MODELING AND CONTROL OF WIND POWER GENERATION SYSTEM WITH BACK TO BACK CONVERTERS

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ABSTRACT*: In order to meet increasing power demand, taking into account economical and environmental factors, wind energy conversion is gradually gaining interest as a suitable source of renewable energy. In this paper, the modeling of the Wind Energy Conversion System (WECS) with Back to Back converters is developed in MATLAB- SIMULINK environment. The control objective of machine side converter is to regulate active and reactive power flow and to achieve maximum power point tracking. The control objective of grid side converter is to maintain constant DC link voltage regardless of the changing rotor power.*

I. INTRODUCTION

With exhausting of traditional energy resources and increasing concern of environment, renewable and clean energy is attracting more attention all over the world to overcome the increasing power demand. Out of all the renewable energy sources, Wind energy and solar energy are reliable energy sources. Now a day, Wind power is gaining a lot of importance because it is cost- effective, environmentally clean and safe renewable power source compared to fossil fuel and nuclear power generation.

A Wind Energy Conversion System (WECS) can vary in size from a few hundred kilowatts to several megawatts. The size of the WECS mostly determines the choice of the generator and converter system. Asynchronous generators are more commonly used in systems up to 2MW, beyond which direct-driven permanent magnet synchronous machines are preferred.

A grid connected WECS should generate power at constant electrical frequency which is determined by the grid. Generally Squirrel cage rotor induction generators are used in medium power level grid-connected systems. The induction generator runs at near synchronous speed and draws the magnetizing current from the mains when it is connected to the constant frequency network, which results in Constant Speed Constant Frequency (CSCF) operation of generator. However the power capture due to fluctuating wind speed can be substantially improved if there is flexibility in varying the shaft speed.

In Squirrel cage Induction Generator (SCIG), the stator is connected to the three phase grid through the two back-to-back PWM converters as shown in Figure1. Such an arrangement provides flexibility of operation at both sub-synchronous and super synchronous speeds.

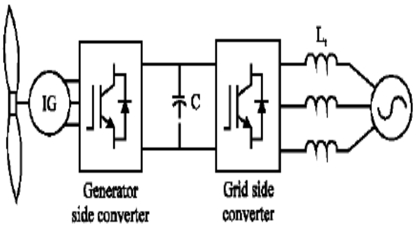

Figure 1: Wind Energy Conversion System

The stator side converter regulates the electromagnetic torque and supplies the necessary reactive power to magnetize the machine. The grid side converter on the other hand controls the power quality generated power to the grid. It accomplishes this task by regulating the real and reactive power delivered to the grid while regulating the DC link voltage. The squirrel cage induction machine is very rugged, brushless, reliable, and cost effective. However, the drawback of using the SCIG is that the stator side converter must be oversized by 30-50% of machine's rated power in order to be able to satisfy the machine's magnetizing requirement. Therefore, although the SCIG itself is cost effective, the necessary power converters for its control are relatively more bulky and expensive.

II.MODELING OF WIND TURBINE

The wind Energy conversion system studied in this paper consists of Wind turbine, Squirrel Cage Induction Generator, Machine Side Converter (MSC) and Grid Side Converter (GSC). Wind energy is transformed into mechanical energy by means of a wind turbine that has one or several blades. The turbine is coupled to the generator system by means of a mechanical drive train. It usually includes a gearbox that matches the turbine low speed to the higher speed of the generator. New wind turbine designs use multi pole, low speed generators, usually synchronous with field winding or permanent magnet excitation, in order to eliminate the gearbox. Some turbines include a blade pitch angle control for controlling the amount of power to be transformed. The electrical generator transforms mechanical energy from the wind turbine into electrical energy. The generator can be Synchronous or Asynchronous. Variable speed systems require the presence of a power electronic interface, which can adapt to different configurations.

The aerodynamic torque(T_m) and mechanical power (P_m) generated by a wind turbine is given by Equation (1) and Equation (2) respectively.

$$T_m = C_t(\lambda)\left[0.5\frac{\rho\pi R_r^3}{\eta_{gear}}\right]V_w^2 \qquad (1)$$

$$P_m = \frac{1}{2}C_p\rho A_r V_w^3 \qquad (2)$$

Where P_m is the power in watts, ρ is the air density in g/m^3, C_P a dimensionless factor called power Coefficient, A_r the turbine rotor area in m^2($A_r = \pi R_r^2$, where R_r is the rotor blade radius), η_{gear} is and V_w the wind speed in m/s. The power coefficient is related to the tip speed ratio (λ) and rotor blade pitch angle $\boldsymbol{\beta}$ according to Equation (3)

$$Cp = 0.73\left(\frac{151}{\lambda i} - 0.58\beta - 0.002\beta^{2.14} - 13.2\right)e^{\frac{-18.4}{\lambda i}} \qquad (3)$$

Where $\lambda_i = \dfrac{1}{\frac{1}{\lambda - 0.02\beta} - \frac{0.003}{\beta^3+1}}$ (4)

And $\lambda = \dfrac{\omega_r R_r}{V_w}$ (5)

$$C_t = \frac{C_p}{\lambda} \qquad (6)$$

In equation (5), ω_r is the angular speed of the turbine shaft. The theoretical limit for C_P is 0.59 according to Betz's Law, but its practical range of variation is 0.2-0.4.

III. MODELING OF INDUCTION GENERATOR

The electrical part of the induction generator is represented by a fourth-order state space model, which is constructed using the synchronously rotating reference frame (dq-frame), where the d-axis is oriented along the stator-flux vector position. The relation between the three phase quantities and the dq components is defined by Park's transformation the voltage equations of the induction generator are

$$V_{ds} = R_s i_{ds} - \omega_s\psi_{qs} + \frac{d\psi_{ds}}{dt} \qquad (7)$$

$$V_{qs} = R_s i_{qs} + \omega_s\psi_{ds} + \frac{d\psi_{qs}}{dt} \qquad (8)$$

$$V_{dr} = R_r i_{dr} - (\omega_s - \omega_r)\psi_{qr} + \frac{d\psi_{dr}}{dt} \qquad (9)$$

$$V_{qr} = R_r i_{qr} - (\omega_s - \omega_r)\psi_{qr} + \frac{d\psi_{dr}}{dt} \qquad (10)$$

where V_{ds}, V_{qs}, V_{dr}, V_{qr} are the d- and q-axis of the stator and rotor voltages; I_{ds}, I_{qs} ,I_{dr}, I_{qr} are the d- and q-axis of the stator and rotor currents; Ψ_{ds}, Ψ_{qs}, Ψ_{dr}, Ψ_{qr} are the d- and q- axis of the stator and rotor fluxes; ω_s is the angular velocity of the synchronously rotating reference frame; ω_r is the rotor angular velocity; and R_s, R_r are the stator and rotor resistances. The flux equations of the induction generator are

$$\psi_{ds} = L_s I_{ds} + L_m I_{dr} \qquad (11)$$

$$\psi_{qs} = L_s I_{qs} + L_m I_{qr} \qquad (12)$$

$$\psi_{dr} = L_m I_{ds} + L_r I_{dr} \qquad (13)$$

$$\psi_{qr} = L_m I_{qs} + L_r I_{qr} \qquad (14)$$

Where L_s, L_r, and L_m are the stator, rotor, and mutual inductances, respectively. From the flux equations (11)–(14), the current equations can be written as

$$I_{ds} = \frac{1}{\sigma L_s}\psi_{ds} - \frac{L_m}{\sigma L_s L_r}\psi_{dr} \qquad (15)$$

$$I_{qs} = \frac{1}{\sigma L_s}\psi_{qs} - \frac{L_m}{\sigma L_s L_r}\psi_{qr} \qquad (16)$$

$$I_{dr} = \frac{1}{\sigma L_r}\psi_{dr} - \frac{L_m}{\sigma L_s L_r}\psi_{ds} \qquad (17)$$

$$I_{qr} = \frac{1}{\sigma L_r}\psi_{qr} - \frac{L_m}{\sigma L_s L_r}\psi_{qs} \qquad (18)$$

Where $\sigma = 1 - \frac{L_m^2}{L_s L_r}$ is the leakage coefficient. Neglecting the power losses associated with the stator and Rotor resistances, the active and reactive stator and rotor powers are given by

$$P_s = -V_{ds}I_{ds} - V_{qs}I_{qs} \qquad (19)$$

$$Q_s = -V_{qs}I_{ds} + V_{ds}I_{qs} \qquad (20)$$

$$P_r = -V_{dr}I_{dr} - V_{qr}I_{qs} \qquad (21)$$

$$Q_r = -V_{qr}I_{dr} + V_{dr}I_{qr} \qquad (22)$$

and the total active and reactive powers of the DFIG are

$$P = P_s + P_r \qquad (23)$$

$$Q = Q_s + Q_r \qquad (24)$$

$$J\frac{d\omega_r}{dt} = T_m - T_e - C_f\omega_r \qquad (25)$$

Where C_f is the friction coefficient, T_m is the mechanical torque generated by the wind turbine, and Te is the electromagnetic torque given by

$$T_e = \psi_{ds}I_{ds} - \psi_{qs}I_{qs} \qquad (26)$$

Where positive (negative) values mean the induction machine acts as a generator (motor).

IV.MODELING OF CONVERTERS

Mathematical modeling of converter system is realized by using various types of models, which can be broadly divided into two groups: mathematical functional models and Mathematical physical models (either equation-oriented or graphic-oriented, where graphic-oriented approach is actually based on the same differential equations).Functional model describes the relationship between the input and output signal of the system in form of mathematical function(s) and hence constituting elements of the system are not modeled separately. Simplicity and fast time-domain simulation are the main advantages of this kind of modeling with the penalty of losing accuracy. This has been a popular approach with regard to SCIG modeling, where simulation of converters has been done based on expected response of controllers rather than actual modeling of Power Electronics devices. In fact, it is assumed that the converters are ideal and the DC-link voltage between them is constant. Consequently, depending on the converter control, a controllable voltage (current) source can be implemented to represent the operation of the rotor-side of the converter in the model. Physical model, on the other hand, models constituting elements of the system separately and also considers interrelationship among different elements within the system, where type and structure of the model is normally dictated by the particular requirements of the analysis, e.g. steady-state, fault studies, etc. Indeed, due to the importance of more realistic production of the behavior of SCIG, it is intended to adopt physical model rather than functional model in order to accurately assess performance of SCIG in the event of fault particularly in determining whether or not the generator will trip following a fault.

4.1MACHINE SIDE CONVERTER CONTROL SYSTEM

The Machine side converter (C_{mach})is used to control the wind turbine output power and voltage or the output power and reactive power measured at the grid terminals.

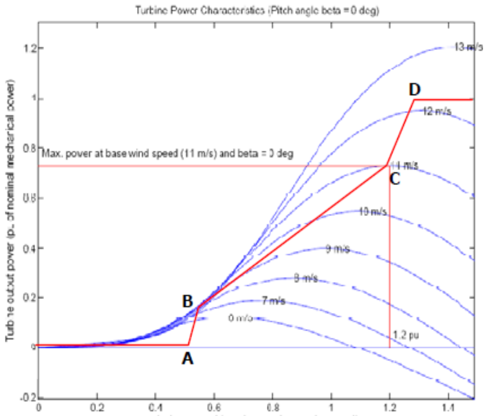

Fig 2: Turbine Power Characteristics

The power is controlled in order to follow tracking characteristic. This characteristic is illustrated by the ABCD curve in Figure. 2 imposed to the mechanical power characteristics of the turbine obtained at different wind speeds. The actual speed of the turbine ω_r is measured and the corresponding mechanical power of the tracking characteristic is used as the reference power for the power control loop. The tracking characteristic is defined by four points: A, B, C and D. From zero speed to speed of point A the reference power is zero. Between point A and point B the tracking characteristic is a straight line. Between point B and point C the tracking characteristic is the locus of the maximum power of the turbine (maxima of the turbine

power versus turbine speed curves). The tracking characteristic is a straight line from point C and point D. The power at point D is one per unit (1 p.u.). Beyond point D the reference power is a constant equal to one per unit (1 p.u.). The generic power control loop is illustrated in Figure 3. For the machine side controller the d-axis of the rotating reference frame used for d-q transformation is aligned with air-gap flux. The actual electrical output power, measured at the grid terminals of the wind turbine is added to the total power losses (mechanical and electrical) and is compared with the reference power obtained from the tracking characteristic.

V_{abc_WT} and I_{abc_WT} are voltages and currents measured at wind turbine in p.u. system. In this the actual voltage after filter is compared with reference value, error is reduced by using PI controller. From this we get Id value from park's transformation. Wind turbine current is converted to dq frame and actual Id is compared to above reference voltage and error is reduced by using PI controller and generates $V_{dref.}$ Wind actual speed is compared with reference speed, error is amplified and reduced using PI controller, leads to I_q. This I_q. is compared to speed controllers Iq, to get $V_{qref.}$.

From V_{dref} and V_{qref} values desired voltage reference can be obtained. As per this desired voltage reference discrete PWM generator will generate triggering pulses for this converter. In this method torque is indirectly controlled

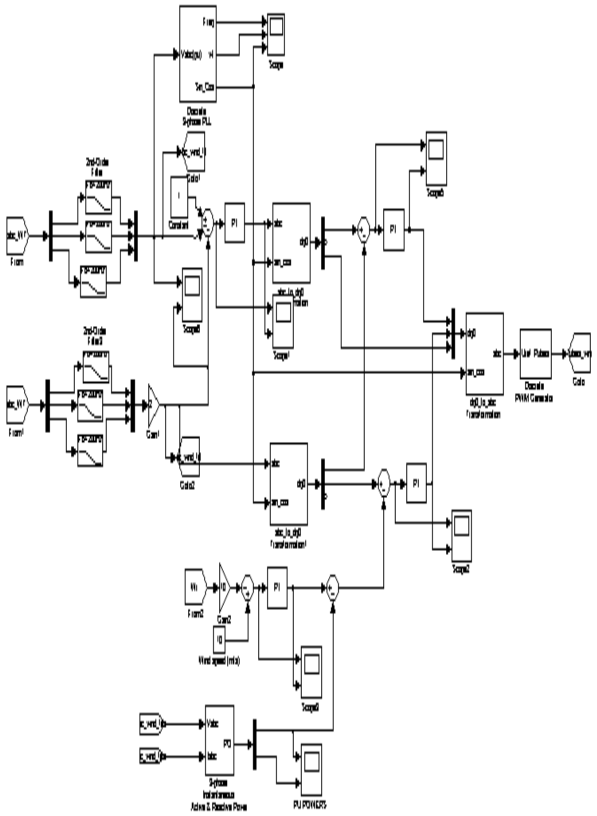

Figure.3. Machine Side Controller Control system

4.2 GRID SIDE CONVERTER CONTROL SYSTEM

The grid-side converter is used to regulate the voltage of the DC bus capacitor. For the grid-side controller the d-axis of the rotating reference frame used for d-q transformation is aligned with the positive-sequence of grid voltage. The grid side control system is shown in Figure 4. And this system consists of

1. Measurement system measuring the d and q components of AC currents to be controlled as well as the DC link voltage V_{dc}.
2. An outer regulation loop consisting of a DC voltage regulator. The output of the DC voltage regulator is the reference current I_{dgc_ref} for the current regulator (I_{dgc} is current in phase with grid voltage which controls active power flow).
3. An inner current regulation loop consisting of a current regulator. The current regulator controls the magnitude and phase of the voltage generated by converter C_{grid} (Vgc) from the I_{dgc_ref} produced by the DC voltage regulator and specified I_{q_ref} reference. The current regulator is assisted by feed forward terms which predict the $C_{\mathbf{grid}}$ output voltage.

This control system is current control system with constant voltage. Load current is transformed into d-q reference frame. Id is compared to reference output from DC inverter, and error is reduced by using PI controller to get V_d*.I_q is compared with zero reference value, error is reduced by using PI controller to get V_d*. From V_d* and V_q* desired voltage reference can be obtained. As per this desired reference value, error is reduced by using PI controller to get V_d*. From V_d* and V_q* desired voltage reference can be obtained. As per this desired voltage reference discrete PWM generator will generate triggering pulses for this converter

the simulink block diagram of WECS with Back to Back converter is shown in Figure 5. The main components of Simulink block diagram are wind turbine,Squirrel cage Induction Generator, Machine side Converter, grid side Converter, Machine side Converter Control System and grid side Converter control System. The considered wind velocity at time t= 0, 0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4,0.45 instants are 0, 8 ,12, 15, 20, 10, 14, 6, 18 and 14 m/s respectively. Wind turbine acts as prime mover for induction generator.

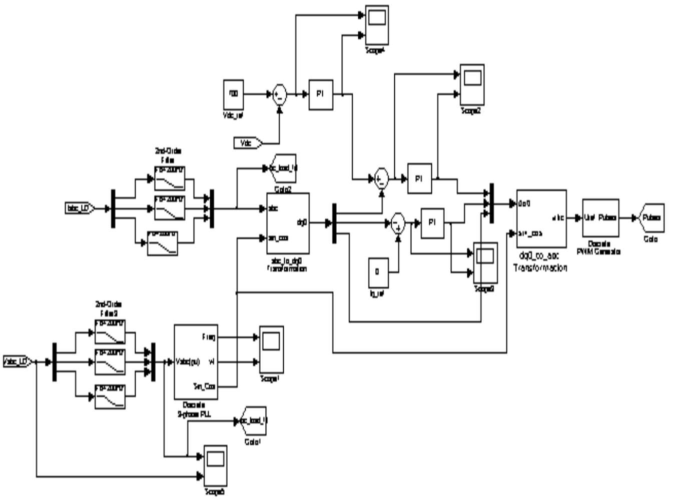

Figure 4. Grid Side Converter Control System

V.SIMULATION RESULTS

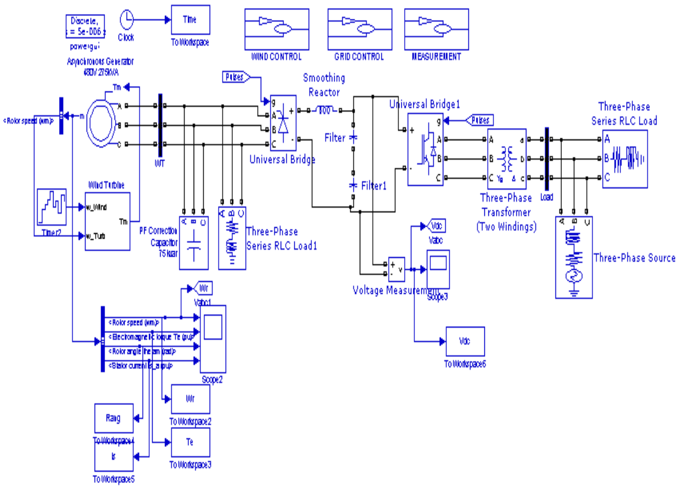

Figure 5: block diagram of WECS with Back to Back ConverteT.

The machine actual speed is shown in Figure 6.

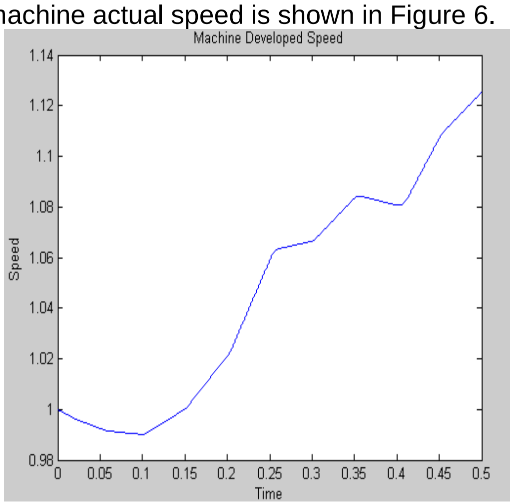

Figure 6: The Machine actual Speed

The torque developed by the machine is shown in Figure 7.

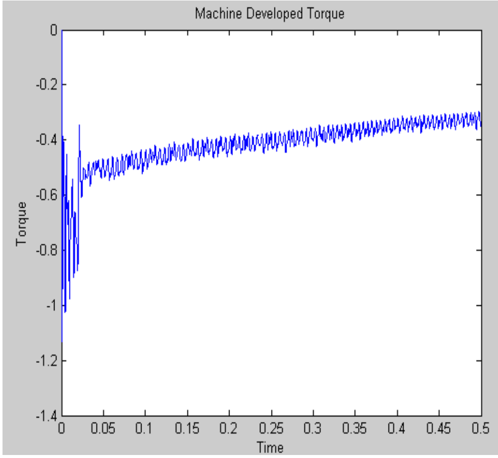

Figure 7 Torque developed by the Machine

The torque developed by machine is negative, so it is acting generator.

The machine Rotor angle is shown in Figure 8.

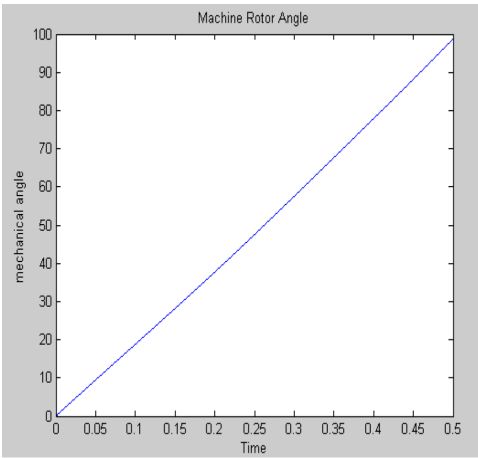

Figure 8: The Rotor Angle of the Machine

The machine stator phase current is shown in Figure 9.

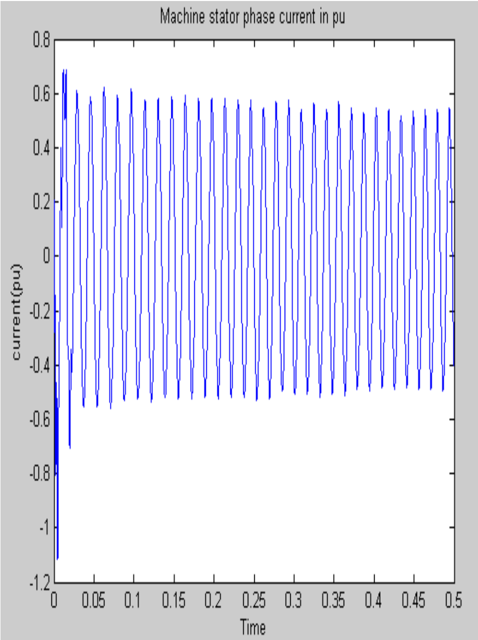

Figure 9: Machine Stator Phase Current in pu

The DC Link Voltage in the WECS is shown in Figure 10.

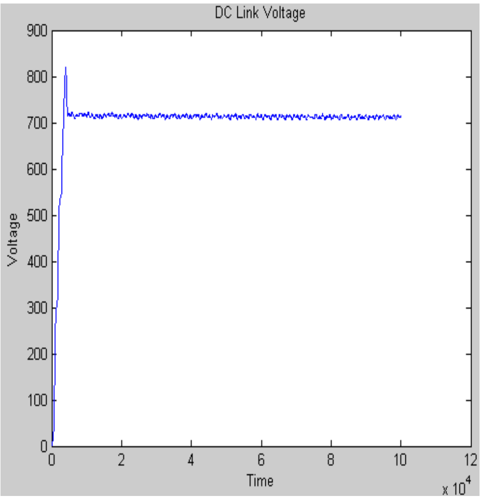

Figure 10 The DC link Voltage

The DC link voltage is almost constant around 700 V.

The machine side converter voltages without and with filter are shown in Figure 11 and Figure12.

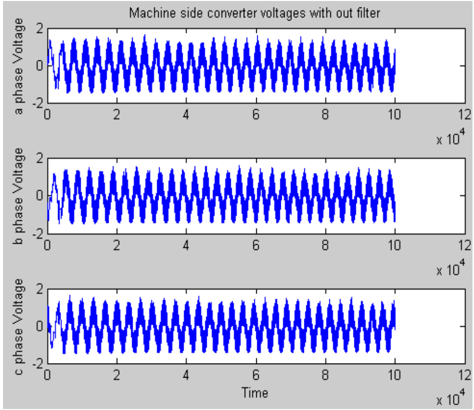

Figure 11: Machine side Converter voltages without filter

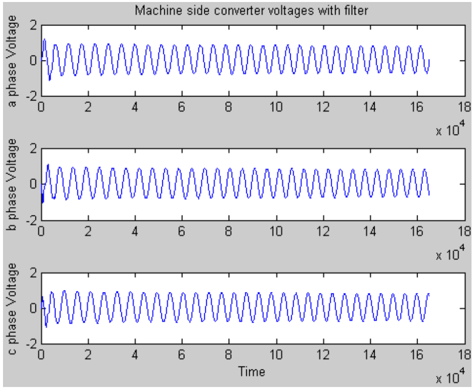

Figure 12: Machine side Converter voltages with filter

The machine side converter Currents without and with filter are shown in Figure 13 and Figure 14.

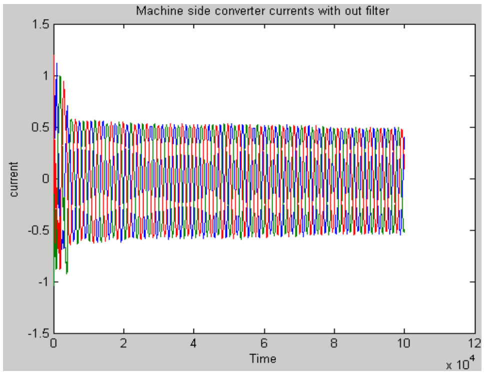

Figure 13: Machine side Converter currents without filter

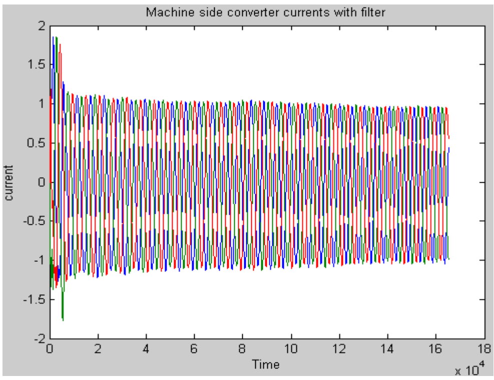

Figure 14: Machine side Converter currents with filter

The Load side converter voltages without and with filter are shown in Figure 15 and Figure16.

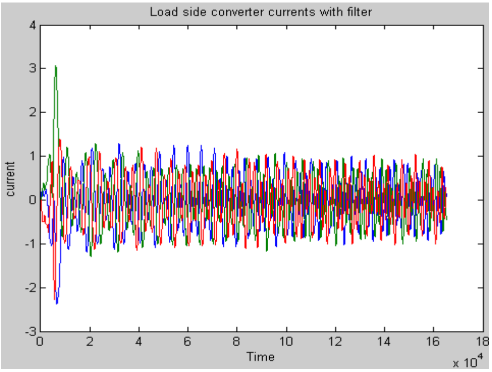

Figure 18: Load side Converter Currents with filter

The Active and Reactive powers produced by the machine are shown in Figure 19.

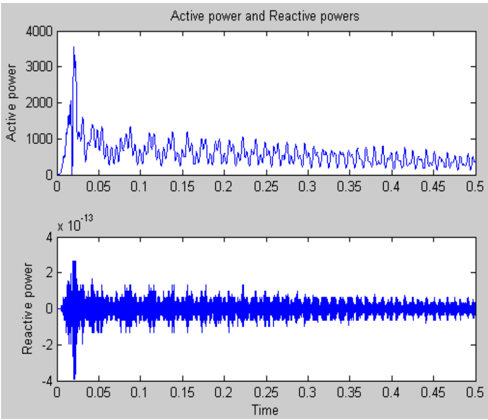

Figure 19: Active and Reactive Powers in the Machine

VI. CONCLUSION

The modeling of grid connected WECS with two Back-to-Back converters is developed in MATLAB-SIMULINK environment. The performance of WECS with variable wind velocity is studied through simulation results. The torque developed by machine is negative, so it is acting generator. The wind turbine output power and voltage or the output power and reactive power measured at the grid terminals is controlled by using machine side converter. The DC Link Voltage is maintained constant at 700 volts by using grid side converter.

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