Control of DFIG using Back-To-Back PWM Converters

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Abstract---The studied system here is a variable speed wind generation system based on Doubly Fed Induction Generator (DFIG). The stator of the generator is directly connected to the grid while the rotor is connected through a back-to-back converter which is dimensioned to stand only a fraction of the generator rated power. In order to improve the operation capacity of wind turbine under critical situation, the intensive study of both machine side converter control and grid side converter control is necessary. The system uses two back-to-back converters in the rotor circuit. The basic concept behind the total system (DFIG with back to- back converters) is that the machine-side converter controls the active and reactive power by controlling the d-q components of rotor current (i.e. i_{dr} and i_{qr}), while the grid-side converter controls the dc-link voltage and ensures the operation at unity power factor by making the reactive power drawn by the system from the utility grid to zero.

I. INTRODUCTION

THE contribution of renewable based distributed generation has been increasing dramatically into the power system for last two decades . A variable speed generator based wind turbine can extract more power from the wind than a fixed speed wind turbine . Doubly fed induction generator (DFIG) is a popular choice for variable speed wind turbine application, as it is able to generate power at constant voltage and frequency while the rotor speed varies. A decoupled control of the real and reactive power is possible. Moreover, a fraction of total system power needs to be controlled, resulting in the reduction of the power losses and the cost of the converters, filters and EMI filters. Figure.1 shows the basic scheme adopted in the majority of systems

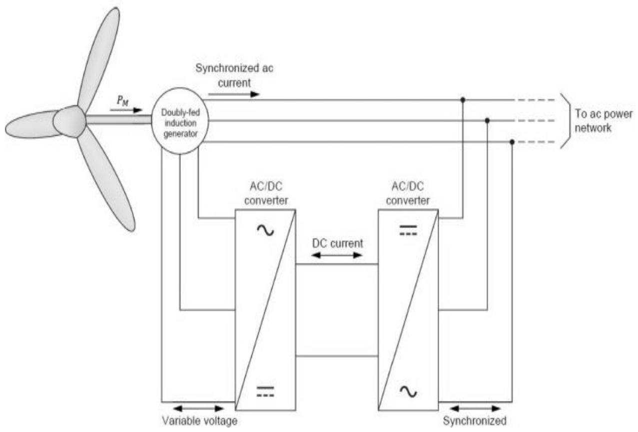

Fig. 1: Schematic Diagram of a Doubly Fed Induction Generator.

Generally, the stator of the DFIG is connected to the grid directly, and the rotor is fed through bi-directional back-to-back PWM converters. These converters are used for exchanging the slip power to and from the grid for variable speed operation. It is possible to control rotor current injection using fully controlled electronic converters to ensure effective operation in both sub- and super-synchronous modes. In sub-synchronous mode, the RSC works as an inverter and GSC as a rectifier and controls the power flow into the rotor. In the case of super-synchronous mode, RSC acts as a rectifier and GSC as an inverter, the direction of power flow is out of the rotor. The back to back converter consists of two converters i.e. Grid Side Converter (GSC) and Rotor Side Converter (RSC) connected back to back through a dc link capacitor for energy storage purpose. In this paper a control strategy is presented for DFIG. Stator Active and Reactive power control principle is also presented. In order to decouple the active and reactive powers Stator Flux Oriented vector control method is used.

II. WIND TURBINES

Wind turbines convert the kinetic energy present in the wind into mechanical energy by means of producing torque. Since the energy contained by the wind is in the form of kinetic energy, its magnitude depends on the air density and the wind velocity. The wind power developed by the turbine is given by the equation

$$P = \frac{1}{2} C_p \rho A V^3$$

where Cp is the Power Co-efficient, ρ is the air density in kg/m3, A is the area of the turbine blades in m2 and V is the wind velocity in m/sec.The power coefficient Cp gives the fraction of the kinetic energy that is converted into mechanical energy by the wind turbine. It is a function of the

tip speed ratio λ and depends on the blade pitch angle for pitch-controlled turbines. The tip speed ratio may be defined as the ratio of turbine blade linear speed and the wind speed

$$\lambda = \frac{R\omega}{V}$$

Substituting (2) in (1), we have:

$$P = \frac{1}{2} C_p(\lambda) A \left(\frac{R}{\lambda}\right)^3 \omega^3$$

The output torque of the wind turbine *Tturbine* is calculated by the following equation

$$T\,turbine = \frac{1}{2} A \rho C_p \left(\frac{V}{\lambda}\right)$$

Where R is the radius of the wind turbine rotor (m) there is a value of the tip speed ratio at which the power coefficient is maximum.

Variable speed turbines can be made to capture this maximum energy in the wind by operating them at a blade speed that gives the optimum tip speed ratio. This may be done by changing the speed of the turbine in proportion to the change in wind speed. Fig.2 shows how variable speed operation will allow a wind turbine to capture more energy from the wind.

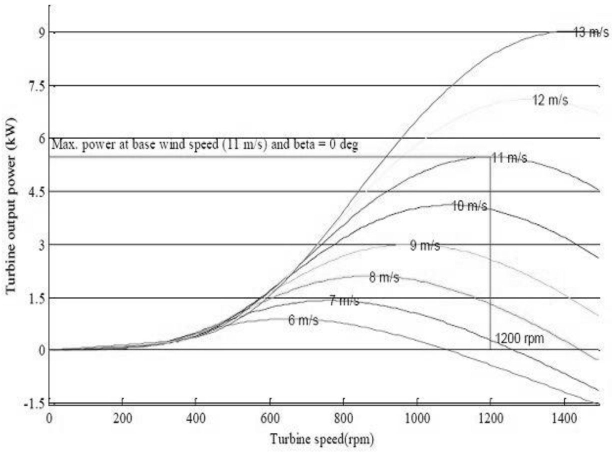

Fig. 1: Power versus speed Characteristics

III. CONTROL OF CONVERTER

A. Rotor-side converter control

The rotor-side converter (RSC) provides the excitation for the induction machine rotor. With this PWM converter it is possible to control the torque hence the speed of the DFIG and also the power factor at the stator terminals. The rotor-side converter provides a varying excitation frequency depending on the wind speed conditions. The induction machine is controlled in a synchronously rotating *dq*-axis frame, with the *d*-axis oriented along the stator-flux vector position in one common implementation. This is called stator-flux orientation (SFO) vector control. In this way, a decoupled control between the electrical torque and the rotor excitation current is obtained. Consequently, the active power and reactive power are controlled independently from each other.

To describe the control scheme, the general Park's model of an induction machine is introduced. Using the motor convention in a static stator-oriented reference frame, without saturation, the voltage vector equations are

$$\bar{v}_s = R_s \bar{i}_s + \frac{d\bar{\psi}_s}{dt}$$

$$\bar{v}_r = R_r \bar{i}_r + \frac{d\bar{\psi}_r}{dt} - j\omega\bar{\psi}_r$$

where v_s is the stator voltage imposed by the grid The rotor voltage v_r is controlled by the rotor-side converter and used to perform generator control. The flux vector equations are

$$\bar{\psi}_s = L_s \bar{i}_s + L_m \bar{i}_r$$

$$\bar{\psi}_r = L_m \bar{i}_s + L_r \bar{i}_r$$

where *Ls* and *Lr* are the stator and rotor self-inductances: *Ls* = *Lm* + *Lls* , *Lr* = *Lm* + *Llr* .

Under stator-flux orientation (SFO), in *dq*-axis component form, the stator flux equations are:

$$\begin{cases} \psi_{sd} = L_s i_{sd} + L_m i_{rd} = \psi_s = L_m i_{ms} \\ \psi_{sq} = 0 \end{cases}$$

Defining leakage factor

$$\sigma = 1 - \frac{L_m^2}{L_s L_r}$$

and equivalent inductance as

$$L_o = \frac{L_m^2}{L_s}$$

The rotor voltage and flux equations are (scaled to be numerically equal to the ac per-phase values):

The stator flux angle is calculated from

$$\begin{cases} \psi_{s\alpha} = \int (v_{s\alpha} - R_s i_{s\alpha}) dt \\ \psi_{s\beta} = \int (v_{s\beta} - R_s i_{s\beta}) dt \end{cases}, \quad \theta_s = \tan^{-1}\left(\frac{\psi_{s\beta}}{\psi_{s\alpha}}\right)$$

where θ*s* is the stator-flux vector position.

$$\begin{cases} v_{rd} = R_r i_{rd} + \sigma L_r \frac{di_{rd}}{dt} - \omega_{slip} \sigma L_r i_{rq} \\ v_{rq} = R_r i_{rq} + \sigma L_r \frac{di_{rq}}{dt} + \omega_{slip} (L_o i_{ms} + \sigma L_r i_{rd}) \end{cases}$$

$$\begin{cases} \psi_{rd} = \frac{L_m^2}{L_s} i_{ms} + \sigma L_r i_{rd} \\ \psi_{rq} = \sigma L_r i_{rq} \end{cases}$$

where the slip angular speed is $\omega_{slip} = \omega_s - \omega_r$.

The control scheme of the rotor-side converter is organized in a generic way with two series of two PI-controllers. Fig. 11 shows a schematic block diagram for the rotor-side converter control. The reference *q*-axis rotor current *irq** can be obtained either from an outer speed control loop or from a reference torque imposed on the machine. These two options may be termed a speed-control mode or torque-control mode for the generator, instead of regulating the active power directly. For speed-control mode, one outer PI controller is to control the speed error signal in terms of maximum power point tracking. Furthermore, another PI controller is added to produce the reference signal of the *d*-axis rotor current component to control the reactive power required from the generator. Assuming that all reactive power to the machine is supplied by the stator, the reference value *ird** may set to zero. The switching dynamics of the IGBT-switches of the rotor converter are neglected and it is assumed that the rotor converter is able to follow demand values at any time.

The control system requires the measurement of the stator and rotor currents, stator voltage and the mechanical rotor position. There is no need to know the rotor-induced EMF, as is the case for the implementation with naturally commutated converters. Since the stator is connected to the grid, and the influence of the stator resistance is small, the stator magnetising current *ims* can be considered constant (Pena et al., 1996). Rotor excitation current control is realised by controlling rotor voltage. The *ird* and *irq* error signals are processed by associated PI controllers to give *vrd* and *vrq*, respectively.

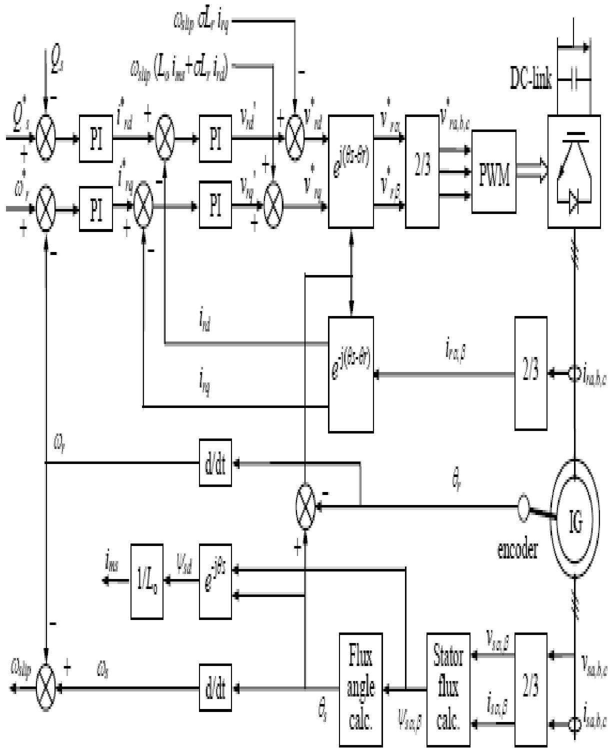

Fig. 2: Vector control structure for rotor-side converter.

From the rotor voltage equations

$$\begin{cases} v'_{rd} = R_r i_{rd} + \sigma L_r \dfrac{di_{rd}}{dt} \\ v'_{rq} = R_r i_{rq} + \sigma L_r \dfrac{di_{rq}}{dt} \end{cases}$$

To ensure good tracking of the rotor *dq*-axis currents, compensation terms are added to *v'rd* and *v'rq* to obtain the reference voltages *vrd** and *vrq** according to

$$\begin{cases} v^*_{rd} = v'_{rd} - \omega_{slip}\sigma L_r i_{rq} \\ v^*_{rq} = v'_{rq} + \omega_{slip}(L_m i_{ms} + \sigma L_r i_{rd}) \end{cases}$$

The electromagnetic torque is

$$T_e = -\frac{3}{2} p \operatorname{Im}\left\{ \bar{\psi}_s \bar{i}_r^* \right\} = -\frac{3}{2} p L_o i_{ms} i_{rq} .$$

For the stator-voltage oriented control the above equation is an approximation. However, for stator-flux orientation, the stator flux current *ims* is almost fixed to the stator voltage. For torque mode control, since it is difficult to measure the torque, it is often realised in an open-loop manner. The torque can be controlled by the *q*-axis component of the rotor current *irq*. Therefore, the *q*-axis reference current, *irqref* can be determined from the reference torque *Teref* as

$$i_{rq}^{ref} = -\frac{2T_e^{ref}}{3pL_o i_{ms}} = -\frac{2T_e^{ref}}{3p\psi_s}$$

B. Grid-side converter control

The grid side converter is used to partly control the flow of real and reactive power from the turbine system to the grid. The grid-side converter feeds the grid via a set of interfacing inductors. The grid-side converter (a voltage source inverter) can generate a balanced set of three-phase voltages at the supply frequency and that the voltage, *E*, can have a controllable magnitude and phase. Load angle control is used to illustrate the basics of real and reactive power control, load angle control uses the angle, *δ*, between the voltage generated by the grid-side converter, *E*, and the grid voltage, *V*, to control the real power, *P*, injected on to the grid. Likewise, reactive power, *Q*, is controlled using the magnitude of the voltage generated by the grid-side converter.

$$P = \frac{VE\sin\delta}{X_s} \quad and \quad Q = \frac{V^2}{X_s} - \frac{VE}{X_s}\cos\delta$$

where *Xs* is the reactance of the interfacing inductance. If *δ* is small the equations can be simplified to

$$P = \frac{VE\delta}{X_s} \quad and \quad Q = \frac{V^2}{X_s} - \frac{VE}{X_s}$$

Showing that *P* can be controlled using load angle, *δ*, and *Q* can be controlled using the magnitude of *E*. Interfacing inductance must be used to couple the output of the grid-side converter. The inductor is sized according to the rating of the converter. Typically, the system will have a transformer on the turbine side of the point of common coupling (PCC). The combination of control and power electronics enables the grid-side converter to produce the necessary voltage magnitude, *E*, and load angle, *δ*, in order to meet a required *Pc* and *Qc* demand set by the main system controller. The controller has to be able to synchronize to the grid frequency and phase, in order to connect and supply power.

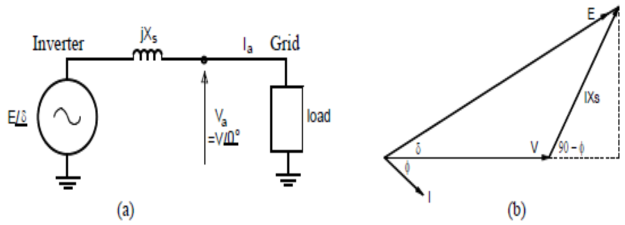

Fig. 5: (a) Single line diagram of steady-state generator-side converter connected to the grid and (b) phasor diagram demonstrating load angle control of the grid-side converter to establish exported real power and control of reactive power.

At any instant, the power exported by the GSC is determined by the state of the DC link voltage. The grid-side converter controller monitors the DC link voltage. If the DC link voltage rises, the grid-side converter can export more real power by increasing the load angle in order that the DC link voltage moves back towards it nominal value. If more power is being exported by the GSC than is currently being generated by the RSC, the DC link voltage will fall below its nominal value. The grid-side controller will then reduce the exported real power to allow the DC link voltage to recover to its nominal value. In essence the DC link voltage indicates power flow balance between the generated energy and the exported energy in the rotor side. If the input and output power to the dc link capacitor do not match then the dc link voltage will change. The grid-side converter controls the flow of real and reactive power to the grid, through the grid interfacing inductance. The objective of the grid-side converter is to keep the dc-link voltage constant regardless of the magnitude and direction of the rotor power.

The vector control method is used as well, with a reference frame oriented along the stator voltage vector position, enabling independent control of the active and reactive power flowing between the grid and the converter. The PWM converter is current regulated, with the *d*-axis current used to regulate the dc-link voltage and the *q*-axis current component to regulate the reactive power. Fig. shows the schematic control structure of the grid-side converter

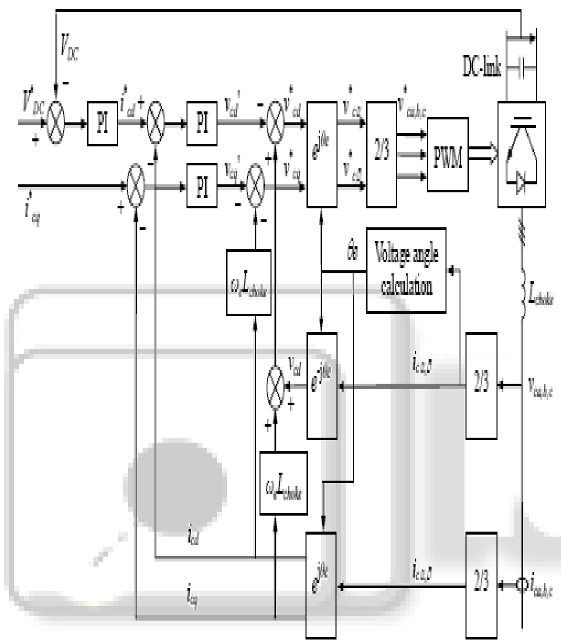

Fig. 6: Vector control structure for grid-side converter.

A similar analysis for the control of the *dq* currents carried out for the grid-side converter can likewise be done for the control of the converter *dq* currents. The voltage equations in synchronously rotating *dq*-axis reference frame are:

$$\begin{cases} v_{cd} = Ri_{cd} + L_{choke}\dfrac{di_{cd}}{dt} - \omega_e L_{choke} i_{cq} + v_{cd1} \\ v_{cq} = Ri_{cq} + L_{choke}\dfrac{di_{cq}}{dt} + \omega_e L_{choke} i_{cd} + v_{cq1} \end{cases}$$

The angular position of the grid voltage is calculated as

$$\theta_e = \int \omega_e dt = \tan^{-1}\left(\frac{v_{c\beta}}{v_{c\alpha}}\right)$$

where $vc\alpha$ and $vc\beta$ are the converter grid-side voltage stationary frame components. The *d*-axis of the reference frame is aligned with the grid voltage angular position θ*e*. Since the amplitude of the grid voltage is constant, *vcq* is zero and *vcd* is constant. The active and reactive power will be proportional to *icd* and *icq* respectively. Assume the grid-side transformer connection is star, the converter active and reactive power flow is

$$\begin{cases} P_c = 3(v_{cd}i_{cd} + v_{cq}i_{cq}) = 3v_{cd}i_{cd} \\ Q_c = 3(v_{cd}i_{cq} + v_{cq}i_{cd}) = 3v_{cd}i_{cq} \end{cases}$$

Which demonstrates that the real and active powers from the grid-side converter are controlled by the *icd* and *icq* components of current respectively. To realise decoupled control, similar compensations are introduced likewise in equation

$$\begin{cases} v_{cd}^* = -v_{cd}' + (\omega_e L_{choke} i_{cq} + v_d) \\ v_{cq}^* = -v_{cq}' - (\omega_e L_{choke} i_{cd}) \end{cases}$$

The reference voltage *vcd** and *vcq** are then transformed by inverse-Park transformation to give 3-phase voltage *vcabc** for the final PWM signal generation for the converter IGBT switching.

IV. CONCLUSION:

The DFIG system costs more than fixed-speed induction generators without converters. However, the performance and controllability are excellent in comparison with fixed speed induction generator systems; they capture more wind energy, they exhibit a higher reliability gear system, and high-quality power supplied to the grid. It saves investment on full-rated power converters, and soft-starter or reactive power compensation devices.

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