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Dynamic Modeling for Improvement in Power Quality Issues of DFIG Wind Farms Interconnected with Grid

K. Umadevi, S.V.N.L. Lalitha, S.H. Chetwani

Abstract: ***This paper depicts improved dynamic modeling of doubly fed induction generator (DFIG) wind farms with a grid-connected system under issues of power quality like voltage sag, swell & harmonics. They have a severe impact due to nonlinear & unbalanced loads fed by DFIG integrated into a grid. Due to this, the synchronous reference frame (SRF) control strategy is proposed for ride through of voltage sag, swell & improve power factor and filters are used to reduce harmonics in DFIG system connected to the grid. The pitch control strategy used to pitch angle control of the turbine blade & maintain rotor speed constant. These control schemes effectively work at varying wind speed in DFIG wind farms and support control active & reactive power. The system is simulated in MATLAB/Simulink using a 2.5MW DFIG wind turbine connected to the grid. The proposed control strategy enhances the performance of the entire system. The results are discussed in detail with and without control strategy.***

Keywords: ***Harmonics, power factor, pitch control, voltage sag, voltage swell, DFIG, grid.***

I. INTRODUCTION

Day by day the population is increasing and the utilization of electricity is also increasing, with an increase in penetration of renewable energy sources. These energy sources are evolving sources that have huge potential compared to traditional energy sources and these are sustainable, reusable, clean and eco-friendly. There are many renewable energy sources available but wind energy is having rapid growth amongst all and a large penetration of wind energy into the power grid and it is promising due to economic viability. There are different types of wind turbine generators are available in the market, out of which, DFIG is more popular [1]. DFIG is a variable wind speed turbine. In DFIG, the stator is connected to the grid directly and operates with fixed speed and fixed frequency and rotor is connected to the grid through back to back converters and operates with variable speed and variable frequency. The variable switching frequency pulse width modulation technique is used to achieve efficient control performance such as fast dynamic response with less harmonic distortion [2]. The rotor power is about 30% of nominal turbine power. The IGBT based power electronic converters are used in the DFIG system and the cost of the system is lower due to partially rated power electronics. The power electronic converters should inject or absorb reactive power to the grid and it operates sub-synchronous and super-synchronous modes [3]. The main drawback of DFIG integration with the grid is that it generates power quality issues [4]. The wind farms interconnected to the grid follows by the Central Electricity Authority (Grid standards) regulations [5]. Fig.1 shows the detailed configuration of DFIG wind farms interconnected with the grid.

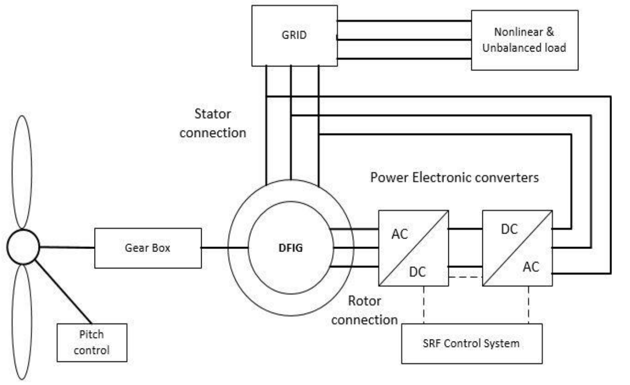

Fig.1 Schematic diagram of DFIG interconnected with grid

Section II of this paper represents equations of an equivalent circuit of DFIG, section III explains power quality issues, section IV explains the proposed method, section V includes the simulation results of DFIG & section VI concludes the findings.

II. MATHEMATICAL MODELING OF DFIG

The rotor rotates and converts kinetic energy to mechanical energy and it is connected to a shaft and spins a generator to generate electricity. The power output of the wind turbine refers (1).

$$P_T = 0.5\, C_P\, A\, \rho_A W^3 \text{ watts} \qquad (1)$$

Here, C_P is the power coefficient of the wind turbine. The value of C_P is being ranged between 0.25 to 0.45, A is the swept area of the rotor in m^2, ρ_A is the Air density in kg / m^3, it depends on atmospheric conditions and W is the wind speed in m/s. At a given wind speed, the coefficient of power decides the maximum power developed by the wind turbine and it is a function of tip-speed ratio and the blade pitch angle.

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The tip speed ratio depends upon the rotational operation of the generator. The tower height is usually equal to 1 or 2 times of rotor diameter if tower height increases then wind velocity will also be increased [6].

The DFIG system comprises a stator & rotor. The stator and rotor are connected to the grid via a three-phase transformer and a back to back converters respectively. The power transfer of these back to back converters composes up to 30% of the nominal power capacity of DFIG wind turbine. Fig.2 shows the equivalent circuit of DFIG.

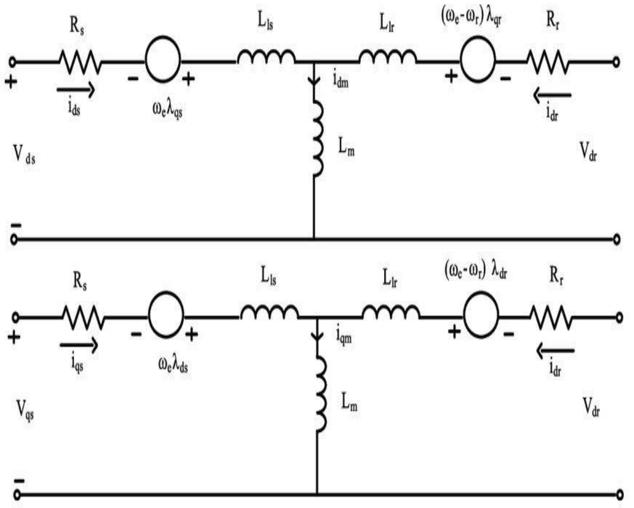

Fig.2 Equivalent circuit of DFIG wind turbine

Equation (2) represents the voltages of stator & rotor in the SRF control method. The flux, voltage & current expressions are taken from a paper [7].

$$
\begin{aligned}
V_{ds} &= R_s i_{ds} + d/dt(\lambda_{ds}) - w_e\lambda_{ds} \\
V_{qs} &= R_s i_{qs} + d/dt(\lambda_{qs}) - w_e\lambda_{qs} \\
V_{dr} &= R_r i_{dr} + d/dt(\lambda_{dr}) - (w_e-w_r)\lambda_{qr} \\
V_{qr} &= R_r i_{qr} + d/dt(\lambda_{qr}) + (w_e-w_r)\lambda_{dr}
\end{aligned} \qquad (2)
$$

Here, V_{ds}, V_{qs} are dq components of stator voltages and V_{dr}, V_{qr} are dq components of rotor voltages. The i_{ds}, i_{qs} are dq components of stator currents and i_{dr}, i_{qr} are dq components of rotor currents. w_e, w_r are the supply and rotor angular frequency respectively. The dq components of stator and rotor flux linkages are λ_{ds}, λ_{qs} and λ_{dr}, λ_{qr} respectively. The stator and rotor resistances are R_s & R_r respectively.

The below equation (3) represents the stator and rotor inductances are L_s, L_r respectively and the flux linkages as per equation (4).

$$
\begin{aligned}
L_s &= L_{is} + L_m \\
L_r &= L_{ir} + L_m
\end{aligned} \qquad (3)
$$

Here, L_{is}, L_{ir} represents the leakage inductances of stator & rotor respectively and L_m is the inductance of magnetization.

$$
\begin{aligned}
\lambda_{ds} &= L_s i_{ds} + L_m i_{dr} \\
\lambda_{qs} &= L_s i_{qs} + L_m i_{qr} \\
\lambda_{dr} &= L_m i_{ds} + L_r i_{dr} \\
\lambda_{qr} &= L_m i_{qs} + L_r i_{qr}
\end{aligned} \qquad (4)
$$

The direct axis controls the stator reactive power (Q_s) and quadratic axis controls the stator active power (P_s) as per equation (5).

$$
\begin{aligned}
P_s &= 1.5\,(V_{qs}i_{qs} + V_{ds}i_{ds}) \\
Q_s &= 1.5\,(V_{qs}i_{ds} - V_{ds}i_{qs})
\end{aligned} \qquad (5)
$$

III. POWER QUALITY ISSUES

The DFIG wind farms when operated as grid-connected system, leads to the fluctuation in power generated. It will be reflected in voltage and frequency levels such as voltage sag, voltage swell, harmonics & it has a severe impact due to nonlinear and unbalanced loads fed by DFIG interconnected to the grid.

Voltage sag & swell occurred due to power system faults i.e sudden load increases or decreases. Due to these issues' equipment should be shut down, a data error occurs and harmonics generate heat, it reduced equipment life span, misfiring in variable speed drive [8] [9].

According to the guidelines of Central Electricity Authority (grid standards), in DFIG wind farms the frequency should not be behind -1.5% and beyond 0.5% of nominal frequency. The voltage should be in between $\pm$ 10% of nominal voltage. The percentage of harmonic present in the system should not exceed 2.5 %. The critical clearing time for fault occurred at grid side is 160ms. For smooth operation of DFIG wind farms the voltage unbalance limit should be less than 2%. The voltage fluctuation for step changes which may occur is 1.5%, other than step changes 3% of nominal voltage.

IV. PROPOSED METHOD

A. Pitch Control

The pitch control method used in wind turbines control the angle of the wind turbine blade and this angle is proportional to the wind speed changes as per equation (6).

$$P_T \; \alpha \; w^3 \qquad (6)$$

In order to control wind turbines, pitch control has been used to control the pitch of the blade. This method in order to maximize output for all wind speeds [10] [11]. Fig.3 illustrates a schematic diagram of pitch control. The input reference is pitching attitude and a servomotor controls the pitch angle of the blade. The motor operates in a closed loop which is a servo mechanism that uses position feedback sensor to regulate its motion and final position, many servomotors use optical rotary encodes to measure the output shaft speed and a variable speed drive is used to control the motor speed. The rate limit of pitch controller is set to a value and it prevents over-speed both normal and during faults, pitch angle controls directly, the speed of the generator. The Fig.3 shows a schematic diagram of pitch control of the wind turbine.

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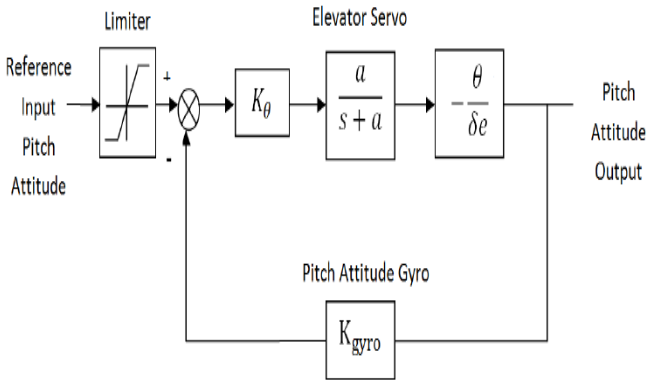

Fig.3 Schematic diagram of wind turbine Pitch control

B. Synchronous Reference Frame Control

The major Power quality issue for DFIG is harmonics. The harmonic distortions are increased by using power electronic converters. Here the active power filters (APF) are preferred over passive filters because APF is dynamic, fast and to compensate power quality issues. The converters are IGBT based three phase, three leg bridge, and six pulse converters. These are containing a common DC-link. The synchronous reference frame (SRF) control method generates reference signals of voltage and current. In DFIG wind farm the series SRF control scheme used at rotor side converter (RSC) and the shunt SRF control scheme used at grid side converter (GSC). The fig.4 shows a schematic diagram of SRF control at RSC.

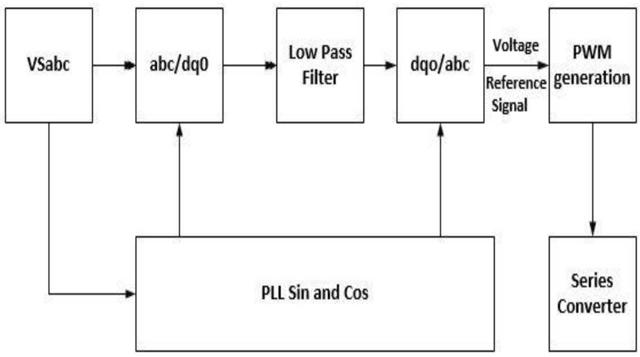

Fig.4 Schematic diagram of SRF control at RSC

The series SRF control scheme mainly adapt to grid-related voltage power quality difficulties. Those are voltage sag, voltage swell & harmonics. The series APF injects series voltage and to supply the load reactive power. The SRF control method is used to generate reference signals of the corresponding to compensate voltage. By using dq0 transform the three-phase reference voltages are converted from abc to dq0 frame and the phase-locked loop (PLL) generated theta signal required for this transformation. The dq0 transform converts AC to DC quantities. These are extracted easily by using a low pass filter. Here the reference voltage signals are generated. The reference & measured source voltages are

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin(wt) & \sin(wt-\frac{2\pi}{3}) & \sin(wt+\frac{2\pi}{3}) \\ \cos(wt) & \cos(wt-\frac{2\pi}{3}) & \cos(wt+\frac{2\pi}{3}) \\ \sqrt{\frac{1}{2}} & \sqrt{\frac{1}{2}} & \sqrt{\frac{1}{2}} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (7)$$

passed into a pulse width modulation (PWM) controller. The PWM generates switching pulses for RSC. Equation (7) represents dq0 transformation of voltage.

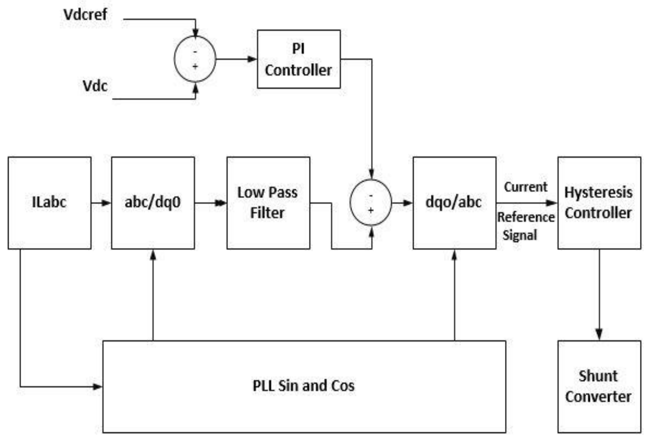

Fig.5 Schematic diagram of SRF control at GSC

The shunt APF is used to compensate currents and reducing rotor inrush currents of power quality issues. This filter handles the required current of maintaining the DC link voltage. The Fig.5 shows a schematic diagram of SRF control at GSC.

$$\begin{bmatrix} I_d \\ I_q \\ I_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(wt) & -\sin(wt) & \frac{1}{2} \\ \cos(wt-\frac{2\pi}{3}) & -\sin(wt-\frac{2\pi}{3}) & \frac{1}{2} \\ \cos(wt+\frac{2\pi}{3}) & -\sin(wt+\frac{2\pi}{3}) & \frac{1}{2} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad (8)$$

The SRF control method is used for generating reference signals of the corresponding to compensate currents. By using dq0 transform the stator currents are converted from abc to dq0 frame. The phased locked loop generates theta signal required for this transformation. The dq0 transform converts AC to DC quantities. These are extracted easily by using a low pass filter. Here the reference current signals are generated, the reference & measured source currents are passed into a hysteresis current controller. This controller generates switching pulses for GSC. Equation (8) represents dq0 transformation of current. The proposed schemes are developed in MATLAB/Simulink software.

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V. SIMULATION RESULTS

In DFIG system without a controller, rotor speed increases with respect to wind speed. By using pitch control method, the rotor blades are kept at the optimum angle and the Fig.6 (a) shows rotor speed is maintained constant and the value is 1.2pu, electromagnetic torque is also maintained constant. The DC link voltage calculated is kept more than two times of nominal voltage of wind turbine. The Fig.6 (b) shows DC link voltage of back to back converters maintained constant and the value is 1380 volts.

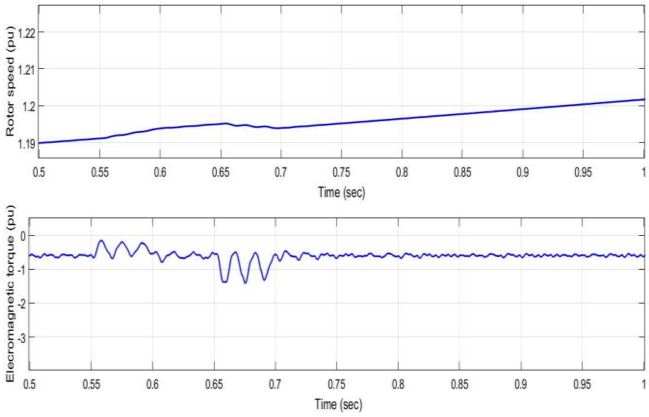

Fig.6 (a) Rotor speed, Electromagnetic torque

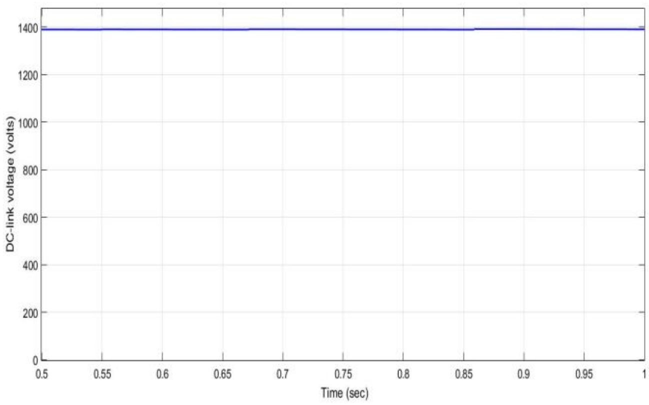

Fig.6 (b) DC link voltage

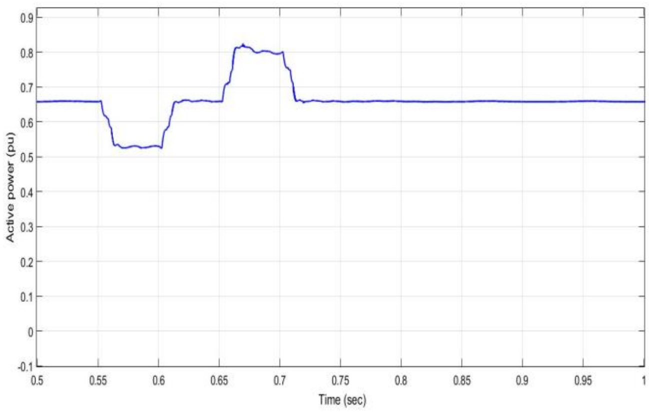

Fig.6 (c) Active power at stator connected grid

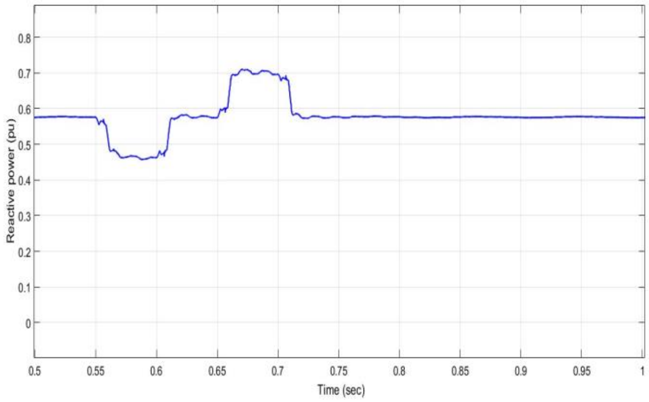

Fig.6 (d) Reactive power at stator connected grid

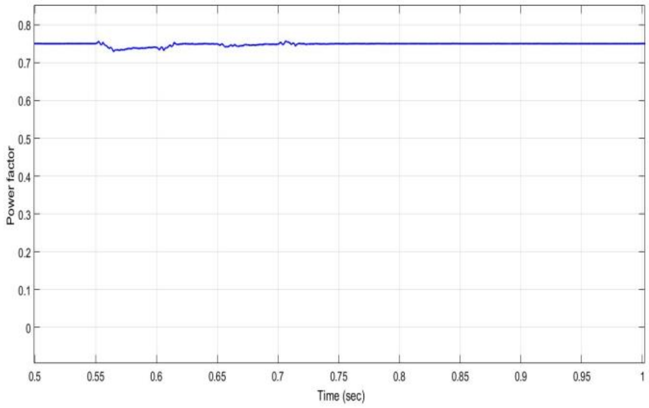

Fig.6 (e) power factor

The below figures show a comparison between with and without controller of voltage and current waveforms of RSC, GSC, and stator connected to the grid. Fig.7 (a) represents waveforms of voltage and current at RSC without controller, the currents are inrush with respect to wind speed which creates an unreliable power. The shunt SRF control compensates rotor currents, Fig.7 (b) represents controller waveforms at RSC with currents compensated. The Fig.7 (c) represents waveforms of voltage and current at GSC without controller with respect to rotor signals. The series SRF control compensates GSC voltages, Fig.7 (d) represents with controller waveforms, at which the GSC voltages are compensated. The Fig.7 (e) & Fig.7 (f) represents without and with controller waveforms of voltage & current at stator connected to grid. Fig.6 (c) & Fig.6 (d) represents the active power & reactive power at the stator connected to the grid. Fig.6 (e) shows improved power factor measured at stator connected to the grid and the value is 0.75. Fig.7 (g) represents THD of source current without a controller is 22.87 % and Fig.7 (h) represents the THD of the source current with a controller is 1.52%. Finally, the THD of source current is drastically reduced.

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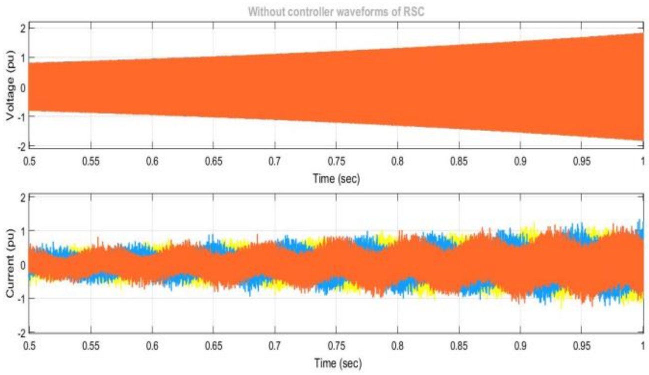

Fig.7 (a) Waveforms of V & I without control scheme at GSC

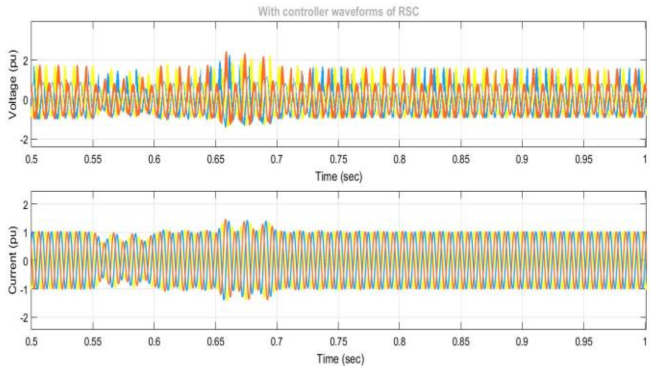

Fig.7 (b) Waveforms of V & I with control scheme at GSC

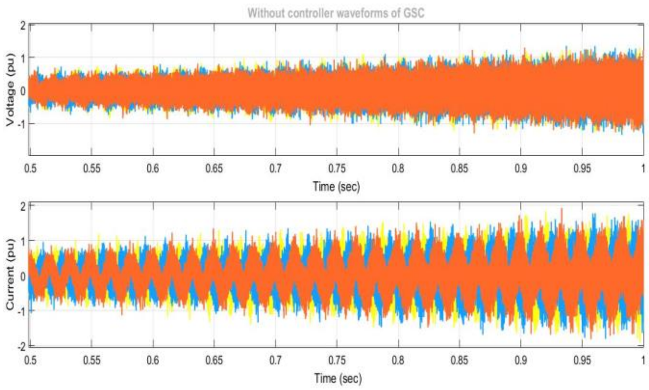

Fig.7 (c) Waveforms of V & I without control scheme at RSC

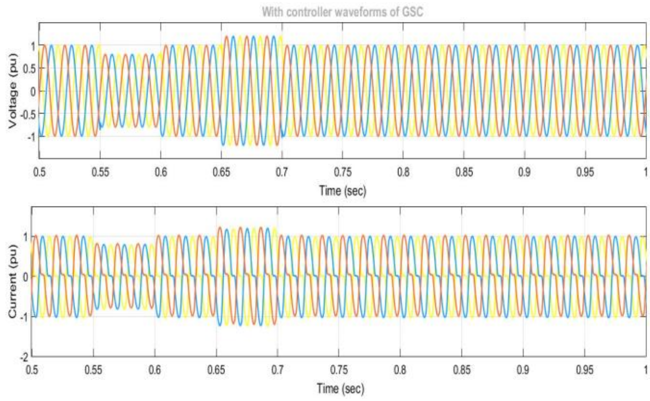

Fig.7 (d) Waveforms of V & I with control scheme at GSC

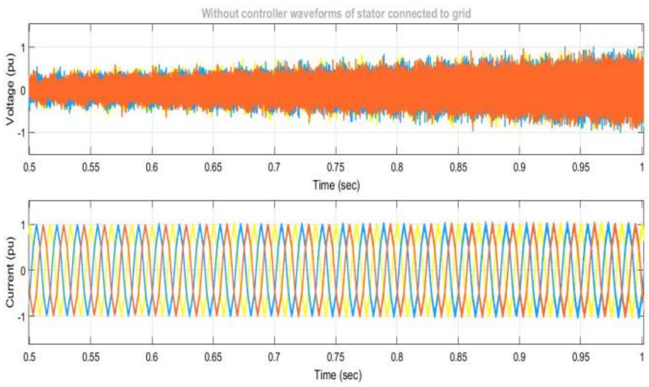

Fig.7 (e) Waveforms of V & I without control scheme at stator

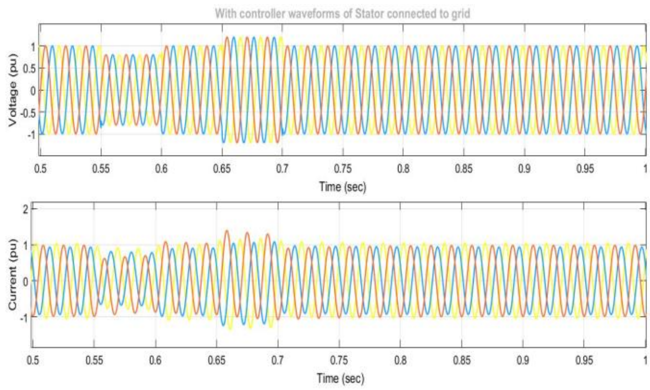

Fig.7 (f) Waveforms of V & I with control scheme at stator

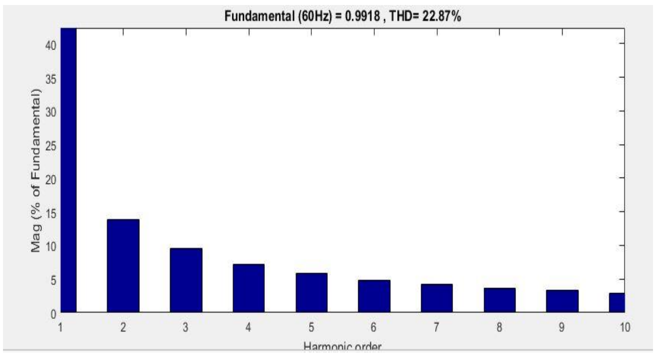

Fig.7 (g) The THD of source current without a controller

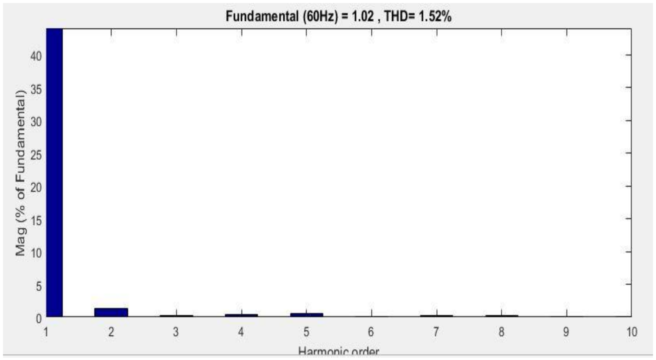

Fig.7 (h) The THD of a source current with a controller.

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VI. CONCLUSION

The proposed control schemes used in the incorporation of DFIG wind turbine modeling to achieve ride through capability of power quality issues such as voltage sag, swell & harmonic reduction. The power factor of the DFIG wind turbine system is also improved there by improving the performance of the entire system. The advantage of the proposed scheme used in this paper is, it can be implemented very easily compared to the other control schemes. In future, by using this method flicker can also be mitigated.

TABLE-I
THE SIMULATED DFIG PARAMETERS

Mechanical output power	2.5MW
Voltage (line-line)	690V
Rated frequency	60 Hz
Pole pairs	4
Synchronous speed	1200 rpm
Stator resistance R_s	0.00488 Ω
Stator leakage inductance L_{ls}	0.09231 H
Rotor resistance R_r	0.00549 Ω
Rotor leakage inductance L_{lr}	0.09955 H
Mutual inductance L_m	3.9579 H
Inertia constant	3.25 MJ/MVA
Friction factor	0.05479

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