Modeling and Analysis of a Dynamic VAR Compensator for Wind Energy Conversion System

S. Vamshi Kumar, P. Raghuvedran, K. Sri Vidya Savithri

Abstract:- In wind energy conversion system voltage control and reactive power compensation is the main problem. This paper presents vector oriented control of three-phase voltage source pulse width modulation (PWM) inverter which aims to control of active and reactive power injected into the grid. A wind driven Induction Generator in Self excited mode feed power to load through a ac-dc-ac converter.

The modulation index of the inverter is adjusted using vector oriented control to enhance the active power export and reduce the reactive power requirement. The scheme is modeled in Matlab/Simulink and simulation is carried out to study the performance at varying wind speed.

Keywords— Self-excited induction generator (SEIG), voltage source inverter (VSI), wind energy conversion system (WECS).

I. INTRODUCTION

Today wind energy is the fastest growing energy source. Wind generation system is attracting attention as a clean and safety renewable power source .Among the renewable sources of energy available today for generation of electrical power wind energy stands foremost. Presently wind power meets the electricity needs of more than 35 million people.

In case of grid-connected system induction generator can get the reactive power from grid/capacitor banks, whereas in case of isolated/autonomous system reactive power can only be supplied by capacitor banks.

In addition, most of the loads are also inductive in nature, therefore, the mismatch in generation and consumption of reactive power can cause serious problem of large voltage fluctuations at generator terminals especially in an isolated system.

The terminal voltage of the system will sag if sufficient reactive power is not provided, whereas surplus reactive power can cause high voltage spikes in the system, which can damage the consumer's equipments or affect their performance. Therefore wind system requires proper control of reactive power to maintain the voltage within specified limits.

Until recently, most wind power plant and utility have utilized capacitor banks to correct power factor to near unity. The capacitors are switched in and out by means of mechanical contractors. Unfortunately, because these contactors are relatively slow, they are unable to react to sudden momentary dips in voltage commonly seen in weak grid and can add greater stress to the utility grid.

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The three phase self excited induction machine can be made to work as a self-excited induction generator provided capacitance should have sufficient charge to provide necessary initial magnetizing current[1]. In an externally driven three phase induction motor, if a three phase capacitor bank is connected across its stator terminals, an EMF is induced in the machine windings due to the self excitation provided by the capacitors. The magnetizing requirement of the machine is supplied by the capacitors. For self excitation to occur, the following two conditions must be satisfied:- i. The rotor should have sufficient residual Magnetism. ii. The three capacitor bank should be of sufficient value [2].

If an appropriate capacitor bank is connected Across the terminals of an externally driven Induction machine and if the rotor has sufficient residual magnetism an EMF is induced in the machine windings due to the excitation provided by the capacitor. The EMF if sufficient would circulate leading currents in the capacitors. The flux produced due to these currents would assist the residual magnetism. This would increase the machine flux and larger EMF will be induced. This in turn increases the currents and the flux. The induced voltage and the current will continue to rise until the VAR supplied by the capacitor is balanced by the VAR demanded by the machine, a condition which is essentially decided by the saturation of the magnetic Circuit.

This process is thus cumulative and the induced voltage keeps on rising until saturation is reached. To start with transient analysis the dynamic modeling of induction motor has been used which further converted into induction generator Magnetizing inductance is the main factor for voltage buildup and stabilization of generated voltage for unloaded and loaded conditions. The dynamic Model of Self Excited Induction Generator is helpful to analyze all characteristic especially dynamic characteristics [3]-[5].

Voltage source inverters have evolved as the most preferred power conversion method for ac drive applications. Voltage source Inverter is selected as the heart of the interfacing system. Three-phase voltage-source AC/DC/AC (PWM\) converters have been increasingly used for many applications such as uninterruptible power supply (UPS) systems, boost converters and wind energy conversion systems. The attractive features of them are constant dc-bus voltage, low harmonic distortion of the utility currents, bidirectional power flow, and controllable power factor [7]-[10].

A conventional proportional and integral (PI) compensator can be applied to the variables in the rotating reference frame so as to achieve a zero steady-state error in response to step commands. Then, variables in the rotating reference frame must be restored in the stationary three-phase reference frame using the inverse– transformation.

A vector current controlled grid connected voltage source inverter (VSI) is proposed as a dynamic VAR compensator System. An analytical model for the VSI connected to the grid and the operating principle of the proposed vector controllers are introduced.

II. SYSTEM DESCRIPTION

The wind energy conversion system considered for study is shown Fig1.The wind turbine driven the Induction generator through gear box and the generator terminals are connected to Excitation capacitance. The power output of the system is fed to load through power conditioning system. This includes Rectifier and Inverter. By controlling the modulation index of the Inverter the reactive power is dynamically controlled for varying wind and load condition.

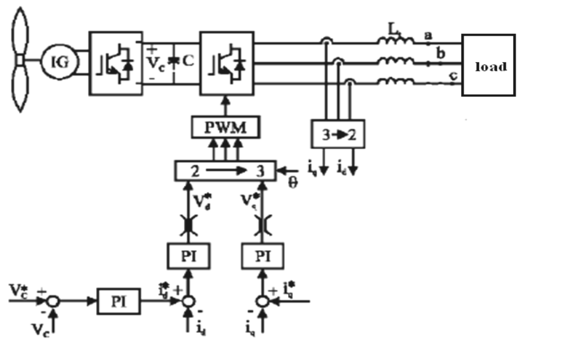

Fig.1 Variable Speed WEG Scheme with Vector Control Inverter.

III. MODELING OF WIND TURBINE

The amount of power capable of being produced by a wind turbine (P_T) is dependent on the power co-efficient (C_P) for the given turbine operating conditions and is given by Eq. (1).

$$P_T = 0.5\, \rho\, A\, c_p(\lambda)\, v^3 \qquad (1)$$

The tip speed ratio is defined as the ratio of the linear speed of the tip of blades to the rotational speed of wind turbine (Allan Mullane et al. 2001) and is given by Eq. (2).

$$\lambda = \frac{\omega_T\ R}{V} \qquad (2)$$

The value of $C_P$changes with rotational speed and wind speed and can be expressed by Eq. (3) and (4).

$$C_p = 0.5\left[\frac{116}{\lambda_1} - 1.4\,\beta - 5\right] e^{\frac{-16.5}{\lambda_1}} \qquad (3)$$

Where

$$\lambda_1 = \frac{1}{\left[\frac{1}{\lambda + 0.089}\right] - \left[\frac{0.035}{\beta^3 + 1}\right]} \qquad (4)$$

β(Deg) is the blade pitch angle. Based on the theory of fluid mechanics, it can be shown that C_P reaches the maximum value of 0.593, referred as the Betz limit. The torque developed by the wind turbine may be expressed as:

$$T_T = \frac{P_T}{\omega_T} \qquad (5)$$

IV. MODELING OF SELF EXCITED NDUCTION GENERATOR

Fig. 2 shows the d q axis equivalent circuit model for a no-load, three-phase, symmetrical induction machine. The per-unit stator and rotor voltage equations using Krause transformation based on stationary reference frame are given in equations from 6 to 13.

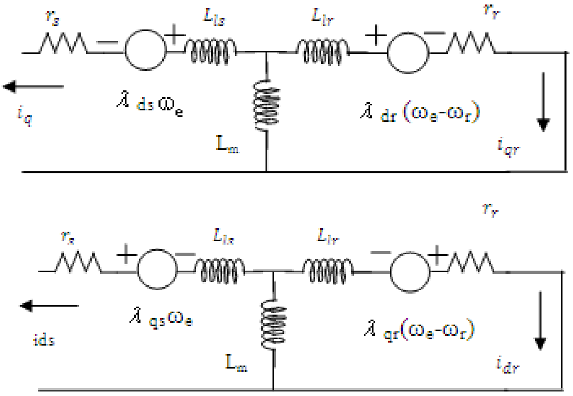

Fig.2 Equivalent Circuit of the Induction Machine in d-q Reference Frame.

The equivalent circuit in the d-q reference frame of the self-excited induction generator is shown in figure 2The loop equations for the d-axis and q-axis equivalent circuits are

$$r_s\, i_{qs} + L_s \frac{d\, i_{qs}}{dt} + L_m \frac{d\, i_{qr}}{dt} = V_{ds}\, \omega_e \qquad (6)$$

$$r_r i_{qr} + L_r \frac{di_{qr}}{dt} + L_m \frac{di_{qr}}{dt} = V_{dr}(\omega_e - \omega_r) \qquad (7)$$

$$r_s\, i_{ds} + L_s \frac{di_{ds}}{dt} + L_m \frac{di_{dr}}{dt} = V_{ds} + V_{qs}\, \omega_e \qquad (8)$$

$$r_r\, i_{ds} + L_r \frac{di_{dr}}{dt} + L_m \frac{di_{ds}}{dt} = V_{qr}\,(\omega_e - \omega_r) \qquad (9)$$

The dynamics of the self-excited induction generator (Krause P. C 1986) can be represented by the following electromechanical equations derived in the synchronously rotating q-d reference frame.

$$p\, i_{qs} = -K_1\, r_s\, i_{qs} - (\omega_e + K_1 L_m\, \omega_r)\, i_{ds} + K_2\, r_r\, i_{qr} - K_1\, L_m\, \omega_r\, i_{dr} \qquad (10)$$

$$p\, i_{ds} = -K_1\, r_s\, i_{ds} + (\omega_e + K_2 L_m\, \omega_r)\, i_{qs} + K_2\, r_r\, i_{dr} + K_1\, L_m\, \omega_r\, i_{qr} - K_1 V_{ds} \qquad (11)$$

$$p\, i_{qr} = K_2\, L_s \omega_r\, i_{ds} + K_2 r_r i_{ds} + (K_1 L_s \omega_r - \omega_e) i_{dr} - \left[\frac{r_r + K_2 L_m r_r}{L_r}\right] i_{qr} \qquad (12)$$

$$p\, i_{dr} = -K_2\, L_s \omega_r\, i_{qs} + K_2 r_s i_{ds} - (K_1 L_s \omega_r - \omega_e) i_{qr} - \left[\frac{r_r + K_2 L_m r_r}{L_r}\right] i_{dr} + K_2 V_{ds} \qquad (13)$$

Where $K_1 = \frac{L_r}{(L_s\ L_r - L_m^2)}$ and $K_2 = \frac{L_m}{L_s\ L_r - L_m^2}$

Equations (6)-(13) are derived assuming that the d-axis is aligned with the stator terminal voltage pharos (i.e., V_{qs}=0). In self-excited induction generators, the magnitude of the generated air-gap voltage in the steady state equation is given by

$$V_g = \omega_e L_m |i_m| \qquad (14)$$

Where

$$|i_m| = \sqrt{(i_{qs} + i_{qr})^2 + (i_{ds} + i_{dr})^2}$$

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The magnetizing inductance L_m is a function of the magnetizing current i_m is given as

$$L_m = f(|i_m|) \quad (15)$$

The relationship between L_m and i_m is obtained by using synchronous speed test and described by a set of linear piecewise approximate equation as below (Li Wang and Jian-Yi Su, 1999).

L_m = 1.41566 / (i_m + 0.1317   0.3578 < i_m
= 1.59267/ (i_m + 0.1929)   0.3075< i_m ≤ 0.3578
= 1.79031/ (i_m+0.255)   0.2188<i_m ≤ 0.3075
= 2. 67838 / (i_m+ 0.49)   0.1081< i_m ≤ 0.2188
= 3.997 i_m ≤ 0.1801
(16)

V. MODELING OF VECTOR CONTROL INVERTER

The power circuit of three-phase VSI is shown in Figure 3.

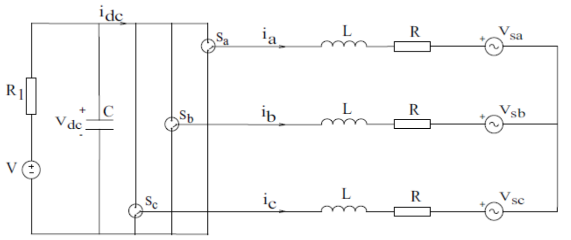

Figure .3 VSI power topology

The dc and ac side equivalent circuits of the VSI are depicted in Figure 4

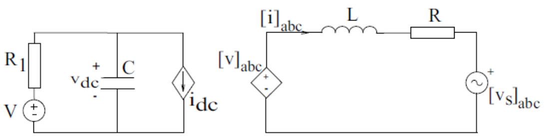

Figure .4 Equivalent circuit of the VSI

Mathematical model of the equivalent circuit is given by:

$$C\frac{dV_{dc}}{dt} + i_{dc} = \frac{V - V_{dc}}{R_1}$$

$$L\frac{d[i]_{abc}}{dt} + Ri = \Delta[v]_{abc} \quad (17)$$

$$i_a + i_b + i_c = 0$$

$$\Delta\,[v]_{abc} = [v]_{abc} - [v_s]_{abc} \quad (18)$$

To the current $[i]_{abc}$ we have:

$$i_d = \frac{2}{3}[i_a cos\omega_1 t + i_b \cos(\omega_1 t - 120°) + i_c\cos(\omega_1 t + 120°) \quad (19)$$

$$i_q = \frac{2}{3}[i_a sin\omega_1 t + i_b \sin(\omega_1 t - 120°) + i_c\sin(\omega_1 t + 120°) \quad (20)$$

And similarly to the voltage $[V]_{abc}$ we have:

$$v_d = \frac{2}{3}[\Delta v_a cos\omega_1 t + \Delta v_b \cos(\omega_1 t - 120°) + \Delta v_c \cos(\omega_1 t + 120°) \quad (21)$$

$$\Delta v_q = \frac{2}{3}[\Delta v_a cos\omega_1 t + \Delta v_b \cos(\omega_1 t - 120°) + \Delta v_c\cos(\omega_1 t + 120°) \quad (22)$$

The instantaneous power in a three-phase system is given by:

$$P(t) = V_A i_A + V_B i_B + V_C i_C = \begin{bmatrix} V_A & V_B & V_C \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} \quad (23)$$

Using the transformation matrix and substituting the voltage and current vectors from (19-22) into (23) results in:

$$P = \frac{3}{2}(V_d i_d + V_q i_q) \quad (24)$$

The orientation of the rotating reference frame is done along the supply voltage vector to obtain a decoupled control of the active and reactive power. V_q=0 and V_d=|V|, so the equation of active power can be simplified in the rotating reference frame as:

$$P = \frac{3}{2}|V|i_d \quad (25)$$

In a similar way, the equation of reactive power in the rotating reference frame can be calculated as:

$$Q = -\frac{3}{2}|V|i_q \quad (26)$$

VI. PROPOSED CONTROL SYSTEM

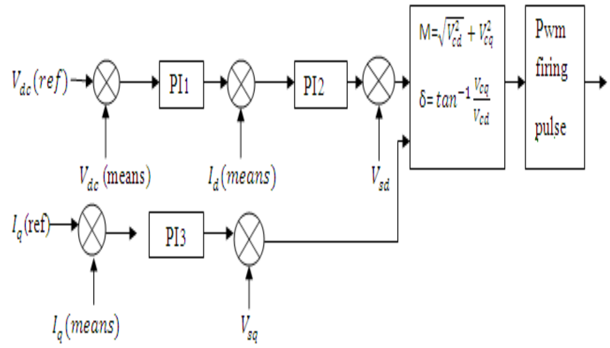

Figure 5. control system

The proposed control system block showed in Fig 5. Using PLL the system frequency is measured. The unit matrix (***θ***) is calculated from frequency.

θ= ω.t= 2πf.t

This angle is used for transforming three phase quantity to two phase stationary reference (αβ frame) frame. Further it is transformed to synchronous rotating frame (d-q frame).From the equation 24 and 25 using i_d and i_q currents individually controlling active and reactive power in the system.

VII. SIMULATION RESULTS

The wind energy conversion system is simulated with the parameter given in appendix. The system response is studied for different wind velocity and results are discussed below.

A. wind turbine characteristic:

Fig.7 shows the power characteristic of the wind turbine for varying rotational speeds at different wind velocities. It shows that the turbine output is250Kw at the rated wind velocity of 15m/s and turbine speed of 40rpm.The power output increase with increase speed and reaches the maximum at different speeds for different wind velocity.

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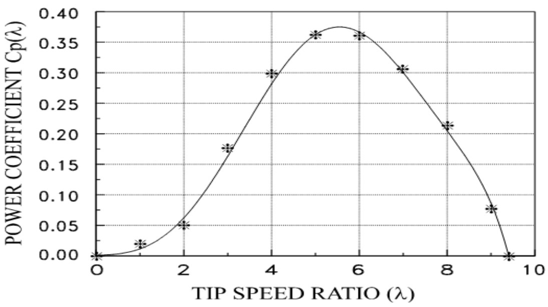

Fig.6 Power Coefficient as a function of Tip Speed Ratio .

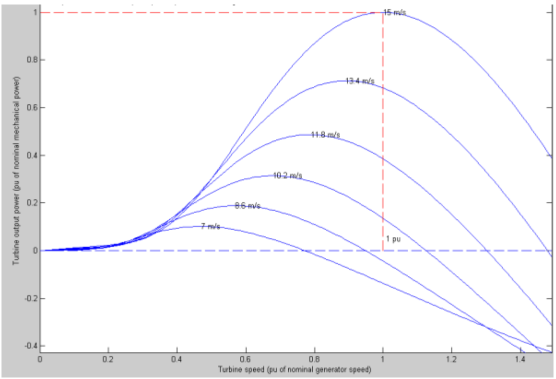

Fig.7 Turbine power characteristics

B. Self excited induction generator:

The dynamic model of the self-excited induction Generator represented by eq 6-10 and simulated using Matlab/ Simulink to study the dynamic performance of the machine. Fig. 8. Shows the self-excitation process is initiated at t = 0s without any load at the stator terminals. It is observed that the voltage build-up reaches the steady state at t = 10 s.

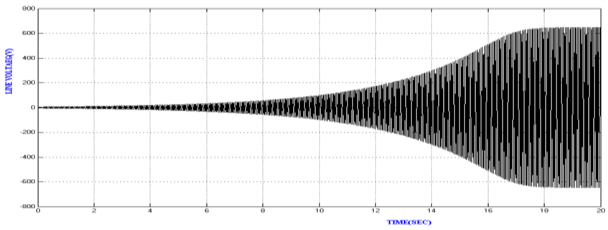

Fig.8 Dynamic response of the induction generator during voltage build-up process at no load

The performance of the generator for varying load resistances at the minimum excitation capacitance is analyzed at the rated wind velocity and the respective generated voltage, current and speed waveforms are obtained as shown in figure 9 .

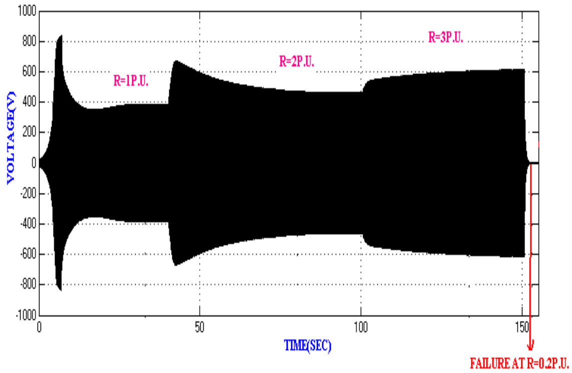

Fig.9 Generated voltage waveform for various loading conditions at minimum Excitation capacitance

The Response of the Inverter without using controller shown in fig 10.The Angle between Voltage and Current is 66.6°.The Response of Inverter with Controller shown in Fig 11.The Angle between Voltage and Current is 30.6° at Rated wind Velocity. It is found that the controller reduce the reactive power requirement by 50% for different wind velocities.

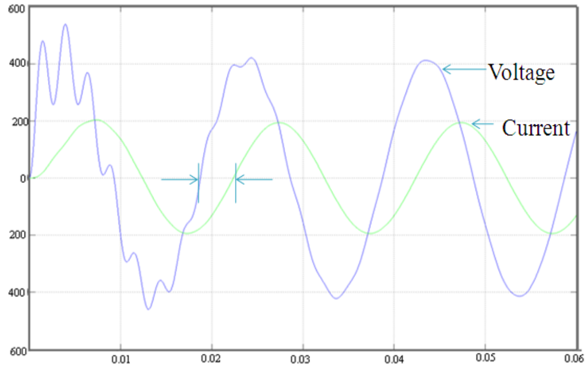

Fig.10 Voltage and Current wave form at Rated wind velocity using without controller

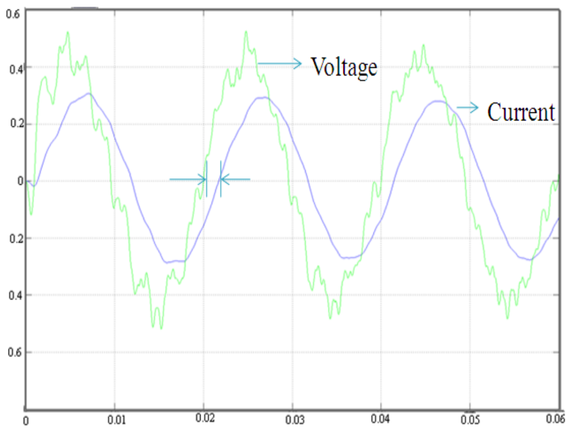

Fig.11 Voltage and Current wave form at Rated wind velocity using with controller

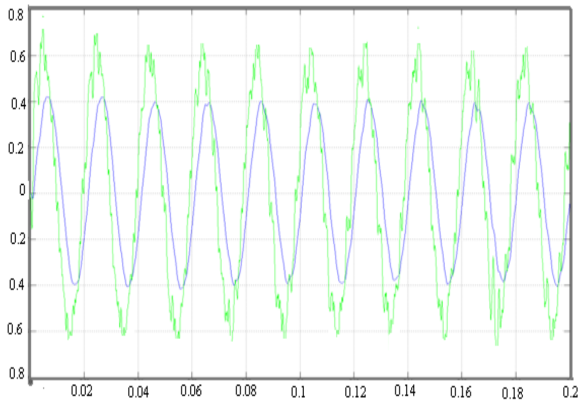

Fig.12 Voltage and Current wave form at Rated wind velocity using with controller (Full Cycle)

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Table.1 comparison of Active power

Vw	Active power	
	Without controller	With controller
11	0.46	0.38
12	0.51	0.43
13	0.54	0.5
14	0.57	0.56
15	0.66	0.64
16	0.68	0.67

Table.2 comparison of Reactive power

Vw	Rective power	
	Without controller	With controller
11	0.37	0.23
12	0.41	0.25
13	0.46	0.27
14	0.49	0.28
15	0.51	0.21
16	0.68	0.22

VIII. CONCLUSION

In this paper the dynamic mathematical model of the wind energy conversion system has been derived. The vector oriented control voltage source inverter has been investigated for high performance control operation. All results obtained confirm the effectiveness of the proposed control system for the SEIG feeding Three-phase bridge rectifiers and connected to load through VOC VSI.

APPENDIX

A. Wind Turbine

Rated power	250KW
No. of blades	6
Rated speed	40rpm
Rotor diameter	29.8mm
Blade pitch angle	-1.1
Gear ratio	1:24.52
Rated wind speed	15m/s

B. Induction Generator

Rated power	250kw
Rated line voltage	415V
Rated current	360A
Rated speed	1018rpm
No. of blades	6

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