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Dynamic Response Study of Fixed Speed and Doubly fed Induction Wind Generators using RTDS

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Abstract: **Wind energy is a clean and renewable source of electric power. However, many challenges must be addressed when integrated with the grid. Wind turbines work under turbulent and unpredictable environmental conditions, and are connected to a constantly varying electrical grid with changing voltages, frequency and power flows. Wind turbines have to adapt to these variations, and thus their efficiency and reliability depend on the control strategy adopted. As wind energy penetration in the grid increases, additional challenges to be met are response to grid disturbances, active power control, frequency regulation, reactive power control and voltage regulation etc.**

A case study example of real-time simulation of wind turbines in atypical power system is presented. A comparison of the dynamic behavior of two different types of wind turbine technologies (WTG's) i.e. fixed speed induction generator and variable speed induction generator for short circuits, frequency variations and variation in mechanical torque (wind speed) is presented in this paper.

***Keywords-** Doubly-Fed Induction Generator (DFIG), Wind Turbine, Real-Time Simulation, Fixed Speed Induction generator (FSIG), Voltage Source Converter (VSC)*

I. INTRODUCTION

Wind is commercially and operationally the most viable renewable energy resource and is emerging as one of the largest source in the renewable energy sector.The Indian wind energy sector has an installed capacity of 21.136 GW (uptomarch 2014) [1]. In terms of wind power installed capacity, India is ranked 5thin the World. Wind turbines can be classified based on the technology used (a) squirrel-cage induction generator (fixed-speed) (b) synchronous generatorand (c) doubly-fed induction generators (DFIG) (both variable-speed).

Older wind farms employ the conventional squirrel-cage induction generators whilst modern multi-megawatt machines make use of either the synchronous or the doubly-fed induction machines. A fixed-speedinduction generator (whose speed variations are very limited) is equipped with a squirrel-cage induction generator and utilizes switched capacitor bank for reactive power compensation and gearbox to match the rotational speed of blades with that of the generator. Mechanical power may be regulated through an inherent aerodynamic stall characteristic of blades or with active control of blade pitch.

The variable speed wind generators comprises of (a) wound rotor induction generator with dynamic slip control generally described as semi-variable speed wind turbine with a speed range of up to 10% above synchronous speed (b) direct driven (gearless) multi-pole synchronous generator connected to the grid through full size power electronic converters and (c) Doubly fed induction generator, i.e. a slip-ringed wound-rotor induction generator, with power electronics connected between the rotor circuit and the grid (rating of the inverter is often only 20– 30% of the generator rating as only the slip power is handled by the inverter). The converters perform the reactive power compensation and allow variable speed operation over a wide range. Presently, the DFIG technology is mostwidely adopted among wind turbine manufacturers for larger wind turbines and isthe predominant technology in most wind farms developed since 2005.

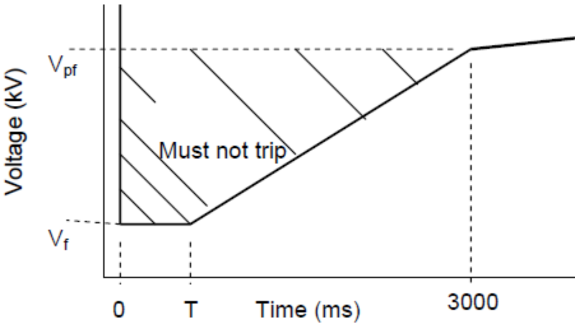
Until late 1990's and early 2000's, most wind turbines were connected at the distribution level. Thus, it was common practice to disconnect the turbine from the system following a fault in the system. In case of conventional induction generators it was a practice for the units to disconnect from the system if the voltage at the terminals of the machine falls below 70 to 80% for more than 100 milliseconds. However, on transmission systems this would mean a high probability that the wind turbine would disconnect for any nearby system fault. Also, with the power levels of individual wind farms approaching those of conventional power plants, and with the increasing percentage of wind in the overall energy mix for electric power generation, grid interconnection standards require the wind generators to remain online and provide similar response and frequency support during grid faults and other disturbances as provided by conventional generators.

This is a major deviation from the earlier philosophy of tripping wind generation off-line for any grid disturbance, and this has led to significant changes in the design of wind turbine control systems. These requirements are often expressed through curves of voltage versus time as shown in figure 1 as per Indian Grid code [2]. The wind plant must stay on-line for any point above the curve implying that the wind turbine technology chosen for the plant must be capable of operating continuously at 80% of nominal voltage, and should not trip for transient voltages as low as 15% of nominal for durations up to 100 ms for 400 kV, 160 msfor 220,132 and 110 kV and 300 ms for 66 kV with the slope shown in the figure 1.

During fault ride-through, the wind turbine generators (WTGs) in the wind farm should have the capability to (a) minimize the reactive power drawl from the grid (b) provide active power in proportion to retained grid voltage as soon as the fault is cleared. At all other times the wind farms are expected to be self sufficient with regard to reactive power.

To contribute to voltage regulation, wind plants are required to have certain level of reactive power management capability. This can range from a requirement to provide sufficient reactive power compensation to provide for the plant's own reactive power consumption to providing fast dynamic voltage control at the wind plant's point ofinterconnection with the transmission system operator. The techniques by which these requirements are met is technology dependent, with variable speed turbines having inherent reactive power control capabilities and fixed-speed machines requiring reactive compensation devices such as switched capacitor banks or dynamic VAr compensators. Indian System requirements for reactive power support from wind plants necessitates that the wind plant should have the capability to operate over a range of power factors from 0.95 lagging to 0.95 leading power factor. Further, the issue of whether reactive power control is to be static (e.g., constant power factor) or dynamic (voltage control) is to be determinedbased on the interconnection studies.

Today, variable speed wind turbines have become more common than traditional fixed-speed turbines. In 2004, the worldwide market share of these wind turbines was approximately 60%. From a power system point of view, the variable speed machines configurations are interesting because the power electronic interface isolates the generators characteristics from the rest of the power system. Only the controlled converter characteristic is seen by the grid.



Where
Vf=15% of nominal system voltages
V_{pf}= Minimum voltages (80% of nominal system voltage)

Fig 1: Voltage versus Time characteristic

II. MODELING AND SIMULATION

The case study illustrates two wind farms each of capacity 300 MW and 250 MW connected to a 220 kV grid having a 25000 MVA short circuit capacity at the grid connection point [Fig 2].The simulations are carried out using Real Time Digital Simulator (RTDS).Each wind farm is simulated as a single wind turbine with the appropriateratings of Wind Turbine Generator (WTG1300 MW and WTG2 250MW). It is assumed that all the generators within the wind farm are identical and operate at the same operating point. Each wind farm is represented as a classical WTG driven by a single wind turbine. In steady-state the wind speeds for each wind turbine are such that the generator WTG1 produces 210 MW and WTG2 produces 175 MW at a speed of 1pu.

A fixed speed induction generator is modeled as an induction machine with no-load reactive power compensation provided by capacitor banks connected at the terminals of the generator (Fig 3). The wind turbine model employed in the study is based on steady state power characteristics of the turbine (equation 1). The wind turbine mechanical power output is a function of rotor speed, wind speed, blade pitch angle, air density, Turbine swept area and the tip speed ratio (equation 1).

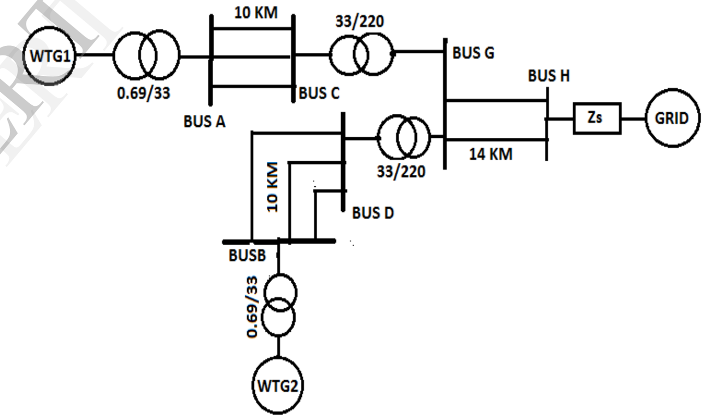


Fig 2. SLD of power system

$$P_m = C_p(\lambda,\beta)\frac{\rho A}{2}V^{3}_{wind} \quad (1)$$

where,

P_m – Mechanical power output of the turbine
C_p – Power Coefficient of the turbine
λ – Tip speed ratio of the rotor blade tip speed to wind Speed
β – Blade Pitch angle (Degrees)
ρ – Air Density (kg/m^3)
V_{wind} – Wind speed m/s
A -Turbine Swept Area (m^2)

The generic equation used to model Cp (λ,β) is given in equation(2) below:

$$C_p(\lambda,\beta) = c_1\left(\frac{c_2}{\lambda_1} - c_3\beta - c_4\right)e^{\frac{-c5}{\lambda_1}} + c_6\lambda$$

$$\frac{1}{\lambda_1} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (2)$$

Where, c_1=0.5176, c_2 =116,c_3=0.4,c_4 =5.0,c_5= 21.0, c_6 :0.0068

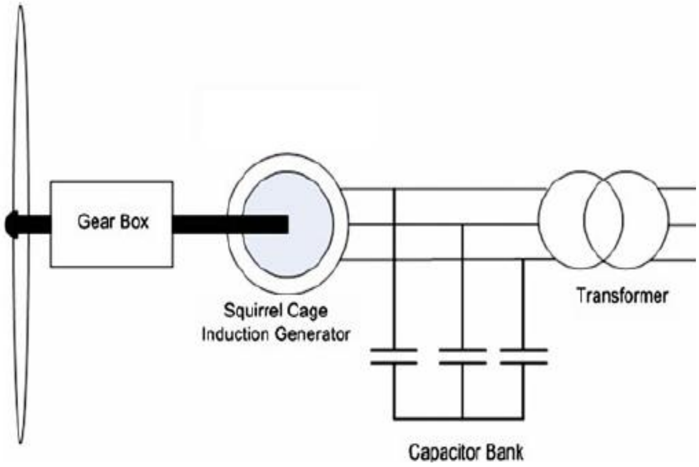


Fig 3: Fixed Speed Induction Generator

The configuration of DFIG system considered in the study is shown in figure4. Wind turbine is connected to the DFIG through a mechanical shaft. The stator of the wound rotor induction generator is directly connected to the grid and the rotor is connected to the grid through a rotor VSC, a DC link capacitor and gridVSC.

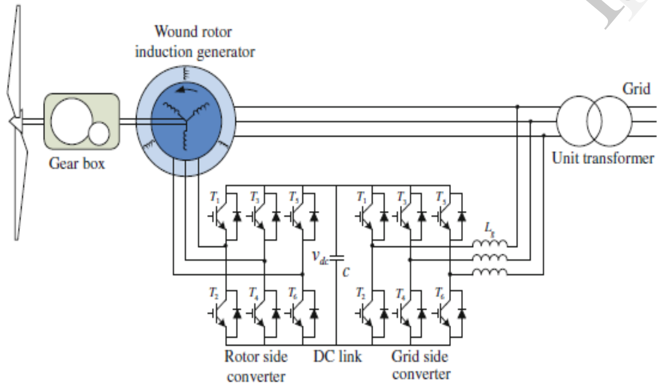


Fig 4: Doubly Fed Induction Generator

The main role of the grid side converter is to provide a path for the active power exchange in the positive or negative direction between the rotor side converter andthe grid.It does so by regulating the DC link voltage regardless of the direction and magnitude of the rotor power. A vector-controlapproach is used, with a reference frame oriented alongthe statorvoltage vector position. This enables independent control of the active and reactive powerflowing between the grid and the grid-side converter.Vector control in the rotor VSC allows the rotor torque and excitation currentto be controlled independently.

The VSC Capacitor and the grid VSC reactor are suitably sized to match the rating of the DFIG. The power rating of the VSC is chosen to be almost 30% of the machinerating.Therated speed of DFIG is chosen to be 1.2 times synchronous speed to ensure extraction of energy from both the rotor and the stator of the machine. The various controls used in the DFIG are as given in [3, 4] and are explained briefly in the following sections.The control strategy presented below was adopted for the DFIG model.

Grid VSC Controls:

The grid VSC is current regulated with thereal component used for regulating the capacitor voltage and the quadrature component used to adjust terminal voltage. For regulation of currents, they are first transformed from three phase to two phase and then applied to a rotating referenceframe, so that the ac fundamental component is extracted (direct –d axis and quadrature – q axis currents).

It can beenshown that the active power (P) and reactive power (Q)flow will be proportional to i_d and i_q respectively (equation (3)) and that the DC-link voltage can becontrolled via i_d(equation 4).

$$P = 3(v_d i_d + v_q i_q)$$

$$Q = 3(v_d i_q + v_q i_d) \quad (3)$$

$$V_{dc} = \frac{2\sqrt{2}}{m_1} v_d \quad (4)$$

Where i_d, i_q andv_d, v_q are the grid side, d and q axis currents and voltages respectively, V_{dc} – voltage across the DC link, m_1-grid side converter modulation index.

The control scheme thus utilizes currentcontrol loops for id and iq(Fig 5 (a)) with the id demandderived from the DC-link voltage error through astandard PI controller(Fig 5(b)). The iq demand determines thedisplacement factor (between voltage and current) on the supply-side of grid VSC.

The output of the d and q current regulators represents the voltage vector required to create the requested current. It is first transformed from the d,q reference frameto its equivalent magnitude and angle, and then to the stationary ac referenceframe, resulting in a modulation reference for each phase. Firing pulses for both the grid VSC and the rotor VSC are produced byPWM technique using the triangle waves and the modulation references.

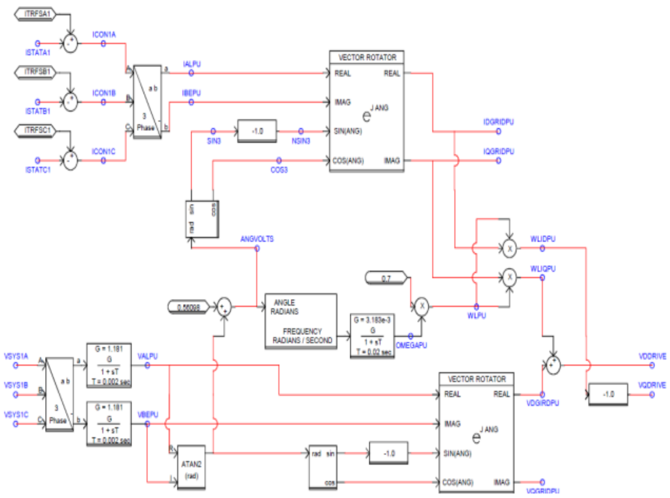


Fig. 5(a): Grid side Converter controller

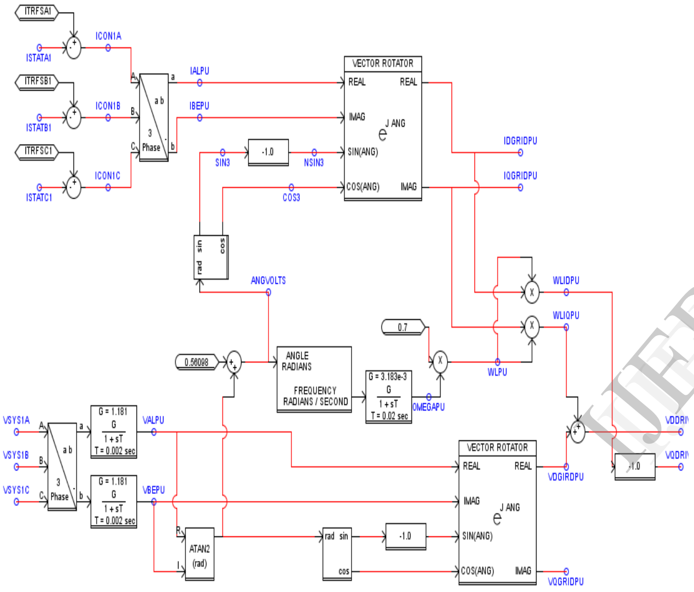


Fig. 5(b): Grid side PI controller

RotorVSC Controls:

The Rotor VSC controls are similar to the Grid VSC controls.The rotor currents are converted with a rotating reference frame to d,q quantitiesand then regulated with PI controls. The rotating reference frame in this case,is computed from the difference between the position of the stator flux vector andthe physical rotor direct axis (referred to as slip angle). By decoupling the d and q rotor currents, the electricaltorque and rotor excitation current is controlled independently.

Vector control of the rotor-connected converter provides for wide speed-range operation. To achieve optimal power out of the wind turbine, optimal torque is calculated and then used to find the reactive rotor current reference. For wind velocities higher than rated, the turbine energy capture is limited by applying pitch control.

Crow Bar Controls:

The excess of either the rotor current limit or the DC-link voltage limit (2.0 pu) will activate the crowbar protection to short-circuit the generator rotor and deactivate the rotor-side converter, while the induction generator and the grid-side converter are kept in connection with the grid. However in this particular simulation the crowbar controls have not been activated.

Wind Turbine Controls:

The wind turbine controls are meant to feather the turbine blades if the turbine speed rises above 1.0 pu.This happens if the wind rises above onepu wind velocity or the power input to the DFIG drops below one pu. A drop in power output typically occurs if the back to back VSCs are blocked or for faults.There is no control action for turbinespeeds at or below onepu and acts as a proportional type control with rate limitsfor turbine speeds in excess of one pu.The regulator is a proportional type as some overspeed in the wind turbine is permissibleand attempting to regulate turbine rotational speed with zero error is unnecessary.Lower limits are placed on the control as well as rate of change limits.

III. REAL TIME DIGITAL SIMULATOR

The simulation tool used in the study is the RTDS which uses electromagnetic transient solution.This method is based on Dommel’s algorithm and trapezoidal rule of integration to produce new solution in each time step. Special high speed processing and signal communication is used for real time execution [5].

Generally, Electro-magnetic Transient Program type (EMTP) simulation uses a typical time stepof 50 µs which is sufficient for events occurring in the rangeof DC to 3 kHz. RTDS software called as RSCAD includes accurate power system component models required to represent many of the complex physical power systems.

However, for modeling of high frequency switching circuits like VSC’s with IGBT used in PWM schemes, small time step simulation (1 to 3 µsecs) is a must as the phenomena of interest take place at higher frequencies. Thus, in the RTDS the main network comprising of power system components like transmission lines, transformers etc are solved with 50 µs time step, where as the VSC circuit is solved with time step of 1 to 3 µsecs. The large time step network is interfaced with the small time-step simulation using the interface transformers.

IV. CASE STUDIES AND DISCUSSIONS

For carrying out studies in which the primary purpose is to examine the impact of the wind farm on system dynamic performance, it is not necessary to represent each wind turbine in the wind farm separately. Aggregated model of the wind farm is considered in this study in which many wind generators in a wind farm are represented with a large wind generator. To observe the response of the FSIG and DFIG wind turbines to power system disturbances, all wind generators in the chosen system are modeled either as all FSIG or as all DFIG's. The model system (fig 2) is run in two different time steps, small time-step normally running at 1 µsec – 4 µsec and large time-step typically running at 50 µsec. Thus two different time-step simulations are interfaced with each other through the interface transformer. Main power system components are solved in large time step and the DFIG and associated controls in small time step. Results from numerical simulation of a FSIG/DFIG system with the parameters given in Appendix I and with controllers outlined in previous sections are presented here.

Simulation results are shown to quantify the effect of wind generation on system frequency, voltage profile and behavior during a short circuit. Thus different types of disturbances have been simulated on the studied network such as (a) Change in wind speed resulting in change of mechanical power (b)Three-phase fault on one of the 220 kV feeder evacuating power to the grid (c) A Grid frequency variation representing loss of generation in the grid .

For all the cases studied here it is presumed that the wind generators are generating about sixty percent of their rated capacity.

(a) Change in Wind speed :

The simulation here corresponds to a linear change in the applied wind speed. Initially the wind speed is 6 m/s which then suddenly changed to 9 m/s over a period of two seconds.

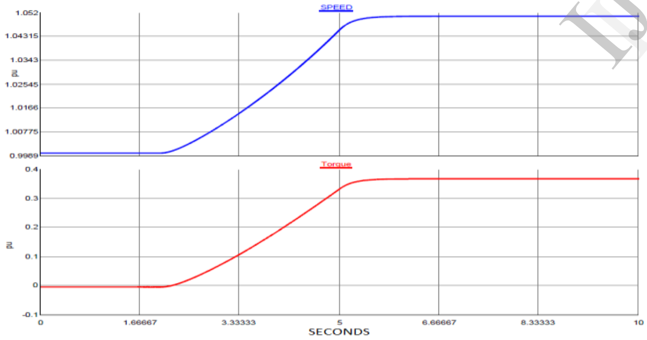


Fig 6(a): Speed, Torque -FSIG for Wind speed Changes

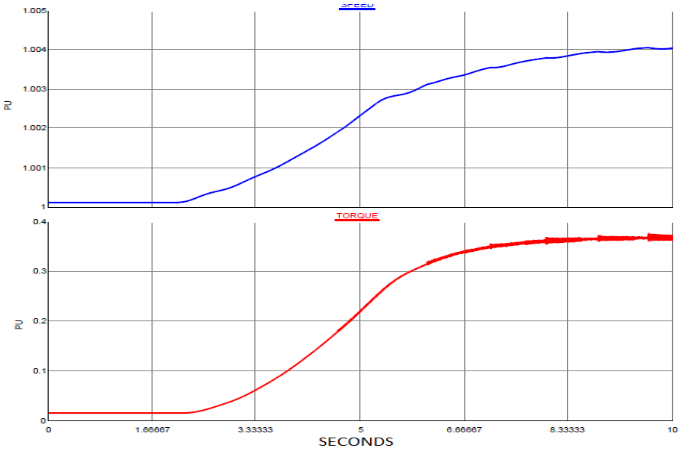


Fig 6(b): Speed, Torque -DFIG for Wind speed changes

Figure (6(a), 6(b)) shows the corresponding plots of rotor speed and the electromagnetic torque. As seen, wind power matches with the wind model, and the grid power tracks the wind power closely. In case of FSIG the changes in the speed and torque are seen immediately, while in the case of DFIG, the maximum power tracking algorithm takes some time to track the power output.

(b) Fault on Transmission Line:

The impact of voltage sag resulting due to a three-phase to ground fault at the terminals of one of the 220 kV transmission line evacuating power to the grid is studied. The wind speed is maintained constant here at 10 m/sec. The duration of fault is considered to be 160 millisecs. Fig 7(a), 7 (b) shows the plots of rotor speed and the grid bus voltage point for the case of FSIG.

The studies show that even though the FSIG's were provided with fixed shunt capacitor compensation, contingencies in their vicinity leading to voltage dips of 0.05 puwould lead to their pulling away from the grid

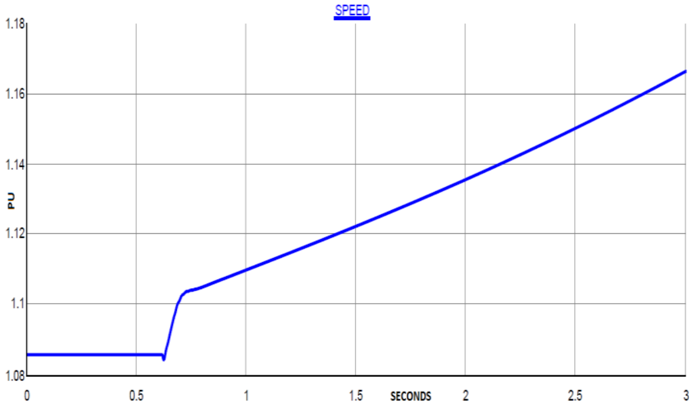


Fig 7(a): Rotor Speed – FSIG – Fault on Transmission

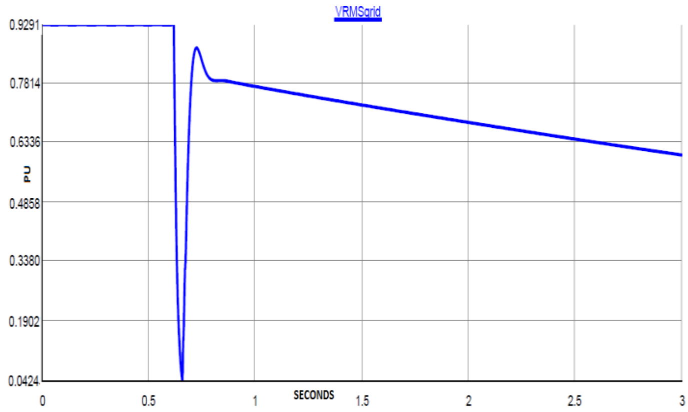


Fig 7(b): Grid bus Voltage – FSIG – Fault on Transmission Line

(Fig 7 (a)). The collapse in grid voltage is shown in fig 7(b). It was also observed that there is large reactive power drawl from the grid.

One of the alternatives investigated to resolve this situation in the case of FSIG was providing of dynamic voltage support i.e. a STATCOM rated 100 MVAr connected at bus B. Fig 8(a), 8(b) illustrates the beneficial impact of such dynamic compensation in providing fast voltage recovery, and consequently a stable performance.

In case of DFIG the variations of rotor speed is shown in Fig 9(a) and Fig 9(b) shows the active and reactive power at the grid terminals. As seen, the reactive power exchange with the grid in steady state was minimal, (as the reactive power exchange is controlled by the rotor side converter) which only momentarily increases during the fault. Also, the DFIG is able to sustain this type of disturbance without getting disconnected from the Grid and thus can be said to be more suitable for meeting the grid code requirements

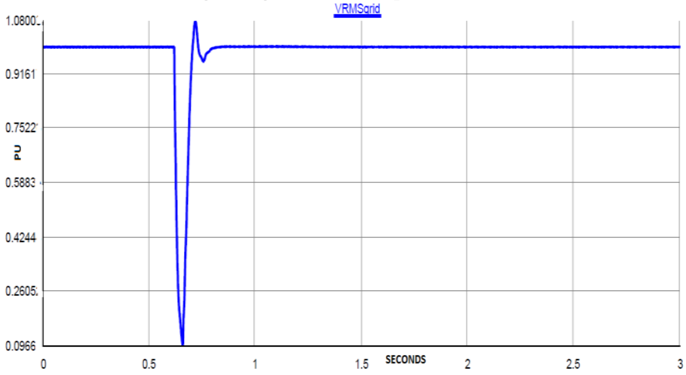


Fig. 8(a): Grid Bus Voltage – FSIG – With STATCOM

(c) Grid Frequency Variation:

The dynamic performance of both the FSIG and DFIG wind turbine generators to variations in grid frequency representative of loss of generation/ increase in load is studied by a step decrease in frequency. Fig 10(a) shows the change in electrical output power and speed for a frequency decrease of one hertz in the Grid

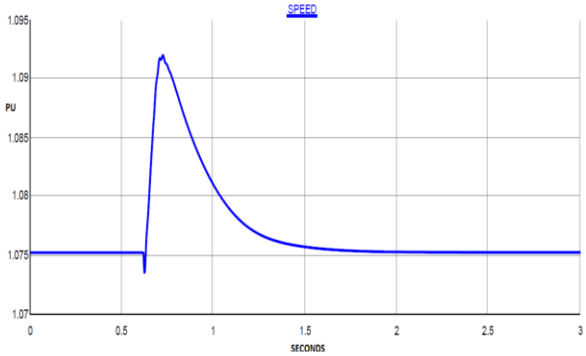


Fig.8 (b): Grid Bus voltage – FSIG – With STATCOM

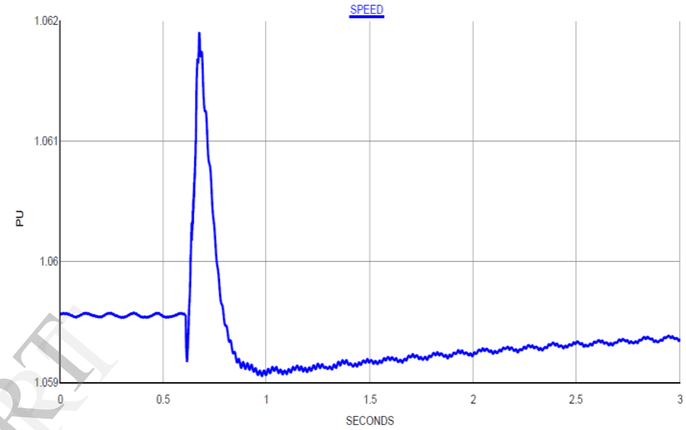


Fig. 9(a): Rotor Speed – DFIG

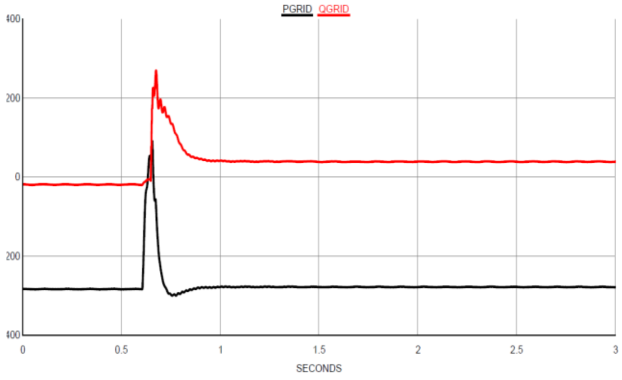


Fig. 9(b): Active and Reactive Power output at Grid

As seen from oscillograms of active and reactive power of WTG’s, for the case of FSIG there is a sudden power surge (Fig 10(a)) which can be attributed as due to the deceleration of the machine (Fig 10(b)) resulting in conversion of kinetic energy of the machine to electric energy. However, in case of DFIG this is not being observed (Fig 11(a), 11 (b)) as the rotor speed is controlled by the rotor side converter controls.

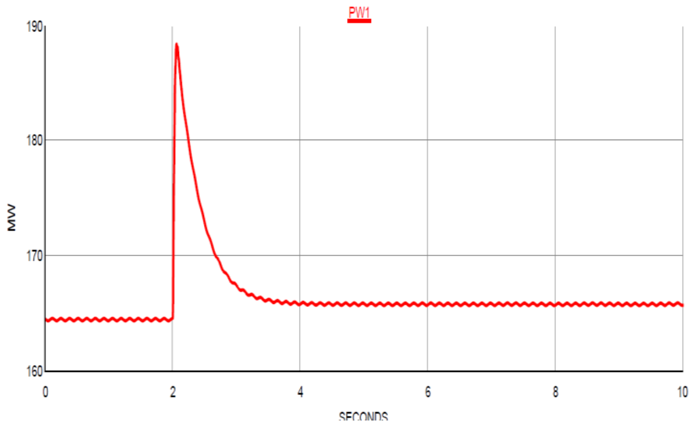


Fig. 10(a): Active Power output of WTG1-FSIG

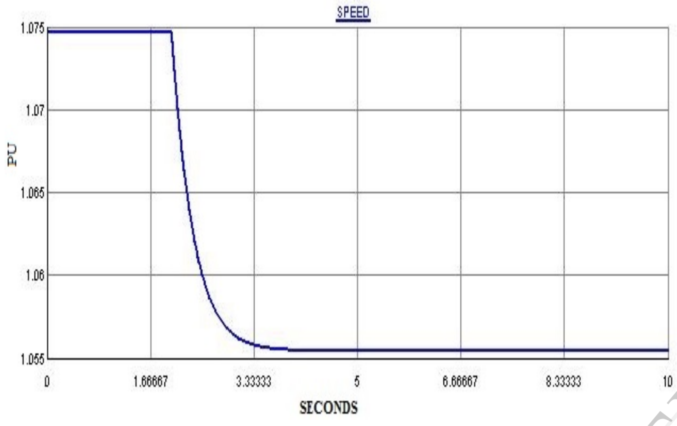


Fig. 10(b): Rotor Speed of WTG1-FSIG

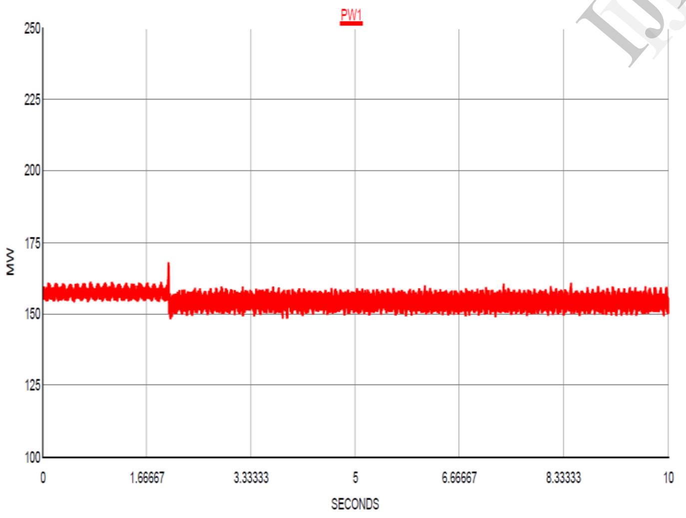


Fig 11(a): Active Power output of WTG1-DFIG

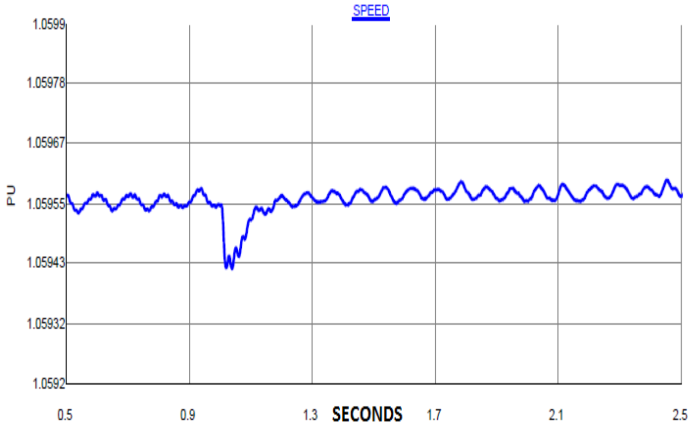


Fig 11(b): Rotor Speed of WTG1-DFIG

V. Conclusions

The modeling and control strategies of fixed speed asynchronous generator and doubly-fed induction generator wind turbines have been described briefly and their dynamic performance compared during power system disturbances. The simulations have been carried out using Real Time Digital Simulator.

A typical Indian power system was used to investigate the effect of three-phase faults, wind speed and frequency variations on the dynamic performance of the different types of wind turbine generators. Based on the study results it is seen that the FSIG when subjected to voltage sag due to a three-phase fault on led to acceleration of the generator rotor and pulling away of the generator. The voltage support, provided by the capacitors in FSIG wind turbines, is insufficient to meet the dynamic reactive power requirements leading to collapse in voltages. Alternately providing of a dynamic compensation device like STATCOM alleviated the situation. In case of DFIG implementing the reactive power controls can result in maintaining the grid bus voltage, thereby offering better grid connectivity performance and ride through capabilities.

With regard to reactive power capabilities, DFIG facilitates minimum reactive power exchange with the grid thereby one of the grid code requirements. The effects of frequency variations in the grid do not affect the performance of DFIG. However FSIG machines are subjected to sudden power variations.

The overall dynamic performance of DFIG machines makes it more suitable for meeting the grid code requirements with respect to reactive and fault ride through capabilities.

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Appendix I

Voltage rating	0.69 kV
MW rating	250 MW
Frequency	50 Hz

Wind Turbine model parameters:

Stator resistance	0.00462 PU
Rotor resistance	0.0060 PU
Stator reactance	0.102 PU
Rotor reactance	0.03596 PU
Magnetising reactance	4.348 PU
Lumped inertia constant (H)	1.5 MW-s/MVA

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