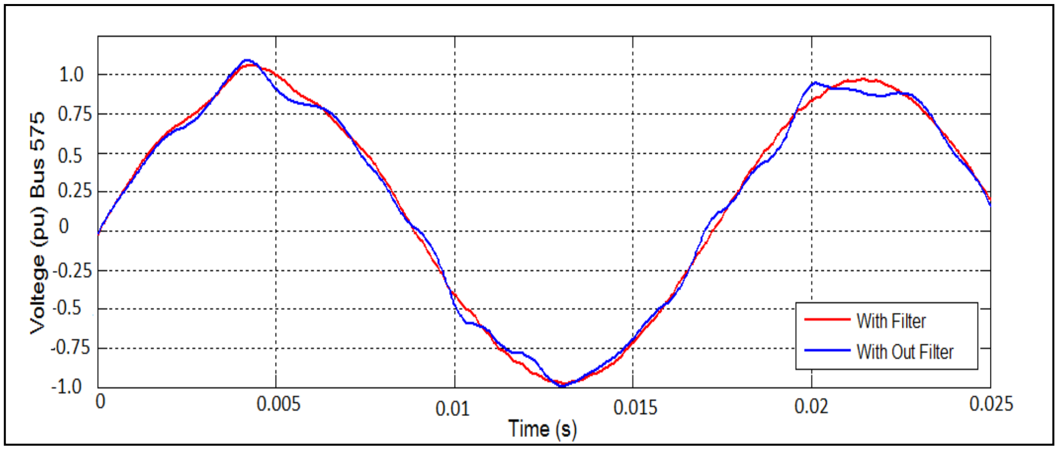

Figure 11. Enlarged scale of voltage (pu) at bus 575

In comparing the results of the two tests cases, form Figures 6 and 9, it can be noted that the 7th order harmonic of the voltage wave has been reduced from 2.16% to 0.17% when expressed as percentage of the fundamental value in the case of filter added. From Figures 7 and 10, it is clear that the 7th order harmonic has been reduced in the output current from 2.39% to 0.4%, expressed as percentage of the fundamental value. In addition, the total harmonic distortion (THD) of the output current and voltage has also been reduced due to the addition of the filter, as shown in Table 4.

Table 4. Summary of simulation results

THD	Without filter	With filter	Percentage of improvement
Voltage wave	4.35%	2.64%	39.3 %
Current wave	3.60 %	3.04%	15.5 %

4. Conclusions

This paper presents an analysis of single-tuned filter connected to a wind farm type synchronous generator (SG) to reduce total harmonic distortion using MATLAB/Simulink software. The single-tuned filter is commonly used because its advantage makes it the best choice in most cases, like simplicity installation and low cost. Single-tuned filters also have some disadvantages such as energy loss and incidence of resonance, but this can be minimized through design by choosing the appropriate value tuning frequency and Q values. The simulation results show that the 7th order harmonic and THD for the output current and voltage of the wind farm can be significantly reduced by the use of the single-tuned filter and also enhances power quality in system. Lastly, the above procedure can be used in different power system to eliminate any harmonic order.

5. Acknowledgements

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