ANALYSIS AND ACTIVE/REACTIVE POWER CONTROL OF DOUBLY FED INDUCTION GENERATOR (DYNAMIC MODELLING)

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ABSTRACT: Increasing size of wind farms requires power system stability analysis including dynamic models of the wind power generation. Nowadays, the most widely used generator type for units above 1 MW is the doubly-fed induction generator. In this paper doubly-fed induction generator the stator is directly connected to the grid and active/reactive power control is done through rotor-side converter. Active/ reactive powers to the DFIG are controlled by injecting the proper rotor voltage derived from controller so as to maintain constant terminal voltage. This paper is proposed to implement on MATLAB/SIMULINK platform.

KEYWORDS: Doubly fed induction generator, Variable speed wind turbine, Pitch control, Dynamic modeling.

NOMENCLATURE

V_s = Stator voltage, [V]

V_r = Rotor voltage, [V]

V_{ds}, V_{qs} = Stator d and q winding voltage, [V]

I_{ds}, I_{qs} = Stator d and q winding current, [A]

V_{dr}, V_{qr} = Rotor d and q winding voltage, [V]

I_{dr}, I_{qr} = Rotor d and q winding current, [A]

V_{so} = Stationary reference voltage, [V]

V_{ro} = Rotor reference voltage, [V]

I_s = Stationary current, [A]

Ir = Rotor current, [A]

T_e = Electromagnetic torque, [N-m]

T_m = Mechanical torque, [N-m]

Q_s = Stator reactive power, [p.u]

Q_r = Rotor reactive power, [p.u]

P_s = Stator active power, [p.u]

P_r = Rotor active power, [p.u]

f_o = Base frequency, [Hz]

L_m = Magnetizing inductance [H]

L_s, L_r = Stator and rotor per phase winding inductance, [H]

L_{ls}, L_{lr} = Stator and rotor per phase Leakage inductance, [H]

R_s, R_r = Stator and rotor per phase Winding resistance, [Ω]

ω_m = Rotor mechanical speed, [rad/s]

ω_o = Base speed, [rad/s]

I. INTRODUCTION

IN RECENT years, there has been an increased attention toward wind power generation. Conventionally, grid-connected cage rotor induction machines are used as wind generators at medium power level. When connected to the constant frequency network, the induction generator runs near synchronous speed drawing the magnetizing current from the mains, thereby resulting in constant speed constant frequency (CSCF) operation. However, the power capture due to fluctuating wind speed can be substantially improved if there is flexibility in varying the shaft speed [1].

In such variable speed constant frequency (VSCF) application rotor side control of grid-connected wound rotor induction machine is an attractive solution. In the system under consideration, the stator is directly connected to the three phase grid and the rotor is supplied by two back-to-back PWM converters (Fig. 1). Such an arrangement provides flexibility of operation in sub-synchronous and super-synchronous speeds both in the generating and motoring modes [2]. The rating of the power converters used in the rotor circuit is substantially lower than the machine rating and is decided by the range of operating speed. Of the two converters, the function of the line side converter is to regulate the dc bus voltage and act as unity power factor interface to the grid for either direction of power flow [3-5]. The machine side converter has to control the torque and flux of the machine or alternatively the active and reactive powers. The present work is concerned with the control of the active/reactive power of DFIG.

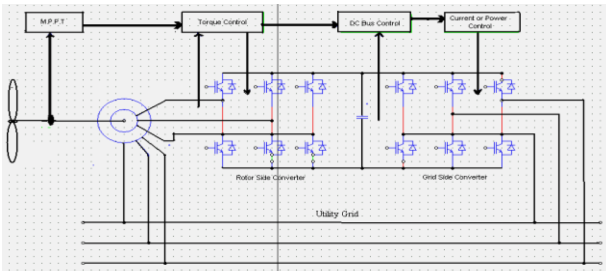

Fig.1 Doubly Fed Induction Generator Wind Turbine

This paper is divided as per the following sections. Section-I gives the overview of the total paper. Section-II presents description about the doubly fed induction generator. Section-III presents the dynamic simulation of doubly fed induction generator in terms of dq windings. Section-IV presents the control strategy adopted for the doubly fed induction generator. Then in Section-V, VI, VII presents the results, conclusion and future scope respectively. The employment of DFIG for this type of application is justified by many factors: the induction generator becomes able to both import and export reactive power, the control of the rotor voltages and current allows the machine to remain synchronized with the grid while the wind speed varies, thirdly the cost of the converter is lower than in all other applications because only 25-30% of the mechanical power is fed to the grid through the converter, the rest is delivered directly from the stator. The power flow through the two converters depends on the speed of the machine, to allow the power flow in both direction, The grid side control strategy has the main objective to keep constant the DC voltage and to keep the reactive power flowing in the rotor as much near zero as possible in order to minimize the power size of the converters and. The rotor side one has the goal to control the electric torque in order to control the electric torque and maximize the extraction of the power and to have the power unity factor.

II. DESCRIPTION OF THE SYSTEM

There are two basic options of wind power conversion fixed speed and variable speed operation. In fixed operation, the aero turbine can be operated at a constant speed by blade-pitch control of the wind turbine even under varying wind speeds. This option was very common because of the cost involved with the power converter needed in the variable speed generation to convert the variable frequency to match the constant grid frequency. In variable speed operation, the aero turbine rotational speed can be allowed to vary with wind to maintain a constant and optimum tip speed ratio. The variable speed operation by active pitch control allows optimum efficiency operation of the turbine over a wide range of wind speeds, resulting in increasing power outputs [7].For variable speed generation, an induction generator is considered attractive due to its flexible rotor speed characteristics in contrast to the constant speed characteristics of synchronous generator. DFIG configuration is best suited for variable speed generation since it can be controlled from rotor side as well as stator side. This is possible since rotor circuit is capable of bidirectional power flow. The doubly-fed machine can be operated in generating mode in both sub-synchronous and super-synchronous modes[8].The rotor will observe slip power from the in sub-synchronous operation and can feed slip power back to grid in super-synchronous operation. The rotor converter needs thus only to be rated for a fraction 25% (Slip Power) of the total output power. All these advantages make the DFIG a favorable candidate for variable speed operation. A commonly used model for induction generator converting power from the wind to serve the electric grid is shown in Figure. 2.

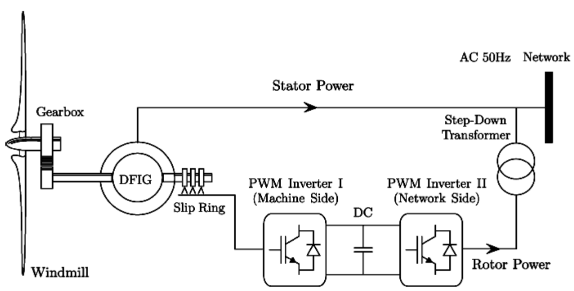

Fig.2. Basic configuration of DFIG Wind Turbine

The stator of the wound rotor induction machine is connected to the low voltage balanced three-phase grid and the rotor side is fed via the back-to-back IGBT voltage-source inverters with a common DC bus. The network side converter controls the power flow between the DC bus and the AC side and allows the system to be operated in sub-synchronous and super synchronous speed. The proper rotor excitation is provided by the machine side power converter.

III. DYNAMIC SIMULATION OF DFIG IN TERMS OF DQ-WINDINGS

A commonly used model for induction generator converting power from the wind to serve the electric grid is shown in Fig.1.The stator of the wound rotor induction machine is connected to the low voltage balanced three-phase grid and the rotor side is fed via the back-to-back IGBT voltage-source inverters with a common DC bus. The network side converter controls the power flow between the DC bus and the AC side and allows the system to be operated in sub-synchronous and super synchronous speed. The proper rotor excitation is provided by the machine side power converter and the general model for wound rotor induction machine is similar to any fixed-speed induction generator as follows.

3.1 Voltage equations

3.1.1. Stator Voltage Equations:

$$V_{qs} = p\lambda_{qs} - \omega\lambda_{ds} + r_s i_{qs}$$
$$V_{ds} = p\lambda_{ds} - \omega\lambda_{qs} + r_s i_{ds} \quad \text{--- (1)}$$

3.1.2. Rotor Voltage Equations:

$$V_{qr} = p\lambda_{qr} + (\omega - \omega_r)\lambda_{dr} + r_r i_{qr}$$
$$V_{dr} = p\lambda_{dr} - (\omega - \omega_r)\lambda_{qr} + r_r i_{dr} \quad \text{-- (2)}$$

3.2 Flux linkage equations

3.2.1 Stator flux equations:

$$\psi_{qs} = (L_{ls} + L_m)i_{qs} + L_m i_{qr} = L_s i_{qs} + L_m i_{qr}$$
$$\psi_{ds} = (L_{ls} + L_m)i_{ds} + L_m i_{dr} = L_s i_{ds} + L_m i_{dr} \quad (3)$$

3.2.2 Rotor flux equations

$$\psi_{qr} = (L_{lr} + L_m)i_{qr} + L_m i_{qs} = L_s i_{qr} + L_m i_{qs}$$
$$\psi_{dr} = (L_{lr} + L_m)i_{dr} + L_m i_{ds} = L_r i_{dr} + L_m i_{ds} \quad \text{- (4)}$$

3.4 Torque Equation

$$T_{em} = -(3/2)(p/2)[(\lambda_{qr} i_{dr} - \lambda_{dr} i_{qr})]$$
$$T_{em} = -(3/2)(p/2)[(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds})] \quad \text{-- (5)}$$
$$T_{em} = -(3/2)(p/2)L_m[(i_{dr} i_{qs} - i_{qr} i_{ds})]$$

IV. CONTROL STRATEGY

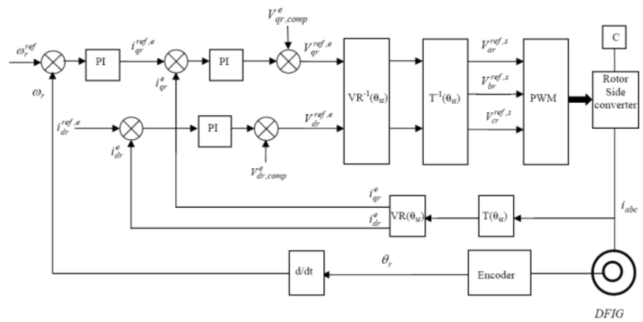

Fig.3. Rotor side Converter control strategy

Doubly Fed Wound Rotor Induction Machine is an attractive solution for variable speed high power generation. In variable speed constant frequency applications, so called slip power recovery scheme is common practice where the power due to rotor slip below/above synchronous speed is recovered to /supplied from power source i.e. grid. In DFIG, electrical power output from the stator is at constant frequency irrespective of the rotor speed. To obtain sub and super-synchronous speed operation, the rotor must be able to handle the slip power in both directions. Among the three power ports, i.e. stator terminals, rotor terminals and the rotor shaft, rotor terminals act as the energy regulating power port balances.

In order to achieve a decouple control of active and reactive power; stator flux oriented vector control scheme is adopted. Based on the previous research the following assumptions are considered:

1. Stator voltage drop across resistance has been neglected as the effect of stator resistance is quite low compared to the grid voltage [5].

2. The DFIG is connected to a stiff grid, i.e., the frequency and amplitude of the stator or grid voltage is assumed constant [7].

3. Magnetizing current of the stator is assumed to be determined by the grid [7].

4. The q-axis is 90^0 ahead of the d-axis and rotating at synchronous speed in the direction of rotation [8].

5. The stator flux vector is aligned with the d-axis of the stator [8].

The above assumptions lead to the following

$$Vds = 0$$
$$Vqs = Vs$$
$$\varphi ds = \varphi s \quad \text{----- (6)}$$
$$\varphi qs = 0$$

And equation (3) & (4) becomes

$$\begin{aligned} \varphi_s &= L_{ss} i_{ds} + L_m i_{dr} \\ 0 &= L_{ss} i_{qs} + L_m i_{qr} \\ \varphi_{dr} &= L_{rr} i_{dr} + L_m i_{ds} \\ \varphi_{qr} &= L_{rr} i_{qr} + L_m i_{qs} \end{aligned} \quad \text{--- (7)}$$

The active and reactive power produced in the stator, the rotor fluxes and voltages can be written in terms of the rotor current as [9]

$$\begin{aligned} Ps &= \frac{-L_m}{L_{ss}} V_s * i_{qr} \\ Qs &= \frac{Vs^2}{\omega_s L_{ss}} - \frac{V_s L_m}{L_{ss}} * i_{dr} \end{aligned} \quad \text{--- (8)}$$

Thus from (8), the q-axis current vector component, i_{qr} can be used to regulate the active power generated by the stator of DFIG while, i_{dr} can be used to control the reactive power produced by the stator. Essentially, control of the active and reactive power is decoupled and a decoupler is not necessary. A block diagram of the control system is presented in Fig. 3.

V. RESULTS AND DISCUSSION

Fig 5.1 shows three phase open circuit voltages V_a,V_b,V_c which are displaced by 120 electrical degrees apart.

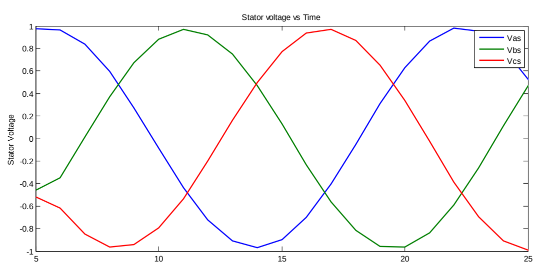

Fig 5.1 Stator Open Circuit Voltages

The figure 5.2 shows the active power generated at the stator terminals. As we are applying negative torque after 10sec therefore from 10 sec onwards the generating action will start. Fig 5.3 shows that the reactive power is generated. Hence it says that depending on the reactive power set value reactive power is limited.

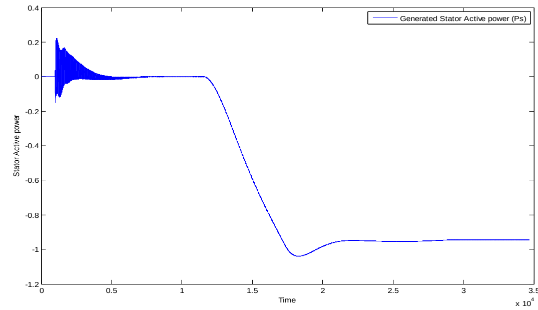

Fig 5.2: Stator Active Power (Generated)

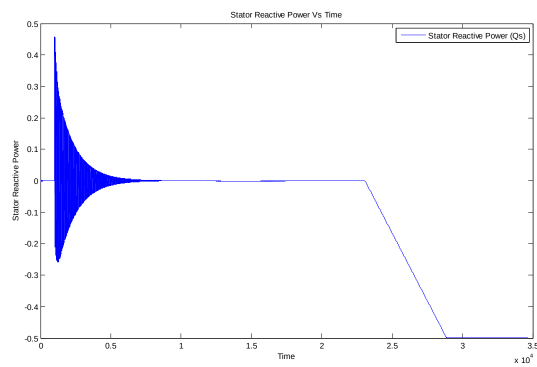

Fig 5.3: Stator Reactive Power (Generated)

Fig 5.4 shows the active power absorbed by the rotor in sub-synchronous mode of operation. Hence the plot says that from 10 sec onwards the rotor is absorbing the active power. Fig 5.5 shows the rotor reactive power absorbed in sub-synchronous mode of operation. Depending on set value of the reactive power the reactive power is limited.

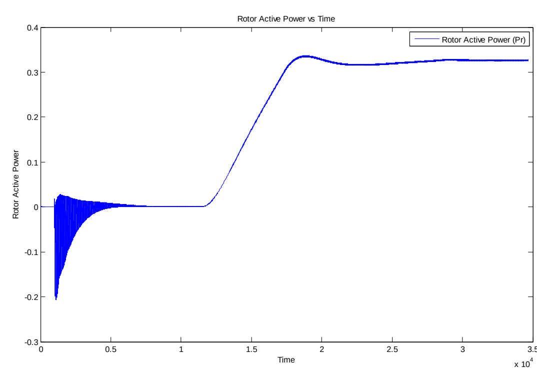

Fig.5.4: Rotor Active Power (Absorbed)

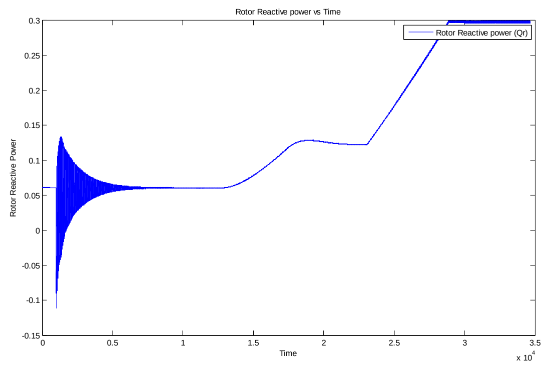

Fig.5.5: Rotor Reactive Power (Absorbed)

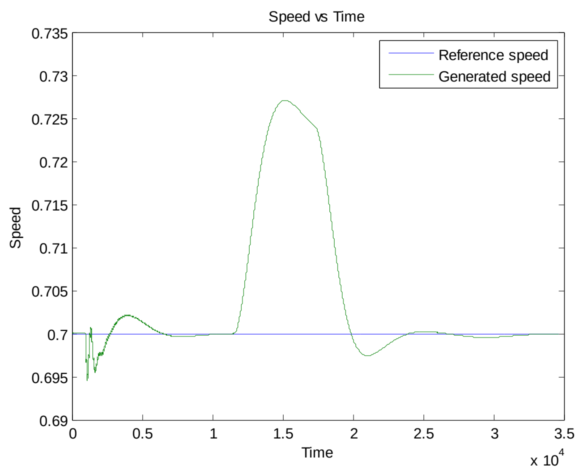

Fig.5.6: Speed of the Generator (Sub-synchronous)

Fig 5.6 shows the speed of the generator in sub-synchronous mode. From the figure it says that when we apply negative torque to the turbine suddenly, the speed of the rotor raises abruptly and again come to the study state.

VI. CONCLUSION

Dynamic modeling is first developed in synchronously rotating reference frame and the control is implemented to the rotor in line voltage oriented reference frame. Independent control of active and reactive power is proved. The opposite sign of power flow in the rotor verifies both, sub synchronous speed and super synchronous speed modes of operation. Stator voltage is maintained constant at 1 p.u. The *d-q* component of stator current also confirms the vector/decoupled control of active and reactive power.

VII. FUTURE SCOPE

1) Develop a controller, which can effectively improve the dynamic stability, transient response of the system during faulty grid conditions. 2) To develop a protection system for power converter and DFIG for large disturbances like 3-phase fault of little cycle duration as the power converter is very sensitive to grid disturbance.

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