Investigation on Performance of Doubly-Fed Induction Generator Driven by wind turbine under Grid Voltage Fluctuation

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Abstract- **To ensure safe and reliable operation of power system based on wind energy, usually plant operators should satisfy grid code requirements such as grid stability, fault ride through (FRT), power quality improvement, grid synchronization and power control etc. To satisfy the grid code requirements of wind turbine, usually grid side converter is playing a major role. So 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. This paper presents the performance analysis of Doubly-fed induction generator (DFIG) under grid voltage fluctuation. The machine uses two back-to-back converters. The grid side converter is modeled to control the active and reactive power independently along with dc-link voltage. The machine side converter is modeled to control the reactive power and maintain the power factor unity irrespective of the transient behavior of the grid.**

Keywords: Doubly-fed Induction Generator (DFIG), Vector control, PWM Converter, Grid-side converter, Machine-side converter

I. NOMENCLATURE

v_{ds}, v_{qs} are the three phase stator voltages in d-q reference frame respectively

i_{ds}, i_{qs} are the three phase stator currents in d-q reference frame respectively

v_{dr}, v_{qr}, are the three phase rotor voltages in d-q reference frame respectively

i_{dr}, i_{qr} are the three phase rotor currents in d-q reference frame respectively

Ψ_{ds}, Ψ_{qs} are the stator flux linkages in d-q reference frame respectively

Ψ_{dr}, Ψ_{qr} are the rotor flux linkages in d-q reference frame respectively

T_e is the electromagnetic torque.

R_s, R_r , X_{lr}, X_{ls} are the machine resistances and reactances per phase

L_s, L_m, L_r are the machine inductances per phase

X_m is the machine mutual reactance per phase

ω_b is the base frequency

ω_r is the angular rotor speed

R is the radius of the swept area

λ_{opt} is the optimum tip speed ratio of a wind turbine

ρ is the air density

$C_{p,opt}$ is the optimum power coefficient

ω_e, ω_{slip} are the synchronous speed and slip speed respectively.

P, Q are the stator side active and reactive power respectively

p is the number of poles

P_{Cur}, P_{Cus} are the rotor and stator copper losses respectively

II. INTRODUCTION

Rapid developments in science and technology have witnessed a disastrous effect on environment. This issue is raised since some decades and reflected as a major agenda in Kyoto protocol and many other climate change summits. Conservation of non-renewable resources motivates to explore the new avenues of resources for electricity generation which remains till date a large polluter when coal like matters is used. Induction machine as a generator has come a long way and preferable over synchronous and dc generator for its obvious advantages. From stand-alone to grid connected a wound rotor machine as a doubly fed induction generator is gaining grounds in many wind farms and hydel generations. Indeed, they are used in small-scale generators in windmills for instance. However, specific applications, such as aircraft, require higher level reliability and long-time maintenance periodicity. To satisfy the grid code requirements of wind turbine, usually grid side converter is playing a major role [1]. Independent control of active and reactive power from the grid or to the grid is possible by vector control of line side converter [2]. A current fed inverter controlled DFIG with a variable rotor side frequency is explained for energy recovery in [3]. The steady state analysis of a DFIG is explained by implementing a current controlled cyclo-converter [4]. Optimal torque speed profile of a wind turbine is tracked by a stator field oriented control strategy for a DFIG system [5]. The traditional voltage oriented control (VOC) of grid side converter has been studied under balanced condition of the 3-

phase grid in [6] and [7]. In this paper various analyses on DFIG system has been made by taking different cases for grid voltage fluctuation into account.

III. MODELING OF DFIG

A 10 h.p. wound rotor induction machine is modeled in synchronous reference frame. The schematic diagram of the overall system is shown in Fig.1. Two voltage fed PWM converters are used in the model, one is used in the grid side and other is in the machine side. The objective of grid side converter is to maintain dc-link voltage constant and the machine side converter control regulates the speed of the prime mover thus making the system suitable for variable speed application system.

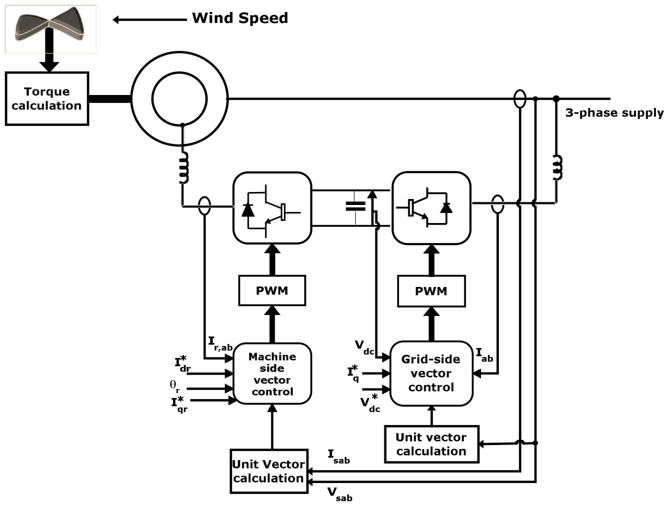

Figure 1. Overall DFIG System

Equations (1)-(4) and (8)-(9) describe the complete machine model in state-space form where Ψ_{qs}, Ψ_{ds},Ψ_{qr},Ψ_{dr} are the state variables. The machine is simulated using MATLAB/SIMULINK.

$$\frac{d\psi_{qs}}{dt} = \omega_b \left[v_{qs} - \frac{\omega_e}{\omega_b}\psi_{ds} - \frac{R_s}{X_{ls}}(\psi_{qs} - \psi_{qm}) \right] \quad (1)$$

$$\frac{d\psi_{qs}}{dt} = \omega_b \left[v_{ds} + \frac{\omega_e}{\omega_b}\psi_{ds} - \frac{R_s}{X_{ls}}(\psi_{ds} - \psi_{dm}) \right] \quad (2)$$

$$\frac{d\psi_{qr}}{dt} = \omega_b \left[v_{qr} - \frac{R_r}{X_{lr}}(\psi_{qr} - \psi_{qm}) - \left(\frac{\omega_e - \omega_r}{\omega_b}\right)\psi_{dr} \right] \quad (3)$$

$$\frac{d\psi_{dr}}{dt} = \omega_b \left[v_{dr} - \frac{R_r}{X_{lr}}(\psi_{dr} - \psi_{dm}) + \left(\frac{\omega_e - \omega_r}{\omega_b}\right)\psi_{qr} \right] \quad (4)$$

Where

$$\psi_{qm} = \frac{X_{ml}}{X_{ls}}\psi_{qs} + \frac{X_{ml}}{X_{lr}}\psi_{qr} \quad (5)$$

$$\psi_{dm} = \frac{X_{ml}}{X_{ls}}\psi_{ds} + \frac{X_{ml}}{X_{lr}}\psi_{dr} \quad (6)$$

$$X_{ml} = \frac{X_m X_{ls} X_{lr}}{X_{ls}X_{lr} + X_m X_{lr} + X_m X_{ls}} \quad (7)$$

The development of torque by the interaction of airgap flux and rotor mmf can be expressed in more general form relating the d-q component of variables. The expression for the electromagnetic torque developed is given in (8).

$$T_e = \frac{3}{2}\left(\frac{p}{2}\right)\frac{1}{\omega_b}\left(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}\right) \quad (8)$$

The speed ω_r in the above equations cannot be treated as constant. It can be related to the torque as

$$T_e = T_m + J\frac{d\omega_m}{dt} = T_m + \frac{2}{p}J\frac{d\omega_r}{dt} \quad (9)$$

IV. GRID SIDE CONVERTER CONTROL

When the voltage in the utility grid changes abruptly due to sudden load changes and abrupt wind speed variations, it makes an effect on the machine, as a result the system voltages available across stator as well as rotor changes. Since the converters are connected back-to-back the same effect is also observed across these two converters and on the dc-link capacitor as well.

The necessary control action is adopted to maintain the dc-link voltage constant. Grid voltage oriented vector control is approached, in which the real axis of the grid voltage vector is chosen as the d-axis. Phase Locked Loop block is used to measure the system frequency and provides the phase synchronous angle θ for the d-q transformations block. The control scheme utilizes current control loops for i_d and i_q with the i_d demand being derived from the dc-link voltage error through a standard PI controller. The i_q demand determines the displacement factor on the grid side of the choke. The active power and reactive power is controlled independently using d-q component of the current governed by (10) and (11). The detail control strategy is shown in Fig.2.

$$P = \frac{3}{2}(v_d i_d + v_q i_q) \quad (10)$$

$$Q = \frac{3}{2}(v_d i_q - v_q i_d) \quad (11)$$

The reference voltage vectors for the grid side converters are found from (12) and (13).

$$v_d^* = v_d + i_q^* \omega_e L - i_d^* R - v'_d \quad (12)$$

$$v_q^* = v_q - i_d^* \omega_e L - i_q^* R - v'_q \quad (13)$$

Where the v'_d and v'_q is found from the current errors through standard PI controllers.

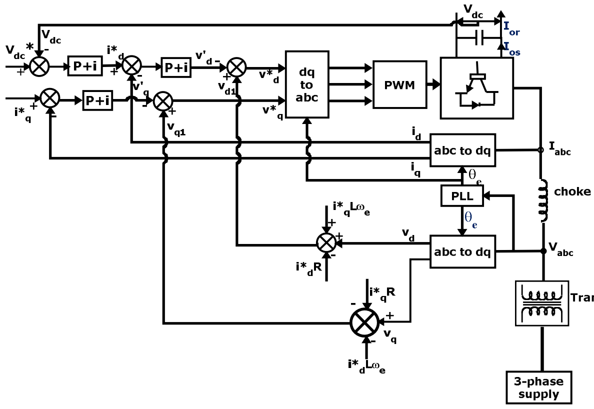

Figure 2. Vector control structure for grid side converter

V. MACHINE SIDE CONVERTER CONTROL

The necessary control action is adopted for the machine side converter to maintain the speed of the DFIG constant and also control the reactive power flow from the utility grid to the machine irrespective of the wind speed.

The unit vector requirement for the d-q transformation is found by using grid voltage orientation where the real axis of the grid voltage vector is chosen as the d-axis as used in case of grid side converter control. The detail control strategy for machine side converter control is shown in Fig.3.

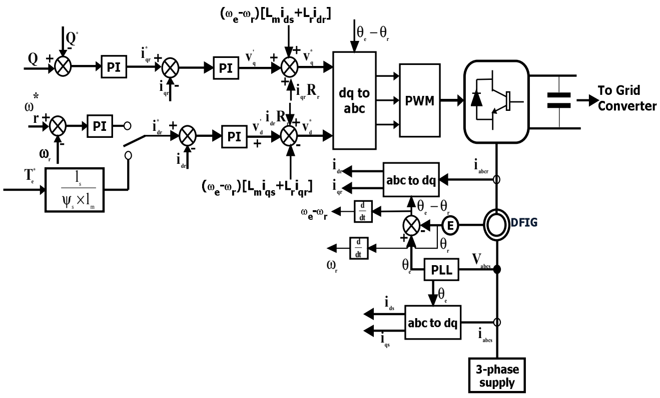

Figure 3. Vector control structure for machine side converter

The reference voltage vectors for machine side converter are being derived using (14) and (15).

$$v_d^* = v_d' + i_{dr}R_r - (\omega - \omega_r)[i_{qr}L_r + L_m i_{qs}] \quad (14)$$

$$v_q^* = v_q' + i_{qr}R_r + (\omega - \omega_r)[i_{dr}L_r + L_m i_{ds}] \quad (15)$$

Where v'_d and v'_q is found from the current errors through standard PI controllers. The reference current i^*_{dr} can be found either from the reference torque given by (16) or form the speed errors through standard PI controllers. Similarly i^*_{qr} is found from the reactive power errors. The reactive power and speed is controlled using the current control loops.

$$i_{dr}^* = \frac{T_e^* \times L_s}{\psi_s \times L_m} \quad (16)$$

Where $T_e^* = \dfrac{P_{mech} - P_{loss}}{\omega_r}$

$$P_{loss} = \text{MechanicalLosses} + \text{ElectricalLosses}(P_{Cur} + P_{Cus})$$

The maximum mechanical power given by (17) can be extracted from the wind is proportional to the cube of the rotor speed.

$$P_{max} = K_{opt}\omega^3 \quad (17)$$

Where $K_{opt} = \dfrac{1}{2}\rho C_{p,opt}\pi \dfrac{R^5}{\lambda_{opt}^3}$

The optimum value of K is found from the typical power versus speed characteristics of a wind turbine. The wind turbine power curves shown in Fig.4 illustrate how the mechanical power that can be extracted from the wind depends on the rotor speed. For each wind speed there is an optimum turbine speed at which the extracted wind power at the shaft reaches its maximum.

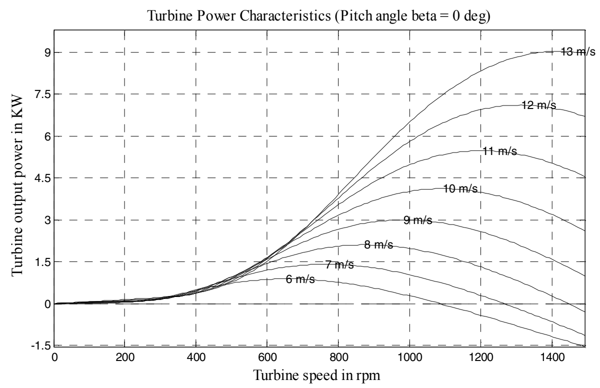

Figure 4. Typical Power versus speed characteristics of a wind turbine

VI. SIMULATION RESULTS AND DISCUSSION

The 10hp machine is simulated with MATLAB/SIMULINK environment by taking various cases into account.

A. Case1:Simulation under voltage sag

The simulation results under the voltage sag are shown in Fig.5. The DFIG system produces active power of 7 kW which corresponds to maximum mechanical turbine output minus electrical losses in generator. When the grid voltage changes suddenly from its rated value i.e.415V the current increases and the active power P suddenly oscillates and then it settles to its rated value. The reference reactive power is set at 0KVAr but when voltage decreases the reactive power suddenly increases then it settles to 0KVAr as per the control strategy made in the rotor side converter. The dc link voltage is set at 850V by the grid side converter but at the time of voltage sag it oscillates and finally settles to its set value and the rotor speed is also maintained constant to its rated (1080rpm) while the wind speed is kept constant at 10m/s. In Fig.5 the behavior of V_{abc}, I_{abc}, P, Q, V_{dc}, ω_r is observed at 0.2s when the voltage decreases to 50%.

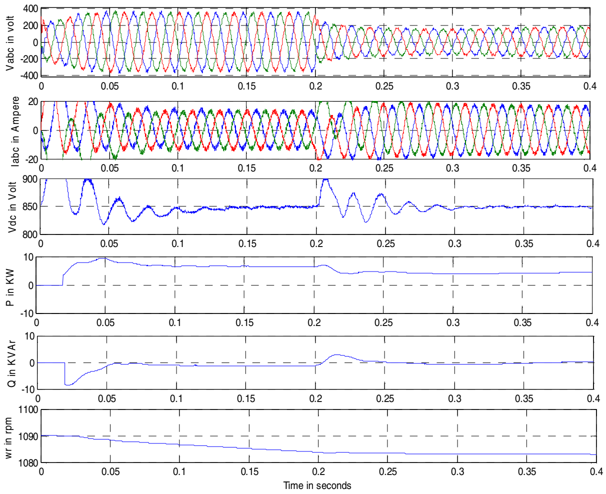

Figure 5. Simulation results under voltage sag

B. *Case2:Simulation under voltage swell*

Simulation results under voltage swell is shown in Fig.6. When the grid voltage increases up to 120% of its rated value the reactive power Q decreases suddenly and then settles to 0KVAr. At the time of voltage swell grid current also decreases. In Fig.6 the behavior of the generator is observed at 0.2s when the voltage rises to 120% of its rated value.

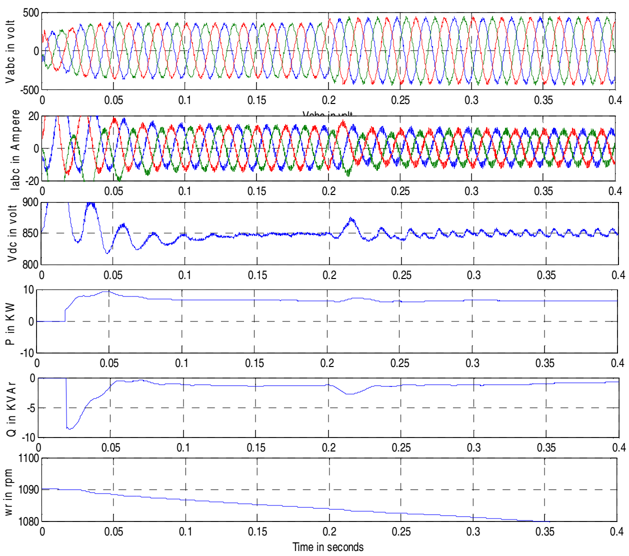

Figure 6. Simulation results under voltage swell

C. *Case3: Simulation under wind speed Variation*

When the wind speed changes suddenly from 10m/s to 15m/s the rotor speed increases gradually and then after few milliseconds it settles to its rated value of 1080 rpm as per the control strategy made in the rotor side converter. The behavior of rotor speed ω_r is shown in Fig.7. and there is no appreciable change in behavior is observed for other parameters.

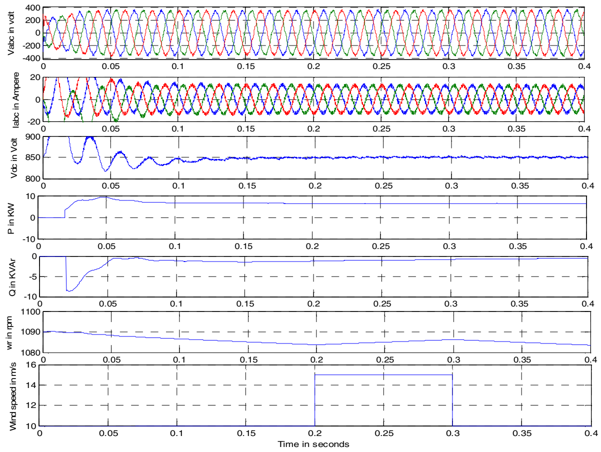

Figure 7. Simulation results under wind speed variation

VII. CONCLUSION

A DFIG system with a back-to-back converter is simulated using standard PI controllers. The investigation on performance of DFIG driven by wind turbine is made under grid voltage fluctuation. It is concluded that the control strategy implemented for the DFIG system under simulation study is suitable under sudden change in grid voltage. The parameters for the study are given as follows. The DC link voltage is 850V and the grid line voltage is 415V for the 7.5 kW wind turbine. The switching frequency of IGBT switches are selected as 3 kHz and the dc-link capacitance is 10000µF.

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