

# CONTROL STRATEGIES FOR GENERATOR SIDE CONVERTER OF DIRECT DRIVEN WIND ENERGY CONVERSION SYSTEM

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**ABSTRACT**-This paper presents a comparative analysis of different controlling strategies for a direct driven PMSG wind energy power system (WECS) connected to the grid. The DC link voltage is controlled by the generator side converter by using a current mode PWM controller and fixed frequency sliding mode controller (FFSMC). The Grid side converter (GSC) controls the grid active power for maximum power point tracking. The validity of the proposed control schemes has been verified by simulation. The merits of the proposed control scheme are, it does not require the measurement of wind velocity, PMSG stator currents are sinusoidal and power injected into the grid at unity power factor. Modeling of Wind turbine, PMSG, controlling of generator side switch mode converter, controlling of the GSC and Simulation results are presented. Simulation is done in MATLAB/POWERSYSTEM environment.

**Index terms**-Variable-speed wind turbine, PMSG,PWM controller, FFSMC,DC link voltage, GSC.

## 1 INTRODUCTION

In recent years, the renewable energy sources have a promising solution for power paucity problems and for a cleaner and economical energy society. Among all available wind energy conversion systems (WECS), the direct driven Permanent magnet synchronous generator variable speed WECS systems integrated with power electronic interfaces are becoming popular due to their capability of extracting optimal energy capture, reduced mechanical stresses and aerodynamic noise [1]. The amount of energy captured from a WECS depends not only on the wind at the site, but depends on the control strategy used for the WECS and also depends on the conversion efficiency. PMSG has received much attention in wind-energy application because of their property of self-excitation, which allows an operation at a high power factor and high efficiency [2]. Direct driven PMSG WECS is needs a full scale power conversion to interface the generator with the Grid. The most popular grid connected topology of a direct driven PMSG variable speed WECS is the back-to-back converter. The characteristics of the back-to-back converter are that the converter utilizes active devices at both the generator side of the rectifier and the grid side of the inverter [3]. The major disadvantage of back-to-back topology is, the controller is complex and expensive. A simple topology for wind turbine generation was introduced in [4] which consist of a diode bridge rectifier, with a DC link to an active IGBT inverter. Although this type of converter is simple and reliable, but the power factor of the generator is low. The other problem is that when the

output voltage of the rectifier is lower than the grid, power cannot be injected to the grid. By summarizing the topology of back-to-back and diode rectifier, it is possible to insert a boost circuit between the diode rectifier and the GSC, in order to solve the issue of generator power factor [5]. For this topology of converter, operation at relatively low wind speeds is possible due to the inclusion of the boost circuit. The boost circuit maintains the DC bus link voltage at a constant value. This topology is utilized in this work.

Conventionally, the dc-link voltage is controlled by the GSC. However, the GSC may be out of control in the case of the grid voltage sags. At a grid fault, the dc-link voltage is increased excessively since the wind turbine continues to generate the power but the grid cannot absorb the fully generated power. Therefore, several literatures regarding the stabilization of dc link voltage have been published, such as of intermediate chopper and exchange of the control roles of two converters i.e, generator side converter is used to regulate the DC link voltage and GSC is controlled to transfer fully PMSG generated power . In [6], constant dc link voltage is maintained by using intermediate dc-dc converter. In [7], constant dc link voltage is obtained by controlling the generator side converter. But this technique involves measuring the power generated by PMSG.

This paper presents a simple control strategies for the generator side SMR and GSC to regulate the dc link voltage and shape the PMSG stator currents as sinusoidal which is derived from the variable structure systems (VSS) theory [8]-[9] and to inject the maximum power into the grid respectively. Effectiveness of the proposed method is verified by the simulations using MATLAB.

## 2. SYSTEM OVERVIEW

Fig. 1 shows the control structure of a generator side converter of PMSG-based variable-speed wind turbine which includes a wind turbine, PMSG, single-switch three-phase switch mode rectifier, and a vector-controlled PWM voltage source inverter. The output of a variable-speed PMSG is not suitable for use as it varies in amplitude and

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frequency due to fluctuating wind. A constant DC voltage is required for direct use, storage, or conversion to AC via an inverter. In this paper, a single switch three-phase switch-mode rectifier is used to convert the ac output voltage of the generator to a constant DC voltage before conversion to AC voltage via an inverter. The single-switch three-phase switch-mode rectifier consists of a three-phase diode bridge rectifier and a dc to dc converter. The output of the switch-mode rectifier can be controlled by controlling the duty cycle of an active switch (such as IGBT) at any wind speed to control the DC link voltage.

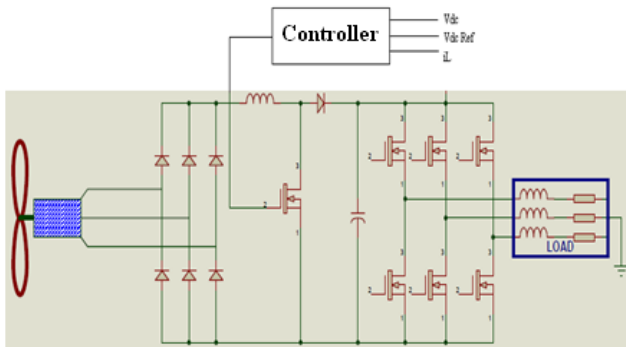


Fig 1. Wind turbine with diode rectifier and boost circuit

## 2.1 Wind Turbine Characteristics

The amount of power captured by the wind turbine (power delivered by the rotor) is given by

$$p_t = 0.5\rho AC_p(\lambda, \beta) \times (v_w)^3 = 0.5\rho AC_p \times \left(\frac{\omega_m R}{\lambda}\right)^3 \quad (1)$$

where  $\rho$  is the air density (kilograms per cubic meter),  $v_w$  is the wind speed in meters per second,  $A$  is the blades' swept area, and  $C_p$  is the turbine-rotor-power coefficient, which is a function of the tip-speed ratio ( $\lambda$ ) and pitch angle ( $\beta$ ).  $\omega_m$  = rotational speed of turbine rotor in mechanical radians per second, and  $R$  = radius of the turbine. The coefficient of performance of a wind turbine is influenced by the tip-speed to wind-speed ratio, which is given by

$$\text{TSR} = \lambda = (\omega_m R / v_w) \quad (2)$$

The wind turbine can produce maximum power when the turbine operates at the maximum cap (i.e., at  $C_{p\_opt}$ ). Therefore, it is necessary to keep the rotor speed at an optimum value of the tip-speed ratio  $\lambda_{opt}$ . If the wind speed varies, the rotor speed should be adjusted to follow the change. The available optimum power from a wind turbine can be written as

$$P_{m\_opt} = 0.5\rho AC_{p\_opt} \times \left(\frac{\omega_{m\_opt} R}{\lambda_{opt}}\right)^3 = K_{opt}(\omega_{m\_opt})^3 \quad (3)$$

Where

$$K_{opt} = 0.5\rho AC_{p\_opt} \times \left(\frac{R}{\lambda_{opt}}\right)^3 \quad (4)$$

$$\omega_{m\_opt} = \frac{\lambda_{opt}}{R} v_w = K_w v_w \quad (5)$$

Therefore, the target optimum torque can be given by

$$T_{m\_opt} = K_{opt}(\omega_{m\_opt})^2 \quad (6)$$

The function of the controller is to keep the turbine operating on the optimum power curve, as the wind velocity varies. It is observed that there is always a matching rotor speed which produces optimum power for

any wind speed. The optimum torque can be calculated from the optimum power given by (6).

## 2.2. PMSG Model

Basically, the mass model of a PMSG is the same as that of a permanent magnet synchronous motor (PMSM). The voltage and torque equations of the PMSM in the  $d - q$  reference frames are given by the following equations [10-13]:

$$v_d = R_a i_d + L_d \frac{di_d}{dt} - \omega_g L_q i_q \quad (7)$$

$$v_q = R_a i_q + L_q \frac{di_q}{dt} + \omega_g L_d i_d + \omega_g K \quad (8)$$

$$T_e = p\{K i_q + (L_d - L_q) i_d i_q\} \quad (9)$$

where  $v_d$  and  $v_q$  are the  $dq$ -axis voltages,  $i_d$  and  $i_q$  are the  $dq$ -axis currents,  $R_a$  is the stator resistance,  $L_d$  and  $L_q$  are the  $dq$ -axis inductances,  $\omega_g$  is the generator rotational speed,  $K$  is the permanent magnetic flux, and  $p$  is the number of pole pairs. The generating operation starts when the electromagnetic torque  $T_e$  is negative. The motion equation of the PMSG is given as follows:

$$T_e = T_\omega + J_{eq} \frac{d\omega_g}{dt} + \omega_g D \quad (10)$$

## 3. CONTROL OF GENERATOR SIDE CONVERTER

In the proposed WECS DC link voltage is regulated by the generator side converter not by GSC which is used conventionally. The control objective is to control the duty cycle of the switch in Fig. 2 to regulate the DC link voltage. Control of switch-mode power supplies can be difficult, due to their intrinsic non-linearity. In fact, control should ensure system stability in any operating conditions and good transient and steady state performances in terms of rejection of wind velocity disturbances and decrease the effect of parameter variations (robustness). In this paper different controlling schemes, which complies with the non-linear nature of switch-mode power rectifier, is represented by the current mode PWM controller and fixed frequency sliding mode control (FFSMC), which is derived from the variable structure systems (VSS) theory.

### 3.1 DC Link Voltage Regulation using a current mode PWM controller

The inner loop current regulator is eliminated and input voltage sensing is not required in the *Predictive current mode controller* [10]. In effect, the duty ratio of the switch is calculated in the predictive current mode controller by solving an equation in the modulator. One side of the equation is a certain function of the sensed current (for example average of the switch current for the NLC) and the other side is the carrier waveform derived after processing the voltage regulator output. In the presented *Predictive current mode controller*, the switch is controlled in such a way that the estimated inductor current will be proportional to the rectified input voltage at the end of the switching period ( $T_s$ )[10]. The estimation of the inductor current is possible since the input voltage is practically constant over a switching period. This enables us to predict the current ripple of the subsequent off period during the on time of the switch itself. The predicted off state ripple current can be added to the on state actual current to determine the current at the end of the switching period. The Predictive current

mode controller has the structure of a standard current programmed controller with a compensating ramp that is nonlinear.

The generalized control objective of a high power factor boost rectifier can be expressed as

$$f(i_g) = \frac{v_g}{R_e} \quad (11)$$

$R_e$  is the emulated resistance of the rectifier and is a function of the inductor current. This function can be different for different control strategies. In the predictive current mode controller the duty ratio of the switch is controlled in such a way that the inductor current becomes proportional to the rectified input voltage at the end of each switching period. Therefore, for Predictive current mode controller the function  $f(i_g)$  is given by (12)

$$f(i_g)_{psm} = i_g[T_s] \quad (12)$$

It may be noted that the inductor current at the end of period is equal to the current at the beginning of the next period, or,  $i_g[T_s]_k = i_g[0]_{k+1} = \frac{v_g}{R_e}$  in CCM. Therefore, when the converter is operating in the CCM the slope of the turn-off current can be predicted during ON time of the switch itself. Then, instead of (12), (13) can be used to the predictive current mode controller

$$i_g[dT_s]_k = i_s[dT_s]_k = \frac{v_g}{R_e} + \left(\frac{V_o - V_g}{L}\right)(1-d)T_s \quad (13)$$

The expression on the right-hand-side of (13) represents the predicted current trajectory, whose initial value is  $\frac{v_g}{R_e} + \left(\frac{V_o - V_g}{L}\right)T_s$  and the slope is equal to  $\left(\frac{V_o - V_g}{L}\right)$ , the slope of the off state inductor current. In PSM the switch turns off when the actual current equals the predictive current trajectory or (13) is satisfied.

We can use the boost converter continuous conduction mode input to output conversion equation of (14) to replace  $v_g$  in (13) by  $v_o$  and  $d$ . Then we get (15) as the duty ratio control function for the PSM

$$v_g = (1-d)V_o \quad (14)$$

$$i_g[T_s] = I_{ref}(1-d) + \frac{V_o T_s}{L} d(1-d) \quad (15)$$

where  $I_{ref} = \frac{V_o}{R_e} = \frac{v_m}{R_s}$  (16)

$R_s$  is the current sensor resistance of the converter and  $v_m$  is the input voltage to the modulator. Under closed loop operation is obtained as the output of the voltage error amplifier loop. In [11] and [12], the right-hand-side expressions of (15) is converted into suitable carrier waveforms by replacing the duty ratio term  $d$  by  $t/T_s$

$$I_c = \frac{V_c(t)}{R_s} = I_{ref} \left(1 - \frac{t}{T_s}\right) + \frac{V_o T_s}{L} \frac{t}{T_s} \left(1 - \frac{t}{T_s}\right) \quad (17)$$

### 3.2 DC Link Voltage Regulation using fixed frequency Sliding Mode Control

According to the Sliding mode control theory [8], all state variables are sensed, and the states are multiplied by the proper gains  $K_i$  and added together to form the sliding function  $\sigma(x, t)$  hysteretic block maintains this function to zero, so that we can define sliding surface as:

$$\sigma(x, t) = \sum_1^N K_i x_i = 0 \quad (18)$$

Where  $N$  is the system order (number of state variables)

For second order systems

$$\sigma = x_1 + \tau x_2 \quad (19)$$

This is a linear combination of the two state variables. In the phase plane, equation  $\sigma = 0$  represents a line, called sliding line, passing through the origin.

We now define the following control strategy

$$\text{If } \sigma > +\beta \Rightarrow u = 0 \quad \text{and If } \sigma > -\beta \Rightarrow u = 1 \quad (20)$$

Where  $\beta$  define a suitable hysteresis band.

The control objective of the regulation problem is to drive the states to zero. In this paper a new variation of Sliding mode control of SMR based on Quasi-Steady-State is proposed.

### System Model

Dynamic behavior of the boost converter can be approximated by the following relations:

$$i_s = i_L \text{sgn}(V_s) \quad (21)$$

$$L \frac{di_L}{dt} = |V_s| - V_{DC} \cdot u_{eq} \quad (22)$$

$$C \frac{dV_{DC}}{dt} = i_L u_{eq} - \frac{V_{DC}}{R} \quad (23)$$

Where  $u_{eq}$  is the average values of the control variable  $u$  ( $u=0$  when switch is on and  $u=1$  when switch is off),  $i_L$  is the boost inductor current,  $i_s$  is the AC source current,  $V_{DC}$  is the boost converter output voltage  $V_s$  is the PMSG rms voltage.

$$\sigma = H_{LP}(s)(i_L - K \cdot u) \quad (24)$$

Note that this sliding surface will satisfy the transversal condition if  $H_{LP}(s)$  is the first order low pass filter ( $H_{LP}(s) = s_0 / (s + s_0)$ ), it can be used to calculating the average value of  $i_L - K \cdot u$  during a switching period. The control law associated with this surface is deduced by using the reaching condition,  $\sigma \cdot \dot{\sigma} < 0$  [8], which yields

$$u = \begin{cases} 1 & \dots \dots \dots \text{when } \sigma > 0 \\ 0 & \dots \dots \dots \text{when } \sigma < 0 \end{cases}$$

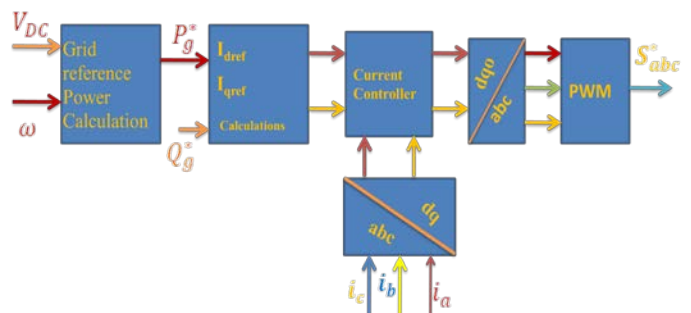
Moreover, a proportional-integral control of  $K$  has been used to make the output voltage be regulated to a reference value  $V_{o ref}$ .

$$K = K_p (V_{DCref} - V_{DC}) + K_i \int_0^t (V_{DCref} - V_{DC}) d\tau \quad (25)$$

In order to implement the proposed sliding surface, a first order low-pass filter, an analog multiplexer, a PI controller and hysteresis comparator are required.

## 4. CONTROL OF GRID-SIDE CONVERTERS FOR MPPT

The GSC is controlled to inject maximum power during the period cut in and rated wind speed. The grid power reference  $P_g^*$  is obtained from the inertial power, the

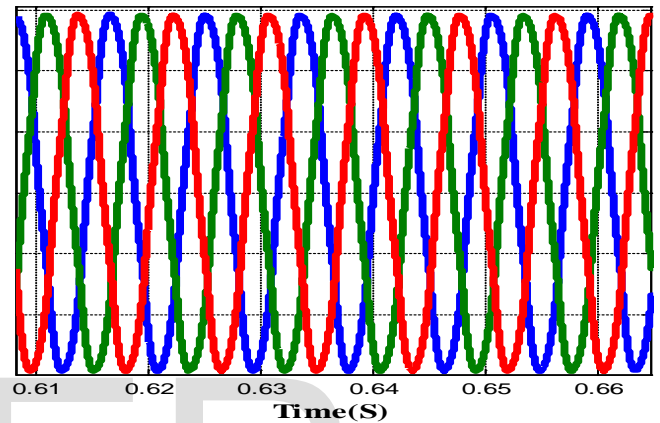
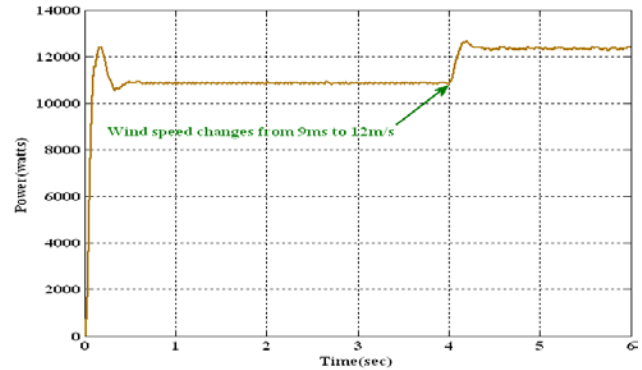


**Fig.2 Proposed Control Strategy for GSC**

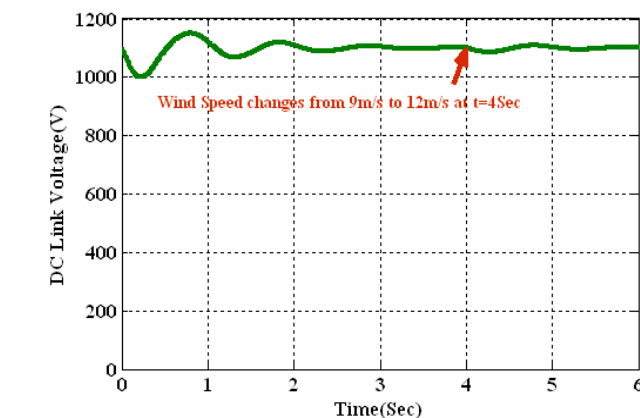
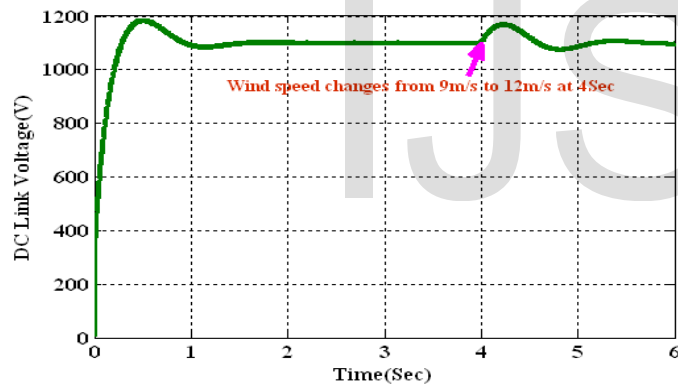
generator loss, the dc-link capacitor power, and the generator power reference obtained by applying the MPPT method from the wind turbines. if the wind speed is greater than the rated speed, then the output power command  $P_g^*$  is set to 1pu. The proposed controller for GSC is shown in Fig.2.

**5.Simulation Results**

The model of the PMSG based wind-turbine system of Fig. 1 is built using Matlab/power system simulation software. The simulation model is developed based on a 15kW PMSG. The power converter and the proposed control algorithms for the generator side converter and GSC are implemented and included in the model. Fig.3. shows in the DC link voltage with current mode PWM controller and FFSMC. Fig.4 shows the wind power and PMSG stator currents when the wind speed is changed from 9m/s to 12m/s at t=4sec. It is observed that the grid voltage, current and PMSG stator currents are sinusoidal. It is seen that the controller tightly regulate the dc link voltage under grid voltage sags and wind fluctuations. The simulation results shows that the FFSMC controller regulate the DC link voltage tightly with good transient response compared with current mode PWM controller.



**Fig.4 Wind Power and PMSG stator currents**



**Fig.3. Dc link Voltage and Grid currents for Current mode PWM controller and FFSMC**

**5. CONCLUSION**

A simple control strategies for a direct drive PMSG variable speed wind turbine has been presented in this paper. The proposed controllers are capable of maintaining the constant dc link voltage of the variable-speed wind turbine under fluctuating winds and under the grid voltage sags. In this control schemes DC link voltage is regulated by controlling the generator side converter. The GSC controls the power injected into the grid according to the power control strategy. The simulation results demonstrate that the FFSMC good dynamic and steady-state performance than conventional current mode PWM controller.

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