A Study of MPPT Schemes in PMSG Based Wind Turbine System

Joydeep Sarkar
PG Student, Electrical Power System
Department of Electrical Engineering, MCOERC
Nasik, Maharashtra, India

Prof. Shridhar S Khule
Associate Professor
Department of Electrical Engineering, MCOERC
Nasik, Maharashtra, India

Abstract- In many research activities related to improving wind turbine efficiency, the major focus has been in improvement of blade design, number of blades that is most suitable, and aerodynamics of design to make the design more strong and efficient. Also, to tackle the irregularities related to the wind pattern, many control systems have been designed to actively adapt to the wind conditions to capture the maximum power.

To improve the energy capture efficiency of wind turbines, many maximum power point tracking algorithms have been developed. In this review paper, we will focus majorly on Permanent magnet synchronous generator based Wind energy conversion system and various maximum power tracking systems designed for such systems and will set a comparative analysis to determine the effectiveness of such control system

Keywords: Wind Energy Conversion System, PMSG, MPPT controller

I. INTRODUCTION

A variety of wind energy systems have been developed and the technological advances have been astounding. Turbine designs nowadays ranges from vertically placed turbines to horizontally placed turbines. But in any design, a basic flow of electrical & mechanical arrangement exists, as shown in fig 1. With the technology development in semiconductor device field, power electronic controller are getting a good market share in grid side and load side converter design sector.

Wind converter topologies are available in very well-known formats (1):

1. Diode-Rectifier → Chopper → DC bus → Inverter
2. IGBT Rectifier → DC Bus → Inverter

The wind market majorly accepts the topology which functions under variable wind speed having a full scale frequency converter. For this design, the doubly fed induction generators (DFIGs) and permanent magnet synchronous generators (PMSGs), allow the extraction of maximum power from a large wind speed range. The PMSG with a higher number of poles for low speed, avoids the necessity of having a gearbox. Some of the important advantages that PMSG has over the DFIG are better efficiency, easier controllability, no need for reactive magnetizing current and they are smaller in size. [1].

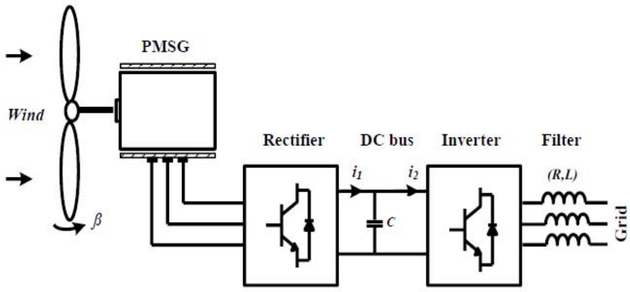

Fig 1- Wind Turbine Systems [1]

Large scale wind turbines nowadays has a highly evolved control system, mainly dealing with maintaining the rotation speed, pitch angle, and tracking the maximum power point (MPPT schemes). A wide variety of MPPT algorithms are developed based on some controllable parameter, with the main goal to absorb maximum power available in the flowing wind. The MPPT controller controls the generator side converter such that maximum active power can always be drawn from the wind turbine under different wind speeds.

II. ESTIMATES OF WIND TURBINE

Each wind turbine design has a unique associated power coefficient function, C_p (γ, β), that describes its power extraction efficiency. Equation below describe the kinetic power in the wind and the mechanical power that is extracted by the wind turbine respectively,

$$P = 0.5\rho A V^3 \quad (1)$$

$$P = 0.5\rho A\, C_p(\gamma, \beta)\, V^3 \quad (2)$$

In this equation, V is wind speed [m/s]; ρ is air density [kg/m^3]; A is rotor swept area [m^2]; ω = turbine rotating speed. The power coefficient, C_p is dependent on two parameters: the tip speed ratio (TSR), which is given by γ and the pitch angle, β. The pitch angle refers to the angle in which the turbine blades are aligned with respect to its longitudinal axis. [2]

$$\gamma = \frac{R\omega}{V} \quad (3)$$

Here, R = radius of turbine blades

The shape of the C_p curve is dependent on pitch angle. There are two main classes of wind turbines, based on pitch angle: variable pitch and fixed pitch. The variable pitch wind turbine allows the rotor blades to twist along its longitudinal axis and so β varies. The blades of a fixed pitch wind turbine however, are bolted to the hub so that β = 0. [3]

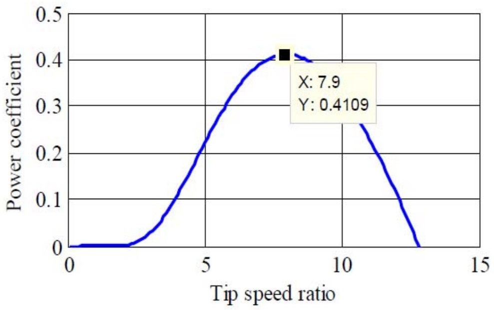

Fig 2 - Power Coefficient Curve [12]

It should also be noted that the maximum C_p value will correspond to a different TSR for each pitch angle. For a variable pitch wind turbine, there will be a set of power curves associated with each pitch. The power obtained from the wind turbine can be expressed as a function of γ as given by:

$$P(\gamma) = 0.5\rho A\, C_p(\gamma, \beta)\left(\frac{R\omega}{\gamma}\right)^3 \quad (4)$$

The equation, based on the modelling turbine characteristics

$$C_p(\gamma,\beta) = C_1\left(\frac{C_2}{\gamma_i} - C_3\beta - C_4\right)e^{(-C_5/\gamma_i)} + C_6\gamma \quad (5)$$

With,

$$\frac{1}{\gamma_i} = \frac{1}{\gamma+0.08\beta} - \frac{0.035}{\beta^3+1} \quad (6)$$

The coefficients C_1 to C_6 are: C_1= 0.5176, C_2= 116, C_3 = 0.4, C_4 = 5, C_5 = 21 and C_5 = 0.0068. The wind model can be used in the simulation study. The aerodynamic power converted by the wind turbine is depending on the power coefficient C_p such as:

$$P_T = \frac{1}{2}\rho\pi R^2 C_p V^3 \quad (7)$$

Where, ρ is the air density (ρ=1.225 kg/m^3), *R* is the blade length and V is the wind speed. Once the power is absorbed by the blades, it is transferred to the shaft of the rotor. The mechanical speed of the synchronous generator can be easily determined using the dynamic equation. The simplified model of this equation is given by (1):

$$J_T\left(\frac{d\omega}{dt}\right) = C_t - C_{em} - f\omega - C_s \quad (8)$$

Where, J_T (kg.m^2) is the total inertia which appears on the shaft of the generator, ω (rad/s) is the turbine rotating speed, C_t (N.m) is the mechanical torque, C_{em} (N.m) is the electromagnetic torque, C_s (N.m) is the dry friction torque and f (N.m.s.rad^{-1}) is a viscous friction coefficient. The rotational speed of the rotor can be either measured using mechanical sensors or can me mathematically calculated, with using any mechanical sensor, using the following equation,

$$\omega_m = \frac{V_{dc} + 2R_s i_L}{\frac{3\sqrt{3}}{\pi}K_m - \frac{P}{20}(L_l + L_S)i_L} \quad (9)$$

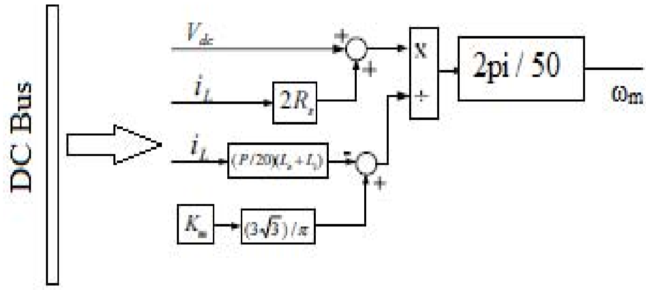

Fig 3 – Sensor-less ω_m estimation

Here, ω_m is the estimated value of rotor speed, K_m is the peak line to neutral back emf constant in V/rpm, R is the stator winding resistance in Ohm, L_s is the stator leakage inductance in mH, L_l is the In-line leakage inductance in mH, and P is the number of poles.

III. UNCERTAINITIES IN WIND POWER CURVE

The power curves shows the mechanical power of wind turbine versus the rotor speed at different wind velocities. In practical plots, the curve forms with a group of points spread around each curve line, as the wind speed always fluctuates, and one cannot measure exactly the column of wind that passes through the rotor of the turbine. Moreover, the wind speed has different values at each point of the blade. The mechanical power developed by the wind turbine not only depends on the wind speed (which is difficult to measure) but also it depends on the air density and the turbine performance coefficient.

According to the ideal gas law, the density of a gas is proportional to its pressure and inversely proportional to its temperature. This fundamental can be shown in the equation representing the changes in density value,

$$\rho = \frac{MP}{RT} \quad (9)$$

where, P is the absolute pressure, M is the molar mass, R gas constant (8.314472JK^{-1}mol^{-1}), and T is the absolute temperature. If the pressure increases by 10% and the temperature decreases by 15%, the air density will increase about 30%.

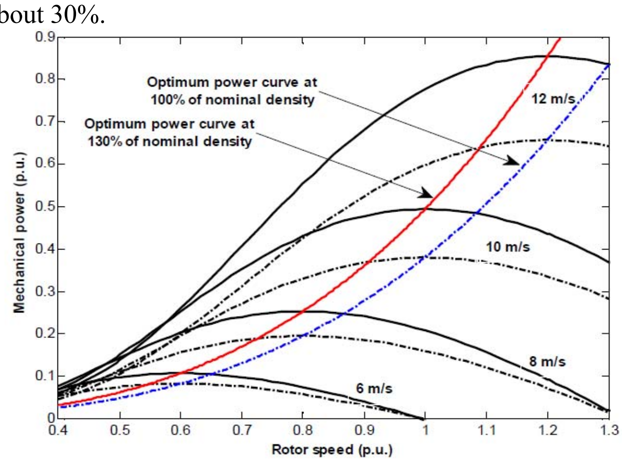

Fig 4- The effect of air density on the C_p [3]

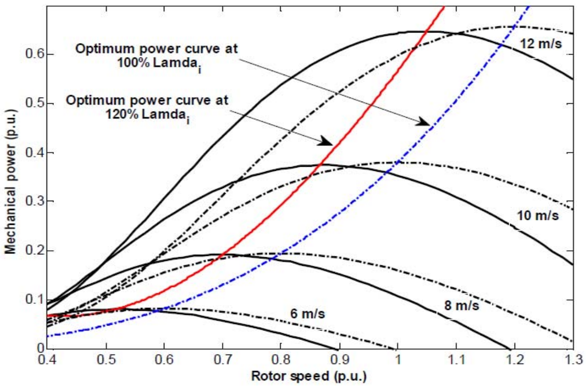

Fig 5- The effect of changing γ_i on the C_p [3]

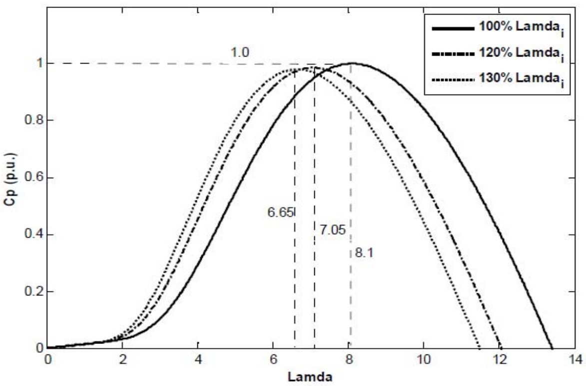

Fig 6- The effect of changing C_p [3]

When the air density increases, the maximum mechanical power output increases, which results in shifting the maximum power point line. [3]. When γi increases the maximum power decreases slightly, but it occurs at different rotor speed, which results in shifting the maximum power loci.

IV. STEADY-STATE OPERATION OF WIND TURBINE

A variable speed wind turbine can be assumed to be working under two zones of operation based on wind speed available. The two zones can be fixed with one wind speed reference, say 8 m/s. and maximum wind speed value rated for the turbine under consideration.

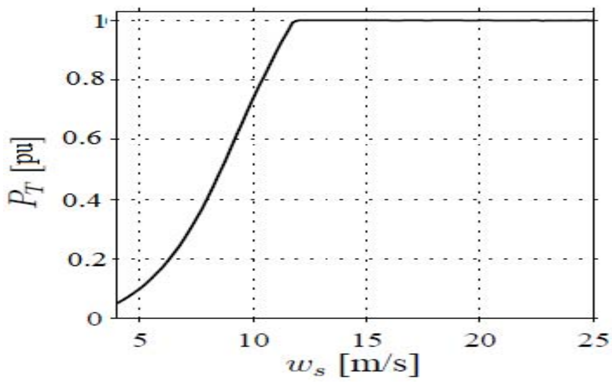

Fig 7 – Power vs. Wind speed

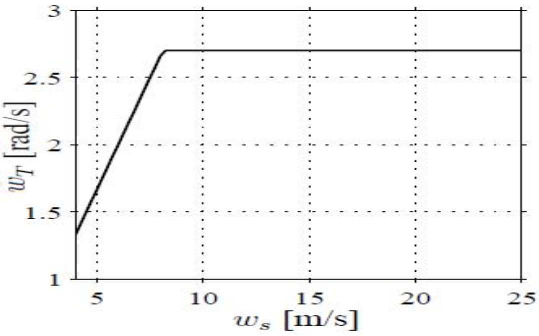

Fig 8 – Rotor Ang. Speed vs. Wind Speed

Low wind speed operation zone and all those points which are more than reference speed comes under High wind speed operation zone. The figure below shows the operation characteristics on these two operation zones. (4) For Low wind speed zone, the rotor speed is controlled to keep the tip-speed ratio (TSR), γ, at its optimal value and the pitch angle is zero.

When the nominal power and maximal rotor speed is reached, the rotor speed controlled to its nominal value. Moreover, when the nominal power is reached, the blades of the turbine are pitch out of the wind in order to control the turbine power level to its nominal value. All the wind speed which are less than reference comes under the control area. The wind turbine provides active power between the critical wind velocity levels to maximum wind velocity level, where the rotor speed is moving around its nominal value while the produced power remains below the rated value of the wind turbine.

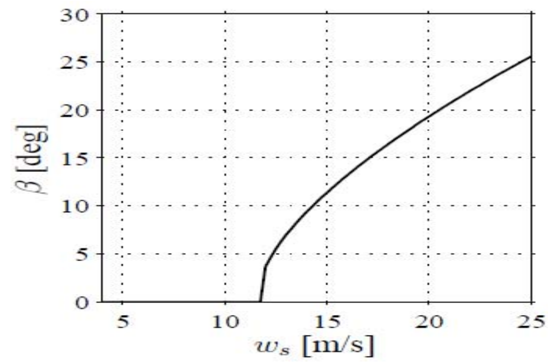

Fig 9 – Pitch Angle vs. Wind Speed

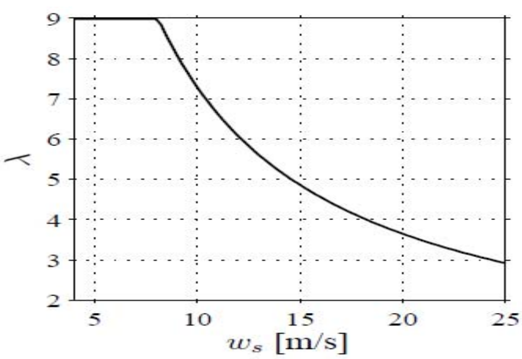

Fig 10 – Tip Speed Ratio vs. Wind Speed

V. TURBINE CONTROL STRATEGY

The wind energy control system (WECS) that is under consideration is a direct-drive system i.e. without gearbox and includes a wind turbine, multi-pole permanent magnet synchronous generator (PMSG) and pulse-width modulation (PWM) based fully controlled power converter with buck-boost converter in the DC bus. The use of buck-to buck PWM full power converter insures that the generator currents and the grid currents are sinusoidal. Moreover, the generator side converter is controlled to achieve maximum power extraction. In partial load region, WECS is controlled by means of MPPT algorithm which maximizes the energy captured by the turbine from the wind's kinetic energy. Many literature shows various kind of maximum power point tracking algorithm, which globally can be classified into two categories, based on whether direct wind speed measurement is taken as input or not:

a) Sensor-less MPPT Control
b) With Sensor MPPT control

While dealing with a direct-drive system using PMSG generator, a sensor-less MPPT control is found to be suitable for variable wind speed conditions, as the wind speed is a constantly changing parameter, and measuring it with some sensor will give unstable reading, which will make it difficult to perform the further control calculations. In the following paragraphs we will understand & compare various control techniques that are used in wind turbine control algorithms in variable speed wind turbine system with drive-less PMSG.

A) Optimal Torque Control

Conventionally, to obtain the maximum power from the wind, we use a simple expression based on wind speed measurement. Using equations (3) & (7), we can get the following maximum power equation,

$$P_m = \frac{1}{2}\rho\pi R^2 \left(\frac{R\omega}{\lambda}\right)^3 C_{pmax} \quad (10)$$

Using this equation, we can derive the condition of optimal power flowing through the turbine by calculating, ω_{opt} as a function of wind speed, v:

$$\omega_{opt} = \lambda_{opt}.\ v / R \quad (11)$$

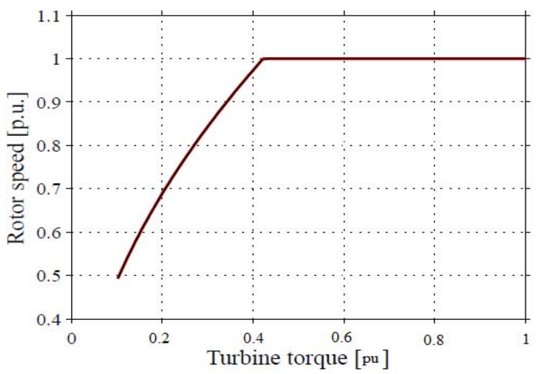

Fig 11- Rotor speed reference vs. Turbine Torque

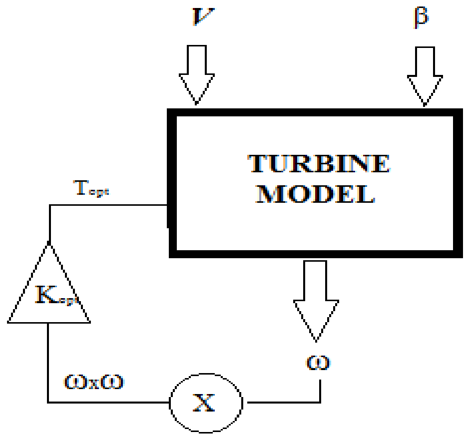

Fig 12 Optimal Torque Control

So, using equation (11) in equation (10), we get

$$P_{max} = K.\ \omega^3_{opt} \quad (12)$$

Here,

$$K = \frac{1}{2}\rho\pi R^2 \left(\frac{R}{\lambda}\right)^3 C_{pmax} \quad (13)$$

Dividing the eqn. with ω_{opt}, we get

$$T_{opt} = K.\ \omega^2_{opt} \quad (14)$$

In order to obtain the turbine optimal torque, control has to adjust the generator torque reference so that maximum power is obtained.

B) Tip Speed Ratio (TSR) Control

Whenever a wind turbine is installed, two parameters are available by measurement, i.e. Wind speed, v and the pitch angle, β corresponding to the wind speed for proper operation. For a particular wind speed available at the turbine blades, we can measure the maximum possible power that can be derived from the turbine system, P_m.

$$P_m = \frac{1}{2}\rho\pi R^2 \left(\frac{R\omega}{\lambda}\right)^3 C_{pmax} \quad (15)$$

For extracting maximum power from a particular wind, control has to adjust turbine speed so that optimum tip speed ratio (λ_{opt}) is always obtained corresponding to maximum power that can be derived from wind.

$$K_{opt} = 0.5\rho\pi R^5 C_{pmax} / (\lambda_{opt})^3 \quad (16)$$

where, R is the radius of wind turbine, ρ is air density and the C_{pmax} is the maximum power coefficient correspond to ω_{opt}. When the wind speed is v, the optimized generator speed corresponding to maximum wind energy can be obtained by:

$$\omega_{opt} = v\ \lambda_{opt} / R \quad (17)$$

Speed reference that achieves maximum power can be obtained in different ways. First, it can be obtained from the measurement of wind velocity by an anemometer, which measures only the wind velocity at one point of the rotor, and also this measurement is affected by the rotor wake. An approximation can be done to make calculations easy.

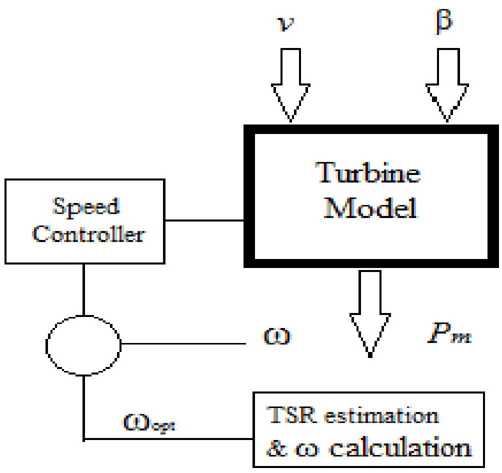

Figure 13- Speed Control Block Diagram

C) Power Signal Feedback Control

The two methods discussed above depends on accurate reading availability from a mechanical wind speed measurement system. With time, such system may induce ageing giving out inaccurate readings. In Power signal feedback control method, a pre-recorded values are recorded in the memory of the control system. The reference point for operation is obtained from simulations or experimental tests conducted earlier, to form the curve of rotational speed with respect to optimal power in the generator.

Assume that, the system is operating under wind speed V_1, giving a shaft speed ω_1, and the generator gives out a maximum output power P_1. Suddenly, the wind speed changes to V_2. Based on standard reading available in the memory of controller, the new optimum output power should be P_2, but the real output power will be P'_2 due to the inertia of the shaft. This reference point will enable the shaft to accelerate under additional turbine torque and operations point will be moved to P_2 and corresponding rotor speed, ω_2. To implement PSF technique, the maximum power is tracked by the shaft speed measurement and corresponding value of reference power determination.

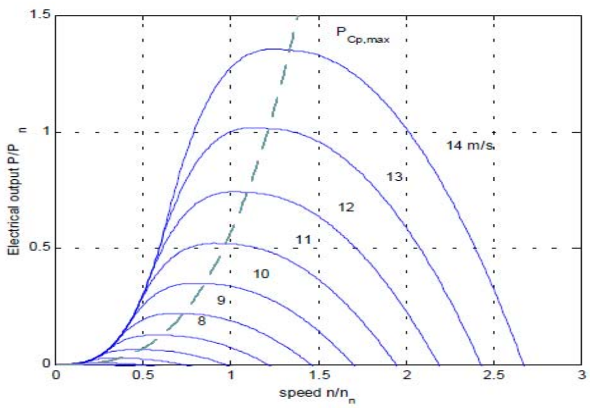

Fig 14- Output Power vs. Turbine Speed Curve for various Wind Speed

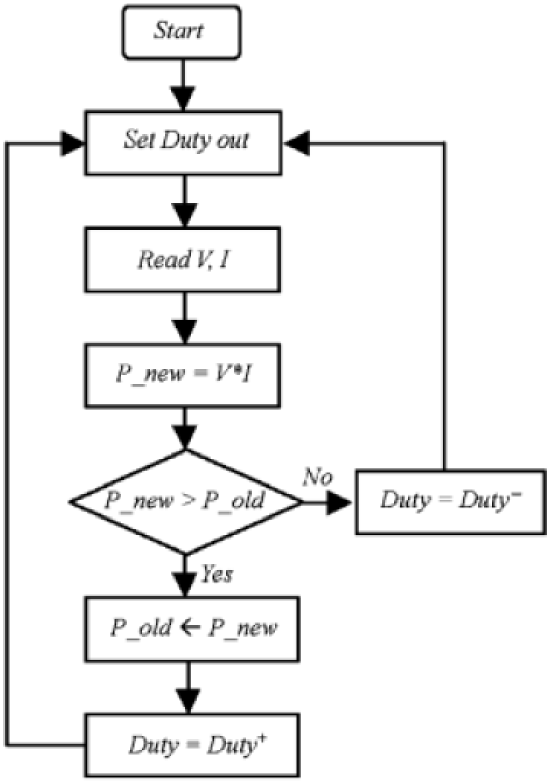

Fig 15- Flowchart of P&O Method (2)

D) Perturb and Observe (P&O) technique

In P&O method, the rotor speed in changed in small steps and the changes in the output power is measured. In the PMSG, the output current is proportional to the rotor torque, and voltage is proportional to the rotor speed. Thus modifying the output voltage of the generator will cause the rotor speed to change to its corresponding value. Variation of the voltage could be performed by adjusting the duty cycle (PWM signal) of the buck converter. Then by observing the resulting power, increase or decrease the duty cycle in the next cycle.

If the increase of duty cycle produces an increase of the power, then the direction of the perturbation signal (duty cycle) is the same as the previous cycle. Contrary, if the perturbation duty cycle produces a decrease of the power, then the direction of perturbation signal is the opposite from the previous cycle.

VI CONCLUSION

The study showcases the controls available for a direct-driven PMSG turbine under variable wind speeds, connected to the grid. A sensor-less system works better for real time control. P&O method provides a better algorithm for power control, enabling its usage in smart controllers (fuzzy/neural), which will eliminates slow response operation of conventional MPPT controls.

REFERENCES

1. M.Mansour, M.N.Mansouri, M.F.Mmimouni, "Study and Control of a Variable-Speed Wind-Energy System Connected to the Grid" Int. Journal of Renewable Energy Research, IJRER, Vol.1, No.2, pp.96, 2011
2. Soetedjo, A. Lomi, W.Mulayanto, "Modelling of Wind Energy System with MPPT Control", International Conference on Electrical Engineering and Informatics, 17-19 July 2011, Bandung, Indonesia
3. Hae Gwang Jeong, Ro Hak Seung and Kyo Beum Lee, "An Improved Maximum Power Point Tracking Method for Wind Power Systems", Energies 2012
4. T.Thiringer, A Petersson, "Control of a Variable-Speed Pitch-Regulated Wind Turbine", Department of Energy and Environment, Chalmers University Of Technology, G¨oteborg, Sweden 2005
5. Remli, D. Aouzellag And K. Ghedamsi, "Full Electrical Strategy Control Of Wind Energy Conversion System Based PMSG", Faculty Of Technology, A. Mira University, Algeria
6. M.Abdullah, Yatim, C.W.Tan, and R.Saidur, "A review of maximum power point tracking algorithms for wind energy systems, Renewable and Sustainable Energy Reviews", 2012.
7. A.M El-Sebaii, M.S Hamad, A.A Helal, "A Sensorless MPPT technique for a grid connected PMSG Wind Turbine System", Arab Academy for Science, Technology and Maritime Transport, Egypt