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Power Quality Improvement of Wind Power Plant using STATCOM and Harmonic Filters

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Abstract: The exponential rise of the demand for power has forced us to increasingly depend on non-conventional sources of energy. The exponential rise of power demand leads to load fluctuations, which in turn results in voltage distortions. This project focuses on controlling the voltage and current in wind power plants that have Self-Excited Induction Generators based on a variety of load conditions. STATCOM-fed SEIG-based wind power plant feeding an isolated load of both R and RL type will make up the distribution generation system. Voltage fluctuations occur in a wind turbine as a result of speed changes and load disturbances. This makes the SEIG the ideal generator for the wind farm. To reduce voltage fluctuations, the SEIG may supply the system with delta- connected three-phase capacitor banks or STATCOM. The effectiveness of Insulated-Gate Bipolar Transistor (IGBT) based STATCOM helps in the voltage control and also in mitigation of voltage and current harmonics for various load scenarios.

Keywords: *Wind farm, Harmonics mitigation, SEIG based Wind Plant, Voltage Harmonics, Harmonic filters*

1. Introduction

The great demand of electric power requires a large amount of green energy production embedded into electric grid. The wind farm is one of the larger resource of the green energy production embedded in to power grid. The green energy generation reduces the atmospheric pollution but introduces power pollution, which has to addressed. Sustainable growth can be achieved by generating more electricity using renewable sources [1] to [9].

Renewable energy types include wind, solar, tidal etc. These sources of energy will be in existence as long as the humans exist, which means that consumers and industries can keep using them indefinitely. There is no pollution or harm to the environment when we use these types of energy. Therefore, sustainable generation of power is made possible through these [10] to [18].

The developed model includes the wind power plant embedded with self-excited induction generator. The self-excited induction generator converts the input mechanical energy to electrical energy. The multi – level DSTATCOM, equipped to the SEIG is used for efficient reactive power compensation. This resulted in the mitigation of voltage and current harmonics on the load side thereby increasing the power quality [19] to [25].

I.1. Problem formulation

Electricity has invaded our lives and became vital in all aspects of our society. As the world economy continues to grow, the energy consumption is also expected to grow. It is said that a country's development is measured in the amount of electricity it uses for its activities. So, it is important that quality electricity is distributed to the consumers [1] to [10].

To meet the rising demand, it is necessary to discover efficient ways of generating electricity. It can be made possible using the renewable energy sources which includes wind farm [11] to [15].

The objectives of the article are achieved by connecting the self-excited induction generator which is embedded with STATCOM to the wind energy system. The STATCOM helps in effective reactive power compensation. This developed model helps in mitigating the voltage and current harmonics in the system and ensures that the constant terminal voltage is maintained on the load side irrespective of the load perturbations [16] to [25].

I.2 Objectives of the Article

1. Design a wind turbine with Self-Excited Induction Generator including capacitor bank.

2. To design and develop STATCOM to provide constant terminal voltage against various load scenarios in an isolated system.

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3. To mitigate the voltage and current harmonics in the system.

2. Wind Power Plant

The Fig.1 illustrates the system model, the wind turbine receiving the two basic inputs, one is pitch angle in degrees, and the second one is the wind speed in m/sec. These are the two parameters on which wind power P_w has shown in the below equation (1) is dependant. The wind turbine is connected to the Asynchronous Generator fed by the STATCOM, which is used to supply the necessary reactive power to the system.

II.1 Modelling Equations of Wind Turbine

According to equations (1) and (2), the power coefficient C_p determines the wind power generation P_w. P_w stands for wind power, ρ for air density, C_p for coefficient of performance, A for area in front of the wind, and v for wind speed. The relationship between the blade tip speed ratio and the power coefficient is nonlinear. The equation (4) and 1/x in terms λ and R, are used to calculate the blade tip speed, which is the ratio of the angular rotor speed of the wind turbine to the linear wind speed at the tip of the blades.

$$P_w = \frac{1}{2}(C_p(\lambda,\beta)AV^3) \quad (1)$$

$$C_p = 0.22(\frac{116}{x} - 0.4\beta - 5)e^{\frac{-12.5}{x}} \quad (2)$$

$$\frac{1}{x} = \frac{1}{(\lambda - 0.08\beta)} - \frac{0.035}{(1+\beta^3)} \quad (3)$$

$$\lambda = \frac{wR}{v} \quad (4)$$

In the block diagram as depicted in Fig.1, it is observed that wind available helps in rotation of the blades of the wind mills. The available energy form is converted into rotational energy by the wind turbine. This rotational form of energy is used as mechanical input for the self-excited induction generator. The self-excited induction generator converts the input mechanical energy to electrical energy. STATCOM is used as an effective means for reactive power compensation and to improve the power quality and maintain steady supply irrespective of the changes at the load side [7].

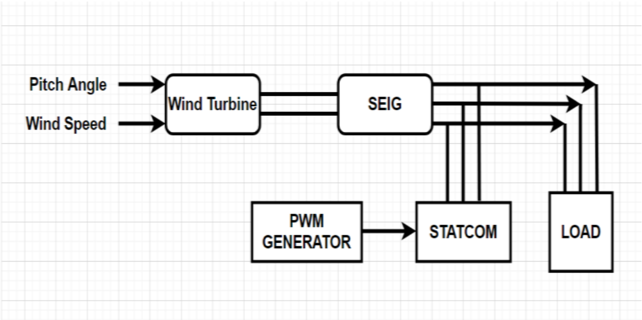

Fig.1 Wind farm with STATCOM

3. Asynchronous Generators

Asynchronous generators have been classified into three categories and it is working with adjustable speeds unlike synchronous generators, which works with a constant speed only. The following categorization is holds good for Induction generators.

III.1. Types of Induction Generators

There are three types of wind generators are available in literature

1. Grid connected Induction Generators
2. Doubly Fed Induction Generators
3. Self-Excited Induction Generators

III.2. Grid Connected Generator

The grid connected Asynchronous machine is excited by absorbing the reactive power from the grid and it converts the mechanical energy fed by wind turbine into electrical energy which exclusively supplies active power to the grid and Fig.2 shows the Grid Connected Asynchronous Generator.

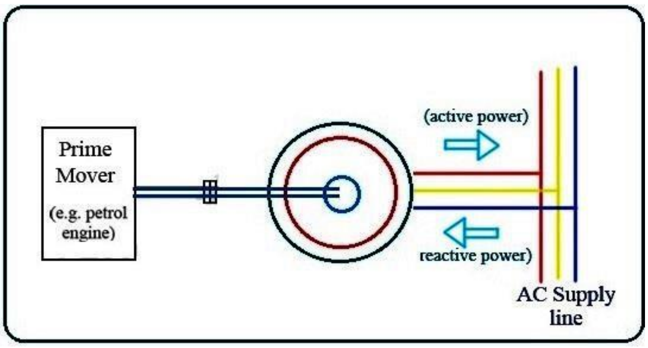

Fig.2 Grid Connected Asynchronous Generator

III.3. Doubly Fed Induction Generator

DFIG is equipped with two converters one is machine side converter and second is grid side converter and Fig.3 illustrates the Doubly Fed Induction Generator (DFIG). The reactive power control as well as frequency control against speed variations can be addressed most effectively with DFIG.

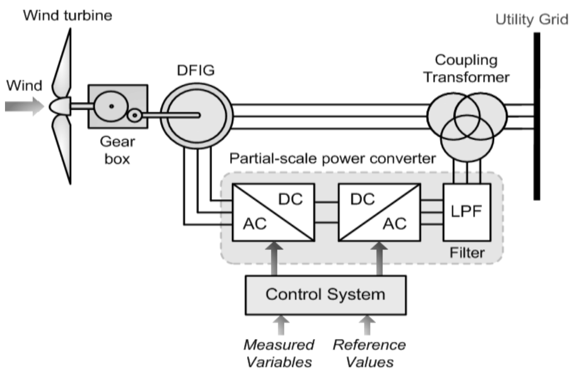

Fig.3 Doubly Fed Induction Generator

III.4. Self-Excited Induction Generator

The Self Excited Induction Generator (SEIG) is supported by the 3-ph delta connected capacitor bank connected in parallel for injecting necessary reactive power to the machine for self-excitation. Fig.4 depicts the Self-Excited Induction Generator and Fig.5 illustrates the Torque - Slip characteristics of Induction Machine.

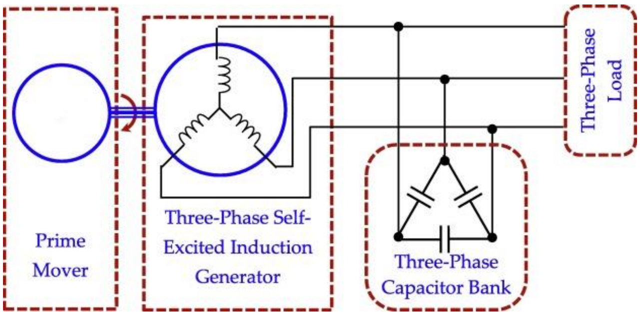

Fig.4. Self-Excited Induction Generator

III.4.1. Motoring Region

In this mode of operation, the rotor always rotates at speeds slower than the synchronous speed and power is applied to the stator sides. The induction motor torque ranges from zero to full load torque as the slip fluctuates.

III.4.2. Generating Region

In this mode of operation, the induction motor exceeds the synchronous speed and is driven by a prime mover. The stator winding is connected to a three-phase power supply and provides electrical energy.

III.4.3. Braking Region

In the Braking mode, the polarity of the voltage is switched so the motor begins to rotate in opposite direction and eventually halts. Plugging is another name for this braking technique.

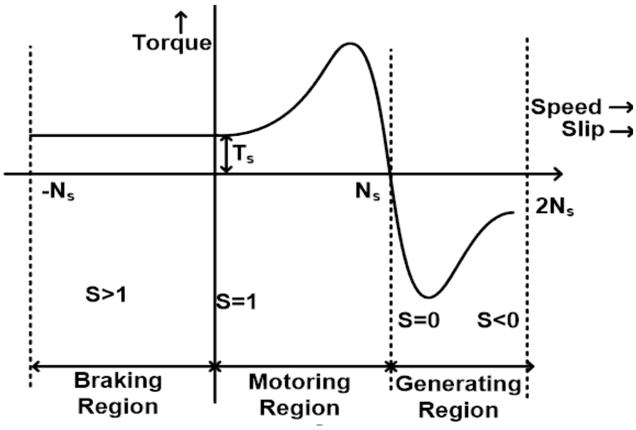

Fig.5 Torque - Slip characteristics of Induction Machine

Asynchronous generator mathematical modelling has described with the equations from (5) to (8), equations (5) and (6) describes the stator side modelling and equations (7) and (8) describes the rotor side modelling and equations

Stator Side Equations

$$V_{abcs}^{a} = r_s(i_{abcs}^{a}) + \frac{d\lambda_{abcs}^{a}}{dt} \quad (5)$$

$$\lambda_{abcs}^{a} = (L_s + M)(i_{abcs}^{a}) + L_{sr}(i_{abcr}^{a}) \quad (6)$$

Rotor side Equations

$$0 = r_r(i_{abcr}^{a}) + \frac{d\lambda_{abcr}^{a}}{dt} \quad (7)$$

$$\lambda_{abcr}^{a} = (L_r + M)(i_{abcs}^{a}) + L_{sr}(i_{abcs}^{a}) \quad (8)$$

4. IV. Static Synchronous Compensator (STATCOM)

IV.1 IGBT based STATCOM with PWM Control

To reach the necessary range of output values, a converter is utilized to transform one sort input into another. Power factor control is made simple by the switch power converters. This means that the current can be utilized to generate either active or reactive power, giving the reactive power feed a wide range of control. They switch on and off as per the gate pulse given to them to achieve the required output voltage and frequency values Fig.6 shows the STATCOM Power Circuit and Fig.7 depicts the V-I Characteristics of STATCOM.

In the developed model, IGBT based STATCOM is designed. The firing angle is used to adjust the AC voltage. IGBT is used in the STATCOM as the on- stage voltage drop is low; it supports for high values of current and voltage range. There is controlled on and off implemented in the process. Moreover, the frequency range is good enough to include daily life appliances and the conduction losses are also low in the IGBT. Because of these characteristics, IGBT is used as a switch in the converter of the STATCOM [15].

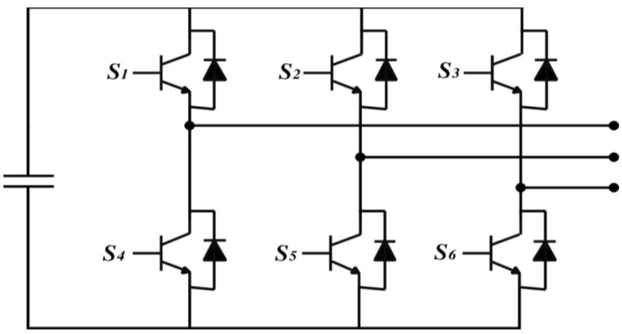

Fig.6 STATCOM Power Circuit

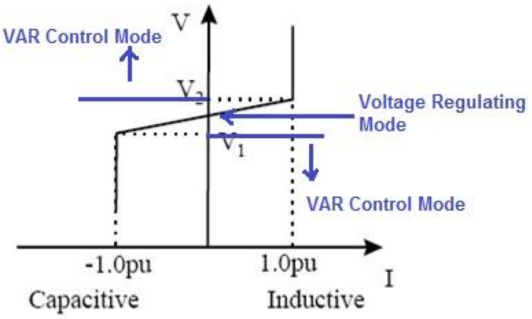

Fig.7 V-I Characteristics of STATCOM

IV.2 SPWM Generator

A typical inverter without Pulse Width Modulation (PWM) technology alters its output voltage in response to the load's power requirements. By adjusting the width of the switching frequency in the oscillator section, PWM technology corrects the output voltage in accordance with the value of the load. As a result, the AC voltage produced by the inverter varies according to the switching pulse's width. Amongst all PWM techniques, Sinusoidal Pulse Width Modulation (SPWM) technique is employed as it is less costly, can be easily implemented on the circuits and it gives the best control of switches in a circuit. SPWM denotes the production of pulse width modulation outputs using a sine wave as the modulating signal. By contrasting a reference sinusoidal wave with the obtained output wave, it is possible to determine the switching time of a PWM signal. In industrial applications, this kind of pulse width modulation is frequently utilized.

IV.3 Mathematical modeling of STATCOM

The following equations from (9) to (13) describes the mathematical modelling of STATCOM, for active power, reactive power of STATCOM shown in equations (9) and (10), remaining equations from (11) to (13) describes the voltage equations of STATCOM

$$P = \frac{V_t V_C}{X_L} \sin \sin \alpha \quad (9)$$

$$Q = \frac{V_t V_t}{X_L} - \frac{V_t V_C}{X_L} \cos \cos \alpha \quad (10)$$

$$L\frac{di_{ac}}{dt} = Ri_{ac} + V_{ac} - V_{at} \quad (11)$$

$$L\frac{di_{bc}}{dt} = Ri_{bc} + V_{bc} - V_{bt} \quad (12)$$

$$L\frac{di_{cc}}{dt} = Ri_{cc} + V_{cc} - V_{ct} \quad (13)$$

IV.4 LC Filter

A LC high pass passive filter is connected in the developed model to mitigate the harmonics further. The inductor is connected in series and the capacitor in parallel in the circuit. The LC filter exhibits a low ripple factor compared to another filter. This filter has a good load regulation and also has no loading effect on the rectifier. Therefore, a passive LC filter is used to mitigate the harmonics efficiently and Fig.8 shows the LC Filter Structure.

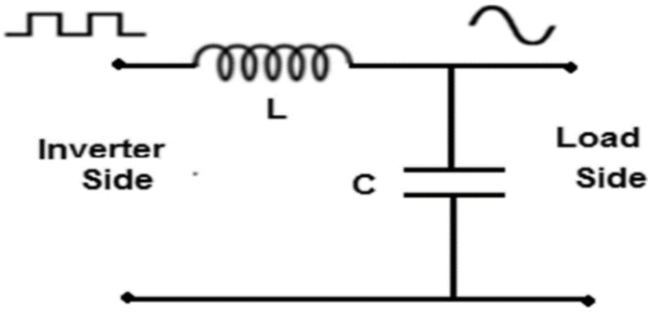

Fig.8 LC Filter Structure

5. Case Study and Result Analysis

The wind farm is designed and developed with a wind turbine embedded with a reactive power support for self-excitation. The wind farm is used to feed both resistive and inductive loads supported by the STATCOM. The system is also embedded with passive filters for harmonics mitigation. The system is simulated for both the loads resistive as well as inductive loads without and with filters. Fig.9. illustrates the wind farm with Asynchronous Generator and Compensator and the Fig.10 shows the Simulink model of Compensator. The harmonic analysis has been performed without and with compensators and presented the results in the following section.

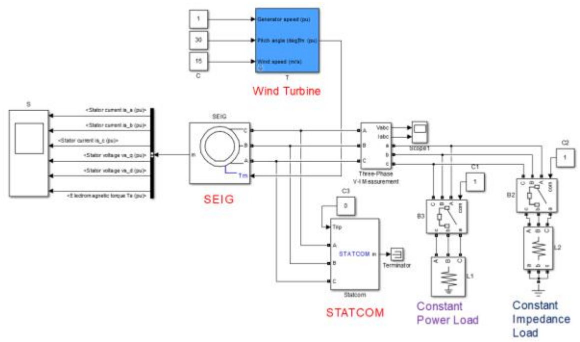

Fig.9. Wind farm with Asynchronous Generator and Compensator

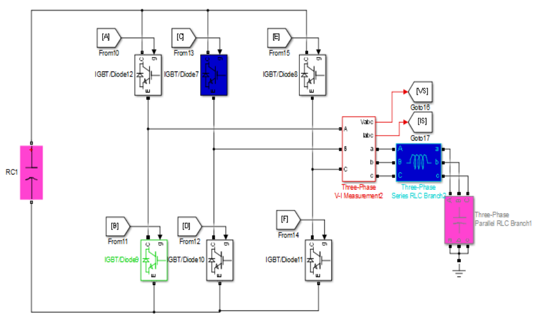

Fig.10 Simulink model of Compensator

The following section the result analysis of the wind power plant with the following description as Fig.11 illustrates the STATCOM Closed Loop Control Circuit with the usage of park's transformation and its inverse transformation in between the digital Proportional and Integral (PI) controller embedded to obtain the required output from the STATCOM using firing pulses.

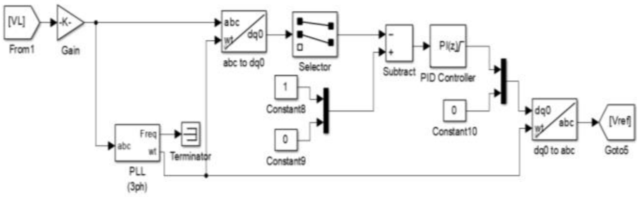

Fig.11. STATCOM Closed Loop Control Circuit

The following section presents the result analysis of the said system with resistive loads without power quality compensator. Fig.12 depicts the voltage harmonics without compensator for resistive load and THD is 65.92%, Fig.13 illustrates the current harmonics without compensator for resistive load and THD is 65.91%.

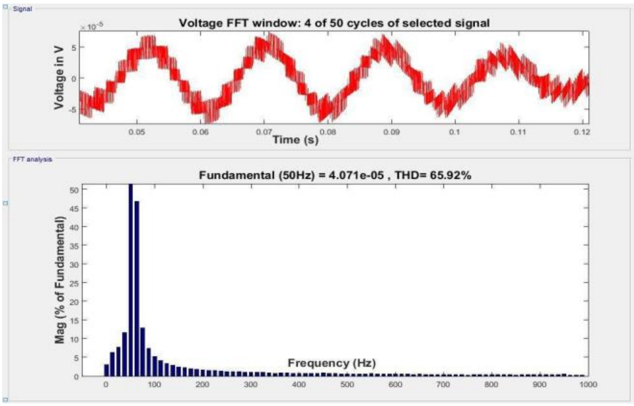

Fig.12 Voltage harmonics without compensator for resistive load

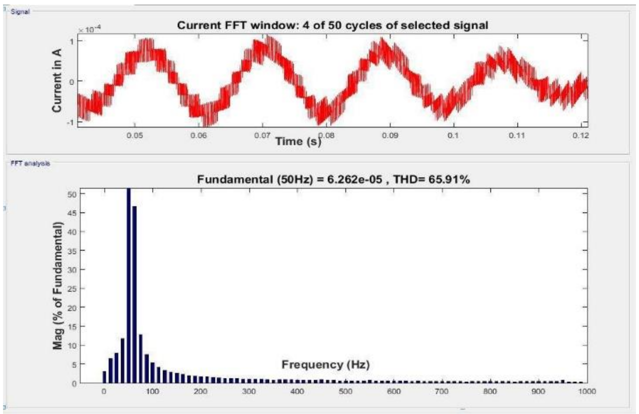

Fig.13 Current harmonics without compensator for resistive load

The following section presents the result analysis of the said system with inductive loads without power quality compensator Fig.14 shows the voltage harmonics without compensator for inductive load and THD is 66.39% and Fig.15 illustrates current harmonics without compensator for inductive load and THD is 67.3%.

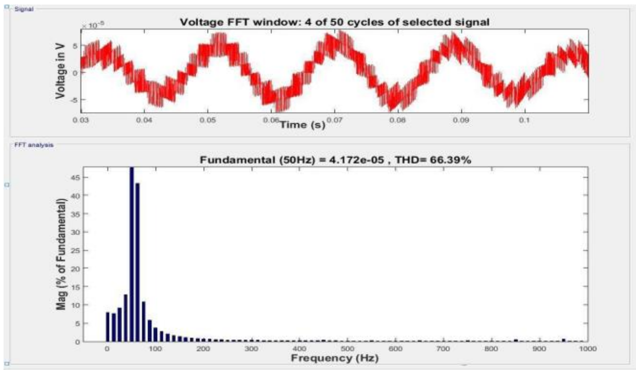

Fig.14 Voltage harmonics without compensator for inductive load

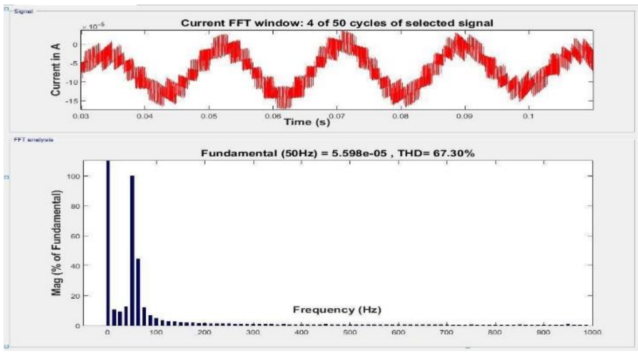

Fig.15 Current harmonics without compensator for inductive load

The following section presents the result analysis of the said system with resistive loads with power quality compensator. Fig.16 depicts the FFT Analysis of Output voltage with Power Quality Compensator for R load 1 as THD of about 1.79%, Fig.17 illustrates the FFT Analysis of Output current with Power Quality Compensator for R load 2 as THD of about 1.79% which is very low and highly accepted by IEEE norms.

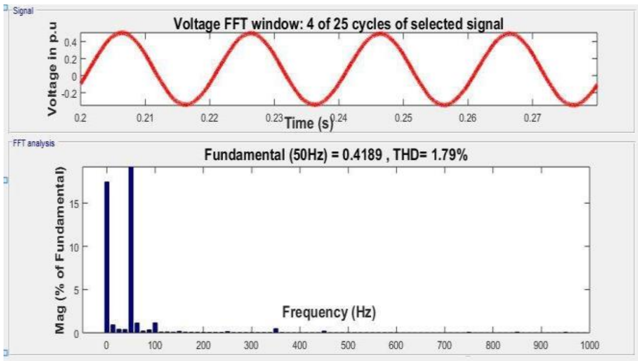

Fig.16 Voltage harmonics with compensator for resistive load

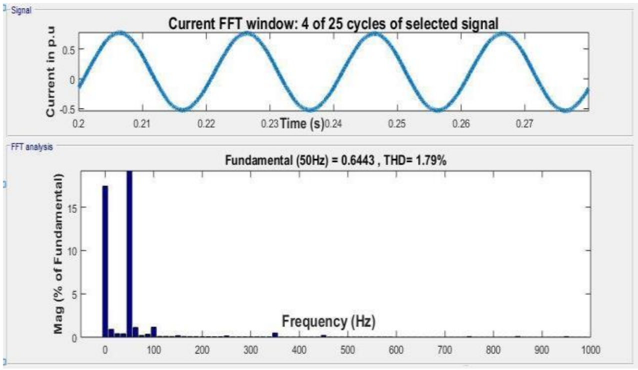

Fig.17 Current harmonics with compensator for resistive load

The following section presents the result analysis of the said system with inductive loads with power quality compensator. Fig.18 shows the FFT Analysis of Output voltage with Power Quality Compensator for RL load 1 as THD of about 0.93% and Fig.19 illustrates the FFT Analysis of Output current with Power Quality Compensator for RL load 2 as THD of about 3.28%.

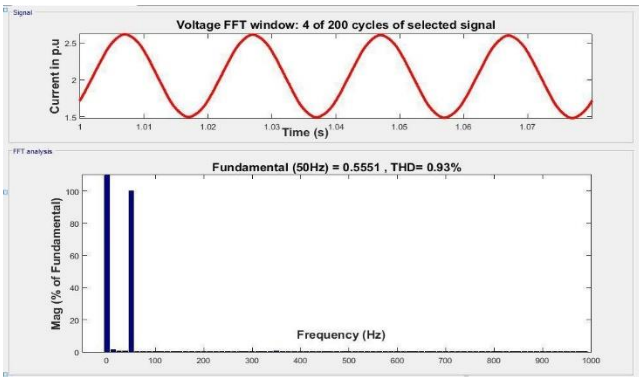

Fig.18 Voltage harmonics with compensator for inductive load

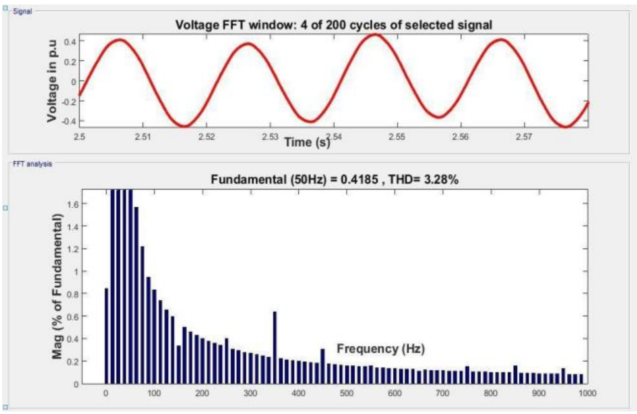

Fig.19 Current harmonics with compensator for inductive load

6. Conclusions

The wind farm is designed and developed with a wind turbine embedded with a reactive power support for self-excitation. The wind farm is used to feed both resistive and inductive loads supported by the STATCOM. The system is also embedded with passive filters for harmonics mitigation. The harmonic analysis has been performed without and with compensators and presented the results in the following section.

The result analysis of the said system proven that the harmonics presented in the system with resistive loads without power quality compensator is very high and unaccepted and THD is about 65% for both voltage as well as currents. Subsequently the result analysis of the said system with inductive loads without power quality compensator is also very high and also unacceptable with THD values of about 66% for both voltage as well as currents. The same system is simulated with compensators and the THD of both voltage as well as current has been minimized and is about less than 4% for both resistive and inductive loads and highly accepted by IEEE norms.

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