Implementation of DSTATCOM in Wind Energy Conversion System

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ABSTRACT

Permanent magnet synchronous generator now-a-days play a major role in the Wind energy conversion system.One of the preferred technologies in variable speed wind turbines (VSWT) is formed by a wind rotor, permanent magnet synchronous generator (PMSG), three-phase bridge rectifier (BR) with a bulky capacitor, and power electronics converter for grid interface. High-intensity, low-frequency harmonic currents flows into the PMSG as electric load has a non-linear characteristic and it get reflected in the inverter side. This paper presents an analysis and simulation of a Static Compensator using MATLAB Simulink for harmonic mitigation in wind turbines generators for the balancing of linear and non-linear loads by eliminating the harmonics at inverter side. Currents are represented in d-q synchronous reference frame (SRF).

Keywords : *Static Compensator (STATCOM), Wind Turbines, Permanent Magnet Synchronous Generator, Harmonics, Power Quality*

1. INTRODUCTION

Small-scale wind turbines interfaced to an ac grid via grid-connected inverters have wide-spread applications inhousehold and community level power generation. Developments in gearless, variable-speed generators with power electronics grid interface leads to a generation of quiet, reliable, economical wind turbines.

The most usual technology of this direct-driven wind turbine is composed by a multi-pole permanent magnet synchronous generator (PMSG), three-phase bridge rectifier with a bulky capacitor, and current-controlled voltage source inverter (CC-VSI) with active harmonic compensation to grid interface. Three-Phase Bridge Rectifier with bulky capacitor presents a non-linear characteristic and consequently harmonic current content flows into PMSG and get reflected at the inverter side and degrade the quality of voltage and is inferred by huge amount of harmonics. Asynchronous components in the air-gap field induces eddy currents in the solid rotor iron, increasing PMSG losses and temperature.

An alternative to mitigate harmonic content into PMSG is to use power electronics converter that actively cancel harmonic currents, providing a sinusoidal waveform. One of the ways to compensate harmonic content is to use the Static Compensator. It is being used with success to reduce harmonic content in industry and distribution lines. This paper presents an analysis and simulation of a Static Compensator using MATLAB Simulink for harmonic mitigation in wind turbines generators for the balancing of linear and non-linear loads by eliminating the harmonics at inverter side. Currents are represented in d-q synchronous reference frame (SRF).A dynamic wind turbine model and the STATCOM are implemented on MATLAB simulink. Simulations show that the proposed active filtering configuration can mitigate harmonic content into the PMSG.

2. WIND ENERGY CONVERSION SYSTEM MODEL

The basic diagram of the wind energy conversion system to be analyzed on this paper is illustrated in Fig. 1. The system is composed by a wind rotor which transforms the kinetic energy from the wind with wind speed in mechanical torque in the shaft. The shaft drives directly the PMSG, which generates power with variable-frequency and alternate current. A rectifier bridge with a bulky capacitor Clink is responsible for AC-DC conversion to form the DC link.

The Static compensators connected on main bus between generator and bridge rectifier. It consists of a six-switch, three-phase voltage source inverter (VSI), a CDC capacitor on the DC side of the inverter, and a LF to suppress high-frequency currents originated by the switching of the VSI. A bank of capacitors C is used for filter high-frequency voltage occasioned by the inverter.

2.1 Wind Rotor

The fundamental dynamics of VSWT can be expressed by this simple mathematical model:

$J\, dw_m/dt = T_a - T_f - T_e$ (1)

where J is the moment of inertia (rotor inertia plus generator inertia), Wm is the mechanical angular speed, Ta is the aerodynamic torque; Tfis the friction torque (rotor fiction plus generator friction); and Te is the electrical load torque from wind turbine.

Aerodynamic torque Ta is determined by:

$T_a = C_T(\lambda, \beta)\rho A(D/2)u_{Wind}^2/2$ (2)

where CT is the rotor torque coefficient; p is the air density; A is s the rotor swept area; D is the rotor diameter; and $u_{Wind}$is the wind speed. Torque coefficient is a non-linear function of the tip-speed ratio λ and blades pitch angle f3. This relation can be found by computational simulations or experimentally. Tip-speed ratio is expressed by:

$\lambda = \omega_m.(D/2)/u_{Wind}$ (3)

For a fixed-pitch blade rotor, C_T is a function of λ only. The C_T(i) curve to be used on this work is illustrated on Fig. 2.

Friction torque is determined by: $T_f = B\omega_m$(4)

where B is the friction coefficient.

2.2 PMSG

Dynamic modelling of PMSG can be described in d-q reference system [7]:

$V_q = -(R+pL_q)i_q - \omega_e L_d i_d + \omega_e \lambda_m$(5)

$V_d = -(R+pL_d)i_d + \omega_e L_d i_q$ (6)

where R is the stator winding resistance; Ld and Lq are stator inductances in direct and quadrature axis, respectively; id e iq are the currents in direct and quadrature axis, respectively; We is the electrical angular speed of the generator; Am is the amplitude of the flux linkages established by the permanent magnet viewed by the stator windings, and p is the operator d/dt.

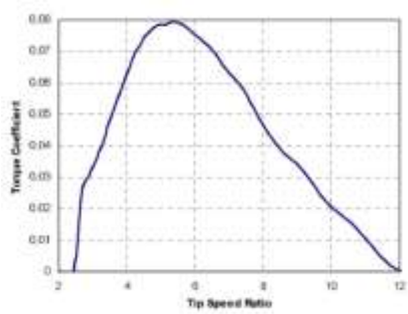

Fig.1: Torque coefficient C_T versus tip-speed ratio λ.

The expression for the electromagnetic torque can be described as:

$T_e=(3/2)(P/2)[(L_d-Lq)i_q i_d- \lambda_m i_q]$ (7)

where P is the number of poles. The relation between electrical angular speed ω_e and mechanical angular speed ω_m is expressed by

$\omega_e = \frac{P\omega m}{2}$ (8)

2.3 Bridge Rectifier and DC load

The WECS uses the well-known three-phase six-pulse bridge rectifier. The DC link is formed by the capacitance C_{link} Load characteristics applied to the wind turbine can be easily represented by changing the value of the resistor R_{load} seen on fig.1.

High-intensity, low-frequency harmonic currents flows into the PMSG as BR has a non-linear characteristic. A study case is presented showing the PMSG output currents at WECS full load condition (20 kW resistive load, C_{link} =500μF, R_L=6.5Ω,V_L= 360V) using a conventional BR, at steady-state operation. The wind speed in this case is 12m/s. A detail of the PMSG WECS simulated output current and line-to-line voltage (divided by 4), for the rated power deliver situation at 12m/s wind speed, is shown in fig3. The Harmonic content and the total harmonic distortion (THD) of the output PMSG current and voltage were obtained using Fourier analysis. The results are summarized in **Fig.** 4 and **Fig.** 5.

3. SYSTEM DESIGN AND MODEL

The **Fig.2** shows the single-line diagram of the shunt-connected STATCOM at the inverter side. The dc capacitor connected at the dc bus of the converter acts as an energy buffer and establishes a dc voltage for the normal operation of the DSTATCOM system. The DSTATCOM can be operated for reactive power compensation for power factor correction or voltage regulation.

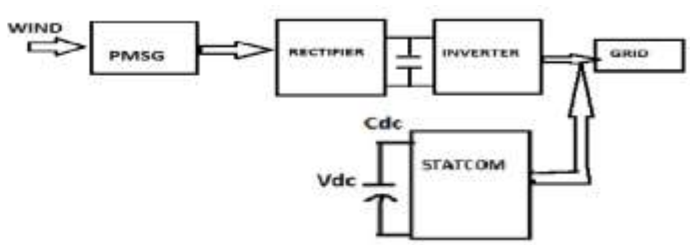

Fig.2: Basic Diagram of Wind Energy Conversion system

3.1 DC Capacitor Voltage

The minimum dc bus voltage of VSC of DSTATCOM should be greater than twice the peak of the phase voltage of the system[17]. The dc bus voltage is calculated as

$$V_{dc}=\frac{2\sqrt{2}V_{LL}}{\sqrt{3}m} \quad (9)$$

Where m is the modulation index and is considered as 1, and V_{LL} is the ac line output voltage of DSTATCOM. Thus, V_{dc} is obtained as 677.69 V for V_{LL} of 415 V and is selected as 700 V.

3.2 DC Bus Capacitor

The value of dc capacitor (C_{dc}) of VSC of DSTATCOM depends on the instantaneous energy available to the DSTATCOM during transients [17]. The principle of energy conservation is applied as

$$(1/2)C_{dc}[(v_{dc})^2 - (v_{dc1})^2] = 3V\,(aI)\,t \quad (10)$$

Where V_{dc} is the reference dc voltage and V_{dc1} is the minimum voltage level of dc bus, a is the overloading factor, V is the phase voltage, I is the phase current, and t is the time by which the dc bus voltage is to be recovered.

Considering the minimum voltage level of the dc bus, V_{dc1} =690 V, V_{dc}= 700 V, V = 239.60 V, I = 27.82 A, t = 350 μs,a = 1.2, the calculated value of $C_{dc}$is 2600 μF and is selected as 3000 μF.

3.3 AC Inductor

The selection of the ac inductance (L_f) of VSC depends on the current ripple $i_{cr,p-p}$, switching frequency f_s, dc bus voltage (V_{dc}), and L_f is given as [17]

$$L_f=\frac{\sqrt{3}mV_{dc}}{12af_s i_{cr(p-p)}} \quad (11)$$

Where m is the modulation index and a is the overload factor.

Considering, $i_{cr,p-p}$ = 5%, f_s= 10 kHz, m = 1, V_{dc}= 700 V, a = 1.2, the L_f value is calculated to be 2.44 mH. A round-off value of L_f of 2.5 mH is selected in this investigation.

3.4 Ripple Filter

A low-pass first-order filter tuned at half the switching frequency is used to filter the high-frequency noise from the voltage at the PCC. Considering a low impedance of 8.1 Ω for the harmonic voltage at a frequency of 5 kHz, the ripple filter capacitor is designed as C_f= 5 μF. A series resistance (R_f) of 5 Ω is included in series with the capacitor (C_f). The impedance is found to be 637 Ω at fundamental frequency, which is sufficiently large, and hence, the ripple filter draws negligible fundamental current.

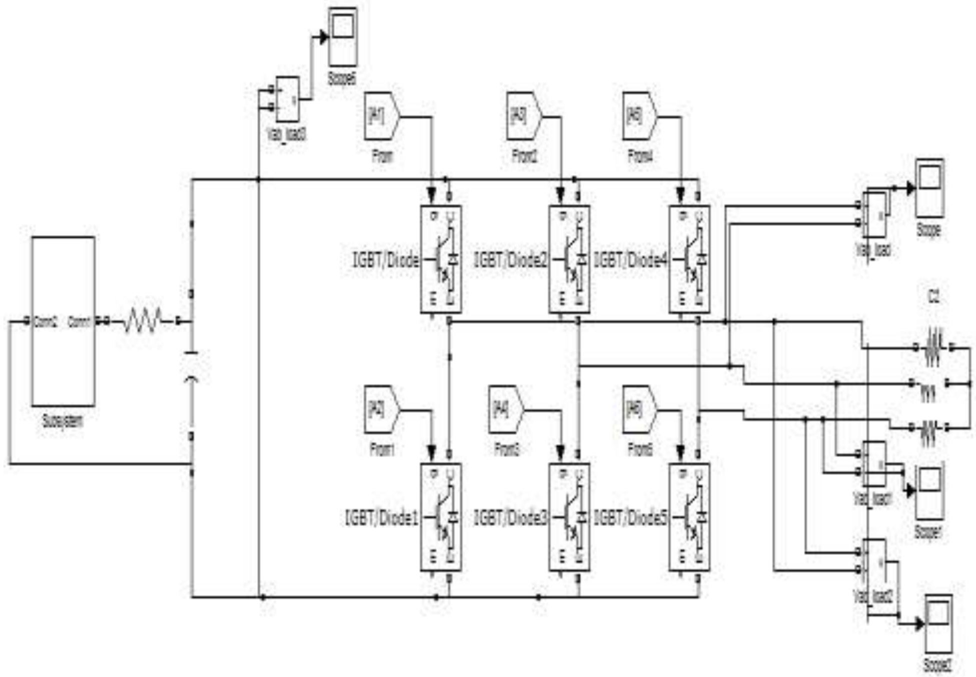

Fig.4: Inverter side of the Wind Energy Conversion System

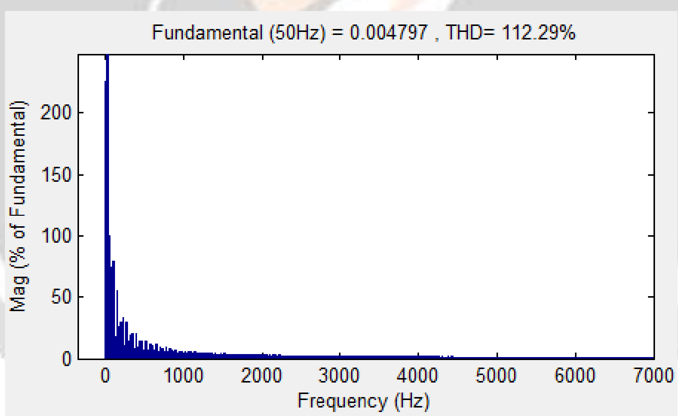

Fig.5: Stator Current Harmonics of PMSG

4. CONTROL OF STATCOM

The control approaches available for the generation of reference source currents for the control of VSC of DSTATCOM for three-phase four-wire system are instantaneous reactive power theory (IRPT), synchronous reference frame theory (SRFT), unity power factor (UPF) based, instantaneous symmetrical components based, etc. [12], [13]. The SRFT is used in this investigation for the control of the DSTATCOM.

A block diagram of the control scheme is shown in **Fig.** 4. The load currents (i_{La}, i_{Lb}, i_{Lc}), the PCC voltages (v_{Sa}, v_{Sb}, v_{Sc}), and dc bus voltage (v_{dc}) of DSTATCOM are sensed as feedback signals. The load currents from the *a–b–c* frame are first converted to the *α–β–o* frame and then to the *d–q–o*frame using

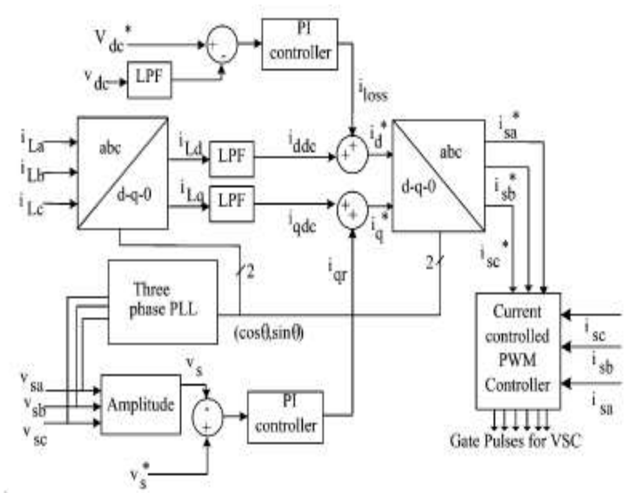

Fig. 6: Control algorithm for the three-leg-Voltage Source Converter-based STATCOM

$$\begin{bmatrix} i_{Lq} \\ i_{Ld} \\ i_{L0} \end{bmatrix} = (2/3) \begin{bmatrix} \cos\Theta & \cos(\Theta - 2\Pi/3) & \cos(\Theta + 2\Pi/3) \\ \sin\Theta & \sin(\Theta - 2\Pi/3) & \sin(\Theta + 2\Pi/3) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad ..(12)$$

wherecosθ and sin θ are obtained using a three-phase phase locked loop (PLL). A PLL signal is obtained from terminal voltages for generation of fundamental unit vectors [18] for conversion of sensed currents to the d–q–o reference frame.

The SRF controller extracts dc quantities by a low-pass filter, and hence, the non-dc quantities (harmonics) are separated from the reference signal. The d-axis and q-axis currents consist of fundamental and harmonic components as

$iL_d = i_{d\,dc} + i_{d\,ac}$ (13)

$iL_q = i_{qdc} + i_{qac}$ (14)

5. OPERATION OF STATCOM

5.1 UPF Operation of DSTATCOM

The control strategy for reactive power compensation for UPF operation considers that the source must deliver the mean value of the direct-axis component of the load current along with the active power component current for maintaining the dc bus and meeting the losses ($i$loss) in DSTATCOM. The output of the proportional-integral (PI) controller at the dc bus voltage of DSTATCOM is considered as the current ($i$loss) for meeting its losses

$$i_{loss}(n) = i_{loss}(n-1) + K_{pd}(v_{de}(n) - v_{de}(n-1)) + Ki_d v_{de}(n) \quad (15)$$

where $V_{de}(n) = v^*_{dc} - V_{dc}(n)$ is the error between the reference(v*dc) and sensed (v_{dc}) dc voltages at the nth sampling instant.K_{pd} and $K_{id}$are the proportional and integral gains of the dcbus voltage PI controller.

The reference source current is therefore

$i^*_d = i_{ddc} + i_{loss}$.(16)

The reference source current must be in phase with the voltage at the PCC but with no zero-sequence component. It is therefore obtained by the following reverse Park's transformation with i^*_d as in (12) and i^*_q and i^*_0 as zero

$$\begin{bmatrix} Ia \\ Ib \\ Ic \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta + \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \begin{bmatrix} Id \\ Iq \\ Io \end{bmatrix} \quad ..(17)$$

5.2 Zero-Voltage Regulation (ZVR) Operation of DSTATCOM

The compensating strategy for ZVR operation considers that the source must deliver the same direct-axis component i^*_d as mentioned in (12) along with the sum of quadrature-axis current (i_{qdc}) and the component obtained from the PI controller (i_{qr}) used for regulating the voltage at PCC. The amplitude of ac terminal voltage (V_S) at the PCC is controlled to its reference voltage (V^*_S) using the PI controller. The output of PI controller is considered as the reactive component of current (*iqr*) for zero-voltage regulation of ac voltage at PCC. The amplitude of ac voltage (V_S) at PCC is calculated from the ac voltages (v_{sa}, v_{sb}, v_{sc}) as

$V_S = (2/3)^{1/2} (v^2sa + v^2sb + v^2sc)^{1/2}$.(18)

Then, a PI controller is used to regulate this voltage to a reference value as

$I_{qr}(n) = I_{qr}(n-1) + K_{pq}(V_{te}(n) - V_{te}(n-1)) + K_{iq}V_{te}(n)$(19)

Where $V_{te}(n) = V^*_S - V_S(n)$ denotes the error between reference(V^*_s) and actual ($V_{S(n)}$) terminal voltage amplitudes at the *n*th sampling instant. *Kpq* and *Kiq* are the proportional and integral gains of the dc bus voltage PI controller. The reference source quadrature-axis current is

$i_q = i_{qdc} + i_{qr}$. (20)

The reference source current is obtained by reverse Park's transformation using (13) with i^*_d as in (12) and i^*_q as in (16) and i^*_o as zero

5.3 Current-Controlled Pulse width Modulation (PWM) Generator

In a current controller, the sensed and reference source currents are compared and a proportional controller is used for amplifying current error in each phase before comparing with a triangular carrier signal to generate the gating signals for six IGBT switches of VSC of STATCOM.

6. SIMULATION AND RESULTS

The three-leg Voltage Source Converter based DSTATCOM connected to the inverter side of the Wind Energy Conversion system is modeled and simulated using the MATLAB with its Simulink. The control algorithm for the STATCOM is also modelled in MATLAB. The reference source currents are derived from the

sensed voltages (V_{sa}, V_{sb}, V_{sc},), load currents (i_{La}, i_{Lb}, i_{Lc}), and the dc bus voltage of STATCOM (V_{dc}). A PWM current controller is used over the reference and sensed source currents to generate the gating signals for the IGBTs of the three-leg Voltage Source Converter of the STATCOM.

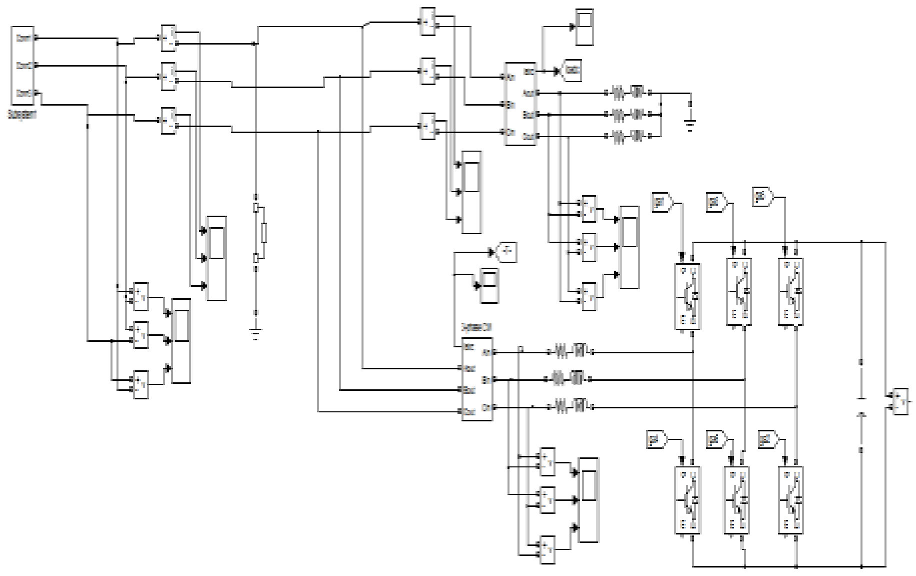

Fig.6: Static Compensator at the inverter side

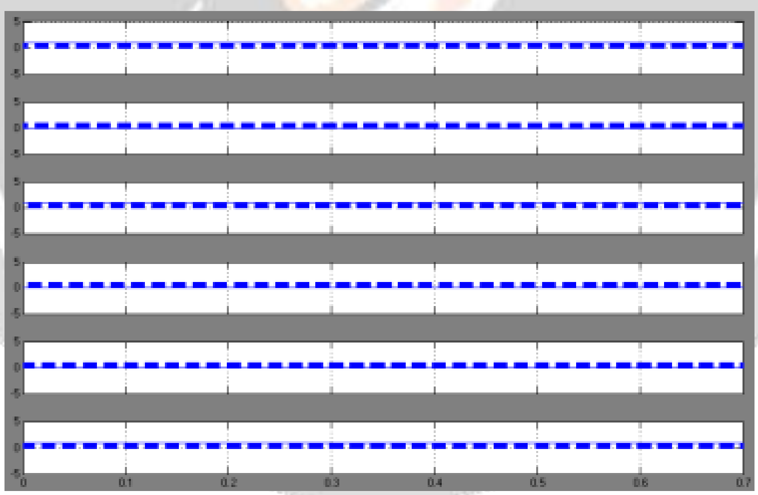

Fig.7: Pulses Generation for Switches in STATCOM using Synchronous Reference Frame

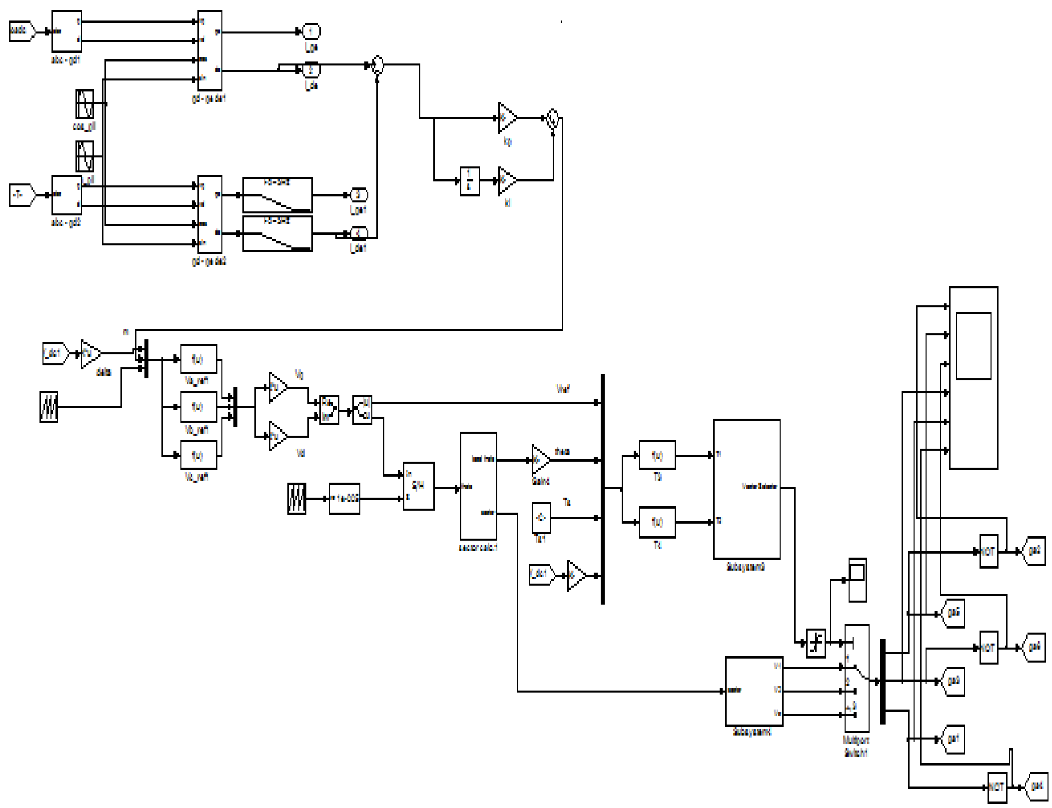

Fig.8: Synchronous Reference Frame Model

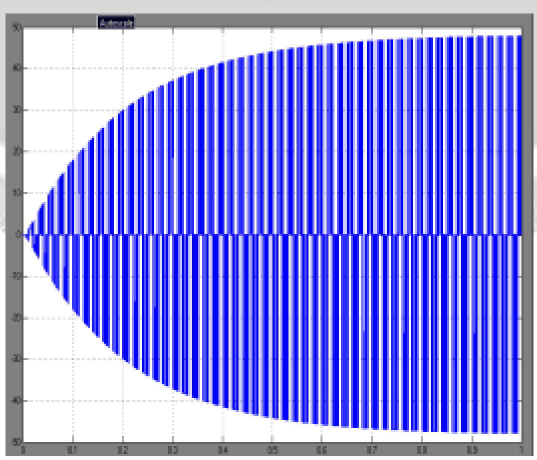

Fig.9: Inverter Output Voltage

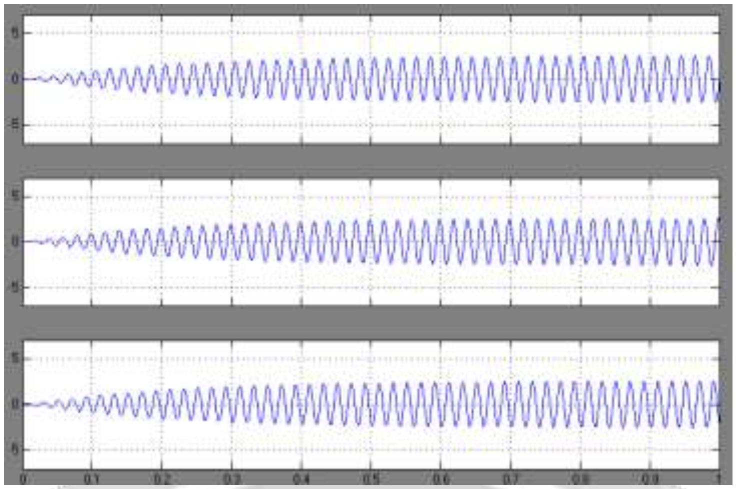

Fig.10: Output Voltage of STATCOM

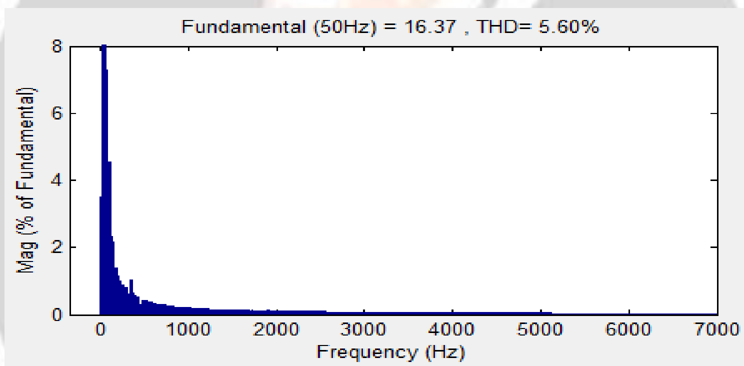

Fig.11: Harmonic Content of Inverter Output Voltage

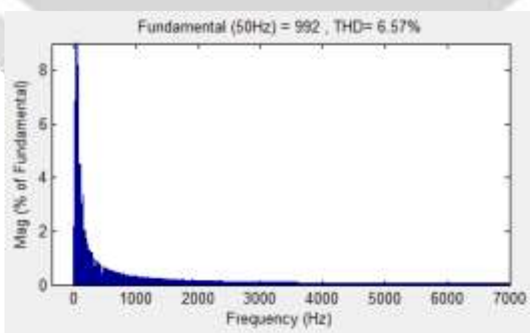

Fig.12: Harmonic content of Inverter Output Current

The three leg Voltage Source Converter based three-phase Static compensator is demonstrated for power factor correction and voltage regulation along with harmonic reduction, load balancing, and neutral current compensation. The developed model is analyzed under varying loads and the results are discussed shortly. The **fig**.6 shows the Static Compensator implemented at the inverter side to reduce the harmonics reflection from the generator to the inverter, **fig**.7 shows the pulses Generation for Switches 2,1,4,3,5,6 in STATCOM using Synchronous Reference Frame theory. The fig.8 implies the synchronous reference frame model

For the pulse generation of Static compensator, **fig**.9, 10 shows the output voltage at the inverter level and the Output Voltage of STATCOM. The **fig.**11, 12 shows the Reduced Harmonic Content of Inverter Output Voltage and the Current.

7 CONCLUSION

The use of Static Compensator in wind energy generation systems for harmonic mitigation was analyzed andcomputationally simulated. The STATCOM is able to mitigate harmonic content of current that flows on the inverter side. A capacitor bank filter was used to suppress high-switching frequency voltage component generated by the Static Compensator on inverter. The d-q synchronous reference frame synchronization using the angular rotor speed had worked, and its physical implementation using sensors must be investigated.

The STATCOM could diminish voltage core losses. Overall wind energy conversion system efficiency is lower as well, so the use of STATCOM could bejustified if only the PMSG could have a larger life cycle.Thus this can able to compensate current unbalance,load current harmonics, load reactive power demand and load neutral current.

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