Space Vector PWM based Two Level Inverter Topology for WECS

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Abstract— There has been a rapid growth in the field of wind energy system for past 12 years. The energy from wind has less pollution and resource is inexhaustible. The steady growth of wind energy pushed the research and development of power converters toward full-scale power conversion. The global electrical energy consumption is rising every day and there is a steady demand to increase the power capacity. This paper is on wind energy conversion systems with full power converter using sine and space vector PWM. The wind energy conversion system mainly consists of a wind turbine, electric generator, power converter and a suitable controller. In this paper simulation of topology and control methods for wind energy conversion system is proposed. Here fractional-order control strategy based PI controller is used for WECS. A two level converter topology is selected. Simulation studies and results should help to adequately assessing the quality of the power injected into the electrical grid

Keywords - Fractional PI Controller, Permanent Magnet Synchronous Generator, Space Vector Pulse Width Modulation, Wind Energy Conversion System

I. INTRODUCTION

The wind energy conversion system mainly consists of a wind turbine, electric generator, power converter and a suitable controller. There are two types of wind turbine generators, fixed speed and variable speed. One of the major problem with fixed speed turbine operation is that the maximum coefficient of performance is obtained only at a particular speed of wind turbine. In earlier days wind turbine in conjunction with induction generators are commonly used for WECS. The major problem with such generators are low efficiency, poor power quality and high mechanical stress. But for large wind farms the best suited option is a variable speed wind turbine with a multipole PMSG. PMSG has low maintenance less losses due to gear less construction. The lack of wind turbine sites on lands due to increased population, offshore is an alternative. Wind energy become a viable source of clean energy. In rural areas, such as residences away from grid, small wind turbine have a great potential to supply electricity. The output power from a wind turbine varies with the wind speed. For any applications, it must provide a fixed frequency, fixed voltage supply. Therefore it is necessary to extract maximum power from the wind turbine at any instant of time. Wind power can be controlled mechanically by changing the pitch angle. But this strategy is not viable for small wind turbines. The most new development in wind turbine technology is because of the developments of power electronic equipment. The development of power electronic equipment with better power handling capability and cost/kW encourages the manufacturers to employ sophisticated power electronic equipment. In fact, power electronics is the basis for most new developments in wind turbines. Figure 1 shows the configuration of a simple wind energy conversion system. A WECS simply consists of blades, a generator, a power electronic converter, and power grid.

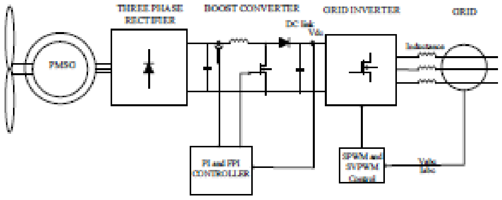


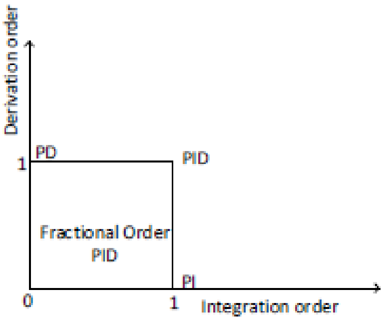
Fig 1.1 Wind energy conversion system

II. CONVENTIONAL TOPOLOGY

The power flow in a wind energy conversion system is unidirectional and from the wind turbine to the grid. A three phase Diode bridge rectifier [6] is used in the generator side to convert the AC power to DC power. A Boost regulator is used to increase the level of dc voltage obtained from the rectifier. In process control and industrial applications PID controllers are used widely. The significance of using PID controllers are its simplicity of design and good performance.ie small settling time and low percentage overshoot. In PI control method, the optimum value of KP and Ki is obtained by any of the tuning methods or by trial and error method.

III.PROPOSED TOPOLOGY

A. Fractional order controller strategy To achieve better performance integral and derivative actions are implemented using fractional calculus. Most of the controllers uses integer order models because of the absence of solution methods for fractional order differential equations. The fractional order PID is a generalised form of integer order PID controller. Also it moves representation on a point to a plane. This will creates more flexibility and accuracy for the controller design.



Fractional PID representation

In fractional order calculus, instead of integers, the order of differential equation is fractional values. In general an n-term fractional order differential equation is given by

$$a_n D^{\alpha_n} y(t) + a_{n-1} D^{\alpha_{n-1}} y(t) + \cdots a_1 D^{\alpha_1} y(t) + a_0 D^{\alpha_0} y(t) = b_m D^{\beta_m} u(t) + b_1 D^{\beta_1} u(t) + b_0 D^{\beta_0} u(t) \qquad (1)$$

Here $D^{\alpha} = {}_0D_t^{\alpha}$ is Caputo fractional derivative of order α_k;k=1,2,3….n and $\beta_l (l = 0,1,2,3 \ldots\ldots m)$ are arbitrary constants.

We can assume that 0=$\alpha_0 < \alpha_1 < \alpha_2 \ldots . < \alpha_n$ and $\beta_0 < \beta_1 < \beta_2 \ldots . < \beta_n$

Definition for Caputo fractional derivative is given as

$$ {}_aD_t^{\alpha} f(t) = \frac{1}{\Gamma(n-\alpha)} \int_a^t \frac{f^n(\tau)}{(t-\tau)^{\alpha-n+1}} d\tau \qquad (2)$$

$$(n-1) \leq \alpha < n$$

${}_aD_t^{\alpha}$ is a differintergal operator, which represents differ integration of operation f the order α at time t. The function f(t) has history from time a to t.n is integer and not α necessarily an integer. The Laplace transform of the fractional-order derivative,$D^{\alpha} y(t)$; $0 < \alpha \leq 1$ is given by

$$\int_0^{\infty} D^{\alpha} y(t) e^{-st} dt = s^{\alpha} Y(S) - \sum_{k=0}^{N} s^{\alpha-k-1} y^{(k)}(0) \qquad (3)$$

Similarly the Fractional Integrals [6] of y is expressed as ${}_0J_t^{-\alpha} y(t)$

The transfer function of Fractional-order system with zero initial conditions is given as

$$G_p(s) = \frac{b_m s^{\beta_m} + b_{m-1} s^{\beta_{m-1}} + \cdots + b_1 s^{\beta_1} + b_0 s^{\beta_0}}{a_n s^{\alpha_n} + a_{n-1} s^{\alpha_{n-1}} + \cdots + a_1 s^{\alpha_1} + a_0 s^{\alpha_0}} \qquad (4)$$

The fractional order PID Controller is of the form

$$G_c(s) = K_p + \frac{K_i}{s^{\lambda}} + K_d s^{\mu} \qquad (5)$$

There are five parameters to be tuned to obtain the optimum required results. This will increase the flexibility of the controller. But the complexity is more. Three parameters can be tuned to achieve the desired results such as steady state performance and robustness. The parameters can be chose either using trial and error method or with help of optimisation toolbox in MATLAB. The Fractional PID controller is generally represented as$PI^{\lambda}D^{\mu}$. The parameters that can tune are K_p, K_i , K_d , λ and µ.FOMCON toolbox in MATLAB is used for model identification. Generally ode15s or ode23tb is used for solving simulation containing fractional blocks. This should ensure high efficiency and accuracy.

In this particular paper only PI^{λ} controller is used. The differential equation is given as

$u(t)=K_p e(t)+K_i D_t^{-\lambda} e(t)$ (6)

For example the transfer function of Fractional order PI^{λ} controller for a value of λ=0.6 is given as

$G(s)=K_p+K_i s^{-0.6}$ (7)

The tuning of parameter for this paper is done by trial and error method.

B. Boost converter model

The integral part of Boost converter design is to choose proper values of an inductor (L) and Capacitor (C) because the output voltage depends on the L and C values. The inductor and capacitor also play a major role in filtering the output from the circuit to provide stiff DC. In order that the boost converter operates in CCM, optimum values of inductor and capacitor must be chosen because if their values are higher, then the cost of winding, core size will also be high. If their values are low, then the high switching frequency is needed to obtain the same voltage level. This increases the cost of the switch involved. Therefore it is necessary to choose optimum values of L and C.

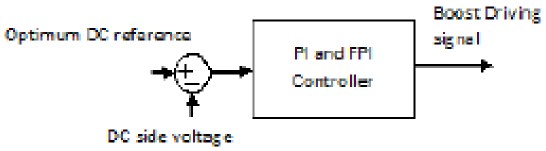


Fig 2.Controlling DC-side voltage using a PI Controller

IV.MODELLING OF WECS AND PMSG

Wind turbine and a direct driven PMSG are connected together. The kinetic energy of wind is converted to mechanical energy by the wind turbine. The characteristic of wind turbine can be described by the relation

$$P_w = \frac{1}{2} \rho C_p A v_{wind}^3 \qquad (8)$$

Where

P_w= total power in the wind

ρ =Air density in kg/m^3

A =swept area in m^2

$A = \pi R^2$,R is the rotor radius in meters

v_{wind}=Wind speed of the turbine in m/s

Normally a part of the kinetic energy of wind is converted to mechanical power, which is given as

$$P_m = C_p P_w \qquad (9)$$

Where

P_m=mechanical power of wind turbine in Nm/s

C_p=Power coefficient of the turbine

A German physicist Albert Betz concluded in 1919 that no wind turbine can convert more than 59.3% of the kinetic energy of the wind into mechanical energy turning a rotor. This is known as the Betz Limit. The theoretical maximum power efficiency of any design of wind turbine is 0.59. This is called the "power coefficient". The power coefficient depends on the aero dynamic characteristics of the blades. The value of C_p is taken as 0.59.This is also called as Betz • fs limit. C_p also be expressed in terms of pitch angle(β) and tip speed ratio(λ)

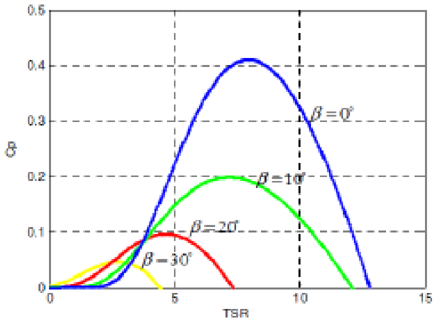


Figure 3.Power coefficient versus tip-speed ratio

The torque developed can be calculated as

$$T_m = \frac{P_m}{w_{turbine}} \qquad (10)$$

also

$$P_m = f(w_{turbine} v_{wind}) \qquad (11)$$

Tip speed ratio λ is defined as

$$\lambda = \frac{w_{turbine} R}{v_{wind}} \qquad (12)$$

If the wind speed is constant tip-speed ratio will vary proportionally to the speed of wind turbine rotor. The highest value of Cp is typically obtained for the λ values 8 to 9.Which means that when the tip of the blades moves 8 to 9 times faster than incoming wind speed[3]. Recently in wind turbines, it is possible to adjust the pitch angle of the entire blade through servo controllers. If Cp - λ curve is known for specific wind turbine with a turbine rotor radius R, it is easy to plot the curve of Cp against rotational speed for any wind speed.

C. Power and torque analysis of a PMSG

For any PMSM, the electrical power input can be expressed in the abc reference [5] frame as follows:

$$P_{abc} = v_{as} i_{as} + v_{bs} i_{bs} + v_{cs} i_{cs} \qquad (13)$$

or in the dq-axes reference frame as follows:

$$P_{dq} = \frac{3}{2}\left(v_{ds} i_{ds} + v_{qs} i_{qs}\right) \qquad (14)$$

As a part of the input power, in the motoring mode, the active power is the power that is transformed to mechanical power by the machine, which can be expressed as follows[3]:

$$P_{em} = \frac{3}{2} w_e \left(\lambda_d i_{qs} - \lambda_q i_{ds}\right) \qquad (15)$$

Hence, the electromagnetic torque developed by a PMSM can be deduced as follows:

$$T_e = \frac{P_{em}}{w_e / \frac{p}{2}} = \frac{3}{2}\left(\frac{p}{2}\right)\left(\lambda_d i_{qs} - \lambda_q i_{ds}\right) \qquad (16)$$

Also can be written as

$$T_e = \frac{3}{2}\left(\frac{p}{2}\right)\left(\lambda_r i_{qs} + (L_d - L_d) i_{qs} i_{ds}\right) \qquad (17)$$

Where$p$, is the number of poles of the machine.

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V.GRID SIDE CONTROL METHOD

In direct-drive PMSG wind turbine systems, grid-connected converters play an important role in transforming the DC power to AC power. As introduced earlier, there are three system variables that need to be strictly controlled. Namely, these variables are the speed of the PMSG, the DC bus voltage, and the complex power (active and reactive power) injected into the grid. As the generator-side converter controls the speed of the PMSG, the grid-side converter regulates the DC bus voltage while controlling the active power and reactive power injected into the grid. In this chapter, the control approach for the grid-side converter is analysed. This converter is assumed to be operating on the basis of the principle of the space vector pulse width modulation (SVPWM), which will be elaborated on here. Sine PWM based inverter strategy is also simulated for entire WECS. The results are compared. Furthermore, the simulation results will be obtained and given here to validate the proposed control strategy.

A. Space vector PWM

Space vector PWM is an advanced method which widely used in power electronics applications. The DC bus utilisation is enhanced here, in linear modulation range. Many algorithms are used to implement SVPWM technique for the inverter. Each modulation technique is try to lower the switching losses, harmonic content and improve the bus utilisation. The performance of a SVPWM scheme can easily be judged by knowing the maximum output voltage and THD of output voltage.

A three phase voltage can be represented by a vector, which rotates at an angular speed of $\omega = 2\pi f$.The vector is called reference vector V_{ref}. This logic is used in SVPWM. So the concept of SVM is to generate the vref by properly choosing the different combinations of switching states. There are eight switching states for a two level inverter.

Voltage source inverter (VSI) are widely used to generate variable frequency, variable voltage, three phase voltages. Here each leg of the inverter is a Single Pole Double-Through (SPDT) switch. Every terminal of the motor or grid is connected to the one of the inverter legs. So it is connected either to the positive DC bus or negative DC bus. The pole voltages are measured with respect to the DC bus point marked as (O).That is$\mp 0.5Vdc$. As every phase can be connected either the positive or the negative bus, the three phases together can have 23 or 8 switching states.

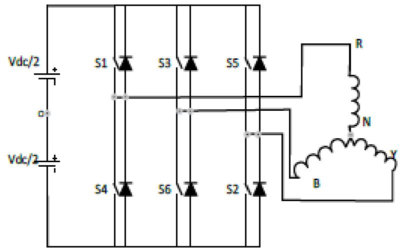

Figure4.Two Level VSI

Here there are six active states and two zero states. In case of the states --- (0) and +++ (7),all the three poles are connected to same bus, results in shorting of the load .There is no transfer of power from source to load .Hence it is “zero states”. But in case of other six states, Power is transferred from source to load. Hence these states are known as “active states”SVM refers to a special way of selecting the switch sequence and the space vectors. The six active vectors form the axes of a hexagon. The angle between two adjacent non zero vector is 60 degrees.

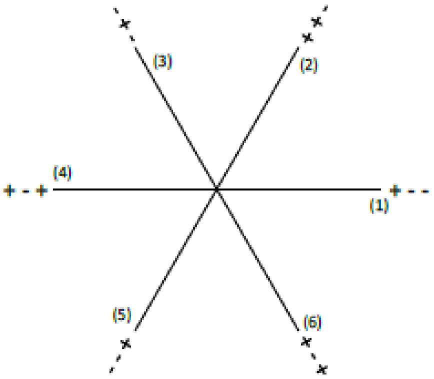

Figure5. Inverter states and voltage vectors

B. Space vector transformation of 3phase voltages

The two phase voltages V_α, V_β can be expressed as

$$V_\alpha = V_{RN} + V_{YN}\cos 120^0 + V_{BN}\cos 240^0 = \frac{3}{2}V_{RN} \tag{18}$$

$$V_\beta = V_{YN}\cos 30^0 + V_{BN}\cos 150^0 = \frac{\sqrt{3}}{2}(V_{YN} - V_{BN}) \tag{19}$$

For balanced star connected load, $V_{RN} + V_{YN} + V_{BN} = 0$
Three phase quantities sum up to zero. Hence can be represent by only two independent quantities.

Here pole voltages,

$$V_{RO} = \pm 0.5V_{DC}, V_{YO} = \pm 0.5V_{DC}, V_{BO} = \pm 0.5V_{DC}$$

$$V_\alpha = \frac{3}{2}V_{RN} = \frac{1}{2}(V_{RY} - V_{BR}) \tag{20}$$

$$= \frac{1}{2}(2V_{RO} - V_{YO} - V_{BO}) \tag{21}$$

$$V_\beta = \frac{\sqrt{3}}{2}(V_{YN} - V_{BN}) = \frac{\sqrt{3}}{2}(V_{YO} - V_{BO}) \tag{22}$$

For the eight inverter states, by knowing the values of V_{RO},V_{YO},V_{BO} it is easier to calculate V_α *and* V_β.Here(SVPWM) revolving voltage vector is taken as reference vector where as in sine triangle PWM sine wave is taken as reference.

C. Average Voltage vector over a sub cycle

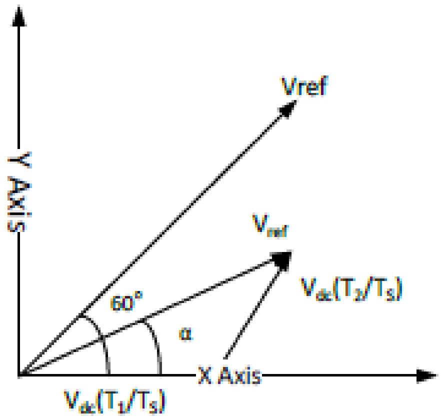

Figure6.Reference vector in sector1

By applying volt second balance

$$V_{ref}T_s = V_1T_1 + V_2T_2 + V_ZT_Z \tag{23}$$

Here $T_s$is the sub cycle time interval [8].Normally equivalent to 15^0.T_1, T_2, T_Z be the time periods for which V_1, V_2, V_0 are applied.

$$V_{ref} = V_1\left(\frac{T_1}{T_S}\right) + V_2\left(\frac{T_2}{T_S}\right) \tag{24}$$

$V_1 = V_{DC} < 0^0$ And $V_2 = V_{DC} < 60^0$

Dwell times can be calculated as follows

$$V_{ref}T_s = V_1T_1 + V_2T_2 + V_ZT_Z \tag{25}$$

Decomposing along α-β axes

$$T_S = T_1 + T_2 + T_Z \tag{26}$$

$$T_1 = \frac{V_{ref} * \sin(60-\alpha)}{V_{DC} * \sin 60}T_S \tag{27}$$

$$T_2 = \frac{V_{ref} * \sin\alpha}{V_{DC} * \sin 60^0}T_S \tag{28}$$

$$T_Z = T_S - T_1 - T_2 \tag{29}$$

D. Conventional SVPWM

The sinusoidal pulse width modulation (SPWM) approach and the space vector pulse width modulation (SVPWM) approach are two of the most commonly used modulation methods for such VSIs. In the SPWM approach, three sinusoidal modulation signals are compared with a triangular carrier signal to generate the PWM pulses. Compared to the SVPWM approach [3], the SPWM approach possesses the merits that it requires less computation effort and is easier to implement. However, the SPWM approach also has the drawbacks that it generates more harmonics in the AC outputs and requires higher DC bus voltage than that of the SVPWM approach to generate the same ac side voltage magnitudes. In the SVPWM approach [3], the reference signals are modified according to the operating conditions of the system in every sampling period, which can greatly improve the power quality of the AC outputs, that is, lower harmonic distortion. This section will present the principles and implementation of the SVPWM approach.

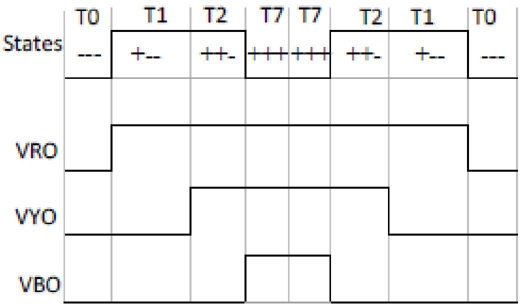

Figure7. Pole voltage during switching interval in sector 1

E. Implementation of the SVPWM

The objective of the SVPWM method is to generate the reference voltage vector, V_{ref} by properly turning the power switches of the VSI "ON" or "OFF". Here considering sampling time, T_x is small enough such that the reference voltage space vector can be regarded as constant during the sampling time. Thus, the reference voltage space vector, V_{ref}, can be synthesized by its adjacent active space vectors and zero space vectors. Based on the analysis above, when given the reference voltages, the process of implementing the SVPWM approach can be divided into the following steps:

1. Determination of the amplitude of the reference voltage space vector and its angle.ie generation of reference vector.
2. Determine the sector in which the reference vector is laying at each instant of time.
3. Calculate the dwell times corresponding to three switching vectors.
4. Switch the devices based on the above conditions.

VI.SIMULATION RESULTS

The entire WECS is modelled in MATLAB/Simulink. This paragraph includes the simulated results and MATLAB model under variable wind speeds. From the waveforms obtained for fractional PI controller based boost output it can be seen that the settling time is reduced as the value of λ changes from 0 to 1.This will very effective for very large interconnected systems.

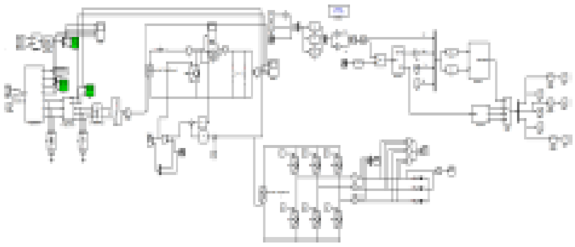

Figure 8.Overall WECS with machine side and grid side converter(SVPWM)

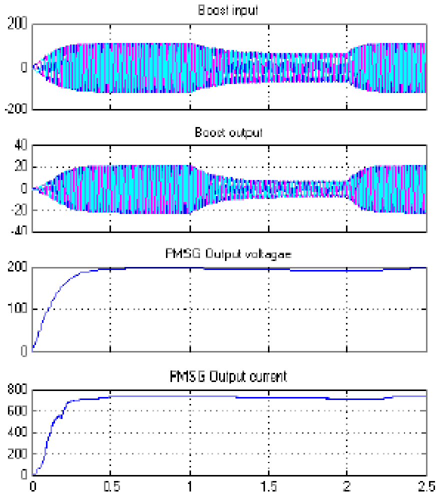

Figure 9. WECS various waveforms for varying wind speed

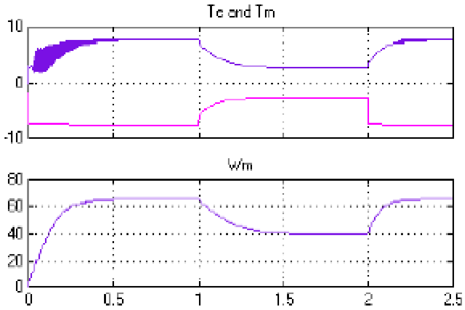

Figure 10. Torque, generator speed for varying wind speed

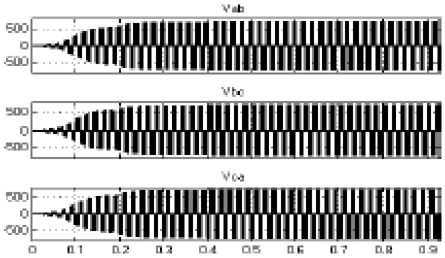

Figure 11.Space vector PWM Inverter output voltages with PI Controller at Boost side

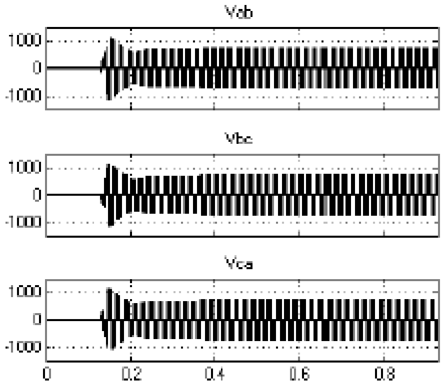

Figure 12.Space vector PWM Inverter output voltages with FPI Controller at Boost side

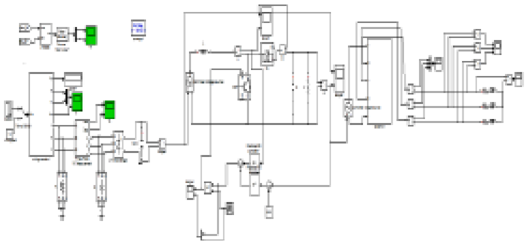

Figure 13.Overall WECS with machine side and grid side converter(SPWM)

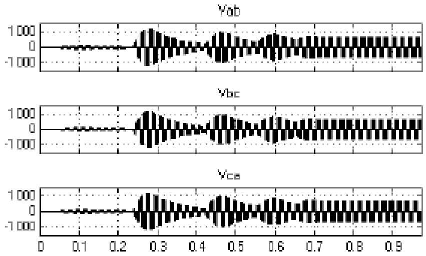

Figure 14.Sinusoidal PWM Inverter output voltages with PI Controller at Boost side

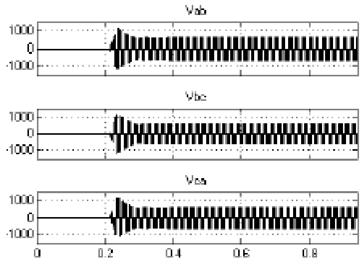

Figure 15.Sinusoidal PWM Inverter output voltages with FPI Controller at Boost side

Table I. Comparison of Line voltage THD values of inverter output for 1st 8 cycles

Modulation Index	Parameters	Sine PWM	Space Vector PWM
0.4	THD	0.003098	0.001339
	RMS value(Va)	41.44	56.12
0.5	THD	0.002088	0.001306
	RMS value(Va)	52.8	70.05
0.6	THD	0.002416	0.001137
	RMS value(Va)	62.55	84.38
0.7	THD	0.00219	0.001425
	RMS value(Va)	73.71	98.88
0.75	THD	0.002091	0.001507
	RMS value(Va)	78.73	105.6
0.8	THD	0.002254	0.002118
	RMS value(Va)	83.46	113
0.85	THD	0.002852	0.001186
	RMS value(Va)	89.37	119.8

VII.CONCLUSION

Wind energy system with PI and fractional order PI controller is modelled. The wave forms obtained for variable speed of operation evaluates the accuracy of model. Under varying wind speed, the controller is capable to provide a constant DC at inverter input. The result obtained from simulation shows that, there is a reduction in the settling time while using fractional PI controller. Also there is one more variable to fine tune the boost output. The THD level for SVPWM based inverter is reduced compared to sine PWM inverter. The DC bus voltage utilization is improved in SVPWM based inverter. MPPT technique can also implemented on the entire WECS. The effective shardware implementation of Fractional order controller is one of the future scope.

APPENDIX

TABLE II

PARAMETERS OF TURBINE

Parameter	Value
ρ, air density	1.08 kg/m3
A area swept by the blades	31.98 m2
v, base wind speed	6m/s

TABLE III

PARAMETERS OF SYNCHRONOUS GENERATORS

Parameter	Value
Pr Rated Power	1.6 kW
Ld Stator d-axis inductance	0.01H
Lq Stator q-axis inductance	0.01H
R rotor resistance	0.425Ω
Pn Pole pairs	5

RFERENCES

[1] R. Melício, V.M.F. Mendes and J.P.S. Catalão“Modelling and Simulation of a Wind Energy System with Fractional Controllers” International Conference on Renewable Energies and Power Quality (ICREPQ’10) Granada (Spain), 23th to 25th March, 2010

[2] I.Podlubny.”Fractional–order sytems and PI-lamda-D-mu-controllers”,IEEE Transactions on Automatic control,volume44,pp..208-214,(1999)

[3] M Kubeitari,A Alhusayn,M Alnahar “Space vector PWM simulation for three phase DC/AC inverter”World academy of science,Engineering and technology,Issue 70,2012

[3] Haque, M.E., Negnevitsky, M. and Muttaqi, K.M.,“A novel control strategy for a variable-speed wind turbine with a permanent-magnet synchronous generator,” IEEE Transactions on Industry Applications, , vol. 46, no. 1, pp. 331-339, Jan/Feb. 2010

[4] T. Ahmed, K. Nishida, M. Nakaoka, "Advanced control of PWM converter with variable-speed induction generator", IEEE Transactions on Industry Applications,Volume 42, pp. 934-945, (2006).

[5] Y. Errami, M. Ouassaid “Modelling and control stratergy of PMSG Based variable speed Wind energy conversion system”,IEEE Transactions on Energy conversion

[6] A. Biswas. S. Das. A. Abraham. S. Dasgupta.”Design of fractional-order $PI\lambda D$μ Controllers with an improved differential evolution, Eng.Appli.Artif.Intell22 (2009) 343-350.Elsevier

[6] Jiacheng Wang, Student Member IEEE, Dewei Xu, Member IEEE, Bin Wu, IEEE and Zhenhan Luo “A Low-Cost Rectifier Topology for Variable-Speed High-Power PMSG Turbines ”IEEE Transactions on Power Electronics,Vol.26,No.8,August2011

[7] Yangquan Chen, Ivo Petr´aˇs and Dingy¨u Xue “Fractional Order Control - A Tutorial” 2009 American Control Conference Hyatt Regency Riverfront, St. Louis, MO, USA June 10-12, 2009

[8] Hyo-Sung Ahn†, Varsha Bhambhani‡ and YangQuan Chen‡ “Fractional-order integral and derivative controller design for temperature profile control” 2008 Chinese Control and Decision Conference (CCDC 2008) Pages4766 - 4771

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