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Design of an Internal Model Control strategy for Grid side Converter for the Permanent Magnet Synchronous Generator

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***Abstract*— Permanent Magnet Synchronous Generator is the one more wide application in wind power conversion system. To attain the largest wind power at different wind speeds, the generator is connected to the electric network by a full scale AD-DC-AC converter. This paper presents the design of back to back converter and its related control strategy. The PMSG side converter control is used to conduct the generator rotor velocity at an optimal value, while the grid side converter control is achieved using voltage oriented control based on Internal Model Control which separately regulates active and reactive power injected to the network. The performance of the proposed design is verified with Matlab/Simulink. The simulation results demonstrate that the proposed structure has good performance.**

***Keywords*—wind turbine, Permanent Magnet Synchronous Generator, Grid-side converter, Internal Model Control.**

I. INTRODUCTION

Recently wind energy conversion system is one of the most growth renewable energy sources for generation of the electrical energy. There are many different configurations of wind energy conversion system which are diverse in the types of generators, power converters and control circuits. Besides variable speed wind turbine based on Permanent Magnet Synchronous Generator (PMSG) is considered a popular wind turbine concept which is known with its main characteristics of eliminating the gear box, smaller size and full controllability of the system under MPPT algorithm.

In addition, the wind energy is required to participate in electric network operation through a suitable generation control techniques. So the overall wind energy system consists of wind turbine related to Permanent Magnet Synchronous Generator connected to the grid through a full scale back to back converter. Therefore the control of the injected power in the network has a major importance for grid demand necessities.

This paper presents the model of the grid side converter in order to synchronize the voltage generated through the generation system with the grid. The control of the inverter is achieved by voltage oriented control based on Internal Model Control. The Internal Model Control is relatively a new trend in converter control design. It has a simple structure and can ensure an arrangement between closed loop performance and robustness.

This paper first introduces the general configuration of overall wind system in section II. Section III is dedicated to the control strategy of the generator side converter. The proposed control design of the inverter using internal model control is developed in section IV and V. The simulation results using MATLAB/Simulink and the analysis of the performance of the proposed design are conducted in section VI.

II. SYSTEM OVERVIEW

A. System description

Fig.1 shows that the generator is directly coupled to the rotor of the wind turbine without using the gearbox. To achieve the interface between the PMSG and the electric network a fully controlled back to back converter is used. The strategy of the control of the generator side converter is the use of Field Oriented Control (FOC) which controls separately the electromagnetic torque and the magnetic flux via the stator currents employing the rotating dq reference frame. The dc link voltage is maintained at the reference value via the control of the grid side converter. The control of the inverter operates the grid voltage oriented decoupled control strategy which regulates independently the active and reactive power transferred from the dc bus to the grid.

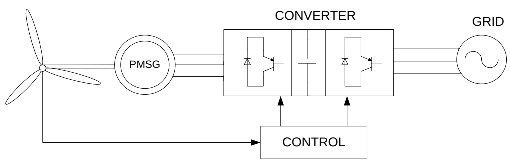

Fig.1 system configuration of wind turbine

B. Generator modelling

The electric power is generated using Permanent Magnet Synchronous Generator. The dynamic model of the PMSG is projected on a reference rotating synchronously frame with

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the magnet flux. The voltage and the torque equation are given by the following equations [1],[2],[3]

$$v_d = R_s i_d + L_d \frac{di_d}{dt} - L_q i_q \omega_e \quad (1)$$

$$v_q = R_s i_q + L_q \frac{di_q}{dt} + L_d i_d \omega_e + \omega_e \phi \quad (2)$$

where v_d and v_q are the voltages, and i_d and i_q are the currents along the d and q axis respectively, R_s is the stator resistance, $L_d = L_q$ are the inductance of the generator, ϕ is the permanent magnetic flux, ω_e is the electrical rotating speed of the generator, $\omega_m = \frac{\omega_e}{p}$ in which p is the number of pole pairs.

The motion equation is expressed as follows

$$T_m - T_{em} = J \frac{d\omega_m}{dt} + f \omega_m \quad (3)$$

Where J is the moment of inertia, T_m is the mechanical torque developed by the rotor of the turbine and f is the friction coefficient.

III. Control strategy of the generator side converter

The control of the PMSG side converter is achieved through a rectifier. This control consists of two control loops as shown in Fig.2 in which the q-axis current reference is obtained from the control of the electromagnetic torque and the d-axis component current is set at zero in order to reduce the copper loss. The optimal speed reference is obtained using maximum power point tracking technique. Then the controller provides the reference voltage v_d^* and v_q^* in which compensation voltage of both q and d axis were combined into the control loop. [4],[5],[6]

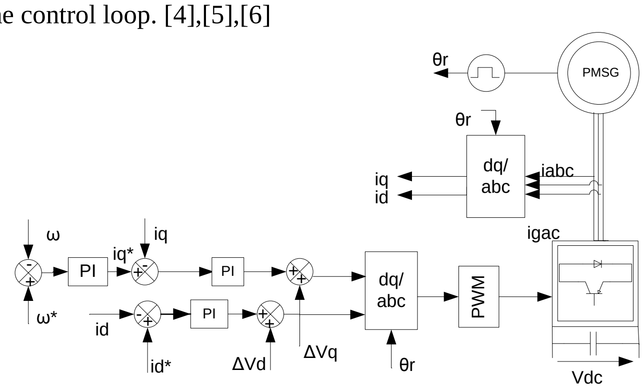

Fig.2 Generator side converter control structure

IV. Design of the grid side converter

A. Grid side converter model

The inverter is used to supply the energy from the generator side to the distribution electric network and adjust the dc circuit voltage to regulate the active and reactive power delivered from the generator to the grid.

The inverter voltage is expressed as follows

$$\begin{aligned} v_{ga} &= v_g \cos \omega_g t \\ v_{gb} &= v_g \cos(\omega_g t - \frac{2\pi}{3}) \\ v_{gc} &= v_g \cos(\omega_g t + \frac{2\pi}{3}) \end{aligned} \quad (4)$$

where v_g is the peak grid phase voltage and ω_g is the angular frequency.

Considering the Fig.3, the relationship between the line currents and the grid side converter can be expressed in stationary abc frame as follows

$$\begin{bmatrix} v_{ia} \\ v_{ib} \\ v_{ic} \end{bmatrix} = R_f \begin{bmatrix} i_{ga} \\ i_{gb} \\ i_{gc} \end{bmatrix} + L_f \frac{d}{dt} \begin{bmatrix} i_{ga} \\ i_{gb} \\ i_{gc} \end{bmatrix} + \begin{bmatrix} v_{ga} \\ v_{gb} \\ v_{gc} \end{bmatrix} \quad (5)$$

where v_{ia} , v_{ib} , v_{ic} are the inverter output voltage, R_f and L_f are the filter resistance and the filter inductance respectively, i_{ga} , i_{gb} , i_{gc} are the line currents.

The model of the inverter can be written in dq reference frame which is rotated with the grid voltage angular speed.

$$\begin{bmatrix} v_{id} \\ v_{iq} \end{bmatrix} = R_f \begin{bmatrix} i_{gd} \\ i_{gq} \end{bmatrix} + L_f \frac{d}{dt} \begin{bmatrix} i_{gd} \\ i_{gq} \end{bmatrix} + \begin{bmatrix} v_{gd} \\ v_{gq} \end{bmatrix} + L_f \omega_g \begin{bmatrix} -i_{gd} \\ i_{gq} \end{bmatrix} \quad (6)$$

Where v_{id} and v_{iq} are the d-axis and the q-axis output inverter voltage, i_{gd} and i_{gq} are the d and q axis grid currents.

In the point of common coupling of the grid side, the instantaneous active and reactive power delivered from the inverter to the grid are given by

$$\begin{aligned} P &= \frac{3}{2}(v_{gd} i_{gd} - v_{gq} i_{gq}) \\ Q &= \frac{3}{2}(v_{gq} i_{gd} - v_{gd} i_{gq}) \end{aligned} \quad (7)$$

Referring to the alignment of the d-axis of the rotating frame with the AC voltage, the active and reactive power absorbed from the utility grid can be expressed as

$$\begin{aligned} P &= \frac{3}{2} v_{gd} i_{gd} \\ Q &= -\frac{3}{2} v_{gd} i_{gq} \end{aligned} \quad (8)$$

B. The dc-link design

The dc-link is designed to related the ac and dc side of the inverter, then the voltage equation is given by

$$C \frac{dv_{dc}}{dt} = -i_{dc,grid} + i_{dc,generator} \quad (9)$$

$$v_{dc} i_{dc,grid} = \frac{3}{2} v_{gd} i_{gq} \quad (10)$$

Considering an ideal inverter with large frequency modulation, the dc-link voltage is selected as function of the line to line voltage on the AC side v_{LL} .[7],[8],[9]

$$v_{dc} = \frac{2\sqrt{2}v_{LL}}{m\sqrt{3}} \quad (11)$$

Where m is the modulation index $0 \le m \le 1$

The sizing of the DC link capacitor of the back to back converter is chosen as follows

$$C = \frac{0.9 I_{peak}}{4\pi\sqrt{2} f \Delta v_{dc}} \quad (12)$$

where I_{peak} is the peak AC line current, f is the grid frequency, Δv_{dc} is the ripple dc-link. If the dc-ink voltage is approximated to $2v_{gd} = v_{dc}$, then equation (9) can be written as

$$C\frac{dv_{dc}}{dt} = -\frac{3}{4} v_{gd} i_{gd} + i_{dc,generator} \quad (13)$$

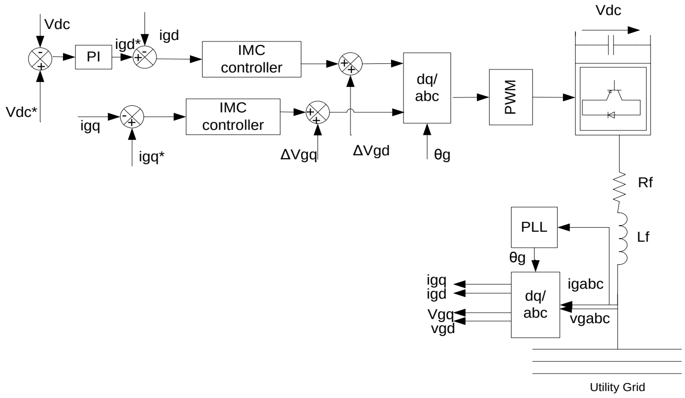

Fig.3 Grid side control structure

V. Proposed Control Strategy of the Grid Side Converter

The main objectives of the inverter control strategy are the adjustment of the dc bus voltage and the adjusting of the active and reactive power. Fig. 3 shows the voltage oriented control scheme performed in the dq reference frame. The control consists of two control loops. The external control loop regulates the dc link voltage using the PI controller while the internal control loops regulate both of d and q axis current using IMC controllers.

The dc-link voltage is rectified to its reference value v_{dc}^* which provides the production of the active power through the d-axis current. The d-axis reference current i_{gd}^* is fixed according to the desired dc-link voltage and the q-axis reference current i_{gq}^* is calculated from the grid reactive power reference which is set at zero. The references voltages component v_{gd}^*, v_{gq}^* are provided through the current control loops.

The control design of the inner current loops is expressed as follows

$$\begin{aligned} v_{gd} &= v'_{gd} + \Delta v_{gd} \\ v_{gq} &= v'_{gq} + \Delta v_{gq} \end{aligned} \quad (14)$$

which v'_{gd} and v'_{gq} are the state equation between the voltage and current on d and q axis respectively and Δv_{gd} and Δv_{gq} are the decoupling signals joined to the current controllers outputs.

$$\begin{aligned} \Delta v_{gd} &= v_{gd} - L_f i_{gq} \omega_g \\ \Delta v_{gq} &= v_{gd} + L_f i_{gd} \omega_g \end{aligned} \quad (15)$$

The outputs signals from the controllers are used for switching signal generation through space vector modulation.

Referring to phase locked loop (PLL) the detection of the grid voltage angle is achieved by adjusting the d axis aligned with the grid voltage vector. So then the q-axis voltage is equal to zero. [2],[9],[10],[11]

A. Internal Model Control design

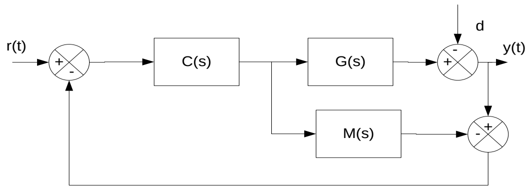

Fig.4 Internal Model Control structure

The internal model control is advised as a robust control strategy [12]. As shown in Fig.4 its basic structure consists of the process G(s) , the model of the process $M(s)$, the controller C(s) and the disturbance $D(s)$. This control structure can be arranged in the classical feedback form as shown in Fig.5 in which the control action is expressed as follows

$$\mathrm{K}(s) = \frac{C(s)}{1 - C(s)M(s)} \quad (16)$$

Since the internal model $M(s)$ is perfect, $G(s) = M(s)$ and the closed loop is stable if $M(s)$ and G(s) are both stable. Therefore, the controller is given by $C(s) = G^{-1}(s)$.

Referring to [12] the inversion method proposed is based on the gain A which the controller is expressed as

$$C(s) = \frac{A}{1 + AM(s)} \quad (17)$$

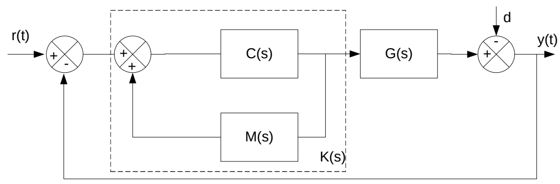

Fig.5 IMC rearranged structure

In the direction of making the system more robust, the controller is raised by a filter. The filter treated is the low-pass filter which is given by

$$L(s) = \frac{1}{(1+\varepsilon s)^n} \tag{17}$$

where ε is the time constant filter, n is the order of filter.

B. Current control design

Considering equation (6), the transfer function reflects $V_{id,q} - V_{gd,q}$ as input and $I_{gd,q}$ as output and includes only the inductance and the resistance is given by (18). The voltage decoupling signals between d and q axis have been neglected.

$$V(s) = \frac{k_e}{1+T_e s} \tag{18}$$

Where $k_e = \frac{1}{R_f}$, $T_e = \frac{L_f}{R_f}$

VI. SIMULATION RESULTS

In order to analyze the performance of the proposed wind turbine converter system, the model of overview system is built using MATLAB/Simulink. The Field oriented flux strategy control is considered for the adjustment of the generator side converter while the grid inverter is regulated through the proposed design based on internal model control.

Fig.6 shows the considered waveform of wind speed. The wind speed started with 9m/s, increased at 1 sec to 12m/s then changed at 1.5 sec from 12m/s to 10m/s. The generator control system provides a good tracking reference speed which begins at 26rad/s and increases with the rise of wind speed to attain 38rad/s and as the wind speed change to 10m/s, the PMSG speed tracks its reference value settled at 30rad/s as shown in Fig.7.

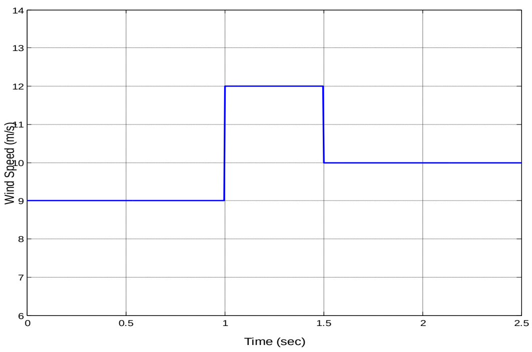

Fig.6 Wind speed waveforms

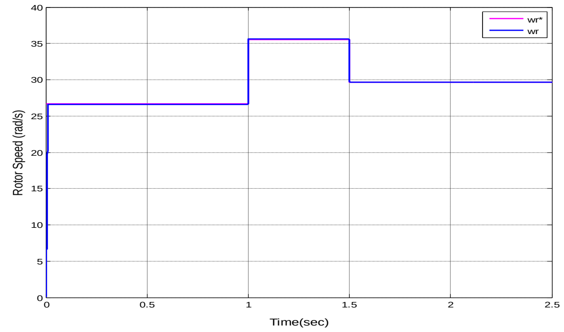

Fig.7 Rotor speed

Fig.8 illustrates the dc-link voltage of the back to back converter. It can be seen that the dc voltage is kept at constant value equal to 600V.

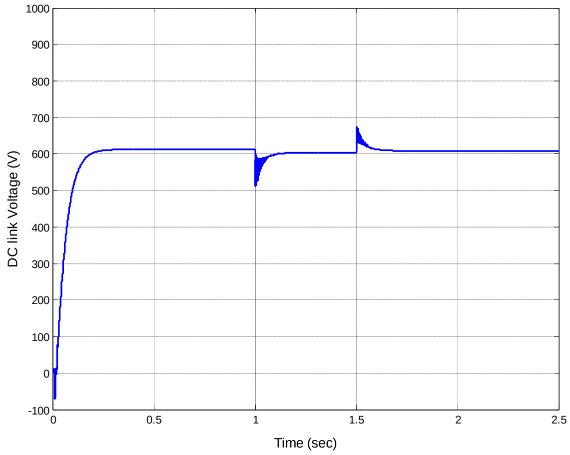

Fig.8 dc-link voltage

Space vector pulse width modulation technique is employed to generate the maximum power to the grid. Fig.9 shows the outputs responses of the grid side inverter. They vary sinusoidally at a regular frequency equal to 50Hz.

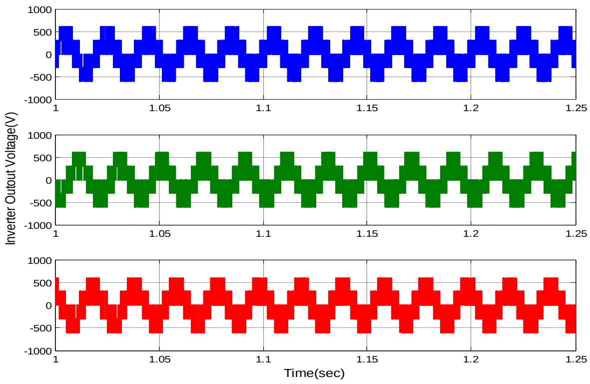

Fig.9 inverter output three-phase voltage

The d and q axis-components of the current are plotted in Fig. 10. It can be seen that the q axis current reaches its reference value calculated from the reactive power which is set at zero while the d axis current presents the same behaviour of the reference value derived from the active power. It started at 16 A, changed to 39A at 1s and back to 23A at 1.5s. Fig.11 illustrates the grid active power which reaches it reference value, it started at 5KW, increased to 12.9KW at 1s and changed at 1.5s from 12.9 to 7.2KW while the reactive power is kept equal to zero.

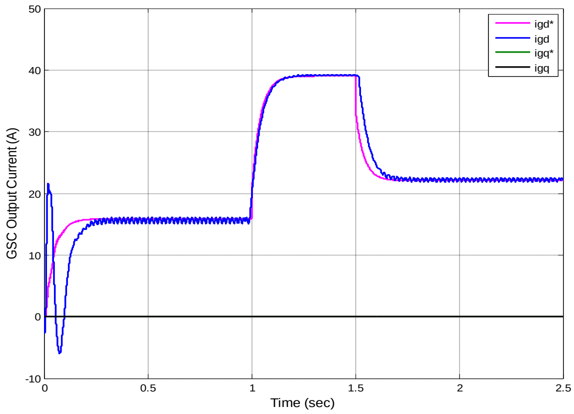

Fig.10 dq axis grid currents responses

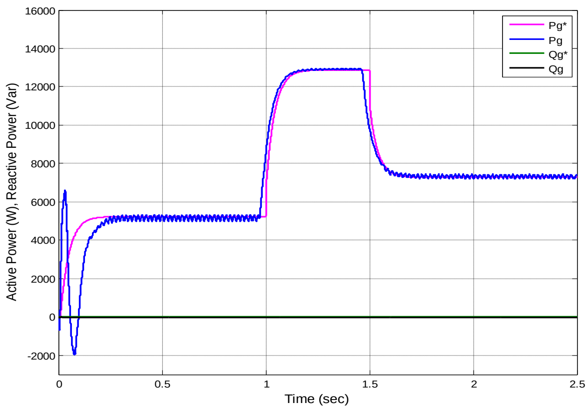

Fig.11 Active and reactive power responses

It can be seen from Fig.12 that the current injected to the grid follows very well the grid voltage which is admit 220V as amplitude with a constant frequency kept at 50Hz. It can be seen that the PLL algorithm can accurately track the grid side converter. From the simulation results it can be clearly noted that the proposed control can accurately the adjustment of the reactive and active power and can offer a good performance of the system.

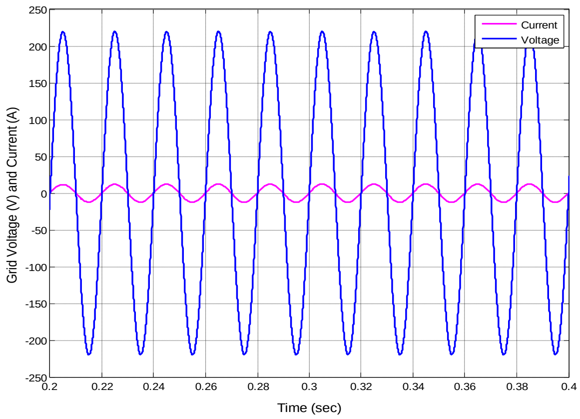

Fig.12 Grid phase-voltage and current

VII. CONCLUSION

This paper presents the simulation model of grid side inverter of PMSG wind turbine using Matlab/Simulink. The designed control allows keeping the dc-link voltage at a constant value for variable wind speed through PI controller. In order to adjust the quantity of active and reactive power injected to the electric network a proposed design was employed based on an internal model control. Simulation results demonstrate that the control of back to back converter can completely accomplish the wind turbine with PMSG control objectives with good performance. The analysis of the proposed control design proves that the control works very well with good dynamic and performance.

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