Power Quality Improvement in DFIG-Based Wind Energy Systems Using Shunt Active Power Filter

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Abstract:

Doubly Fed Induction Generator (DFIG) is a key component in modern wind energy systems due to its ability to operate efficiently under variable wind speeds and capture more power. However, integration of non-linear loads such as rectifiers, cycloconverters, variable speed drives, and arc furnaces introduces significant harmonic distortions into the power system, adversely affecting power quality. This study investigates the use of a Shunt Active Power Filter (SAPF) for harmonic mitigation and power quality improvement in a DFIG-based wind energy system. A detailed simulation model has been developed using MATLAB/SIMULINK, wherein the SAPF is connected in parallel with the load to inject compensating currents that are equal in magnitude and opposite in phase to the harmonic currents. Fast Fourier Transform (FFT) analysis confirms that the Total Harmonic Distortion (THD) is reduced to 9%, aligning with the limits set by IEEE Standard 519-1992. The simulation results demonstrate that the proposed SAPF effectively mitigates current harmonics, enhances waveform quality, and ensures compliance with power quality standards.

Keywords: Doubly Fed Induction Generator, Total Harmonic Distortion, Shunt Active Power Filter, Power Quality

1.1 Introduction

Wind energy is the circumlocutory appearance of solar energy. Wind consequence by the cause of the discrepancy heating of earth and its environment by the sun. The fundamental conception following the wind energy system is that, the wind reaper renovates the “kinetic energy” of wind into the “electrical energy”. This energy does not infect the surroundings rather it is unlimited. The greater part of the produces wants to standalone with most extreme wind turbine size of 20KW. The normal wind entrance rate is most extreme in the pumping field. The most extreme wind turbine size increments if there should be an occurrence of network association.

In this thesis, the model of DFIG based variable speed direct drive wind turbine generating system WTGs is developed. The main feature of the proposed topology is that the energy storage elements, such as inductors and capacitors, can be reduced in order to improve the reliability, and reduce size and total cost. The basic structure, control design, and MATLAB/SIMULINK results are presented.

In order to calculate the losses of the generator, the equivalent circuit of the induction generator with inclusion of magnetizing losses has been used. For the DFIG system, the voltage drop across the slip rings has been neglected. Moreover, the stator to rotor turns ratio for the DFIG is adjusted so that maximum rotor voltage is 75% of the rated grid voltage. This is done in order to have safety margin, i.e., a dynamic reserve to handle, for instance, a wind gust. Observe that instead of using a varying turn’s ratio, the same effect can also be obtained by using different rated voltages on the rotor and stator.

The reason that the generator losses are larger for high wind speeds for VSIG system compared to the DFIG system is that the gearbox ratio is different between the two systems. This implies that the shaft torque of the generators will be different for the two systems, given the same input power. It can also be noted that the losses of the DFIG are higher than those of the VSIG for low wind speeds. The reason for this is that the flux level of the VSIG system has been optimized from an efficiency point of view while for the DFIG system the flux level is almost fixed to the stator voltage. This means that for the VSIG system a lower flux level is used for low wind speeds, that is, the magnetizing losses are reduced.

The effect of such non-linearity may become sizeable over the next few years. Hence it is very important to overcome these undesirable features. Classically, shunt passive filters, consist of tuned LC filters and/or high passive filters are used to suppress the harmonics and power capacitors are employed to improve the power factor. But they have the limitations of fixed compensation, large size and can also exile resonance conditions. Active power filters are now seen as a viable alternative over the classical passive filters, to compensate harmonics and reactive power requirement of the non-linear loads. The objective of the active filtering is to solve these problems by combining with a much-reduced rating of the necessary passive components. Various topologies of active power filters have been developed so far.

1.2 LITERATURE REVIEW

N.K. Swami Naidu et al. [1] present a synchronized model of the Doubly-Fed Induction Generator (DFIG), focusing on rotor-side control and its performance under both linear and nonlinear load conditions. B.V.D.N. Ganga et al. [2] validate the proposed DFIG system under wind turbine stalling conditions, demonstrating its ability to compensate for harmonics and reactive power of local loads. They also introduce a modified Grid Side Converter (GSC) control to enhance harmonic and reactive power compensation. B. Chitti Babu et al. [3] describe wind turbine modeling aimed at extracting maximum mechanical power from wind based on parameters such as wind velocity, tip-speed ratio, and a vectorized dynamic approach. Abderrahmane Kanchani et al. [4] implement a dual-controller system based on Nonlinear Model Predictive Control (NMPC), where one controller optimizes DFIG performance, and the other, applied to a Shunt Active Power Filter (SAPF), compensates for harmonics produced by nonlinear loads. Yogesh Murthy N. et al. [7] review power electronic applications in wind energy systems, comparing different generator-converter configurations and exploring the electrical topologies and potential applications of power electronics in wind farms. E. Muljadi et al. [9] discuss challenges in wind energy systems, including variable power output, voltage fluctuations, and inconsistent frequency—highlighting the need for careful system design to manage these variations. Balasubramaniam Babypriya et al. [10] develop a dynamic steady-state simulation model of the DFIG in MATLAB to analyze characteristics such as torque-speed and real/reactive power across varying speeds. E. Spahic et al. [11] explain the fundamental control strategy for DFIGs, focusing on rotor current and voltage regulation using current regulators, AC/DC voltage controllers, and hysteresis control. S. Muller et al. [12] conduct simulations to assess the performance of vector-controlled DFIGs, analyzing parameters like line current, rotor current, output power, and Total Harmonic Distortion (THD) in the line current. Morten Lindholm et al. [13] examine the frequency spectrum of stator and rotor currents in DFIGs and propose methods to suppress higher-order and interharmonics. Finally, Ambrish Chandra et al. [14] propose enhancements for Shunt Active Filters to improve voltage regulation, harmonic elimination, power factor correction, and load balancing under nonlinear conditions.

Musa Yusup Lada et al. [15] highlight the growing demand for improved power quality, emphasizing Active Power Filters (APFs) as the most widely adopted solution. APFs are effective in eliminating unwanted harmonics, improving power factor, and mitigating voltage sags. Arpit Shah et al. [16] address the adverse effects of the widespread use of power electronic devices in distribution systems, such as arc furnaces, variable frequency drives, and computer power supplies. These devices significantly degrade power quality by injecting harmonics into the utility supply. As a solution, shunt active power filters are proposed for effectively eliminating these harmonics and maintaining the quality of power supply. T. Rajesh et al. [17] describe a shunt active filter system where pulses for a current-controlled current source inverter are generated using a synchronous reference frame technique combined with a hysteresis current control loop. Shunt filters are recommended due to their simple design, cost-effectiveness, and high efficiency in addressing harmonic-related issues. S.U. Bhople et al. [19] differentiate between passive and active harmonic filters, noting the limitations of passive filters and advocating for active filters, particularly shunt APFs. They emphasize the importance of reference current generation and various techniques employed for this purpose. Hideaki.

Power Quality (PQ) primarily addresses maintaining a stable voltage at the Point of Common Coupling (PCC) across various distribution voltage levels, regardless of voltage fluctuations. Key objectives include ensuring a near-unity power factor for the power drawn from the supply, preventing voltage and current imbalances from propagating upstream through the distribution network, and minimizing voltage and current harmonics within the system. Traditionally, passive LC filters and fixed compensating devices—such as thyristor-switched capacitors and thyristor-controlled reactors—were employed to enhance the power factor of AC loads. However, these conventional methods suffer from limitations including fixed compensation levels, bulky physical size, aging effects, and potential for resonance. In response to these drawbacks, modern solutions utilizing power semiconductor devices—such as Active Power Filters (APFs) and Active Power Line Conditioners (APLCs)—have become more prevalent. These systems offer dynamic, real-time compensation with greater flexibility and improved performance in addressing diverse PQ issues.

2.1 MATHEMATICAL MODELING OF WIND TURBINE

This system, see Figure 2.1, consists of a wind turbine with DFIG. This means that the stator is directly connected to the grid while the rotor winding is connected via slip rings to a converter. This system has recently become very popular as generators for variable speed wind turbines. This is mainly due to the fact that the power electronic converter only has to handle a fraction (20–30%) of the total power. Therefore, the losses in the power electronic converter can be reduced. In addition, the cost of the converter becomes lower.

The output power of the wind turbine is given by,

$$P_{mech} = \frac{1}{2}\rho A_r\ C_p\,(\lambda) w^3 \tag{2.1}$$

Where A is the swept area of wind turbine rotor. The performance of wind turbine is characterized by the non dimensional curve of coefficient of performance c_p and λ, as a function of tip-speed ratio . c_p as a function of λ & β is expressed by equation (2.1) .

$C_p(\lambda,\beta)$ = 0.5176*(116/(1/(1/(λ+0.08*β)-0.035/(β^3+1)))-0.4*β-5)*exp(21/(1/(1/(λ+0.08*β)-0.035/(β^3+1))))+0.0068*λ (2.2)

The tip-speed ratio is given by the expression,

$$\lambda = \frac{\Omega_r R_r}{w} \tag{2.3}$$

Where w is the wind speed, Ω_r is the rotor speed, R_r is the rotor plane radius, ρ is the air density. In general,

$$P_t = T_t\, W_m \tag{2.4}$$

Combining eq^n (2.14), eq^n(2.15), eq^n (2.16) , the expression for torque developed is expressed as,

$$T_t = \frac{1}{2}\rho A_r\ \frac{C_p\,(\lambda)}{\lambda}\ w^2 \tag{2.5}$$

The shunt active power filter based on current controlled voltage source type PWM converter has been proved to be effective even when the load is highly non-linear. Most of the active filters developed are based on sensing harmonics and reactive volt-ampere requirements of the non-linear load and require complex control. A new scheme has been proposed in which the required compensating current is determined by sensing load current which is further modified by sensing line currents only.

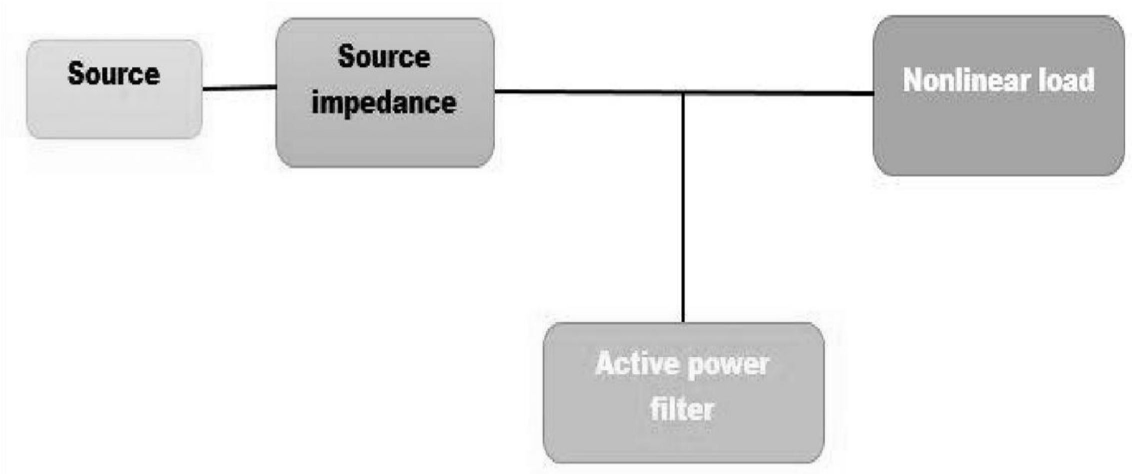

Figure 2.1 Schematics of a system with the shunt active power filter

Figure 2.1 shows an active power filter connected in parallel with the main path invalidates all the harmonic current and reactive current from nonlinear loads.

3.1 SIMULATION OF THE TEST MODEL

A model is constructed in MATLAB Simulink to create WECS using DFIG. The samples of the voltage and current waveforms are taken for further analysis of the proposed power system. The system consists of a DFIG and a back-to-back voltage source converter with a DC link capacitor. The stator directly fed the grid while rotor fed power to grid through a back to back converter. The back-to-back converter consists of a Grid-Side Converter (GSC) and a Rotor-Side Converter (RSC). The proposed model is constructed in MATLAB Simulink.

The GSC for supplying harmonics in addition to slip power transfer. The Rotor Side Converter (RSC) is used for attaining maximum power extraction and to supply required reactive power to DFIG. Here the turbine has three inputs which are generator speed which is actually the speed of the rotor. Then pitch angle which is set at 0 values and lastly the speed of the wind. We can feed a constant wind speed to the wind turbine system. By using various equations which are explained before the wind turbine model generate PU torque output. In the rotor side control, rotor over-current can be avoided but over-voltage cannot be avoided. According to rotor voltage equation, rotor voltage mainly depends on the rotor flux differential. The control circuit for RSC is shown in figure 3.3. Here the three phase voltage and current is sensed. Then from three phase current we get two phase current i.e. i_d & i_q . Using PI controller from reference ac voltage and magnitude of actual voltage i_{qref} is calculated. Similarly from reference dc voltage and actual voltage across the capacitor the i_{dref} is calculated by the help of a PI controller. Then a PID controller scheme is used to calculate two phase voltage i.e. V_d & V_q From actual current i_d & i_q and reference current i_{dref} & i_{qref} . Again the reference three phase voltage is generated using these reference V_d & V_q.

From the reference V_d , V_q the magnitude and phase of the reference voltage . Then using voltage magnitude, phase angle of the voltage and the output wt from the PLL block the reference three phase signal is generated which is shown in figure 3.4. The required equation for reference three phase generation is shown below.

$$V_a = V_m \sin(\omega t + \theta) \qquad (4.1)$$

$$V_b = V_m \sin(\omega t - \frac{2\pi}{3} + \theta) \qquad (4.2)$$

$$V_c = V_m \sin(\omega t + \frac{2\pi}{3} + \theta) \qquad (4.3)$$

Using the hysteresis controller gate pulses for the rotor-side VSI converter are generated by comparing the reference and actual rotor voltages. The converter control is tested without a protection circuit for fault ride-through in a DFIG wind turbine. Improving the control strategy and DFIG model can help manage minor faults and be integrated into a broader protection system. A three-phase 50 HZ, 120 kV, 10 MVA grid is connected with a WECS using DFIG system . The DFIG power generating station fed power to grid through a 30 km π transmission line. The generators are simulated with a Simplified dual fed induction machine block

4.2 RESULTS OF THE TEST MODEL

The generated three phase output wave form of DFIG system with THD analysis is shown in figure 4.1 and 4.2. The generated three phase source voltage, load voltage, source current, load current wave form of DFIG system with linear load along with their THD analysis is shown in figure 4.3, 4.4, 4.5, 4.6 respectively.

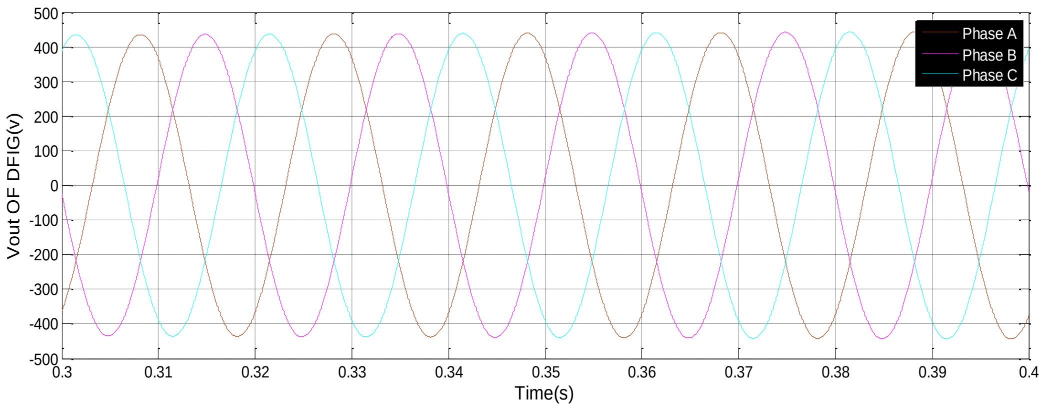

Figure 4.1 Output waveform of DFIG

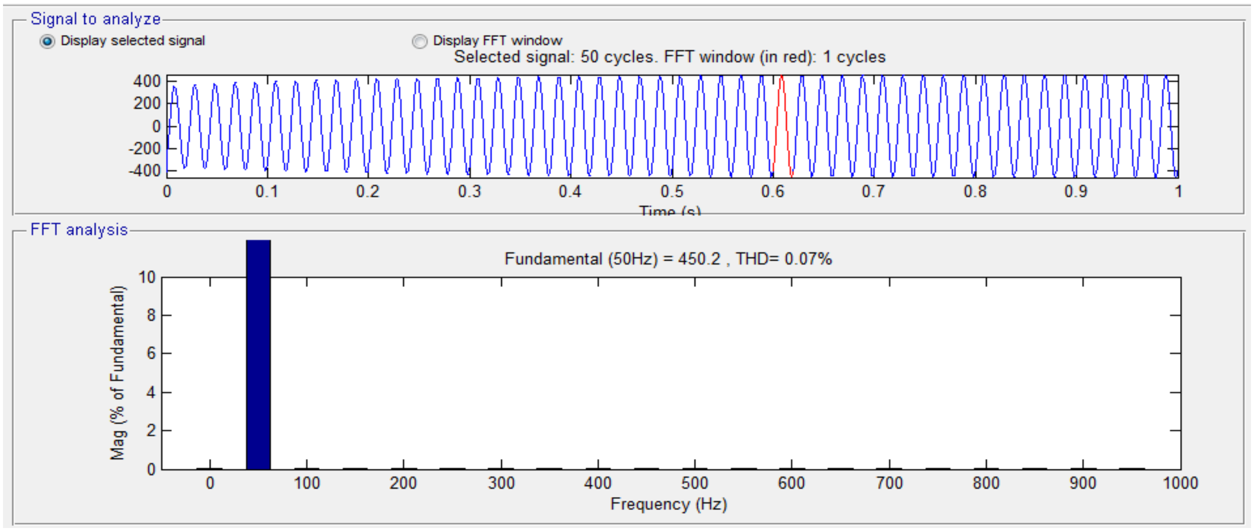

Figure 4.2 %THD of Output waveform of DFIG

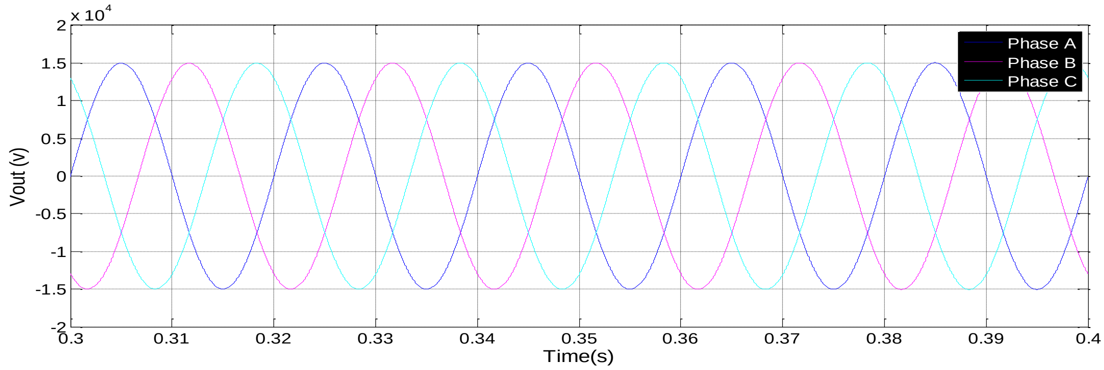

Figure 4.3 Source Voltage & Load Voltage output waveform of DFIG with linear load

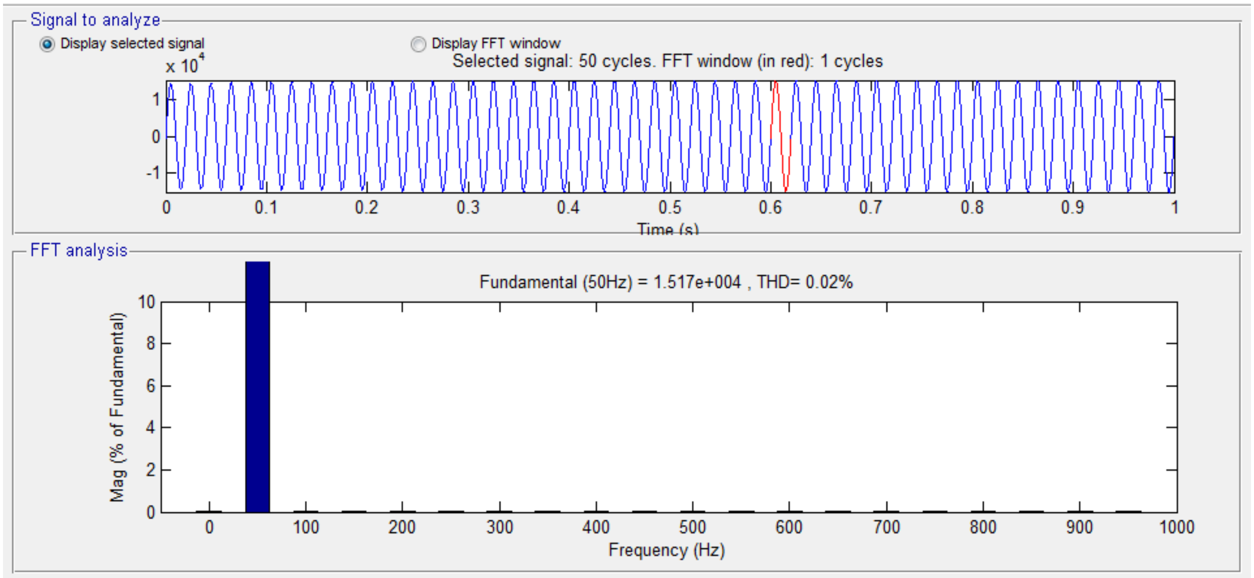

Figure 4.4 % THD of Source voltage & Load Voltage output waveform of DFIG with linear load

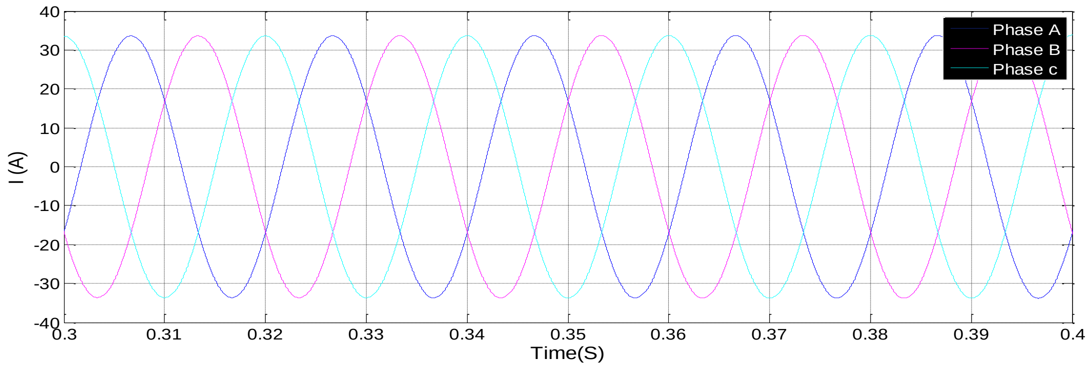

Figure 4.5 Source Current & Load Current output waveform of DFIG with linear load

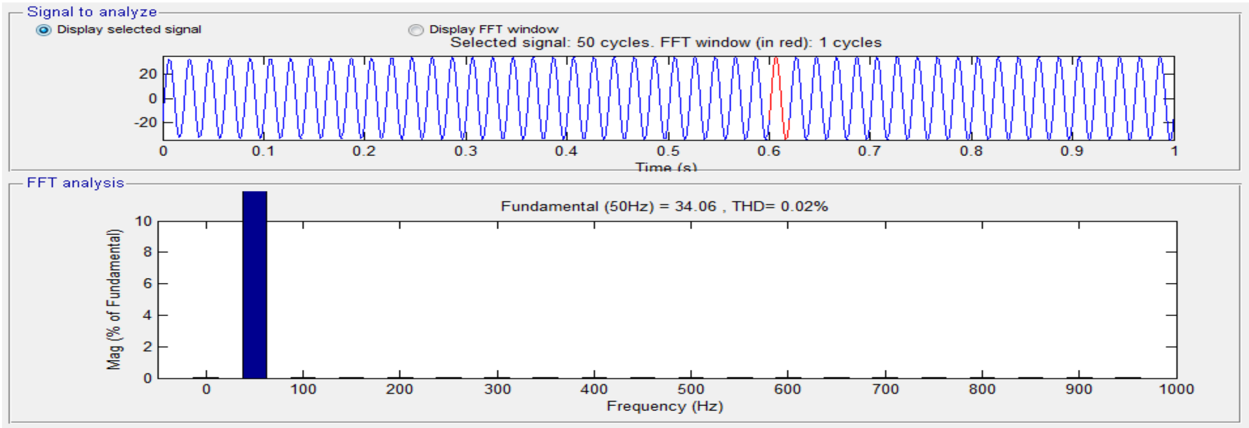

Figure 4.6 % THD of Source Current & Load Current output waveform of DFIG with linear load

The generated three phase source voltage, load voltage, source current, and load current wave form of DFIG system with non linear load along with their THD analysis is shown in figure 4.7, 4.8, 4.9, 4.10.

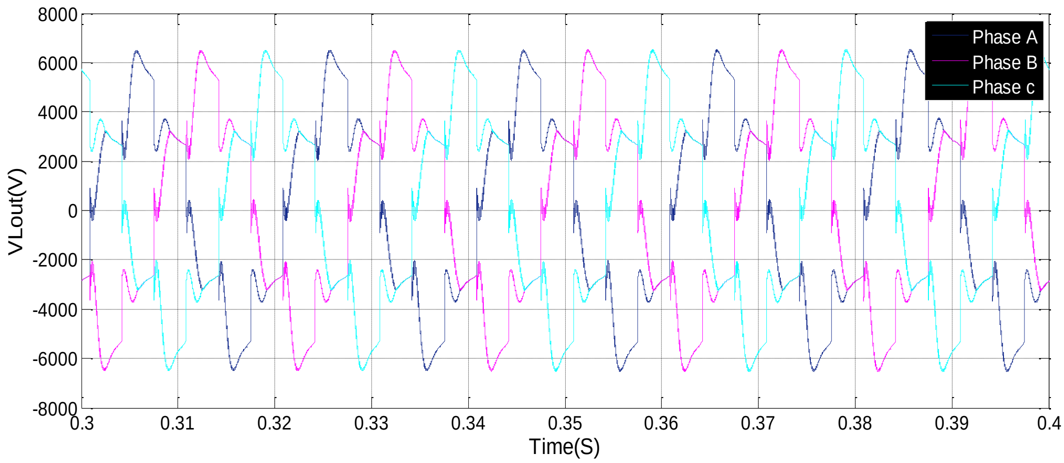

Figure 4.7 Source Voltage & Load Voltage output waveform of DFIG with non linear load

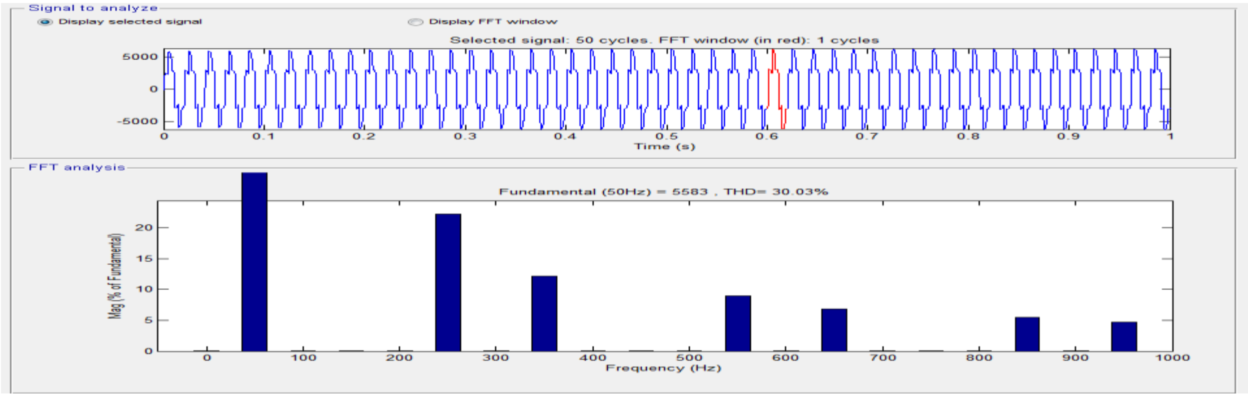

Figure 4.8 % THD of Source Voltage & Load Voltage output waveform of DFIG with non linear load

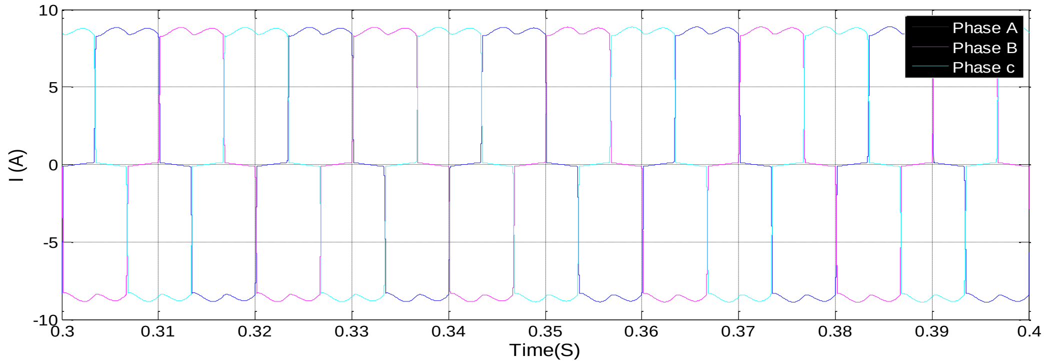

Figure 4.9 Source Current and Load Current output waveform of DFIG with non linear load

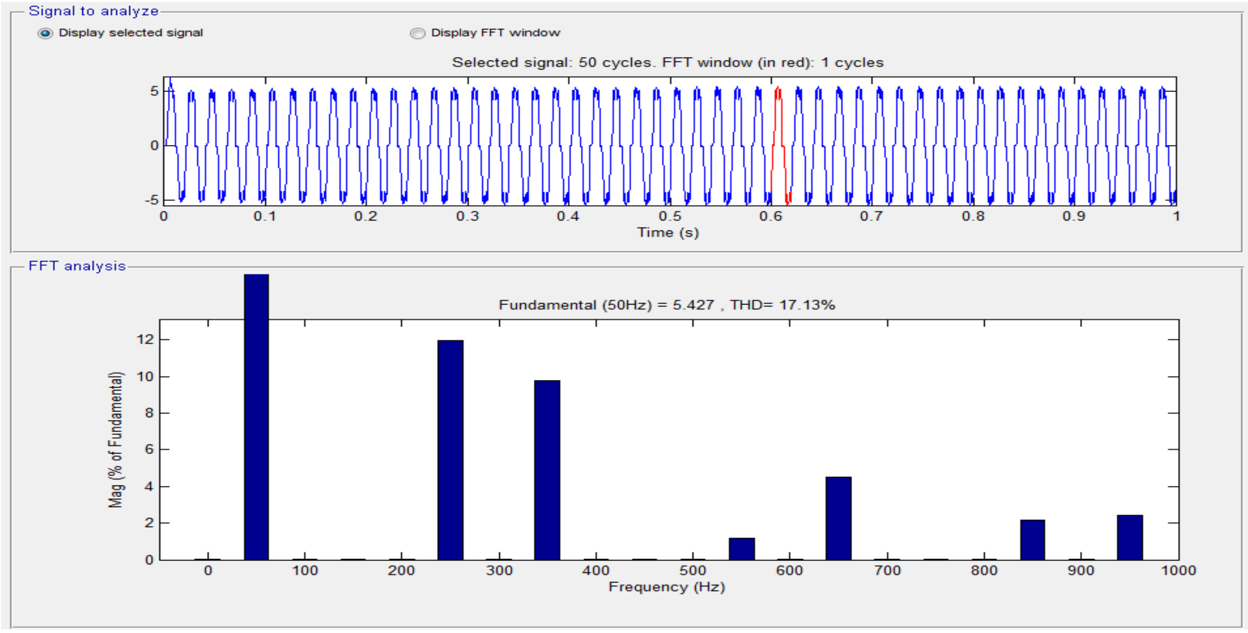

Figure 4.10 % THD of Source Current & Load Current output waveform of DFIG with non linear load

The generated three phase source voltage, load voltage, source current, load current, and the compensating filter current wave form of DFIG system with non linear load with SAF along with their THD analysis is shown in figure 4.11, 4.12 respectively.

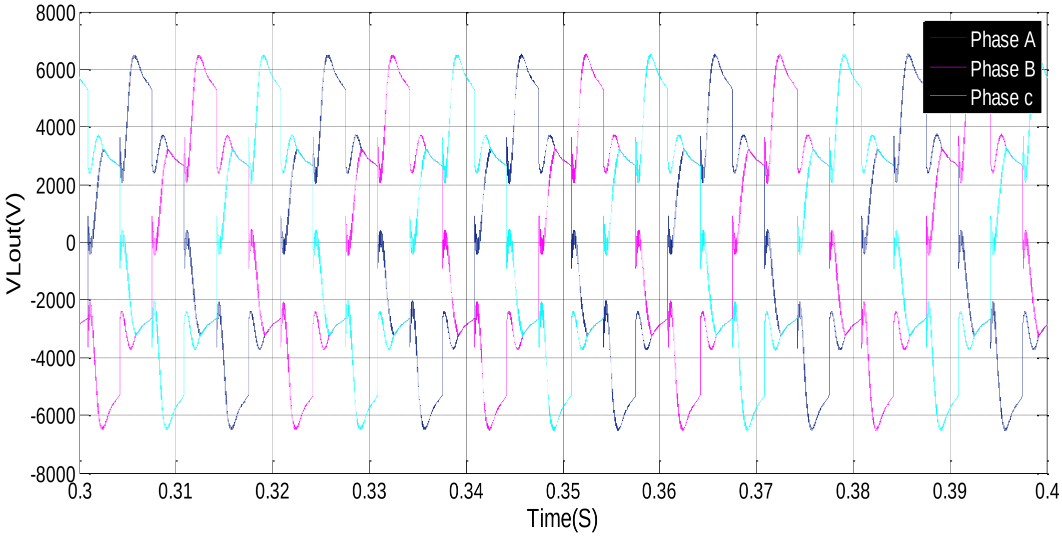

Figure 4.11 Source Voltage & Load Voltage output waveform of DFIG with non linear load & SAF

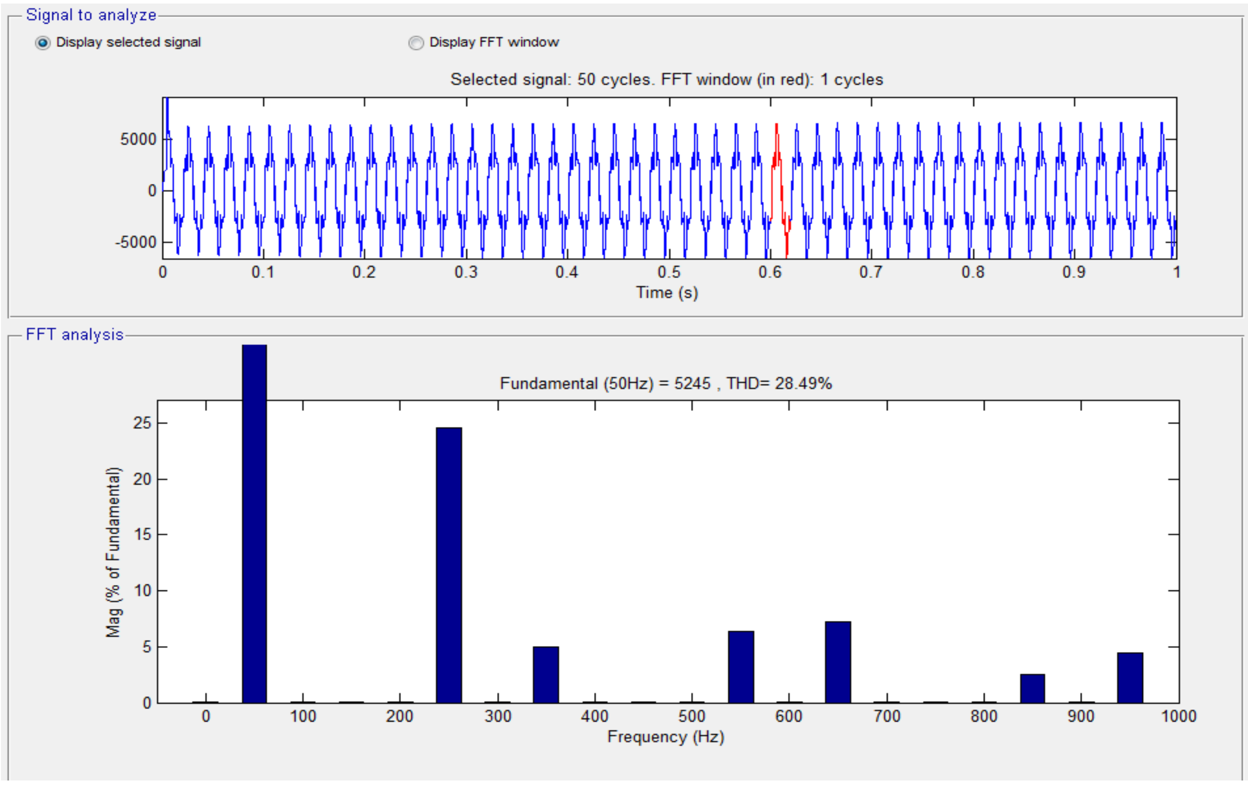

Figure 4.12 % THD of Source Voltage and Load Voltage output waveform of DFIG with non linear load & SAF

CONCLUSION

Doubly Fed Induction Generators (DFIGs) are widely used in wind farms due to their ability to operate at variable speeds, allowing for more efficient wind energy capture. In DFIG systems, the stator is directly connected to the grid and operates at constant frequency, while the rotor is fed through power electronic converters. However, non-linear loads such as rectifiers, cyclo-converters, variable speed drives, arc furnaces, and asymmetrical loads introduce significant disturbances into the power system, resulting in harmonic distortion. To address these issues, a shunt active power filter (SAPF) is employed to enhance power quality. The SAPF is connected in parallel with the load and injects compensating currents that are equal in magnitude but opposite in phase to the harmonic components. Simulation studies conducted in the MATLAB/SIMULINK environment demonstrate the effectiveness of this approach. Using FFT analysis, the Total Harmonic Distortion (THD) was observed to reduce to 9%, approaching the limits specified in IEEE Standard 519-1992. The results confirm that the SAPF effectively mitigates current harmonics, reduces waveform distortion, and improves overall power quality by producing a more sinusoidal current waveform

REFERENCES

[1] N. K. Swami Naidu, Member, IEEE, and Bhim Singh, Fellow, IEEE "Doubly Fed Induction Generator for Wind Energy Conversion Systems with Integrated Active Filter Capabilities" IEEE Transactions on Industrial Informatics, Vol. 11, No. 4, August 2015**.**

[2] B V D N Pourna Ganga Tejaswi, G T P Naidu, "Wind Energy Conversion Systems using DFIG with Integrated Active Filter Capabilities", International Journal of Science Engineering and Advance Technology, IJSEAT, Vol. 4, Issue 11, November 2016.

[3] B.Chitti Babu, K.B.Mohanty, "Doubly-Fed Induction Generator for Variable Speed Wind Energy Conversion Systems Modeling & Simulation" International Journal of Computer and Electrical Engineering, Vol. 2, No. 1, February 2010.

[4] Abderrahmane EI kachani , EI Mahjoub Chakir, Anass Ait Iaachir, Tarik Jarou, Abdelkader Hadjoudja, " Nonlinear Model Predictive Control Applied to a DFIG-Based Wind Turbine With a Shunt APF" IEEE Press, September 2016**.**

[5] Yogesh Murthy.N, "A Review on Power Electronics Application on wind turbines", IJRET, Vol. 2, Issue 11, November 2013.

[6] M. T. Abolhassani, P. Enjeti, Hamid Toliyat, "Integrated Doubly Fed Electric Alternator/Active Filter (IDEA), a Viable Power Quality Solution, for Wind Energy Conversion Systems," IEEE Transactions on Energy Conversion, vol. 23, June 2008.

[7] Eduard Muljadi, Mohit Singh, and Vahan Gevorgian, " Doubly Fed Induction Generator in an Offshore Wind Power Plant Operated at Rated V/Hz", IEEE Energy Conversion Congress and Exhibition Raleigh, North Carolina, Conference Paper, June 2012.

[8] Balasubramaniam Babypriya, Rajapalan Anita, "Modeling, Simulation and Analysis of Doubly Fed Induction Generator For Wind Turbines", Journal of Electrical Engineering, Vol. 60, No. 2, pp.79–85, 2009.

[9] E. Spahic, J. Morren, G. Balzer and G. Michalke, “Mathematical Model of the Double Fed Induction Generator for Wind Turbines and its Control Quality”, IEEE Press, April 2007.

[10] Müller, M. Deicke, & RIK W De Doncker, “Doubly Fed Induction Generator for Wind Turbines,” IEEE Industry Applications, May/June 2002.

[11] Morten Lindholm, Tonny W. Rasmussen, “Harmonic analysis of Doubly Fed Induction Generators”, IEEE Trans.2005.

[12] Ambrish Chandra, Senior Member, IEEE, Bhim Singh, B. N. Singh, Member, IEEE, and Kamal Al-Haddad, Senior Member, IEEE, “An Improved Control Algorithm Of Shunt Active Filter For Voltage Regulation, Harmonic Elimination, Power-Factor Correction, And Balancing Of Nonlinear Loads”, IEEE Transactions On Power Electronics, Vol. 15, No. 3, May 2000.

[13] Musa Yusup Lada, Ismadi Bugis and Md Hairul Nizam Talib, “Simulation a Shunt Active Power Filter using MATLAB/Simulink”, IEEE, the 4th International Power Engineering and Optimization Conference, June 2010.

[14] Arpit Shah, Nirav Vaghela, “Shunt Active Power Filter for Power Quality Improvement in Distribution Systems”, International Journal of Engineering Development and Research, ISSN: 2321-9939, February 2005.

[15] T.Rajesh, S.Aravindhan, M.Sowmiya, S.Thenmozhi, “Design of Shunt Active Filter for Reduction of Harmonics”, IJESC, Volume 6, Issue No. 4, 2016.

[16] S.U.Bhople, Santosh Kumar Rayarao, “Reduction of Harmonics using Shunt Active Power Filters”, IJERT, Vol.4, Issue07, July 2015.

[17] Hideaki Fujita and Hirohmi Akagi, Member, IEEE, “A Practical Approach to Harmonic Compensation in Power Systems-Series Connection of Passive and Active Filters”, IEEE, Transactions On Industry Applications, Vol. 21, No. 6, November/December 1991.

[18] Arun Shankar V.K., Senthil Kumar N., “Implementation of Shunt Active Filter for Harmonic Compensation in a 3Phase 3Wire Distribution Work”, 1st International Conference On Power Engineering, Computing And Control, March 2017.

[19] Pichai Jintakosonwit, Student Member, IEEE, Hideaki Fujita, Member, IEEE and Hirofumi Akagi, Fellow, IEEE, “Control and Performance of a Fully-Digital Controlled Shunt Active Filter for Installation on a Power Distribution System”, IEEE Transactions on Power Electronics, Vol. 17, No. 1, January 2002.