Design, Control and Simulation of PMSG-Based Wind Energy Conversion System

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Abstract: *Due to several limitations of conventional sources of energy such as high cost of fossil fuels, contribution towards pollution and environmental damage, scarcity in resources, there is an urge for the utilization of renewable sources of energy. Among several forms of renewable sources of energy, specifically wind energy conversion system is the most cost effective and technologically improvable. In variable speed operation, it is important that the generated power from PMSG should be optimized. Thus to capture as much power as possible from wind during change in wind speed, maximum power point tracking is implemented. Among several methods, the most efficient MPPT technique is Perturbation and Observation (PnO) which has its own virtues. Here simulation evaluation is done to know the working of MPPT and successfully optimize the generated power during a step change in wind speed. A PMSG based stand-alone WECS with MPPT control is designed, modeled and simulated under MATLAB/SIMULINK environment.*

Index Terms **- WECS, MPPT, PnO, PMSG.**

I. INTRODUCTION

Increasing concerns on energy crisis as well as environment pollution have significantly promoted renewable energy utilization nowadays. In India, Solar Energy and wind energy are the most attractive solutions as abundant in nature. Near coastal/hilly areas, wind energy conversion system is more favorable which converts wind energy into different forms of electrical energy using a wind turbine and power conversion system.

Literature reveals various types of wind generation systems, variable – speed and fixed speed wind generation system. Fixed speed system (FSS) has advantages like low cost, robust structure and also no requirement of power converter. But its operation is limited when optimization of extracted power is requisite. Also, it requires regular maintenance of gearbox [1]. On the other hand, Variable – speed system (VSS) can operate over entire speed range and doesn't require regular use of gearbox. Thus it is majority accepted due to its high energy production efficiency and low torque spikes [2]. Such system has to be operated on the maximum power point tracking (MPPT) to capture maximum wind energy by adjusting speed of the shaft. For maximum power extraction from large wind speed range, permanent magnet synchronous generator (PMSG) and asynchronous machine such as doubly fed Induction generator (DFIG) [3].

PMSG is suitable for VSS as it has advantages such as with high number of poles for low speed there is no need of gearbox thus making system power dense with higher efficiency and high reliability. Also, in absence of gearbox, constructional, operational and maintenance cost is reduced [4, 5]. These advantages made PMSG – based wind turbine generator system most appropriate configuration for off-shore applications [6]. A comparative analysis of control strategies and circuit topologies for MPPT were proposed in [7] but these were complicated because of wind turbine structures and use of speed sensor. In absence of rotor and wind speed sensors, two different power based algorithms are employed to control maximum power evacuation from wind system but larger power variations are caused by variation in wind [8]. This misinterpretation of MPP, system can drive off.

Another sensor-less MPP tracking is discussed in [9] in which system operate on a pre-obtained curve i.e. optimum power curve. Problem with this curve is that a shaft speed sensor is similar to the system in which $V_{dc}^{*}(w)$ is used [10]. Control system of PMSG's for grid connection uses a decoupled current control method in a synchronized dq-frame. Performance of these current regulated vector controls depends on the accuracy of rotor position information. For generating accurate decoupled signals using Park transformation, an electro-mechanical position sensor is essential [11]. A direct – torque control scheme is discussed in [12] to remove the dependence of the system on different rotor position and various machine parameters. In [13], a sliding mode approach is developed for determining rotor position for sensor-less control. Also, in [14], a stator flux observer based on sliding – mode control is developed. This has merits of high robustness and simple control strategy. But in order to achieve sliding mode, a high sampling frequency is requisite, thus consume much computing resource which creates problem in practical realization. Also, there exists chattering problem associated with use of sign switching function which is major issue that has to carefully handle.

In this paper, a PnO based MPPT controller is modeled and simulated under MATLAB/SIMULINK environment and tested against PMSG based stand-alone conversion system driven by varying wind speed. A DC-DC converter is used for MPP tracking. A sensor-less algorithm is opted for coercing optimum power where power- speed curve is not required. For grid connection, regulation of DC voltage converter is done to get grid voltage synchronization and for frequency, PLL is required so that whatever is the speed of wind, output of inverter connected at grid-side should operate on same voltage and frequency as grid is having. Fig. 1 represents the basic block diagram of Wind power system. Wind turbine is coupled to a generator (synchronous/asynchronous).

Maximum power can be tracked using a DC-DC converter by varying the duty cycle. For grid synchronization, a converter is needed whose switching is controlled for keeping the frequency and voltage fixed by regulating DC voltage output from DC-DC converter.

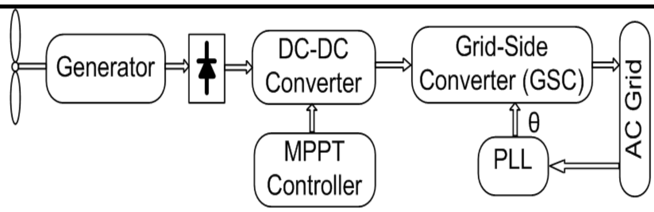


Fig. 1 System Configuration

II. Modelling of System

A. Wind Turbine Modelling

The aerodynamic power of wind in form kinetic energy is captured by the turbine and shaft connected to the generator, given by:

$$P = \frac{1}{2}\rho A v^3 C_p \qquad (1)$$

where, P indicates mechanical power output, ρ is the air density, A is swept-area, C_p is co-efficient of power and v is the velocity of the wind.

The ratio of the power captured by turbine to the total power is given by C_p (Co-efficient of power). Maximum value of this ratio lies between 0.4-0.5 depending on type of turbine used. It is basically related to Tip-speed Ratio(TSR)(λ) and pitch-angle (β) which is given as:

$$\lambda = \frac{\Omega R}{v} \qquad (2)$$

Thus,

$$C_p(\lambda,\beta) = 0.5176\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{-\frac{21}{\lambda_i}} + 0.0068\lambda_i \qquad (3)$$

where, $\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}$

Fig. 2 provides the variation in C_p with variation in λ(lambda) and β(Beta).

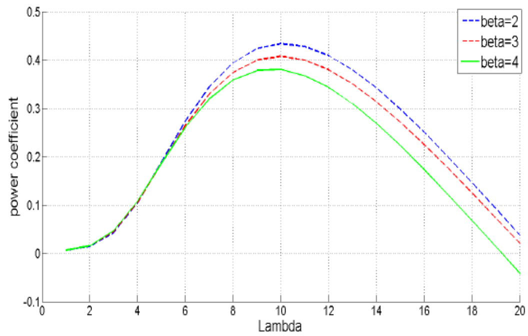


Fig. 2 Variation in C_p with variation in λ and β

Thus, aerodynamic power(P) is given by:

$$P = \frac{1}{2} pi r_o R^2 C_p(\lambda,\beta) v^3$$

Mechanical torque proportional to power given by following equation:

$$T = \frac{1}{2}\frac{pi r_o R^2 C_p(\lambda,\beta) v^3}{W_t} \qquad (4)$$

System is described by an electro-mechanical equation:

$$J\frac{dW}{dt} = T_m - T_{em} - BW \qquad (5)$$

where, B represents friction and J is the inertia.

B. PMSG Modelling

PMSG is basically used due to its advantages over DFIG like higher efficiency , higher reliability and high power density. This is basically responsible for conversion of mechanical energy (M.E.) into electrical energy (E.E.). Equations of PMSG in dq-frame can be expressed as:

$$\left.\begin{aligned} v_d &= -R_s i_d - L_d\frac{di_d}{dt} + L_q i_q w_r \\ v_q &= -R_s i_q - L_q\frac{di_q}{dt} + L_d i_d w_r + \varphi_f w_r \end{aligned}\right\} \qquad (6)$$

where w, Rs and φ_f represents angular velocity, stator resistance and magnetic flux, respectively.

Thus active and reactive power can be given as:

$$\left.\begin{aligned} P_s &= \tfrac{3}{2}\left(v_d i_d + v_q i_q\right) \\ Q_s &= \tfrac{3}{2}\left(v_q i_d - v_d i_q\right) \end{aligned}\right\} \tag{7}$$

III. Control Strategy

A. MPPT (Maximum Power Point Tracking)

These techniques are basically of two types i.e. from wind turbine using speed sensors or from generator side using power electronic equipment. In power electronic equipment duty is varied according to variation in the operating generator speed so that able to track maximum power from the turbine. For tracking the optimum power it follows optimum power line as shown in Fig. 3.

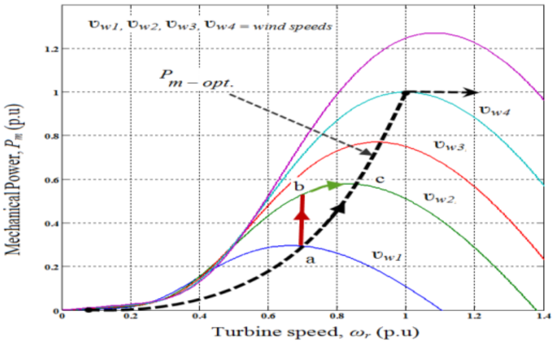


Fig. 3 Optimum Power Curve or Optimum Power Line

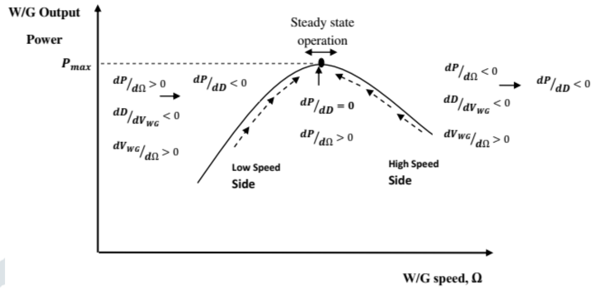


Fig. 4 MPPT process of WG

The perturbation and observation method of control is an efficient optimization method which uses the principle of searching for the local optimum point of a given function. It is used to search the optimal operating point and hence it will help to maximize the extracted energy. This control technique is based on introducing a small step size variation in a control variable and observing the changes in the target function till the slope of the function becomes zero. The controller guides the operating point by locating the position and the distance of the operating point from the peak point. The operating point moves towards right if it is in extreme left side and vice versa. In this method the duty cycle of the boost converter is perturbed and the dc link power is observed. In this method wind speed measurement is not required hence the mechanical sensors are not used. Therefore this method of control is more reliable and cost effective. The total MPPT process has been shown in the Fig. 4.

The maximum power point of operation is obtained mathematically when the condition is satisfied i.e. $\frac{dP_{dc}}{dV_{dc}} = 0$. Where P_{dc} is the DC link power and V_{dc} is the dc link voltage. Like the power vs. speed graph, the function P_{dc} (V_{dc}) has also a single operating point where maximum power can be achieved. This indicates that tracking of maximum power can be performed by step by step searching the rectified dc power rather than measuring the environmental conditions such as wind speed.

Duty-cycle adjustment is guided by the direction of slope of the function i.e. $\frac{dP_{dc}}{dV_{dc}}$, the duty-cycle value is increased in the high-speed side of the WG characteristic. Hence WG rotor-speed decreases and power increases till the controller reaches the Maximum Power Point is reached. In the same way when the starting point is in the low-speed side, following the direction of slope of the function i.e. $\frac{dP_{dc}}{dV_{dc}}$, which results in decrease of the value of duty cycle. Hence the WG rotor speed is gradually and the controlling variable subsequently converges at the MPP.

B. Grid-Side Converter Control(VF Control)

This controller implements an algorithm which is based on synchronous reference frame (SRF) theory. Main objective is to compute reference source currents. The load currents and the terminal three phase generated voltages are sensed as feedback signals and used for mathematical computation of amplitude of terminal voltage and system frequency. The load currents are transformed from abc to dq frame using park`s transformation.

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{8}$$

The three phase voltages from load is converted into two phase dc components i.e. d-axis and q-axis component using the unit vectors so obtained. In order to filter the undesired ac harmonic components, low pass filters are used. The fundamental components along with harmonic components are given as:

$$\left.\begin{aligned} i_{ld} &= i_{ddc} + i_{dac} \\ i_{lq} &= i_{qdc} + i_{qac} \end{aligned}\right\} \tag{9}$$

IV. Simulation Results and Discussions

Performance of the proposed system is simulated under MATLAB/Simulink environment to check the reliability of the system. Table 1 shows the specifications of PMSG and turbine used for performance evaluation.

Table 1. Specifications of PMSG and Wind Turbine

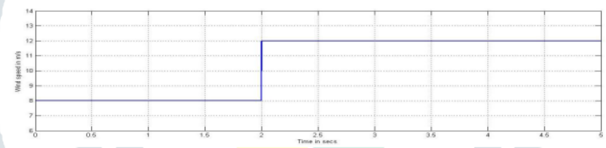
PMSG Specifications	
Variables	**Specifications**
Rating	10.5 kW
Stator resistance	0.434 ohm
Armature inductance	0.000834H
Flux linkage	0.5
Inertia	0.001197J
Damping	0.001189F
Poles pair	2
Wind Turbine Parameters	
Variables	**Specifications**
Nominal mechanical power	10.5KW
Base power of generator	10.5/0.9 KVA
Base wind speed	0.8
Base rotational speed	1.2
Pitch angle	0

A. MPPT Control(During wind speed change):

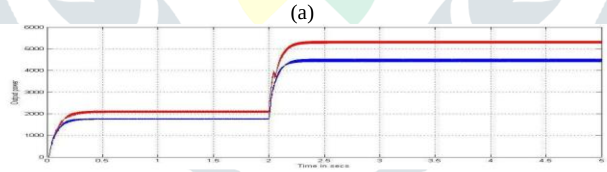
The simulation of PMSG based SWECS with MPPT control is carried out with step change in wind speed. The initial value of wind speed was 8 m/s. Due to step change at t= 2secs, the wind speed increased to 12m/s which is high enough to produce more power from PMSG. Thus, the generated voltages, source current, wind power, DC link voltage and current increases. The output power has increased but it's not the optimized power. Fig 5(a) shows the step change in wind speed from 8 m/sec to 12 m/sec at t= 2 secs.

When the wind speed is 8 m/sec, output generated power without MPPT control is around 1.5 kW. After wind speed increases to 12 m/sec, the output generated power without MPPT control is around 4.2 kW. Now with MPPT control, the generated power during low wind speed is around 2.2 kW and during high wind speed is around 6 kW. Fig 5(b) shows the difference in generated output power with and without MPPT control. The red plot indicates the output power with MPPT control whereas the blue plot indicates the generated power without MPPT control.

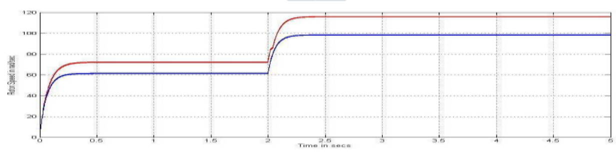
Before change in wind speed, the rotor speed without MPPT control is around 60 rad/secs. At t= 2 secs, the wind speed increases from 8 m/sec to 12 m/secs. Hence the rotor speed without MPPT control after step change in wind speed is around 100 rad/sec. similarly with MPPT control the rotor speed before change in wind speed is around 75 rad/sec and after change in wind speed is around 118 rad/sec, which is shown in Fig. 5 (c).



(a)



(b)



(c)

Fig 5.(a) Change in wind speed; (b) Output Power; (c) Rotor Speed

B. VF Control(During wind speed change):

The wind speed is changed in a unit step manner. Initially the wind speed is 10 m/secs and after step change the wind speed is 8 m/sec as shown in Fig 6(a). The three phase source voltage before change in wind speed is 320 V and after change in wind speed to 8m/sec the voltage remains almost around 320 V as shown in Fig 6(b). The imbalances seen in the diagram is due to controlling action of VF controller.

The reference terminal voltage is taken as 320 V. Before change in wind speed the terminal voltage is around 325 V as shown in Fig 6(c). When the wind speed is changed to 8 m/sec, the terminal voltage still remains around 320 V. This shows the voltage is controlled in drastic change in wind speed. The system frequency is 50 Hz. When the wind speed is 8 m/sec, the system frequency is computed using a three phase PLL which gives frequency around 50 Hz as shown in Fig 6(d). When the wind speed changes to 8 m/sec, the system frequency varies very slightly and stays around 50 Hz. This shows that the frequency is controlled properly by the VF controller in drastic change in wind speed.

When the wind speed is 10 m/sec, the load current is around 16 A. When the wind speed is changed to 8 m/sec, due to VF controller the load current is maintained around 16 A as before the change in wind speed as shown in Fig.6(e).The wind power when the wind speed is 10 m/sec is around 8 kW. When the wind speed decreased to 8 m/sec the wind power too decreased in a step down manner to 4 kW as shown in Fig 6(f).

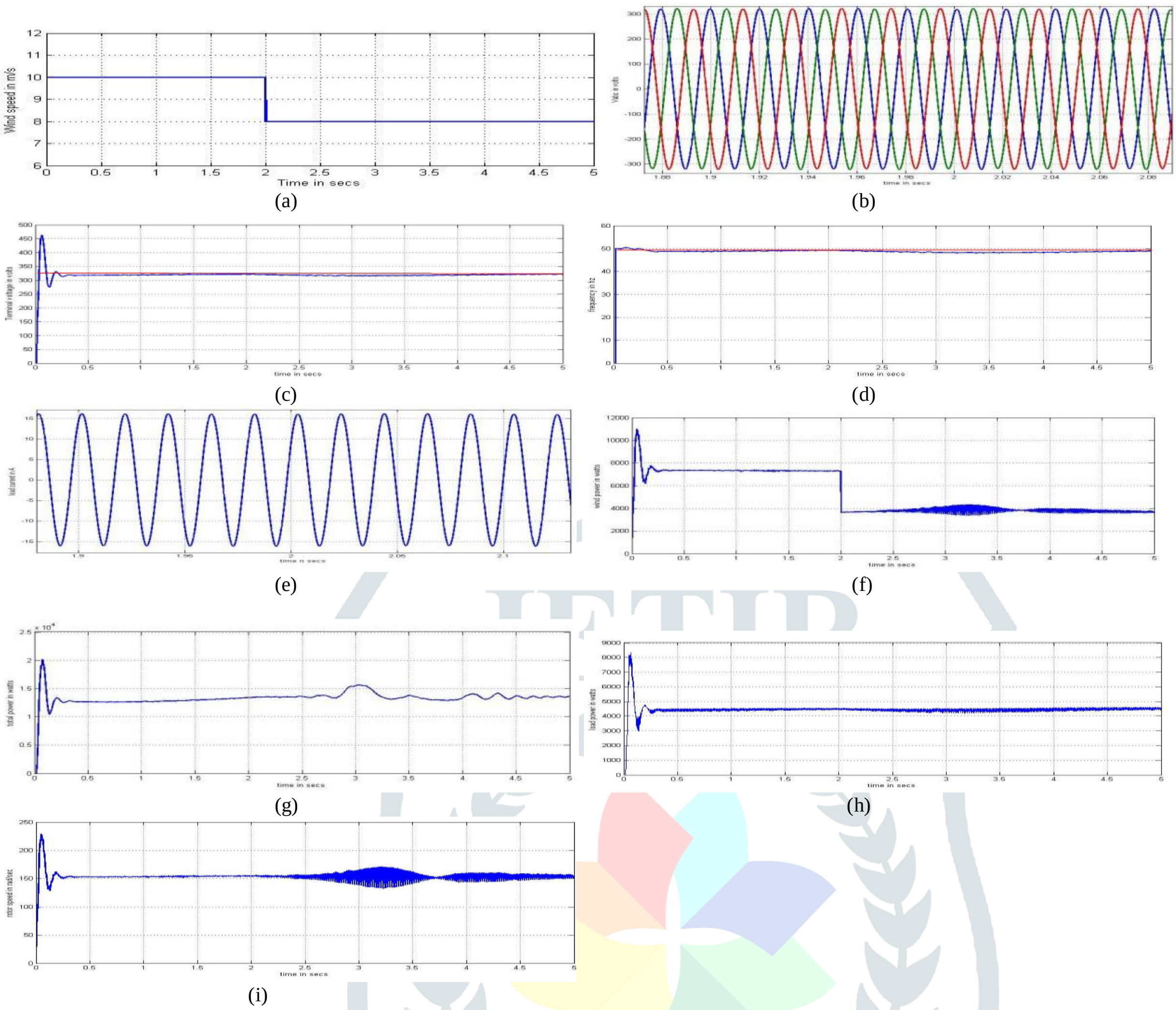


Fig. 6 (a) Variation in wind speed; (b) Three phase generated voltages of PMSG ; (c) Terminal voltage of PMSG; (d) Frequency; (e) Load Current; (f) Wind Power ; (g) Generated power; (h) Load Power; (i) Rotor speed

The generated power before change in wind speed was around 10.5 kW which is the rated power (Fig. 6 (g)). After decrease in wind speed from 10 m/sec to 8 m/sec, the generated power is remained constant around 10.5 kW due to VF controller. This shows the working of VF controller in drastic change in wind speed.

The load power before change in wind speed is around 4.5 kW and after change in wind speed is around 4.5 kW due to VF controlling action (Fig. 6 (h)).The rotor speed before change in wind speed is around 152.8 rad/sec as shown in Fig 6(i). After wind speed changes, the rotor speed remains unchanged due to VF controlling action. The speed is still around 152 rad/sec.

V. CONCLUSION

The PMSG based WECS was modeled and simulated using MATLAB/SIMULINK. The PnO MPPT control technique was implemented using a boost converter. Wind speed was varied in a step up manner from 8 m/sec to 10 m/sec and response of the controller is recorded. The plots of generated output power, dc link voltage, and output three phase voltage was recorded. The proposed model is run for 5 sec first without MPPT control and then with MPPT control. The power generated without MPPT controller was low i.e. 4.5 kW and the power generated with a MPPT controller is around 6 kW. This shows the improvement in the conversion efficiency of the controller. Most of the power loss occurs in VSC switches and converters. Hence the proposed MPPT method is utilized and it is seen that the efficiency of power conversion is increased to around 40%. The SWECS was tested against step change in wind speed from 10 m/s to 8m/s at t= 2secs It is seen from the figures that during change in wind speed at t= 2secs the power extracted from the wind decreases, three phase generated voltage from PMSG decreases, terminal voltage decreases, frequency fluctuation occurs, load power decreases, active power of the system decreases. Hence the system has under-performed.

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