Sliding Mode Control Application in Wind Energy Conversion System Using DSTATCOM

R. S. Bajpai[1]* and Amarjeet Singh[2]

ABSTRACT

This paper deals with sliding mode control of converter and its application to distributed generation. Sliding mode control is used to control the voltage source converter in voltage or current control mode. Modeling and control of H bridge converter system using sliding mode control is proposed. Easily implemented sliding surfaces provide prominent dynamic characteristics against changes in the load and in the input voltage. Distribution static compensator (DSTATCOM) is used to control the voltage of the bus to which it is connected to a balance sinusoid in respect of the harmonic distortion in supply or load side. A variable wind turbine generator is used to produces a variable DC voltage which is placed as input voltage source to converter of DSTATCOM. A control strategy for grid voltage control using DSTATCOM in voltage control mode has been implemented in respect of the wind variation. The results are validated using PSCAD/EMTDC simulation studies.

Keywords : *Sliding mode control, Distribution static compensator (DSTACOM), wind generator, grid voltage control, switching control.*

I. INTRODUCTION

OF all kind of renewable energies, wind energy is facing the fastest development. As a consequence many researchers are fixing their interest in this field. In order to improve research activities related to the control of electrical generators for wind turbines, a controlled test environment is required that does not rely on wind.. The system consists of a variable speed wind turbine model coupled to a wind generator [1]. The varying aerodynamic torque of the wind turbine is incorporated in the simulation with the use of a PSCAD/EMTDC tools in order to obtain the characteristics of wind as desired. Wind generator connected to wind turbine shaft gives variable voltage which is further rectified and placed at the input terminal of an voltage source converter. Control strategy for sliding mode control of converter is discussed for both voltage and output current control mode [2]. However the control application with DSTATCOM is based on voltage control mode. The purpose of DSTATCOM is to regulate the voltage at point of common coupling (PCC) and compensate the load voltage harmonics present in the supply voltage.

II. WIND TURBINE DYNAMICS

The first law of thermodynamics tells us that energy can neither be created nor destroyed, but it can change forms. Anything that is in motion such as moving air contains a form of energy we refer to as kinetic energy. Slowing air down reduces its kinetic energy and that energy has to go some where. Wind turbines extract energy from wind and convert some of the energy to mechanical and electrical energy as shown in Fig 1. Kinetic energy is given as

$$K.E = \frac{1}{2} mv^{2} \tag{1}$$

Where, m is the mass of air in kg and v is the wind velocity in meter per sec.

This allows us to calculate the amount of power in moving air. The power of the wind passing perpendicularly through a circular area is given by [3]

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$$P_{turb} = \frac{1}{2}\rho A C_p v_w^3 \quad (2)$$

where

P_{turb} = Power of wind in Watts

ρ = Density of air in kg per meter cube

v_w = Velocity of wind in meter per sec

A = Area swept by circular rotor in square meter

C_p = Power coefficient

Power coefficient is defined as the ratio of the turbine power to the power of a wind stream. This definition shows that power coefficient represents the efficiency of the turbine. Power coefficient is a function of the tip speed ratio. Tip speed ratio is defined as the ratio of the speed at the tip of the blade to wind velocity as given below:

$$\lambda = \frac{RW_w}{v_w} \quad (3)$$

R = Radius of turbine in meter

W_w = Turbine speed in revolution per min

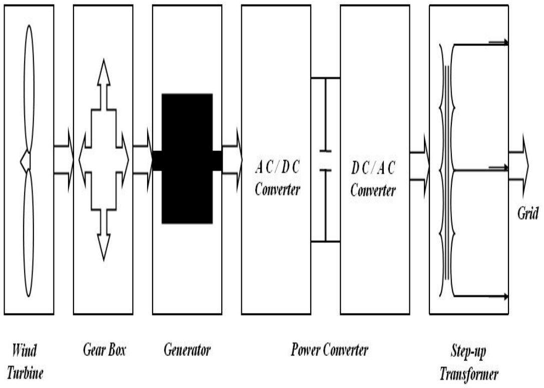

Fig. 1 Block diagram of wind energy conversion system

Wind turbine dynamics are simulated in test model [4] [5], whose parameters are given in table I. Rated wind velocity 13 meter per sec obtained from wind turbine simulator is as shown in Fig 2.

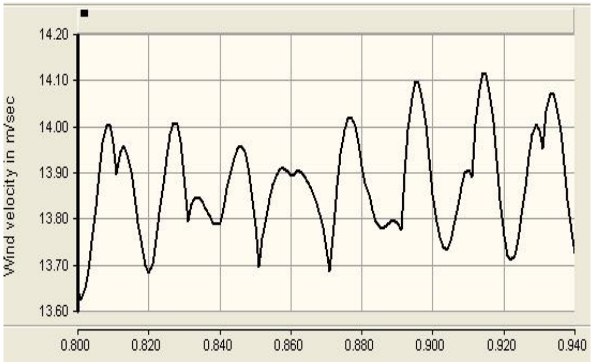

Fig. 2 Wind velocity in m/sec

For rated wind speed, the torque of wind turbine is calculated from (4) as shown in Fig 3.

$$T_{turb} = \frac{1}{2}\rho\pi C_{T(\lambda)} v_w^2 R^3 \quad (4)$$

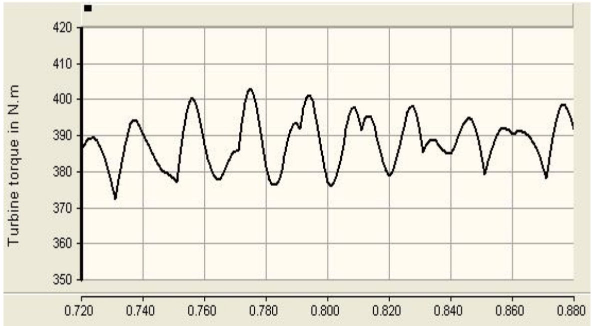

Fig. 3 Rated Torque of wind turbine in N.m

For rated wind speed, wind turbine power calculated from (5) as shown in Fig 4.

$$P_w = \frac{1}{2}\rho\pi C_P v_w^3 R^2 \quad (5)$$

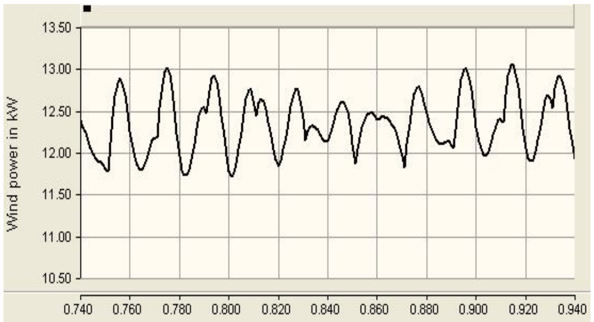

Fig.4 Rated Wind turbine power in kW

where, ρ = 1.185kg/m^3, $C_T(\lambda)$ is the torque coefficient as a function of tip speed ratio as given by (6)

$$C_T = \frac{C_P}{\lambda} \tag{6}$$

Starting torque coefficient of torque is given by (7)

$$C_{TS} = \frac{2T_s}{\rho\pi v_S^{2} R^{3}} \tag{7}$$

Rated torque can be obtained by (8)

$$T_W = \frac{P_w}{W_w} \tag{8}$$

Rated torque coefficient can be calculated from (9) as given below

$$C_{TR} = \frac{2T_w}{\rho\pi v_W^{2} R^{3}} \tag{9}$$

For rated rotating speed and wind speed, tip speed ratio is calculated from (10)

$$\lambda = \frac{RW_w}{v_W} \tag{10}$$

For different wind speed, the coefficient of performance (Cp) versus tip speed ratio (?) is shown in Fig 5.

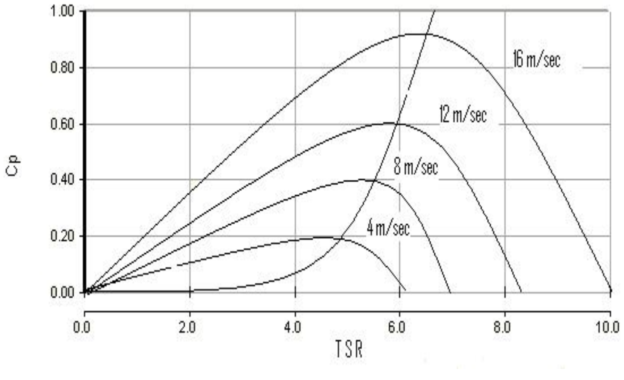

Fig.5 Coefficient of performance vs tip speed ratio

III. CONTROL STRATEGY OF GENERATOR

The motive of generator control strategy is to regulate its voltage and supply max power, demanded by load irrespective of the speed variation [6]. Because the generator is directly connected to wind turbine shaft, voltage generated is fluctuating, which is converted into variable dc voltage connected across dc link capacitor as shown in fig.1.. The modeling and control design of a converter system using sliding mode control is presented. This paper shows a simple process that allows to model the system and proposed sliding surfaces providing prominent dynamic characteristics against changes in the load and in the input voltage.

IV. SLIDING MODE CONTROL OF CONVERTER

This section develops a model for the voltage source converter. The model is used to explain the essential features of sliding mode control while presenting an easy implementation of controller. A voltage source converter circuit as shown in Fig 6. Switched state space model of the converter is shown in (11).

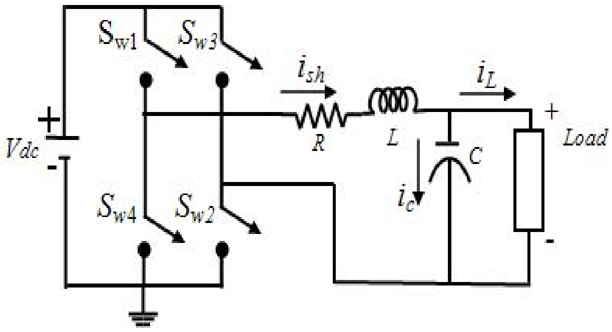

Fig. 6: sliding mode control of an inverter

With reference to Fig.6 the equations of the systems to be controlled are given as:

$$\begin{aligned} uV_{dc} &= R\, i_{sh} + V_c + \frac{Ldi_{sh}}{dt} \\ i_c &= \frac{Cdv_c}{dt} \\ i_{sh} &= i_c + i_L \end{aligned} \tag{11}$$

Capacitor voltage v_c and its derivative $\frac{dv_c}{dt}$ are taken as state variables. In this system both quantities are easily measurable. The system state vector is defined as:

$$x^{T} = \left[v_C \quad \dot{v}_C \right] \tag{12}$$

Where, capacitor voltage v_c is the output quantity to be controlled. In addition, a disturbance is represented by the quantity d defined as:

$$d = -\frac{1}{C}\left(\frac{di_L}{dt}\right) - \left(\frac{R}{LC}\right) i_L \tag{13}$$

Switched state space model of the converter, with state variable [V0 ish] are defined from (14):

$$\begin{aligned} x_1 &= v_C \\ x_2 &= \frac{dv_C}{dt} \\ \frac{dx}{dt} &= Ax + B_1 u + B_2 d \\ y &= cx \end{aligned} \tag{14}$$

where,

$$A = \begin{bmatrix} 0 & 1 \\ -\frac{1}{LC} & -\frac{R}{L} \end{bmatrix}; \quad B_1 = \begin{bmatrix} 0 \\ \frac{V_{dc}}{LC} \end{bmatrix}; \quad B_2 = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 \end{bmatrix}$$

A. Output Current Control

In current control mode, output current of a converter follows the reference value.

- ***Sliding surface selection:***

The controllable canonical model (15) is obtained from (11). Since output is governed by u v_{dc}, canonical model to control output current is given by

$$\frac{di_{sh}}{dt} = -\frac{R}{L} i_{sh} - \frac{v_C}{L} + \frac{uV_{dc}}{L} \tag{15}$$

A suitable sliding surface can be obtained from (17) as

$$e_{ish} = \left(i_{shref} - i_{sh} \right) \tag{16}$$

or $S(e_{ish}, t) = k1\left(i_{shref} - i_{sh} \right) = 0$ (17)

- ***Existence of sliding mode:***

The existence of operation in sliding mode implies that $S(e_{ish}, t) = 0$. Therefore the switching law must ensure the stability condition for the system in sliding mode, as

$$S(e_{ish}, t)\frac{dS(e_{ish}, t)}{dt} > 0$$

The fulfillment of this inequality ensures the convergence of the system trajectories to the sliding surface

$$S(e_{ish}, t) = 0$$

if $S(e_{ish}, t) > 0$ and $\frac{dS(e_{ish}, t)}{dt} < 0$ then $S(e_{ish}, t)$ decreases towards zero

if $S(e_{ish}, t) < 0$ and $\frac{dS(e_{ish}, t)}{dt}$ .0 then $S(e_{ish}, t)$ increases towards zero

- ***Determination of control law:***

After varying the existence condition the switching law can be given as

u= + V_{dc} for $S(e_{ish}, t) > 0$ (18)

u = - V_{dc} for $S(e_{ish}, t) < 0$ (19)

Power converters cannot switch to infinite frequency. Hence a hysteresis comparator is introduced to modify the switching law as

u = + V_{dc} for $S(e_{ish}, t) > \varepsilon$ (20)

u = - V_{dc} for $S(e_{ish}, t) < \varepsilon$ (21)

- ***Simulation results:***

It is observed from Fig. 9 that load current is sinusoidal and it follows the reference current as shown in Fig. 8 in respect of the in put voltage fluctuation Vdc as shown in Fig. 7.

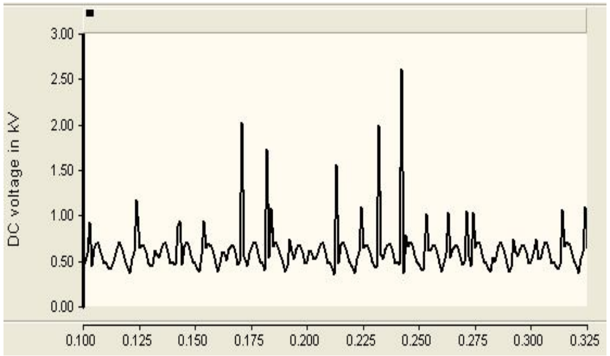

Fig.7 Varying in put voltage (Vdc) in kV

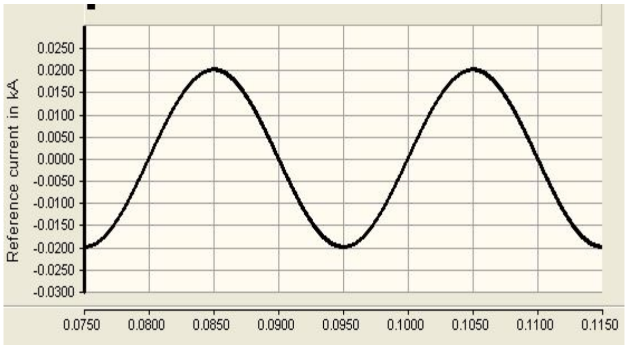

Fig.8 Reference current to be tracked in kA

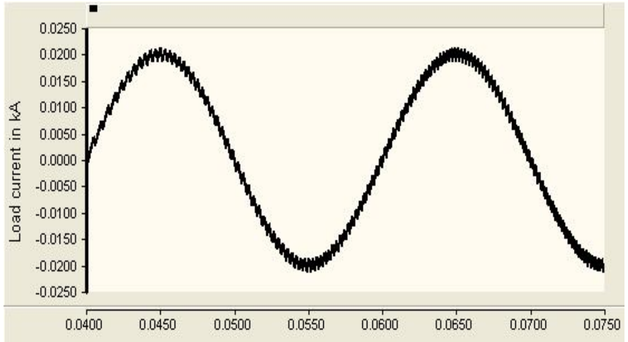

Fig.9 Load current with sliding mode control in kA

B. Output Voltage Control

In voltage control mode, output voltage follows the reference value in respect of the input voltage variation.

Sliding surface selection:

In order to control the output voltage of inverter we have to find out the suitable sliding surface which will directly apply the switching law i.e. from equation (11), sliding surface is introduced as

$$s(e,t) = k_2(\dot{v}_{cref} - \dot{v}_c) + k_3(v_{cref} - v_c) \tag{22}$$

Considering that $e_{vo} = (v_{Oref} - v_o)$, hence sliding surface is

$$S(e_{vo},t) = k_2\dot{e}_{vo} + k_3 e_{vo} = 0 \tag{23}$$

Existence of sliding mode:

Existence condition in sliding mode implies that

$$S(e_{vo},t) = 0$$

Therefore switching law must ensure that stability condition for the system in sliding mode is

$$S(e_{vo},t)\frac{dS(e_{vo},t)}{dt} < 0$$

The fulfillment of this inequality ensures the convergence of the system trajectories to the sliding surface $S(e_{vo},t) = 0$

if $S(e_{vo},t) > 0$ and $\frac{dS(e_{vo},t)}{dt} < 0$ then $S(e_{vo},t)$ will decrease

if $S(e_{vo},t) < 0$ and $\frac{dS(e_{vo},t)}{dt} > 0$ then $S(e_{vo},t)$ will increase

Determination of control law:

Switching law can be written as

$$u = +V_{dc} \quad \text{for} \quad S(e_{ish},t) > 0 \tag{24}$$

$$u = -V_{dc} \quad \text{for} \quad S(e_{ish},t) < 0 \tag{25}$$

For higher switching operation, a hysteresis comparator is introduced which modify the switching law as

$$u = +V_{dc} \quad \text{for} \quad S(e_{ish},t) > \varepsilon \tag{26}$$

$$u = -V_{dc} \quad \text{for} \quad S(e_{ish},t) < \varepsilon \tag{27}$$

Simulation results:

It is observed from Fig. 11 that load voltage is maintained constant with respect to reference voltage as shown in Fig.10. In put DC voltage to invester is fluctuating as shown in Fig.7

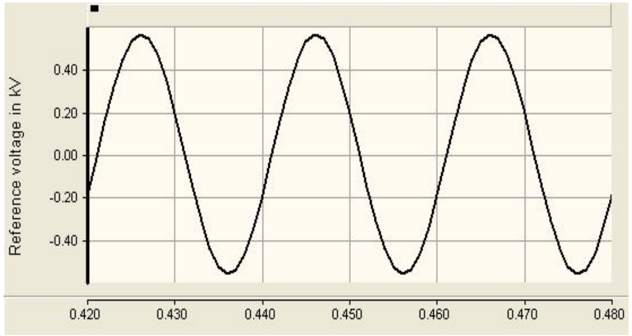

Fig.10 Reference voltage to be tracked in kV

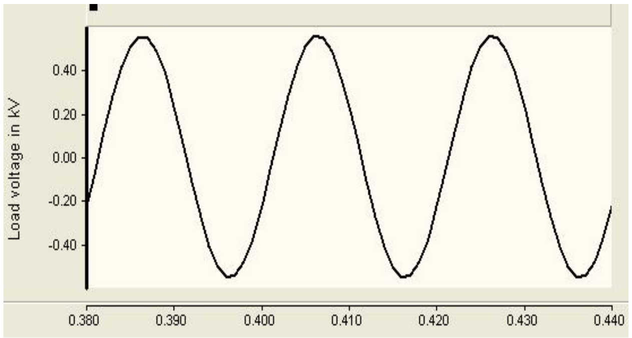

Fig.11 Load voltage with sliding ode control in kV

V. SLIDING MODE CONTROL OF DSTATCOM

The sliding mode control proposed in [7] has been used for the control of grid terminal voltage of the distribution system. In order to design a control law independent of grid and dc bus parameters the following state vector is defined as

$$z^T = \begin{bmatrix} v_t & \dot{v}_t \end{bmatrix} \qquad (28)$$

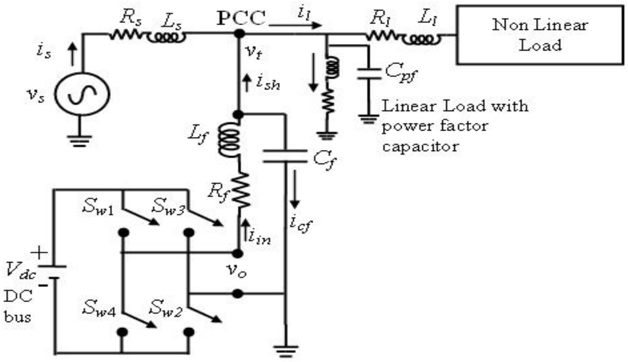

Fig. 12. Single-phase equivalent representation of distribution system showing grid interface of wind generation supported dc

The state variable vt is the terminal voltage and is its derivative. Considering PCC terminal voltage as the output, the state space representation of the system shown in Fig. 12 can be written as

$$\begin{aligned} \dot{z} &= Fz + g_1 u + g_2 d \\ v_t &= h_o z \end{aligned} \qquad (29)$$

where,

$$F = \begin{bmatrix} 0 & 1 \\ -\dfrac{1}{C_f L_f} & -\dfrac{R_f}{L_f} \end{bmatrix}; \; g_1 = \begin{bmatrix} 0 \\ \dfrac{V_{dc}}{C_f L_f} \end{bmatrix}; \; g_2 = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \qquad (30)$$

$$h_o = \begin{bmatrix} 1 & 0 \end{bmatrix}$$

Variable d is considered to be a periodic perturbation that depends upon the shunt current as

$$d = -\frac{1}{C_f}\left(\frac{di_{sh}}{dt}\right) - \left(\frac{R_T}{C_f L_T}\right) i_{sh} \qquad (31)$$

The state vector z(t) is required to track the reference vector $zr_{(t)}$. This reference state vector comprises of the reference for the terminal voltage and its derivative as

$$z_r^T = \begin{bmatrix} v_{tref} & \dot{v}_{tref} \end{bmatrix} \qquad (32)$$

Let us choose a switching surface s_e that is defined by the following control law

$$s_e = K\, z_e = k_1(\dot{v}_{tref} - \dot{v}_t) + k_2(v_{tref} - v_t) \qquad (33)$$

where, K is a feedback gain matrix with two non zero positive gains, k_1 and k_2. If output of the inverter v_o is chosen by the following variable structure control law

$v_o = + V_{dc}$ for $s_e > 0$ (34)
$v_o = - V_{dc}$ for $s_e < 0$ (35)

The system will then operate in the sliding mode and ze in (33) will tend towards the origin. Since the current ic_f through the filter capacitor C_f is the derivative of the grid terminal voltage v_t, the satisfaction of (33), forces the voltage error (v_t - v_{tref}) to decay exponentially to zero as

$$\left(v_{tref} - v_t\right) = A\exp\left(\alpha t\right) \qquad (36)$$

where, A is the initial condition for the voltage error and $\alpha = k_2/k_1$. In order to eliminate the dynamic steady state error (v_t - v_{tref}), the following integral controller is added in (33), leading to a modified sliding mode equation as

$$s_e = k_1(v_{tref} - v_t) + k_2(\dot{v}_{tref} - \dot{v}_t) + k_i \int \left(v_{tref} - v_t\right) dt \qquad (37)$$

where, k_i is the integral gain. In addition to these a resonant controller may also be added as considered in [8], [9] for better tracking characteristics under steady state.

VI. CONTROL STRATEGY OF DSTATCOM

A DSTATCOM is a power electronic converter based device connected in shunt with the distribution system. The control circuit diagram is shown in fig 12. The DSTATCOM injects a current ish into distribution system to cancel out the harmonics components and reactive current of the load current. Active and reactive power transfer between grid and VSI is accomplished by controlling the load angle between two voltages [10]. If output of VSI is in phase with grid terminal voltage and VSI voltage is greater than grid voltage DSTATCOM supplies the reactive power to grid. If VSI voltage is less than the grid voltage, DSTATCOM absorb the reactive power from the grid. By regulating the load angle delta it is possible to control reactive power transfer between DSTATCOM and grid [11]. The reference magnitude of the grid terminal voltage V_{tref} is considered as desired, however the reference phase angle δ of the terminal voltage with respect to the source voltage v_s is considered taking into account of the power flow control through the grid. It has already been established that the DSTATCOM tracks the chosen reference v_{tref}. The active and reactive powers (P and Q) exchange between the PCC and the source are given by the following equations

$$P = \frac{V_S V_t \sin\delta}{X} \tag{38}$$

$$Q = \frac{V_S\left(V_S - V_t \cos\delta\right)}{X} \tag{39}$$

Where, δ is the phase angle between V_s and V_t, and X is the total reactance of the feeder line. The variable V_s and V_t represents the rms values of v_s and v_t. The real power drawn by the load is continuously being monitored from (38). If load demand increases, power transfer to load is increased with corresponding change in phase angle δ. The available wind power is also being monitored from (1). The difference between the two is the reference power P_{ref} to be fed from the source. This reference power is substituted in (38) to obtain the reference phase angle δ on-line. For various values of wind power and reference power, load angle δ is calculated as shown in table II. For starting wind speed of 6 meter per sec, a reference power is generated to calculate the load angle delta as given from (40)

$$3199.84 = \frac{400x400\sin\delta}{8} \tag{40}$$

$$\delta = -9.2$$

For rated speed of 13 meter per sec, load angle delta is calculated from (41)

$$8137 = \frac{400x400\sin\delta}{8} \tag{41}$$

$$\delta = 24$$

The magnitude of desired grid terminal voltage V_{tref}, and δ constitute the net reference as $v_{tref} = V_{tref}\angle\delta$.

VII. SIMULATION RESULTS

Case 1:

Consider the single phase distribution system shown in Fig. 12 The parameters are given in table I and II. In normal operating condition when DSTATCOM is not connected to the grid and, full load is applied to the distribution feeder as shown in fig 14, the terminal voltage is not sinusoidal and reduces significantly from the normal value of 0.4 kV (r.m.s) as shown in Fig 13. This reduces the power delivered to load as well.

Case 2:

In this case DSTATCOM is connected to grid terminal with the same load as shown in Fig 14. Load angle delta increases corresponding to change in wind speed as shown in Fig.16. Wind source generates the max power and grid terminal voltage is maintained constant to 0.4 kV (r.m.s) as shown in Fig. 15. Due to this, the load burden on the main source is reduced and excess power available can be delivered to other feeder.

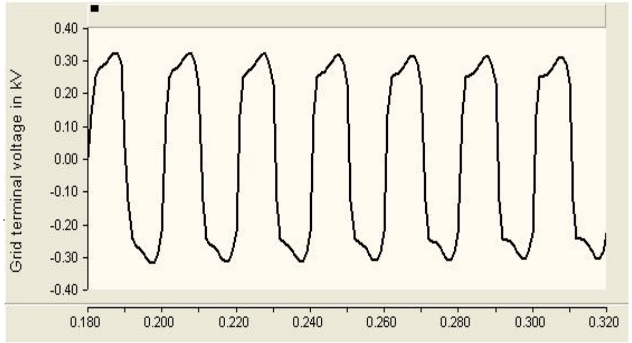

Fig.13 Grid terminal voltage without DSTATCOM

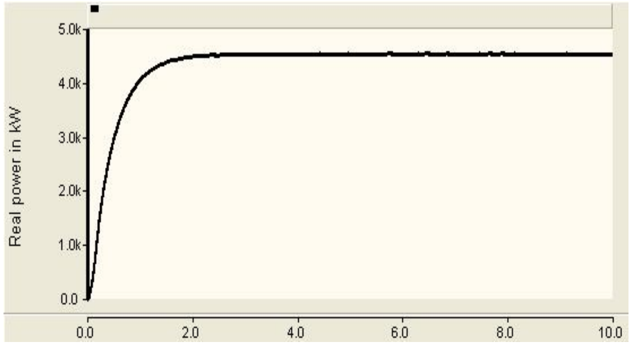

Fig.14 Power consumed at load when DSTSTCOM connected with same load

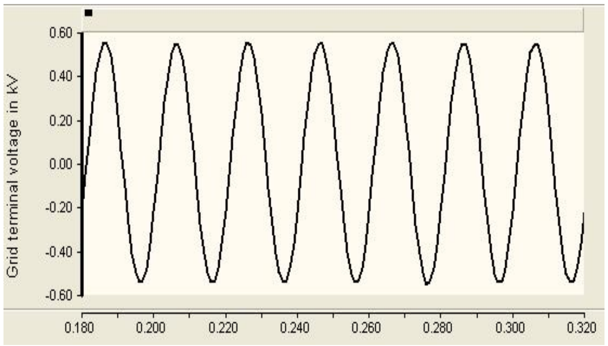

Fig. 15 Grid terminal voltage with DSTATCOM connected and same load

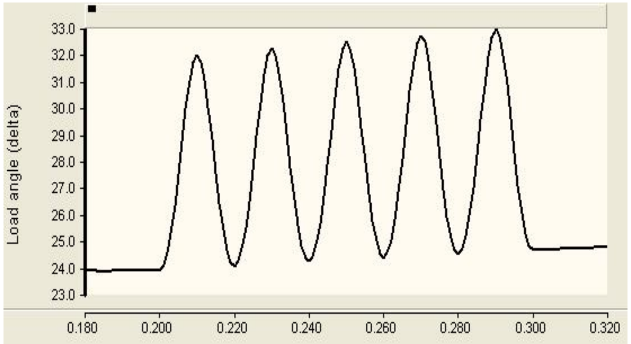

Fig. 16 Variation in load angle when DSTATCOM connected

VIII. CONCLUSION

A wind turbine simulator is designed to emulate wind turbine dynamics for research activities without reliance on natural wind resources. A DSTATCOM is used to regulate the voltage of the terminal bus at a nominal value. The results show that the controller in the sliding mode assures stability, low THD and good performance. The control scheme maintains the power balance at the PCC during load variations.

APPENDIX

Table - I

Wind Turbine Parameters

Symbol	Quantity	Value
R	Rotor radius (m)	2.5
J	Inertia kg.cm^2	.001
P_w	Generator rated MVA	.020
T_w	Turbine rated MVA	.060
W_w	Rated rotating speed (rpm)	300
v_w	Rated wind speed m/sec	13.0
W_m	Max rotating speed (rpm)	500
V_s	Start up wind speed (m/sec)	6
V_{in}	Cut in wind speed (m/sec)	3
V_{off}	Cutoff wind speed (m/sec)	20
T_s	Startup torque (N.m)	15.5

Table - II

Estimation of Wind Power and Load Angle

Wind velocity (m/sec)	Wind power (kW)	Reference power (kW)	Load angle (delta)
6	1236	-3199	-9.2
7	1963	-2463	-7.1
8	2930	-1506	-4.3
9	4172	-264	-.756
10	5723	1287	3.7
11	7617	3181	9.2
12	9889	5453	15.8
13	12573	8137	24
14	15703	11267	34
15	19315	14879	48

Table - III

System Parameter

Parameter	Numerical value
Source voltage (L-G) and frequency	0.400 kV (rms), 50 HZ
Terminal bus voltage	0.400 kV (kV)
Feeder impedance Rs & Ls	(3.9 +j7) ohm
Filter capacitor Cf	77.75 [µF]
Shunt Branch	(1+j 3.14)ohm
DC link capacitor	4400 [µF]

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