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Fixed Frequency Sliding Mode Controller for Direct Driven Wind Energy Conversion System

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Abstract: This paper presents a simple control strategy for a direct driven PMSG wind energy power system (WECS). The dc link voltage is controlled by the generator side converter by using Fixed frequency sliding mode control (FFSMC). The Grid side converter (GSC) controls the grid active power for maximum power point tracking. The validity of the proposed control scheme has been verified by simulation. The merits of the proposed control scheme are, it does not require the measurement of wind velocity,good dynamic response of DC link voltage, 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 GSC and Simulation results are presented. Simulation is done in MATLAB/POWERSYSTEM environment.

Index terms: Variable-speed wind turbine, PMSG, FFSMC, DC link voltage, GSC.

1. INTRODUCTION

In recent years, the renewable energy sources have 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 capture 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]. The use of permanent magnet in the rotor of the PMSG makes it unnecessary to supply magnetizing current through the stator for constant air-gap flux; the stator current need only to be torque producing. Hence, for the same output, the PMSG will operate at a higher power factor because of the absence of the magnetizing current and will be more efficient than other machines.

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 for the rectifier and the grid side for the inverter [3]. The major disadvantage of back-to-back topology is, the controller is complex and expensive because it requires 12-channel Pulse Width Modulation (PWM) signals for the rectifier and the inverter. For this reason, in a practical application, the control system requires at least two or more Micro-Controller Units (MCU), Digital Signal Processor (DSP), Field Programmable Gate Array (FPGA), etc. to control the chips on the board. 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 an 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 strategy 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.In these techniques DC-DC converter switch operates at variable frequency. In the

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proposed technique DC-DC converter in Fig.1. is operating at constant frequency and ensures the same dynamic response of DC link voltage same as [8], [9]. 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 frequency due to fluctuating wind. A constant DC voltage is required for direct use, storage, or converted 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.

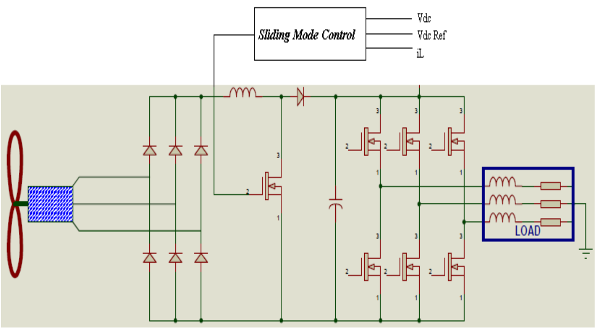

Fig 1. Wind turbine with diode rectifier and boost circuit

2.1 Wind Turbine Characteristics

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

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

where ρ is the air density (kilograms per cubic meter), v_ω 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 (λ) and pitch angle (β). ω_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

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

The wind turbine can produce maximum power when the turbine operates at maximum C_p (i.e., at C_{p_opt}). Therefore, it is necessary to keep the rotor speed at an optimum value of the tip-speed ratio λ_{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

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

Where

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

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

Therefore, the target optimum torque can be given by

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

The mechanical rotor power generated by the turbine as a function of the rotor speed for different wind speed is shown in Fig.2. The optimum power is also shown in this figure. The optimum power curve (P_{opt}) shows how maximum energy can be captured from the fluctuating wind. The function of the controller is to keep the turbine operating on this curve, as the wind velocity varies. It is observed from this figure that there is always a matching rotor speed which produces optimum power for any wind speed. If the controller can properly follow the optimum curve, the wind turbine will produce maximum power at any speed within the allowable range. The optimum torque can be calculated from the optimum power given by (6). For the generator speed below the rated maximum speed, the generator follows (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, ω_g is the generator rotational speed, K is the permanent magnetic flux, and p is the number of pole pairs. Generating operation starts when the electromagnetic torque Te 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 SMR FOR CONSTATNT DC-LINK VOLTAGE

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). A different approach, which complies with the non-linear nature of switch-mode power rectifier, is represented by the sliding

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mode control, which is derived from the variable structure systems (VSS) theory.

3.1 DC Link Voltage Regulation using Sliding Mode Control

According to the Sliding mode control theory [8], all state variables area sensed, and the states are multiplied by 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:

$$\sigma(x,t) = \sum_1^N K_i x_i = 0 \quad (11)$$

Where N is the system order (number of state variables)
For second order systems

$$\sigma = x_1 + \tau x_2 \quad (12)$$

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 (Which is the final equilibrium point for the system).

We now define the following control strategy

$$\text{If} \quad \sigma > +\beta \Rightarrow u = 0 \quad (13)$$

$$\text{If} \quad \sigma > -\beta \Rightarrow u = 1 \quad (14)$$

Where β define a suitable hysteresis band. In this way, the phase plane is divided in two regions separated by the sliding line, each associated to one of the two sub topologies defined by switch status u. When the system status is in P, Since we are in the region $\sigma < -\beta$, the switch is closed and the motion occurs along a phase trajectory corresponding to *u=1*. When the system status crosses the line $\sigma = +\beta$, according to (14), *u=0* and the system status follows a phase trajectory corresponding to *u=1*. observing that the phase trajectories, in proximity of the sliding line, are directed toward the line itself, the resulting motion is made by continuous commutations around the sliding line, so that the system status is driven to the final equilibrium point.

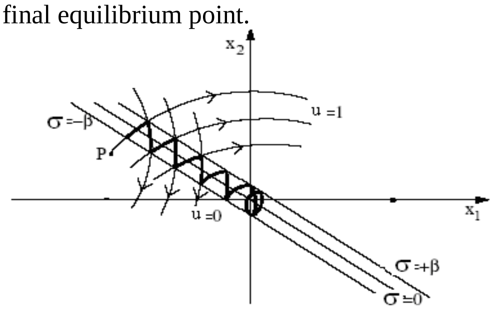

Fig.2. Sliding surface

From this example, in the hypothesis of a suitable small value of β, two important conclusions arise

- When the system is in the sliding mode, its evolution is independent of the circuit parameters. It depends only on the sliding line chosen. In the example shown in Fig.3 the dynamic is of the first order with a time constant equal to τ.
- If N is the order of the original system, the dynamic of the controlled system in sliding mode has order N-1, since the state variables are constrained by the equation $\sigma = 0$.

Note that the switching frequency is determined by the amplitude of the hysteresis band β. The potentialities of this control technique in the application to switch to switch-mode power supplies are now evident: it exploits the intrinsic non-linear nature of these converters and it is able to provide dynamic behaviors that are different from that of the substructures composing the system, and correspond to that of a reduced system.

The control objective of the regulation problem is to drive the states to zero. When matched uncertainty alone is present, the nominal linear system representation is considered when designing the switching function. In this work a new variation of Sliding mode control of SMR based on Quasi-Steady-State is proposed to operate the switch at constant frequency.

3.2. Switching surface design

In the simple case of the second-order systems considered in the previous section, sliding mode control design requires only selection of parameter τ. Selection, must be done in order to ensure the following three constraints The *hitting condition*, which requires that the system trajectories cross the sliding line irrespective of their starting point in the phase plane; The *existence condition*, which requires that the system trajectories near the sliding line (in both regions) are directed toward the line itself; The *stability condition* of the system motion on the sliding line (i.e. the motion must be toward the equilibrium point).

3.3. Existence Condition:

The existence condition requires that the phase trajectories are directed toward the sliding surface in a small volume around the surface itself. It is achieved by defining the appropriate Lyapunov function $V(x,t,\sigma)$. For signal input systems it is ordinarily convenient to choose a Lyapunov function of the form $V(x,t,\sigma) = 0.5\sigma^2(x)$. . To determine the gains necessary to drive the system state to the surface $\sigma(t) = 0$, they may be choose so that

$$V(x,t,\sigma) = 0.5\frac{d\sigma^2}{dt} = \sigma(x)\frac{d\sigma(x)}{dt} = \sigma.\dot{\sigma} < 0 \quad (15)$$

Thus sliding mode does exist on a discontinuity surface whenever the distances to this surface and the velocity of its hange $\dot{\sigma}$ are of opposite signs, i.e. when $\lim_{x\to+0}\dot{\sigma} > 0$ and $\lim_{x\to+0}\dot{\sigma} < 0$

3.4. Stability Condition

Switching surface design is predicted upon knowledge of the system behavior in a sliding mode. This behavior depends on the parameters of the switching surface. In any case, achieving a switching-surface design requires analytically specifying the motion of the state trajectory in a sliding mode. The so called method of equivalent control is essential to this specification.

3.5. Equivalent Control

Equivalent control constitute an equivalent input which, when exciting the system, produces the motion of the system on the sliding surface whenever the initial state is on the surface. Suppose at t_1 the plant's state trajectory intercepts the switching surface, and a sliding mode exists. The existence of a sliding mode implies that, for all $t \geq t_1, \sigma(x(t),t) = 0$ and hence $\sigma(x(t),t) = 0$. Using the chain rule, we define the equivalent control u_{eq} for system satisfying

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$$\dot{\sigma} = \frac{\partial\sigma}{\partial t} + \frac{\partial\sigma}{\partial x}\dot{x} = \frac{\partial\sigma}{\partial t} + \frac{\partial\sigma}{\partial x}f(x,t) + \frac{\partial\sigma}{\partial x}B(x,t)u_{eq} = 0 \quad (16)$$

Assume that the matrix product $\frac{\partial\sigma}{\partial x}B(x,t)$ is nonsingular for all t and x, and one can compute u_{eq} as

$$u_{eq} = -\left[\frac{\partial\sigma}{\partial t}B(x,t)\right]^{-1}\left(\frac{\partial\sigma}{\partial t} + \frac{\partial\sigma}{\partial x}f(x,t)\right) \quad (17)$$

Therefore, given that $\sigma(x(t_1), t_1) = 0$, then for all $t \geq t_1$, the dynamics of the system on the switching surface will satisfy

$$\dot{x}(t) = \left[1 - B(x,t)\left[\frac{\partial\sigma}{\partial x}B(x,t)\right]^{-1}\frac{\partial\sigma}{\partial x}\right]f(x,t) - B(x,t)\left[\frac{\partial\sigma}{\partial x}B(x,t)\right]^{-1}\frac{\partial\sigma}{\partial t} \quad (18)$$

This equation represents the equivalent system dynamics on the sliding surface. The driving term is present when some form of tracking or regulation is required of the controlled system, e.g. when

$$\sigma(x,t) = \sum_1^N K_i.x_i + r(t) = 0 \quad (19)$$

With r(t) serving as a "reference" signal.

3.6. Physical Meaning of the Equivalent Control

A real control always includes a slow component to which a high rate component may be added. So decompose the control structure as

$$u(x,t) = u_{eq}(x,t) + u_N(x,t) \quad (20)$$

Where u_{eq} is only valid on the sliding surface and u_N assures the existence of a sliding mode. And u_N is defined as

$$u_N(x,t) = sgn(\sigma) \quad (21)$$

Where $sgn(\sigma) = \frac{\sigma}{|\sigma|}$

Since a control plant is a dynamic object, its behavior is largely determined by the slow component while its response to the high rate component is negligible. On the other hand, the equivalent control method demands a substitution of the real control in the motion Eq (20) with a continuous function $u_{eq}(x,t)$, which does not contain any high rate component. The equivalent control equals the slow component of the real control i.e. average control value and may be measured by a first order linear filter provided its time constant is small enough as compared with the slow component, yet large enough to filter out the high rate component and approximately matched with the boundary layer width.

3.7 FFSMC for Boost converter

FFSMC controller for DC-DC boost converter as explained in section.3. is designed as follows:

Taking into account that the cut-off frequency of the filter is much higher the line frequency, the resulting close loop dynamic behavior of the boost converter can be approximated by the following relations:

$$i_s = i_L sgn(V_s) \quad (22)$$

$$L\frac{di_L}{dt} = |V_s| - V_{DC}.u_{eq} \quad (23)$$

$$C\frac{dV_{DC}}{dt} = i_L u_{eq} - \frac{V_{DC}}{R} \quad (24)$$

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.

$$\sigma = H_{LP}(s)(i_L - K.u) \quad (25)$$

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

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

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

$$K = K_p(V_{DCref} - V_{DC}) + K_I\int_0^t(V_{DCref} - V_{DC})d\tau \quad (26)$$

Fig.1 shows the block diagram of proposed controller. In order to implement the proposed sliding surface, a first order low-pas filter, an analog multiplexer, and a proportional integral controller are required. Finally, the state of the switch is determined by a hysteresis comparator, according to the control law deduced above.

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 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 grid side converter is shown in Fig.3.

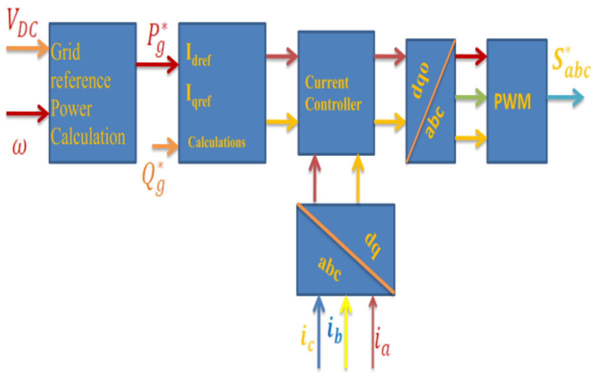

Fig.3 Proposed Control Strategy for GSC

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 Generator side converter and GSC are implemented and included in the model. Fig. 4 shows the dc link voltage and grid current. The proposed control algorithms used to extract maximum power from the wind turbine under fluctuating wind. Fig. 5 shows the wind power and PMSG

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stator currents when the wind speed is changes from 9m/s to 12m/s at t=4sec. It is observed that the grid voltage, current and PMSG stator currents are sinusoidal. Fig. 5 shows the responses of the dc link voltage when grid voltage sag is taking place at t=2sec. It is seen that the controller tightly regulate the dc link voltage under grid voltage sag.

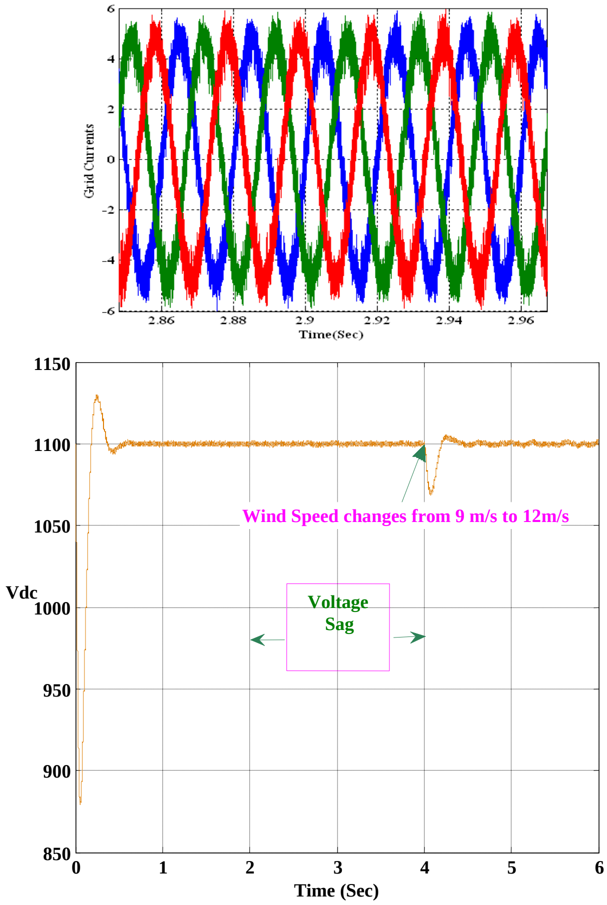

Fig.4. Dc link Voltage and Grid currents

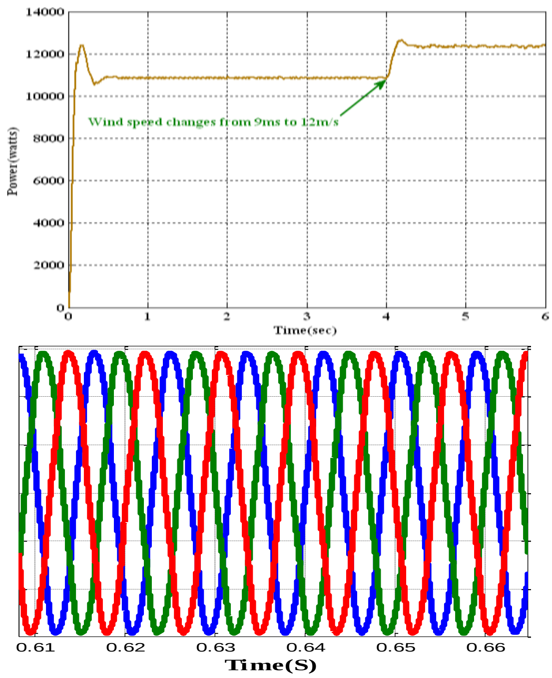

Fig.5 Wind Power and PMSG stator currents

6. CONCLUSION

A simple control strategy for a direct drive PMSG variable speed wind turbine has been presented in this paper. The proposed controller is capable of maintaining the constant dc link voltage of the variable-speed wind turbine under fluctuating wind and under the grid voltage sags. In this control schemes DC link voltage is regulated by controlling the generator side converter, not by GSC which is usually used. A new dc link voltage controller has been designed by using FFSMC. The GSC controls the power injected into the grid according to the power control strategy. The simulation results demonstrate that the proposed controller works very well and shows very good dynamic and steady-state performance.

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