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Indirect Online Estimation of Optimal Tip Speed Ratio with AHCS for PMSG WECS

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Abstract— **This paper deals with modelling of Permanent Magnet Synchronous Generator (PMSG) based Wind Energy Conversion System (WECS) for extracting maximum power from the wind energy using Maximum Power Point Tracking (MPPT) algorithm. This design implements a variable speed wind turbine so that it can be operated at maximum efficiency for all wind speeds within the cut-in and furling speed limit in contrast to the fixed speed wind turbines. This design uses AC-DC-AC topology. The converters use SVPWM to reduce THD (Total Harmonic Distortion). A hybrid MPPT algorithm is implemented using FLC (Fuzzy Logic Controller).Turbine, Generator and Drivetrain assembly is modelled using Two mass model-instead of lumping the inertia of the three masses-to study the dynamic response of the model as the MPPT algorithm changes the rotor speed according to wind speed variations.**

Index Terms: WECS, PMSG, MPPT, FLC

I. INTRODUCTION

The progressive increase in energy demand urges the power engineers to extract maximum energy from Non-Conventional energy resources. Among those alternative energy resources wind energy offers a promising operation and control. The wind turbines are classified as variable speed and fixed speed wind turbines [16]. The classical wind energy systems used fixed speed wind turbines, where SCIG played a vital part [16]. The energy extraction process with varying wind speeds incorporates variable speed wind turbines, where PMSG performs satisfactorily. In the present scenario the PMSG based WECS are rapidly replacing DFIG based WECS with a soul reason which aims to reduce the complexity in control algorithms and reactive power demands for magnetization. Squirrel cage induction generator has rugged and low cost construction which seems to attract the investors but the complexity of maintaining a constant negative slip terminates the idea. However SCIG can be used for low power standalone systems [12], [17].

The variable speed WECS implements a back to back converter topology. This configuration rectifies the AC power from generator. Then the rectified power is inverted to AC power of grid frequency through the DC link. Thus the variable frequency electrical power from PMSG can be fed to the grid at constant frequency.

This paper focuses on extracting maximum power from PMSG based variable speed wind energy conversion systems. The turbine operates at its maximum efficiency for a particular rotor speed corresponding to a particular wind speed. This optimum rotor speed is estimated by various Maximum Power Point Tracking Algorithms. One such algorithm is Adaptive Hill Climb Search (AHCS) algorithm which perturbs the system by varying the rotor speed and observes the change in power. This algorithm is generically called Perturb & Observe (P & O). In [2], [7] HCS has been implemented using AC-DC-AC converter topology. In [10] Advanced HCS is proposed which stores the data given by HCS algorithm in an intelligent memory and uses these data to find the reference speed instead of searching again and this algorithm is generically called Search-Remember-Reuse algorithm. In [18] P & O is used for MPPT for WECS supplying DC micro-grid. The Optimum Relation Based (ORB) algorithm uses relation between system parameters to estimate the reference speed. The Tip Speed Ratio (TSR) algorithm estimates the reference rotor speed using equation (2). In [3] a hybrid MPPT algorithm proposed by combining AHCS and ORB, which uses AHCS to find the relationship between system parameters that can be used to implement ORB later and the configuration uses Diode Bridge Rectifier followed by a DC-DC converter to implement MPPT by controlling DC link current. In [15] another hybrid algorithm is proposed combining P & O and TSR which uses approximate value of TSR as input to TSR algorithm to approximately fix the starting point for searching in P & O algorithm. The proposed hybrid MPPT algorithm merges the two TSR and P & O algorithm, which uses P & O –for the very first time– to estimate the value of optimum TSR.

II. SYSTEM CONFIGURATION

The overall system configuration is shown in Fig.1. The model of this proposed WECS contains five main blocks namely Turbine, drive train, PMSG, back to back VSC, MPPT controller and Pitch angle controller. The wind turbine obtains the wind energy and transfers it to the generator coupled through a drive train. The drive train modelling has a significance of selecting the stiffness coefficient and damping coefficient of shaft. The PMSG has a permanent magnet rotor and a three phase distributed windings in stator.

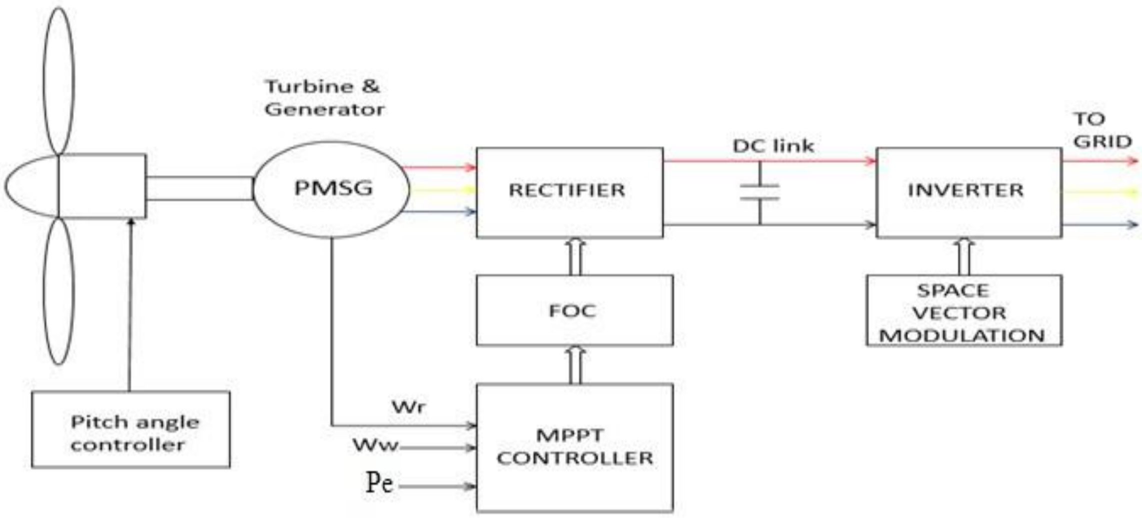

Fig.1.Overall block diagram

The stator windings are connected to grid through a back to back VSC. The back to back VSC is controlled by gating signals generated by SVPWM technique. The system includes two control blocks a pitch angle controller and a MPPT controller. The maximum power extraction at various wind speed is realized by speed control of PMSG. The speed control of machine is achieved by implementing Field Oriented Control in Machine side VSC.

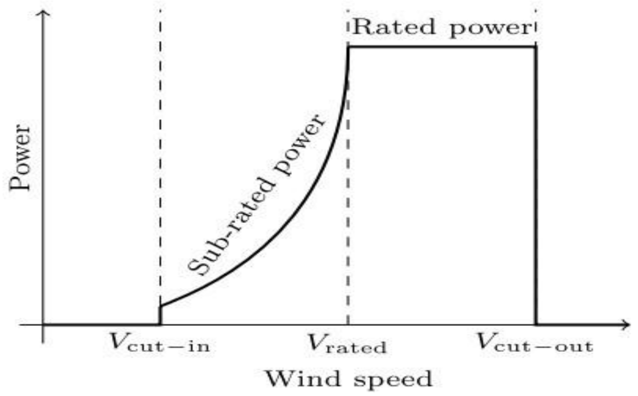

Fig. 2. Regions of operation [19]

The FOC block is commanded by the reference speed signal from the MPPT controller. The MPPT controller takes change in rotor speed $\Delta\omega_r$, wind speed ω_w and change in power ΔP as inputs. The MPPT controller generates a speed reference signal computed using the proposed hybrid algorithm. The pitch angle controller is used to limit the turbine power by varying the angle of attack of the blade [4], [16]. The MPPT controller is put in to operation up to the rated output power or rated rotor speed and pitch angle controller comes in to play after the rated power or speed [4], [16] as shown in fig.2.

III. WECS MODELLING

A. Turbine Model

The power obtained from wind using wind turbine is given by the equation [2]

$$P_T = \frac{1}{2}\rho_{air} * A_{blade} * Cp(\beta,\lambda) * \omega_w^3 \quad (1)$$

$$\lambda = \frac{R_{blade}*\omega_r}{\omega_w} \quad (2)$$

Where,

ρ_{air} (kg/m^3) is the density of air, R_{blade} (m) is the radius of the blade, A_{blade} (m^2) is the area covered by the blade, Cp is the coefficient of performance of turbine, β (degree) is the pitch angle, λ is the tip speed ratio, ω_w (rad/s) is the wind speed, ω_r (rad/s) is the turbine rotor speed which is equal to generator's rotor speed (mechanical) as this is a direct drive machine.

Cp varies as a function of β and λ. For a particular value of β and λ there exists a value of Cp – represented as Cp_{max} – which happens to be the maximum value. For Cp to be maximum for a particular wind speed, pitch angle (β) must be 0 and tip speed ratio (λ) must be λ_{opt} where λ_{opt} is obtained at ω_{r_opt} corresponding to that wind speed.

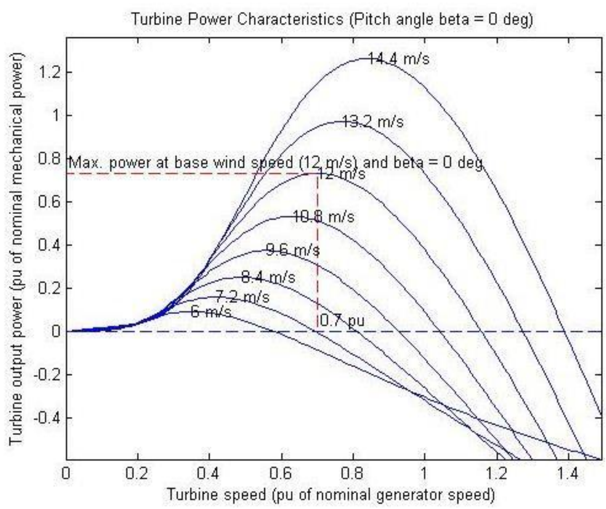

Fig. 3. Turbine power–Turbine speed Curve.

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B. Generator Model

The generator used which is a Permanent Magnet Synchronous Generator is modelled in d-q reference frame (Park Model) [2]. The voltage equations are

$$\begin{bmatrix} v_{sd} \\ v_{sq} \end{bmatrix} = -R_s \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} - \frac{d}{dt} \begin{bmatrix} \psi_{sd} \\ \psi_{sq} \end{bmatrix} + \omega_e \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} \psi_{sd} \\ \psi_{sq} \end{bmatrix} \quad (3)$$

$$\omega_e = p * \omega_r \quad (4)$$

where,

V_{sd}, V_{sq}, i_{sd}, i_{sq}, ψ_{sd}, ψ_{sq} =Direct and quadrature axis voltages, currents, flux.

R_s is the stator resistance.

ω_e is the electrical speed.

p is the pole pair.

The flux linkages are given by the equation [2] (5)

$$\begin{bmatrix} \psi_{sd} \\ \psi_{sq} \end{bmatrix} = \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + \begin{bmatrix} \psi_f \\ 0 \end{bmatrix} \quad (5)$$

Where,

$$L_d = L_{ls} + L_{dm} \quad (6)$$

$$L_q = L_{ls} + L_{qm} \quad (7)$$

L_{ls}= Stator leakage inductance,

L_{dm},L_{qm}=Direct and quadrature axis inductance,

ψ_f=Permanent Magnet Flux.

The electrical torque produced by the generator due to flow of load current is given as

$$T_{em} = p * (\psi_{sd} i_{sq} - \psi_{sq} i_{sd}) = p * (\psi_f i_{sq} - \psi_{sq} i_{sd}) \quad (8)$$

But generally in PMSG i_{sd} is made 0 so that there isn't any magnetizing component current flowing in the stator current [14]. So (8) reduces to

$$T_{em} = p * (\psi_f i_{sq}) \quad (9)$$

C. Two Mass Model

Due to variable nature of the wind that is experienced by the wind turbine the stresses on the wind turbine and the drivetrain will be considerably high [20]. Therefore it's necessary to model the drivetrain that connects the turbine and generator. The two mass model considers generator and turbine as two masses that are connected by a single shaft (direct-drive) [21]. In case of geared systems, the two mass model is obtained by combining the gear box mass with either turbine mass or generator mass. The two mass model is shown in fig.4. The equations governing the two mass model are [21]

$$2H_t \frac{d\omega_t}{dt} = T_t - T_s \quad (10)$$

$$\frac{1}{\omega_B} \frac{d\theta_s}{dt} = \omega_t - \omega_r \quad (11)$$

$$T_s = K_s \theta_s + D_t \frac{d\theta_s}{dt} \quad (12)$$

Where,

H_t is the turbine inertia constant (seconds), ω_t, ω_r, ω_b is turbine speed, rotor speed, base speed T_t, T_s turbine torque, shaft torque (N-m), θ_s is the shaft twist angle (rad), K_s is the shaft stiffness coefficient (N-m/rad), D_t is the shaft damping coefficient (N-m-s/rad).

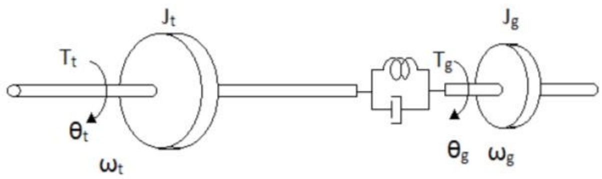

Fig. 4. Two Mass Model

D. Pitch Angle Controller

The pitch angle controller is a servo mechanism which is used to limit the output power of wind turbine during high winds [16]. This is because at higher wind speeds the turbine output power increases and to cope up with this increased power, generator power has to be increased by increasing its speed to maintain the dynamic equilibrium [16]. But the generator power cannot be increased beyond its rated value due to various electrical and mechanical constraints. So the turbine power has to be decreased by decreasing the aerodynamic efficiency of the turbine. This is done by varying pitch angle of the turbine which in turn varies the angle of attack of the blade. Thus the power is maintained at its rated value for higher wind speeds. Due to mechanical constraints the pitch angle can't be varied above certain value and the rate of variation should also be within limits. There are many types of pitch angle controller which take rotor speed or output power as input and compare with the respective reference values. The error value is given to a controller which outputs the pitch angle. This angle is given as reference to a servo mechanism which rotates the blade.

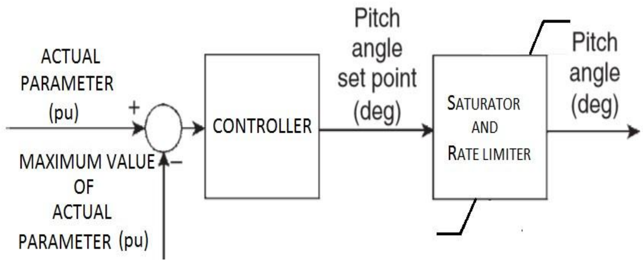

Fig. 5. Pitch Angle Controller [16]

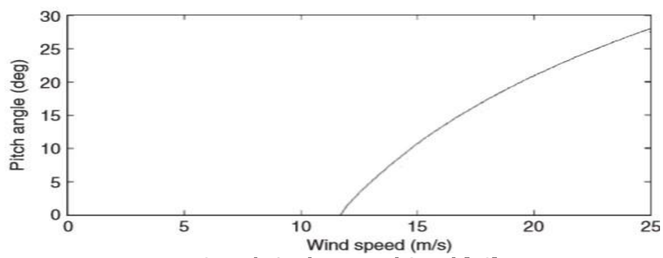

Fig. 6. Pitch Angle vs Wind Speed [16]

E. Machine Side Converter Control

The variable frequency alternating power from the generator has to be rectified so that the inverter can convert this rectified DC voltage to alternating voltage of required frequency (grid frequency). But apart from this rectification, this converter has to control the speed of the generator also. So the functions of the Machine Side Converter are 1- rectification of the voltage coming from PMSG and 2- Speed control of the generator. While rectifying, the pulses are Pulse Width Modulated. This plays a major role because while rectifying there will be distortion in the voltage and current from the generator. This increases the Total Harmonic Distortion (THD) and hence the losses in the generator due to harmonics. Due to harmonics, heat will also be produced which adds to thermal stress of the machine. So PWM scheme which has low THD has to be used which obviously happens to be Space Vector Modulation [14].

Speed control is implemented using Field Oriented Control (FOC) which is a type of vector control [14]. FOC is chosen because it has better transient response than that of ordinary scalar control [22]. Vector control uses rotating reference frame theory where the alternating parameters appear as DC quantities and also the torque producing and field producing component of the stator current are decoupled. The decoupled control of the machine enables us to vary the torque component alone thereby controlling the speed without altering the flux linkage value. In ordinary scalar control the stator current as a whole is controlled considering only the frequency and magnitude but not the phase. This causes a sluggish response in scalar control [22]. In vector control the phase is also considered and hence the name 'vector' control [22]. The rotor field producing component is aligned along with the direct axis and the torque component along the quadrature axis in the rotating reference frame. This alignment is implemented using the vector rotating component obtained from the electrical angle corresponding to actual rotor angle (electrical angle is pole pair times the mechanical angle) [14].

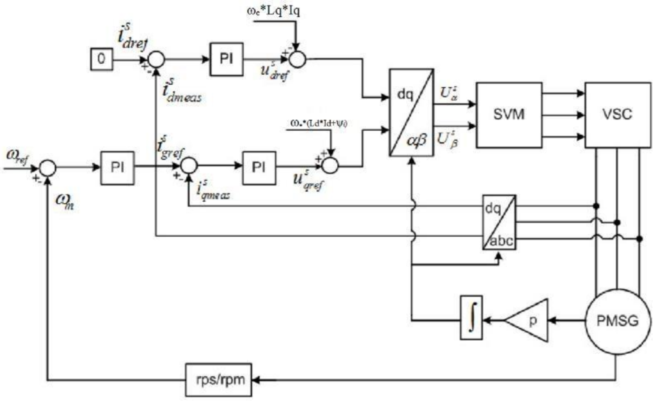

Fig. 7. Block Diagram of FOC [23]

The block diagram of FOC is given in Fig. 7. The reference d-axis stator current (i_{sd}^{*}) is given as 0 so that the total stator current is equal to torque producing component (i_{sq}) [24]. This reference is compared with actual value and the error is given to current controller. This controller gives corresponding direct axis voltage.

The speed reference is given by the MPPT algorithm which is compared with actual speed. This speed error is given to speed controller which gives the reference quadrature axis stator current (i_{sq^*}). This value is compared with actual value and the error is given to current controller. The current controller outputs the corresponding quadrature axis voltage. The d and q axes voltages are transformed to α and β voltages. This is given to SVPWM block which outputs the pulses that drive the Machine Side Converter.

F. Inverter Control

The DC link voltage is inverted to the grid frequency. The inverter firing can be controlled such that the DC link voltage is maintained constant and the real, reactive power flow is controlled [2]. But in this paper, the DC link voltage is inverted to constant grid frequency. The PWM used for this converter is also SVPWM to reduce the Total Harmonic Distortion.

IV. MPPT ALGORITHM

A. Review of existing algorithms

1. Hill climb search

The hill climb search algorithm is often referred to as Perturb & Observe algorithm. In general the algorithm changes a system parameter (rotor speed) and observes the change in the relative parameter (output power). The input to the HCS controller is rotor speed and output power. Here the rotor speed (ω_r) is varied and the change in power ΔP is observed. If the computed ΔP is positive then the rotor speed is varied in the same direction and if it is negative, the direction of variation is changed. The speed of the machine is varied by varying the quadrature axis stator current of the generator. This is implemented using FOC. Fig.8 shows the Turbine power Vs Rotor speed curve obtained for a particular wind speed and algorithm process. The search is exhaustive and it settles at a maximum power for a particular wind speed. The major advantage of this machine is that it doesn't require any prior knowledge of the system [1]. It can be applied to all machines. But the drawback of this algorithm is that it takes a longer period to settle at the maximum power point. This effect is more pronounced in large machines and in places where the wind speed variation is very high [3].

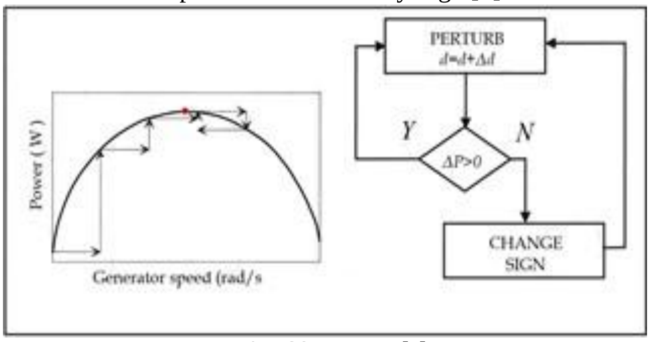

Fig.8. HCS operation [1]

2. *Optimum Relation Based Algorithm*

The ORB algorithm uses relation between various system parameters. This algorithm often uses relations of generator power Vs rotor speed and generator power Vs DC rectifier voltage and the other relation of electrical torque Vs rotor speed is also used. The former algorithms are termed as Power Signal Feedback algorithms and the latter doesn't use any power signal [3]. The other algorithm also uses relation between DC link voltage and current which is a simplified control [3]. This requires system pre knowledge which has to be obtained by laboratory tests. And hence this algorithm cannot be obtained for all machines unlike P & O.

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3. *Tip Speed Ratio Algorithm*

The TSR algorithm varies the turbine speed to settle at optimum tip speed ratio. This is a simple algorithm which estimates the tip speed ratio using equation (2).

Since the TSR algorithm takes radius of blade into account, this algorithm also needs the knowledge of the machine in advance. This algorithm has less computations and settles at the desired speed with quick dynamic response. This trait of algorithm gave rise to an intuitive thought of the proposed algorithm. But this algorithm needs wind speed as input.

Adding an anemometer adds to the cost of the system and also the accuracy of anemometer will not be good always. This can be overcome by estimating the wind speed using the wind turbine itself without using anemometer but by using a wind speed estimator designed and implemented using Artificial Neural Network [20].

B. Proposed MPPT Algorithm

The proposed algorithm is formulated to combine TSR and HCS algorithms. These two algorithms have their own merits and shortcomings. The work is aimed to overcome the limitations of both the algorithms which are discussed in the previous section by switching between the algorithms. The control algorithm is said to have two phases.

i. Estimation phase

This is the initial phase of the MPPT algorithm. The HCS algorithm is used in this phase since it is a generic algorithm which is independent of machine parameters. The HCS algorithm gives a reference speed from which the TSR estimator estimates the optimal value of Tip Speed Ratio when the system is put into operation for the very first time. The HCS algorithm is implemented using fuzzy logic controller. From this settled value of rotor speed at –which maximum power can be obtained– and wind speed the optimal Tip Speed Ratio is estimated as explained in the flow chart shown in fig.9.

ii. Implementation phase

The estimated tip speed ratio in the previous phase is used in the implementation phase where TSR algorithm takes control over the HCS algorithm. The TSR algorithm tracks the change in wind speed and settles at new rotor speed quickly. Fig. 10 shows the flow chart of proposed MPPT. Initial value if optimal TSR is 0. With this zero initial value the controller uses HCS to estimate the reference speed for MPPT purpose. Once the reference speed settles, the TSR estimator estimates the optimal TSR and the moment this value is estimated the controller switches to TSR algorithm and carries out the MPPT using the TSR algorithm. The Fig.11 shows the fuzzy logic rule base used in HCS algorithm.

$\Delta\omega_m$	ΔP_m								
	N++	NB	NM	NS	ZE	PS	PM	PB	P++
N	P++	PB	PM	PS	ZE	NS	NM	NB	N++
ZE	NB	NM	NS	NS	ZE	PS	PM	PM	PB
P	N++	NB	NM	NS	ZE	PM	PM	PB	PB

Fig.11 Fuzzy Rule Base

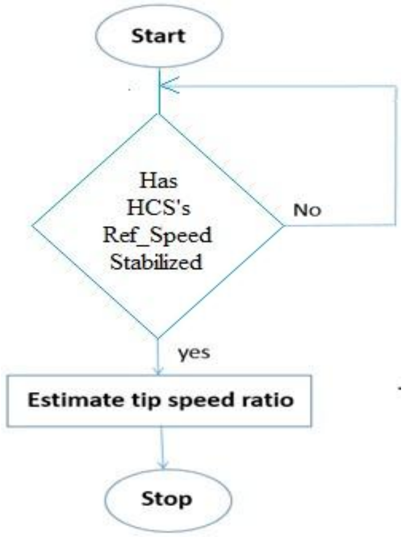


Fig .9. Tip speed ratio estimation

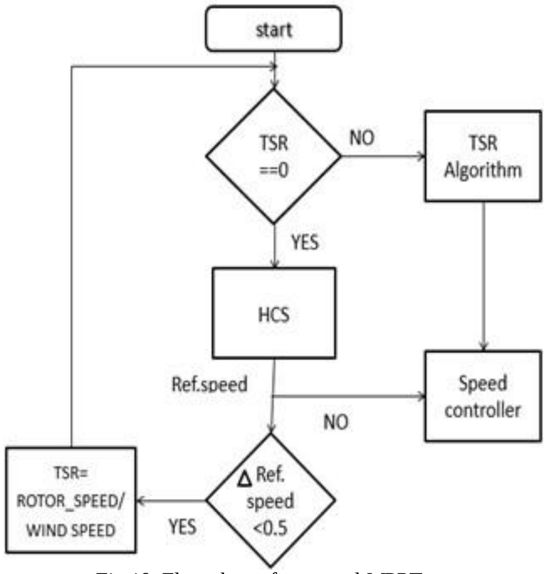
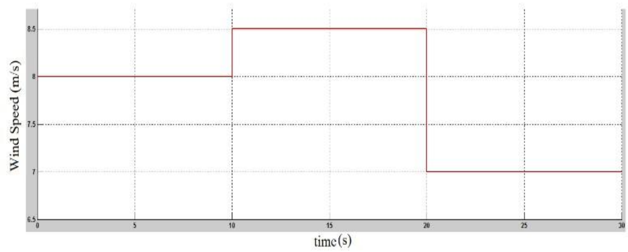
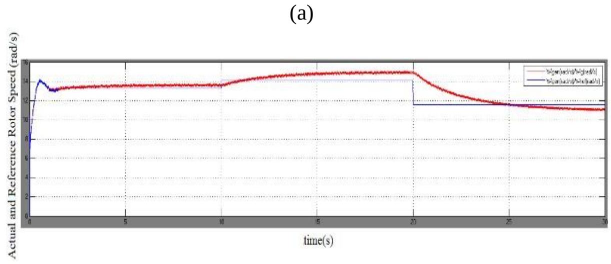


Fig.10. Flow chart of proposed MPPT

V. SIMULATION RESULTS



(a)



(b)

Fig. 12. Simulation Results. A) Wind Speed, B) Actual and

REFERENCE ROTOR SPEED

The wind speed is given using a signal generator in MATLAB-Simulink. The wind speed is varied after some period of time to study the response of the system for variations in the wind speed. However this is not real life wind speed variation. Wind speed can be given as noise signal that can be obtained as a function of harmonic signals [2]. But in this paper wind speed is varied in steps. The wind speed variation used in this work is shown in fig. 12a.

The actual rotor speed (red) of the turbine is shown in fig.12b along with reference speed (blue). The initial reference speed is given by HCS algorithm and after 1.45s the speed is settled and the controller switches to TSR algorithm after estimating the optimal TSR. Also the wind speed is increased from initial value and then decreased with the intention of studying how the system responds to the variations in both directions. It is been verified that the optimal TSR estimated by the proposed MPPT algorithm matches with theoretically calculated value of optimal TSR.
The machine parameters used for simulation are listed in the appendix.

VI. CONCLUSION

This work has combined the existing MPPT algorithms to have a satisfactory operation of a wind energy conversion system. The MPP is achieved by speed control of the PMSG machine using Field Oriented Control. The PMSG based WECS is simulated in MATLAB- Simulink and the results comply with the expected performance of the system. The proposed idea is generic and can be incorporated to all PMSG based WECS irrespective of the machine and turbine parameters. Thus the proposed MPPT algorithm performs optimally and extracts maximum power at all wind speeds.

APPENDIX

Power Rating	5.7KW
Rated Speed	28.27 rad/sec (570rpm)
Voltage	200V
Permanent magnet flux (ψf)	0.76Wb
Pole pair	8
Stator resistance (Rs)	1.5Ω
Stator inductance	14.04mH
Turbine inertia constant(H)	2s
Generator inertia	0.138 kg-m^2

REFERENCES

[1] Jogendra Singh Thongam and Mohand Ouhrouche, “MPPT Control Methods in Wind Energy Conversion Systems” Intech, Fundamental and Advanced Topics in Wind Power, 20, June, 2011.

[2] Shuhui Li, Timothy A. Haskew, Richard P. Swatloski, and William Gathings, “Optimal and Direct-Current Vector Control of Direct-Driven PMSG Wind Turbines,” IEEE Trans. Power Electrons., vol. 27, no. 5, May 2012.

[3] Yuanye Xia, Khaled H. Ahmed, and Barry W. Williams, “A New Maximum Power Point Tracking Technique for Permanent Magnet Synchronous Generator Based Wind Energy Conversion System,” IEEE Trans. Power Electrons., vol. 26, no. 12, December 2011.

[4] Tan Luong Van, Thanh Hai Nguyen, and Dong-Choon Lee, “Advanced Pitch Angle Control Based on Fuzzy Logic for Variable-Speed Wind Turbine Systems,” IEEE Trans. Energy conv., vol. 30, no. 2, June 2015.

[5] Daryoush Mehrzad, Javier Luque, Marc Capella Cuenca, “Vector Control of PMSG for Wind Turbine Applications,” Aalborg University, Institute of Energy Technology, Autumn Semester, 2008.

[6] Daryoush Mehrzad, Javier Luque, Marc Capella Cuenca, “Vector Control of PMSG for Grid-Connected Wind Turbine Applications,” Aalborg University, Institute of Energy Technology, Spring Semester, 2009.

[7] Ali M. Eltamaly, Hassan M. Farh, “Maximum Power Extraction from Wind Energy System Based on Fuzzy Logic Control,” Electric Power Systems Research 97 (2013) 144–150.

[8] Analog Devices Inc., “Implementing Space Vector Modulation with the ADMCF32X”.

[9] M. Singh, E. Muljadi, J. Jonkman, V. Gevorgian, I.Girsang and J.Dhupia, “Simulation for Wind Turbine Generators—With FAST and MATLAB-Simulink Modules,” Technical Report NREL/TP5D00-59195 April 2014.

[10] Quincy Wang and Liuchen Chang, “An Intelligent Maximum Power Extraction Algorithm for Inverter-Based Variable Speed Wind Turbine Systems” IEEE Trans. Power Electrons., vol. 19, No. 5, September 2004.

[11] Whei-Min Lin and Chih-Ming Hong, “Intelligent Approach to MPPT Control Strategy for Variable-Speed Wind Turbine Generation System,” Intech, Wind Turbines, 04, April, 2011.

[12] Dom´ınguez Garc´ıa, Jos´e Luis, “Modeling and control of Squirrel Cage Induction Generator with Full Power Converter applied to windmills,” Oulun Yliopisto, University of Oulu, November 30, 2009.

[13] Muyeen S.M, Tamura.J, Murata T, Stability Augmentation of A Grid Connected Wind Farm- Chapter 2 - Wind Turbine Modeling, 2009.

[14] Bimal K Bose, Modern Power Electronics and Drives, PHI, 2002.

[15] Joanne Hui, “An Adaptive Control Algorithm for Maximum Power Point Tracking for Wind Energy Conversion Systems,” Queen’s University Kingston, Ontario, Canada December 2008. [16]Thomas Ackermann, Wind Power in Power Systems, John Wiley & Sons Ltd,2005.

[17] Trapp J.G, Farret F.A., Fernandes F.T., Corrêa L.C.,Wechenfelder C.M.,” Variable Speed Wind Turbine Using the Squirrel Cage Induction Generator with Reduced Converter Power Rating for Stand-Alone Energy Systems”

[18] V. Nayanar, N. Kumaresan, and N. Ammasai Gounden, “A Single-Sensor-Based MPPT Controller for Wind-Driven Induction Generators Supplying DC Microgrid,” IEEE Trans. Power Electrons., vol. 31, no. 2, February 2016.

[19] Azad Ghaffari, Miroslav Krstic, and Sridhar, “Power Optimization and Control in Wind Energy Conversion Systems Using Extremum Seeking,” IEEE Trans, Control Systems Technology, vol. 22, no. 5, September 2014.

[20] Boubekeur Boukhezzar and Houria Siguerdidjane, “Nonlinear Control of a Variable-Speed Wind Turbine Using a Two-Mass Model,” IEEE Trans, Energy Conversion, vol. 26, no. 1, March 2011.

[21] S. Samanvorakij, P.Kumkratug, “Modeling and Simulation PMSG based on Wind Energy Conversion System in MATLAB/SIMULINK,” Proc. of the Second Intl. Conf. on

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 6 Issue 08, August - 2017

Advances in Electronics and Electrical Engineering — AEEE 2013.
[22] R.Krishnan, Electric Motor and Drive Modelling, Analysis and Control, PHI, 2001.
[23] Andreea Cimpoeru," Encoderless Vector Control of PMSG for Wind Turbine Applications," Aalborg University, Institute of Energy Technology, 2010.
[24] T.J.E.Miller, Brushless Permanent- Magnet and Reluctance Motor Drives, Oxford Science Publications,1989.