Study and Control of the Dynamic Performance of Grid Connected Doubly Fed Induction Generator Driven by Wind Energy

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Abstract—**The objective of the present work is to study the Dynamic behavior of Grid connected Doubly Fed Induction Generator (DFIG) based wind turbine during balance and unbalance grid operating conditions. A 1.5MW grid connected DFIG based wind turbine is molded and analyzed in this study. This study includes the implementation of Flexible A.C Transmission System (FACTs) to protect DFIG based wind turbine interconnected power system from isolating during and after the disturbance. It is found that FACTs devices improve the transient performance and therefore help the wind turbine generator system to remain in service during grid faults. This grid connected wind energy conversion system (WECS) is composed of DFIG and two back-to-back Pulse Width Modulation (PWM) voltage-source converters in the rotor circuit. A mathematical model of the machine; derived in an appropriate dq reference frame, is established. The grid voltage oriented vector control is used for the grid side converter (GSC) in order to maintain a constant DC bus voltage and to compensate for reactive power at the power network. The stator voltage orientated vector control is adopted in the rotor side converter (RSC) control strategy, providing efficient handling of active and reactive power at the stator. The proposed system is simulated for different operating conditions to illustrate the reliability of the control techniques.**

Keywords — Doubly-Fed Induction Generator (DFIG), GSC, RSC, wind energy conversion (WECS), Flexible AC Transmission System (FACTs).

I. INTRODUCTION

Wind Energy plays an increasingly important role in the world because it is friendly to the environment, more controllable and safe renewable power source compared to fossil and nuclear power generation. Wind turbine can either operate at fixed speed or variable speed. For fixed speed wind turbine the generator is directly connected to the grid. For variable speed wind turbine the generator is controlled by power electronic equipment. Variable speed wind generators system is more attractive than fixed speed system because of the more efficiency energy production, decrease of the stresses on the mechanical structure, wide range controllability of both active and reactive power, improved dynamic performance during grid disturbance and increase in the power capture. Also variable speed wind turbines show less fluctuation in the output power compared with fixed speed wind turbine [1, 2]. DFIG is the most popular variable speed WECS. It has several benefits such as better efficiency, easy power factor correction, possibility of four quadrants active and reactive power control and better utilization factor. Another advantage is that the power electronic equipment to control the machine only has to handle a fraction (maximum 20-30%) of the total power, reducing converter cost and losses compared to other variable speed wind turbine where power electronics has to handle the total power of the generator [2-4].A wind energy conversion system using DFIG is shown in Fig.1. In grid connected DFIG based wind turbine, the stator is directly connected to the grid and the rotor is connected to the grid via back-to-back pulse width modulated converter (PWM).The rotor side converter (RSC) would provide the required magnetizing current in rotor winding to control the active and reactive power flow from the stator of the DFIG to the grid. The main task of the grid side converter (GSC) is to keep the DC-link voltage constant. During grid fault, the DFIG experiences over currents, which lead also to increasing DC voltage on converter side to unacceptable value. Due to small capacity of GSC, it cannot provide sufficient reactive power and voltage support and there might be a risk of voltage instability, disconnection of wind turbine from network and damage incur on the DFIG power electronic converters due to high voltage induced in it. Due to the limited reactive power capability of DFIG it cannot provide the sufficient reactive power support without any external dynamic reactive power compensation devices. As stated above, the problem can be solved using dynamic reactive compensation. Shunt Flexible AC transmission System (FACTs) devices such as Static Var Compensator (SVC) or STATCOM have been widely used to provide high performance steady state and transient voltage control [6-9].

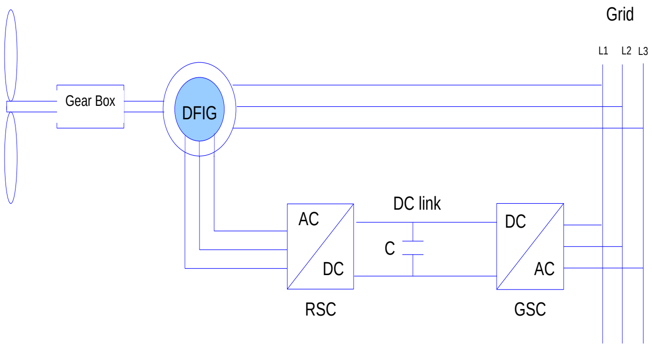


Fig.1. Grid-connected DFIG with back-to-back converter [5]

II. MODELING OF DOUBLY FED INDUCTION GENERATORS

in dq synchronous rotating frame as displayed in Fig.2. The stator voltage vector and rotor voltage vector can be obtained as follow:- [2,4,5,10-12]

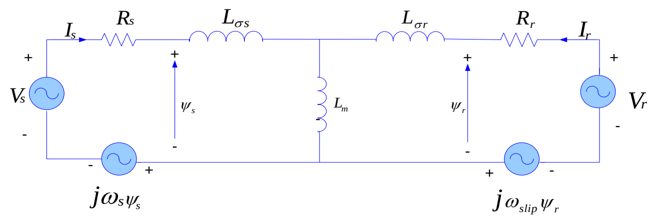


Fig.2. Equivalent circuit of DFIG in dq synchronous rotating reference frame

$$V_s = R_s I_s + \frac{d\psi_s}{dt} + j\omega_s \psi_s \quad (1)$$

$$V_r = R_r I_r + \frac{d\psi_r}{dt} + j\omega_{slip}\psi_r \quad (2)$$

Where:- $V_s = V_{sd} + jV_{sq}$, $V_r = V_{rd} + jV_{rq}$

$I_s = I_{sd} + jI_{sq}$, $I_r = I_{rd} + jI_{rq}$

$\psi_s = \psi_{sd} + j\psi_{sq}$, $\psi_r = \psi_{rd} + j\psi_{rq}$

$\omega_{slip} = \omega_s - \omega_r$

$$\psi_s = L_s I_s + L_m I_r \quad (3)$$

$$\psi_r = L_r I_r + L_m I_s \quad (4)$$

Where: - $L_s = L_{\sigma s} + L_m$, $L_r = L_{\sigma r} + L_m$

Rearranging equation (3), the stator current vector can represent as follow:-

$$I_s = \frac{\psi_s - L_m I_r}{L_s} \quad (5)$$

By substituting I_s in Eq. (5) into Eq. (4), the following equation is obtained:-

$$\psi_r = \frac{L_m}{L_s}\psi_s + L_r I_r \left(1 - \frac{L_m^2}{L_s L_r}\right) = \frac{L_m}{L_s}\psi_s + \sigma L_r I_r \quad (6)$$

Where $\sigma = \left(1 - \frac{L_m^2}{L_s L_r}\right)$

The magnetizing current vector can represent as:-

$$I_m = \frac{\psi_s}{L_m}$$

By substituting (3) in the above equation, the following equation is obtained:-

$$I_m = \frac{L_s}{L_m} I_s + I_r = I_{md} + jI_{mq} \quad (7)$$

By substituting (6) and (7) into (1) and (2), the following equation is obtained:-

$$V_s = R_s I_s + L_m \frac{dI_m}{dt} + j\omega_s \psi_s \quad (8)$$

$$V_r = R_r I_r + \sigma L_r \frac{dI_r}{dt} + j\omega_{slip}\psi_r + \frac{L_m^2}{L_s}\frac{dI_m}{dt} \quad (9)$$

For traditional stator voltage oriented control stator voltage vector Vs and stator flux vector ψs in equation (8) are usually assumed to be constant, so it yields that,

$$\frac{dI_m}{dt} = 0$$

Then the rotor voltage vector can be simplified as below

$$V_r = R_r I_r + \sigma L_r \frac{dI_r}{dt} + j\omega_{slip}\psi_r \quad (10)$$

from equ. (10), dq component of rotor voltage can be represented as below:-

$$V_{rd} = R_r I_{rd} + \sigma L_r \frac{dI_{rd}}{dt} - \omega_{slip}\psi_{rd} \quad (11)$$

$$V_{rq} = R_r I_{rq} + \sigma L_r \frac{dI_{rq}}{dt} + \omega_{slip}\psi_{rq} \quad (12)$$

The stator active power and reactive power can be expressed as following:-

$$P_s = \frac{3}{2}(V_{sd} I_{sd} + V_{sq} I_{sq}) \tag{13}$$

$$Q_s = \frac{3}{2}(V_{sq} I_{sd} - V_{sd} I_{sq}) \tag{14}$$

The electromagnetic torque can be obtained as below:-

$$T_e = \frac{3}{2} p(\psi_{sd} I_{sq} - \psi_{sq} I_{sd})$$

III. Stator Voltage Oriented Control

In this scheme; [2, 11-13], stator voltage vector is oriented along the d-axis.

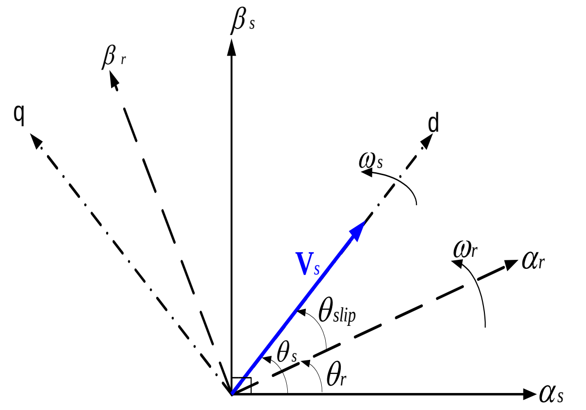


Fig.3. Vector diagram of stator voltage oriented control (SVOC).

Then we can obtain the dq components of the stator voltage vector as following:

$$V_{sd} = V_s \tag{15}$$

$$V_{sq} = 0 \tag{16}$$

Neglecting the stator resistance value, then equation (8) can be adjusted as below:

$$V_{sd} = -\omega_s \psi_{sq} = -\omega_s (L_s I_{sq} + L_m I_{rq}) = V_s \tag{17}$$

$$V_{sq} = \omega_s \psi_{sd} = \omega_s (L_s I_{sd} + L_m I_{rd}) = 0 \tag{18}$$

By substituting equations (15-18) into equations (13) and (14), the stator active and reactive powers can be approximately controlled by I_{rd} and I_{rq} respectively as follows:-

$$P_s = -\frac{3}{2}\frac{L_m}{L_s} V_s I_{rd} \tag{19}$$

$$Q_s = \frac{3}{2}\frac{V_s}{L_s}\left(\frac{V_s}{\omega_s} - L_m I_{rq}\right) \tag{20}$$

In traditional SVOC: - [12]

1-The stator active power and the stator reactive power is controlled by using Equation (19, 20)

2- PI controllers are implemented to regulate the rotor voltage reference by using Equations (11, 12).

3-Space vector PWM control is then used to generate the switch sequence for the IGBTs of the rotor side converter.

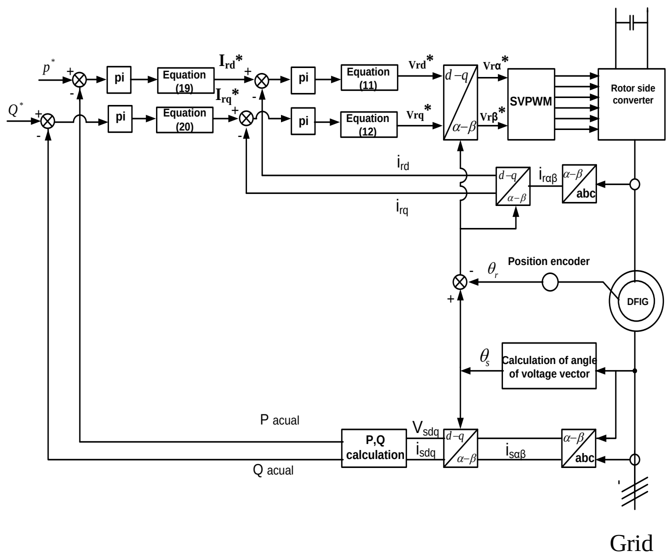


Fig.4. Vector Control for Rotor Side Converter

IV. Grid Side Converter Control

The objective of the grid-side converter; [2, 3, 12, 14-17], is to keep the dc-link voltage constant regardless of the magnitude and direction of the rotor power. The vector control approach is used, 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. (5) Shows the schematic of the grid-side converter.

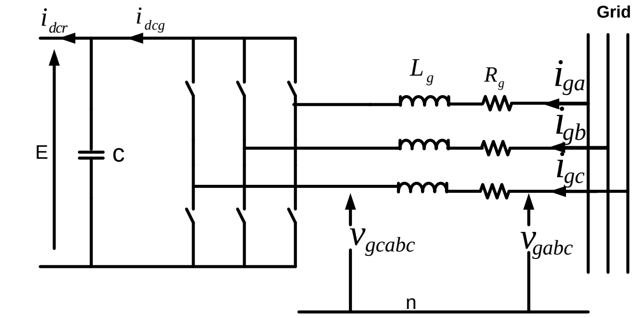


Fig.5. Grid-side PWM voltage source converter

The voltage balance across the inductor is:-

$$\begin{bmatrix} V_{g\,a} \\ V_{g\,b} \\ V_{g\,c} \end{bmatrix} = R \begin{bmatrix} i_{ga} \\ i_{gb} \\ i_{gc} \end{bmatrix} + L_g \frac{d}{dt} \begin{bmatrix} i_{ga} \\ i_{gb} \\ i_{gc} \end{bmatrix} + \begin{bmatrix} V_{gca} \\ V_{gcb} \\ V_{gcc} \end{bmatrix} \tag{21}$$

Where L, R: line inductance and resistance.

Transformation of equation (21) into dq reference frame rotating at w_e (supply angular frequency)

$$\left.\begin{aligned} \therefore\ V_{gd} &= R_g\, i_{gd} + L_g \frac{di_{gd}}{dt} - w_e\, L_g\, i_{gq} + V_{gcd} \\ V_{gq} &= R_g\, i_{gq} + L_g \frac{di_{gq}}{dt} + w_e\, L_g\, i_{gd} + V_{gcq} \end{aligned}\right\} \tag{22}$$

With the scaling factors used in the transformations the active and reactive power flow is:-

$$\left.\begin{aligned} P &= 3(V_{gd}\, i_{gd} + V_{gq}\, i_{gq}) \\ Q &= 3(V_{gd}\, i_{gq} + V_{gq}\, i_{gd}) \end{aligned}\right\} \tag{23}$$

The angular position of the supply voltage is calculated as follow:-

$$\theta_e = \int w_e \ dt = \tan^{-1} \frac{V_{g\beta}}{V_{g\alpha}} \tag{24}$$

Where $V_{g\alpha}, V_{g\beta}$ are the α, β (stationary 2-axis) stator voltage components.

By aligning the d-axis of the reference frame along the stator voltage position given by equation (24) as shown in figure (6)

$\therefore V_{gq} = 0$

As the amplitude of the supply voltage V_d is constant, hence the active and reactive power will be proportional to i_{gd} and i_{gq} respectively.

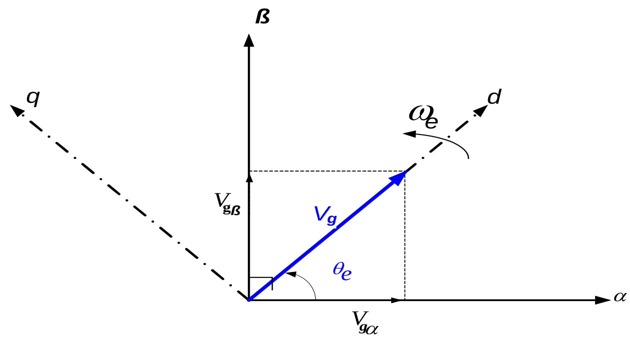


Fig.6.Vector diagram for GSC control

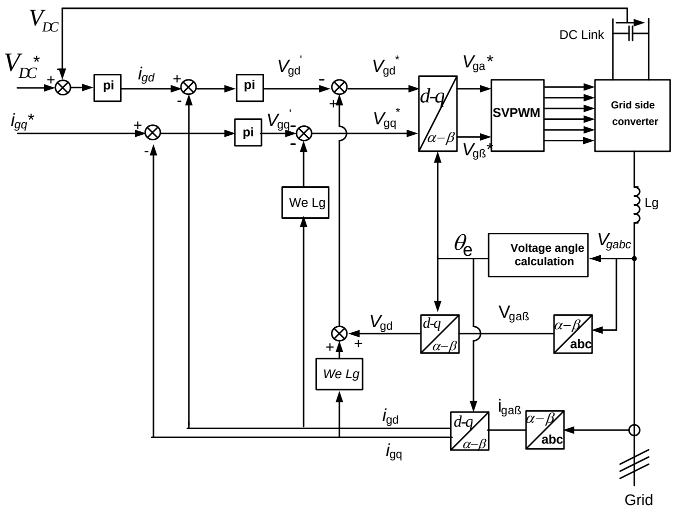


Fig.7. Vector Control for Grid Side Converter

VI. SIMULATION RESULTS

Simulation was done on a 1.5 MW, 690V, 50 Hz, 4 poles DFIG using MATLAB/Simulink. The time response of P_s, Q_s, V_{dc}, $V_{abc\text{-}grid}$, $I_{abc\text{-}grid}$, for different operating conditions are shown in the following figures. The study includes the performance of DFIG in case of balance grid operating conditions. Also simulate the performance of DFIG under the various grid disturbances (We study the following cases: Grid over voltage, Grid under voltage (voltage sage), Three phase to ground fault, Double line to ground fault).Finally, study the impact of FACTs controllers on the dynamic performance of DFIG in case of grid faults. The study includes the implementation of static var compensator (SVC) as dynamic reactive power compensation. FIG (9) to FIG (12) show the performance grid connected DFIG in case of balance grid operation. Set of point active power 1.5MW and set point Reactive power is maintained at zero MW which means all reactive power supply from the grid. The dc bus voltage is maintained constant at 1100 volt.

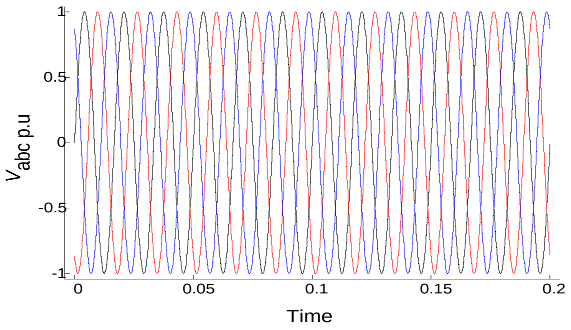


Fig .9. $V_{abc\text{-}grid}$

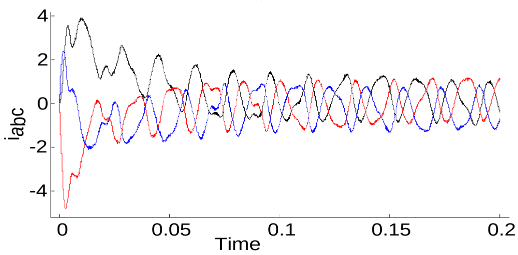


Fig.10. $I_{abc\text{-}grid}$

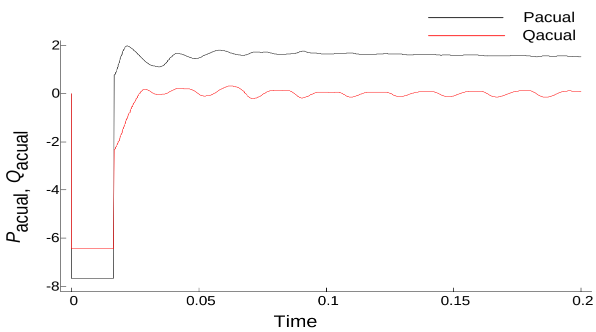


Fig.11. Stator Active and Reactive power

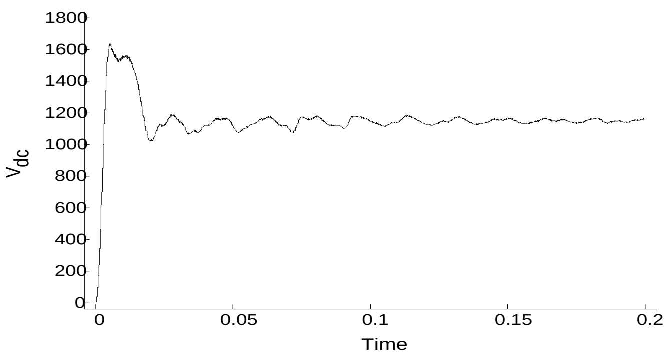


Fig 12. DC Bus Voltage

Fig (13) to Fig (32) shows the Performance of DFIG in case of grid disturbances with and without FACTs. We study four disturbance cases. in case(1) we study the dynamic performance of DFIG in case of three phase to ground fault occur in the grid, results shown from fig(13) to fig(17).in case(2),double line to ground fault occur in the grid ,the performance of the DFIG with and without facts are shown from Fig(18) to Fig(22).in case (3) we assume over voltage occur in the grid ,the performance of the DFIG During and after the disturbance are shown from Fig(23) to Fig(27).finally, we study the performance of the DFIG in case of grid under voltage. Results shown from Fig (28) to Fig. (32).

For FACTs Devices we use static var compensator (SVC) .we impact TCR (Thyristor controlled Reactor) or TSC (Thyristor Switching Capacitor) in the system. In the following curves grid disturbance occur at t=0.1sec. The disturbance was cleared at t=0.14sec. During grid disturbance the DFIG experience over current since line current will increase to unacceptable value (reach 2-3 $i_{nominal}$) as shown in figures(14,19,24,29) which lead also to increasing D.C bus voltage to high level values as shown in figures(17,22,27,32). D.C bus voltage reach from (1.6 to 2.1 $V_{dcnominal}$) which are far away from capacitor specification due to converter design. Immediately after the short circuit clearance, the wind turbine shaft will experience oscillating torque. Oscillation is clearly shown in the active power curve which reach to (2-3$P_{nominal}$) leading to severe stressing of the turbine shaft as shown in figures (15, 20, 25, 30). Due to high level value in current and dc bus voltage, there can be a risk of voltage instability, damages incur on the DFIG and power electronics converters due to high voltage induced in it or disconnection of wind turbine from the network which is not favorable option. Due to the limited reactive power capability of DFIG it cannot provide the sufficient reactive power support without any external dynamic reactive power compensation devices. As stated above the problem can solve using dynamic reactive compensation (shunt flexible ac system (FACTs) devices such as SVC). So, after using FACTs on the system, the increase in the DC bus voltage reaches (1.4 $V_{dcnominal}$). Line current reach to 1.2 $i_{nominal}$ .the active power returns to acceptable value after fault clearance which means low stress in the turbine shaft.

Case (1): Performance of DFIG in case of grid three phase to ground fault. [Q_C=45 MVAR]

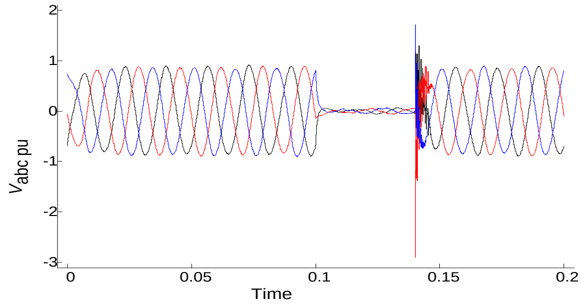


Fig.13. $V_{abc\text{-}grid}$

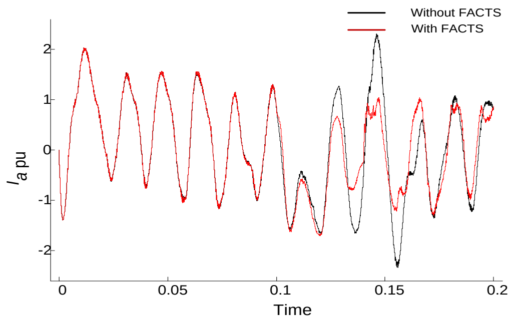


Fig.14. Current in p.u phase ia

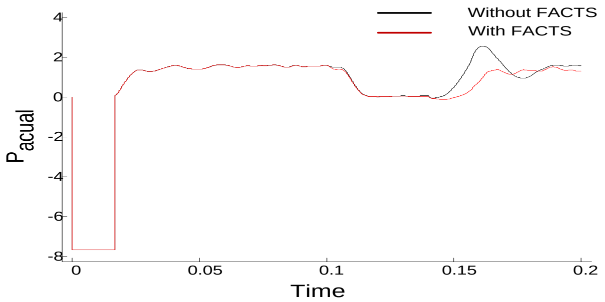


Fig.15. stator Active power

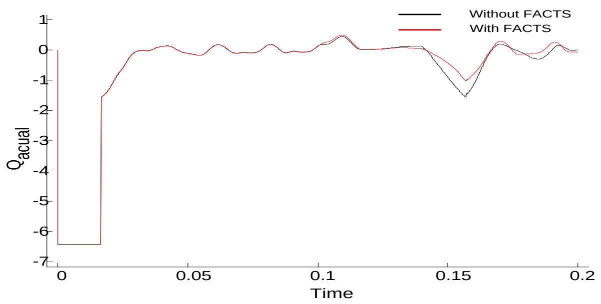


Fig.16. stator Reactive power

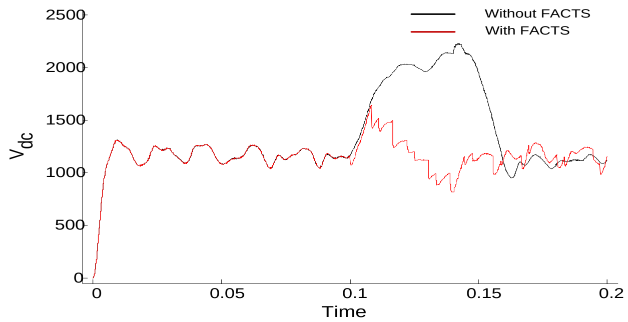


Fig 17. DC Bus Voltage

Case (2): Performance of DFIG in case of grid Double line to ground faults. [QC=9.5 MVAR]

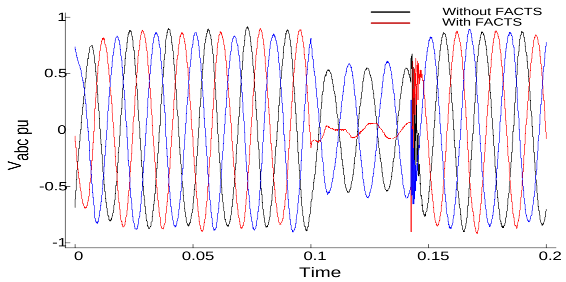


Fig 18. Vabc-grid

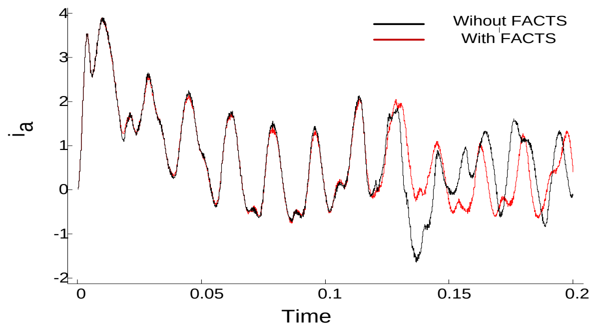


Fig.19. current in pu phase ia

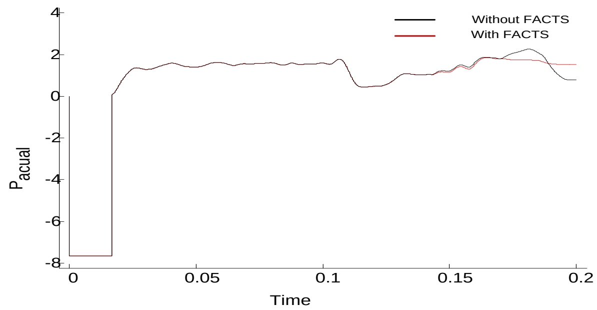


Fig .20. Stator Active power

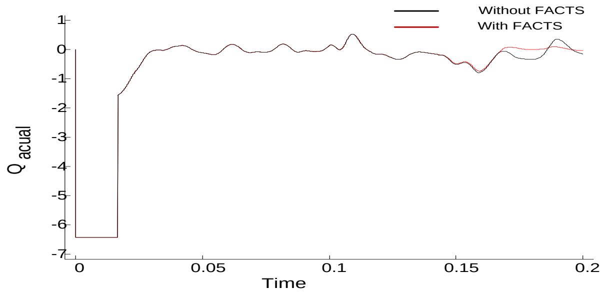


Fig.21. Stator Reactive power

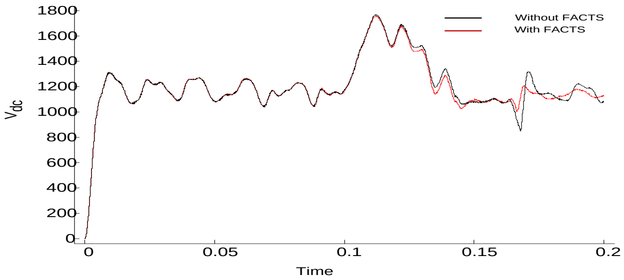


Fig.22. DC Bus Voltage

Case (3): Performance of DFIG in case of grid overvoltage (1.2 P.U) with/without FACTs (TCR) [Q_L=21.5 MVAR]

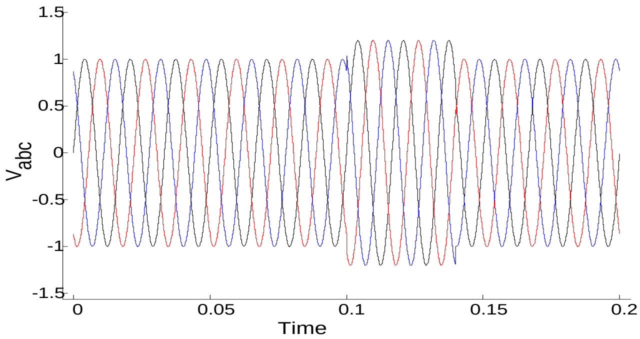


Fig 23. Vabc-grid

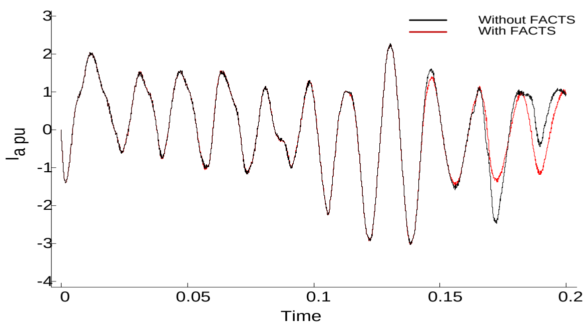


Fig 24. current in pu phase ia

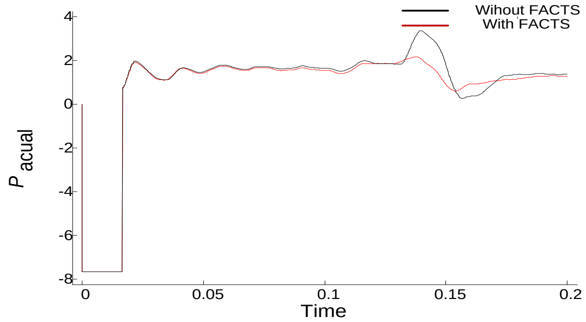


Fig. 25. Stator Active power

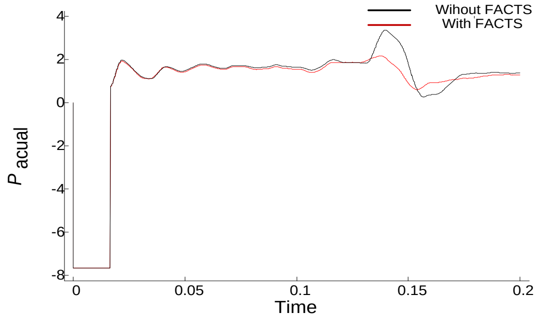
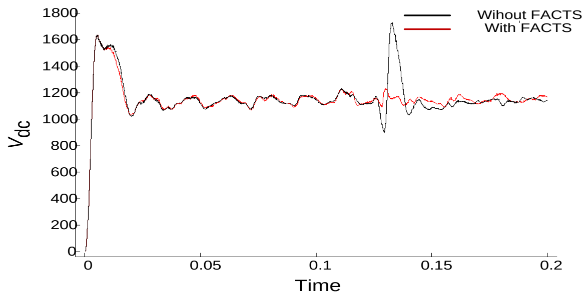


Fig.26. Stator Reactive power



Fig

.27. DC Bus Voltage

Case(4): Performance of DFIG in case of grid under voltage (0.7 P.U) with/without FACTs (TSC) [Qc=7.5 MVAR]

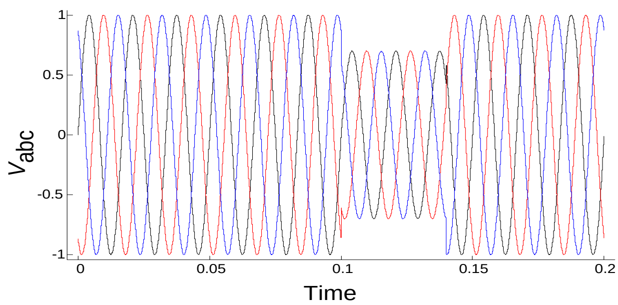


Fig .28. Vabc-grid

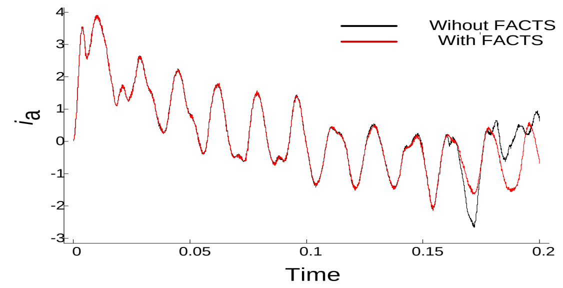


Fig .29. Current in p.u phase ia

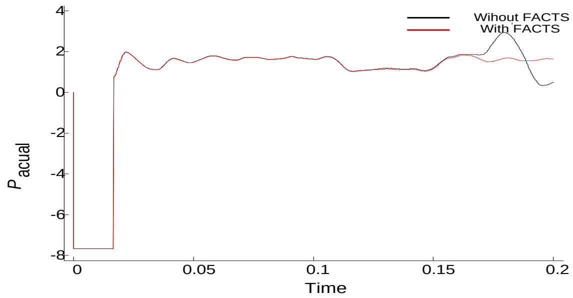


Fig.30. Stator Active power

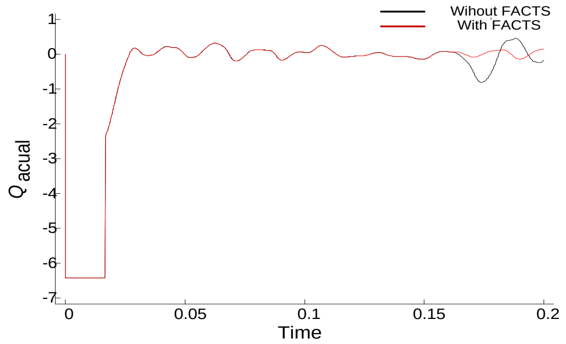


Fig.31. Stator Reactive power

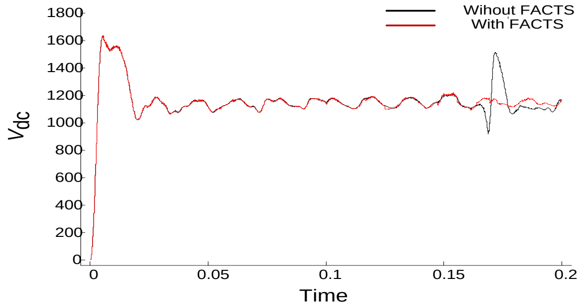


Fig.32. DC Bus Voltage

CONCLUSION

This paper presents the modeling and simulation of grid connected doubly-fed induction generator driven by wind turbine using stator voltage oriented control. The results has been simulated in MATLAB for 1.5MW,690 volt DFIG. The dynamic performance of the system has been shown in case of balance and unbalance grid operation. We impact FACTs devices as a dynamic voltage restorer to maintain stable voltage and thereby protecting DFIG based wind farm interconnected power system from isolating during and after the disturbances.

APPENDIX

A: Generator Data

Rated power	= 1.5 MW
Nominal stator voltage U_n	= 575 V
Nominal Rotor Voltage	=1975 V
Rated frequency f_n	= 60 Hz
Number of pole-pairs p	= 3
Stator resistance R_s	= 0.025 pu
Rotor resistance R_r'	= 0.005 pu
Stator inductance L_{ls}	= 0.18 pu
Rotor inductance L_{lr}'	= 0.16 pu
Magnetizing inductance L_m	= 2.9 pu
Inertia constant	= 0.685

B: NOMENCLATURE

V_s, V_r	Stator, rotor voltage vectors.
I_s, I_r	Stator, rotor current vectors.
V_{sd}, V_{sq}, V_{rd}, V_{rq}	Stator and rotor voltages in dq frame.
I_{sd}, I_{sq}, I_{rd}, I_{rq}	Stator and rotor currents in dq frame.
ψ_s, ψ_r	Stator, rotor flux linkage vectors.
ψ_{sd}, ψ_{sq} ,ψ_{rd} , ψ_{rq}	Stator, rotor flux in dq frames.
R_s, R_r	Stator and rotor resistances.
ω_s, ω_r	Stator, rotor angular frequency.
$L_{\sigma s}$, $L_{\sigma r}$	Stator, rotor leakage inductance
L_s, L_r	Stator, rotor self-inductance.
L_m	magnetizing inductances.
P_s, Q_s	Stator active and reactive power.
Tem	Electromagnetic torque
Vgabc	Three phase grid voltages [V]
gcabc	Three phase grid-side converter . voltages [V]
Iabcr	Three phase rotor current [A]
iga , igb, igc	Three phase grid-side converter .

currents [A]

idcg ,idcr Grid-side and rotor-side DC currents [A]

Rg, Lg Resistance [Ω] and inductance [H] of grid side filter

w_e supply angular frequency

$V_{g\alpha}$,$V_{g\beta}$ the α, β (stationary 2-axis) stator voltage . components

θ_e The angular position of the supply voltage is calculated as follow

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