Subsynchronous Resonance Mitigation in DFIG-Based Wind Farm

Pooja A. Patel[1] Sweta Chauhan[2]
[1]Student [2]Assistant Professor
[1,2]Department of Electrical Engineering
[1,2]PIET, Vadodara, India

Abstract— Environmental pollution and shortage of conventional fossil fuel are the two major concerns which have led to the global emergence of wind energy as an effective means of power production. The increasing presence of wind power in power systems will likely drive the integration of large wind farms with electrical networks that are series-compensated to sustain large power flows. This may potentially lead to subsynchronous resonance (SSR) issues. In this paper, a supplementary controller on the grid-side converter (GSC) control loop is designed to mitigate SSR for wind power systems based on doubly fed induction generators (DFIGs) with back-to-back converters. This damping controller employs the rotor speed as the input signal. The validity and effectiveness of the proposed supplemental control are demonstrated on the IEEE first benchmark model for computer simulations of SSR by means of time domain simulation analysis using Matlab/Simulink.

Key words: Doubly fed induction generator (DFIG), Subsynchronous resonance (SSR), Grid side converter (GSC), Rotor side converter (RSC)

I. INTRODUCTION

Environmental pollution and shortage of conventional fossil fuel are the two major concerns which have led to the global emergence of wind energy as an effective means of power production. Wind generating capacities have increased from negligible levels in the early 1990s to more than 50 GW today. This shift to wind energy will inevitably lead to large wind turbine generators (WTGs) being integrated into electric power grids. Due to the continued growth in the wind energy, power utilities' interests have shifted from power quality issues caused by wind power to potential stability problems. It will be further necessary to transmit the generated power through transmission networks that can sustain large power flows. It is well known that series compensation is an effective means of increasing power transfer capability of an existing transmission network. However, series compensation is shown to cause a highly detrimental phenomenon called subsynchronous resonance in electrical networks in which electrical energy is exchanged with the generator shaft system in a growing manner, which may result in damage of the turbine-generator shaft system.

Flexible ac transmission systems (FACTS) can provide an effective solution to alleviate SSR and thyristor based FACTS controllers have been employed in the field for this purpose. A power system stabilizer (PSS) has also been employed in DFIG-based wind generation to enhance the network damping. Moreover, a combined PSS and active damping controller has been proposed to provide a contribution of both network and shaft damping. The Doubly Fed Induction Generator (DFIG) is one type of wind turbine generators that is very popular among various other techniques of wind power generation due to its higher capability, lower investment, and flexible control. This can be noticed as utilizing the DFIG to improve the power system dynamics. The state-of-the-art wind energy systems use DFIGs with back-to-back power electronic converters. The capability of such converters in maximum power point tracking and voltage/reactive power control, compensation for unbalanced grid conditions and oscillation stability has been explored in the literature. However, the control ability of these converters in mitigating SSR has not yet been investigated fully.

II. STUDY SYSTEM

The study system based on the IEEE first benchmark model for SSR studies is shown in Fig. 2.1, where a DFIG-based wind farm (100 MVA from the aggregation of 2-MW units) is connected to a 161-kV series-compensated line.

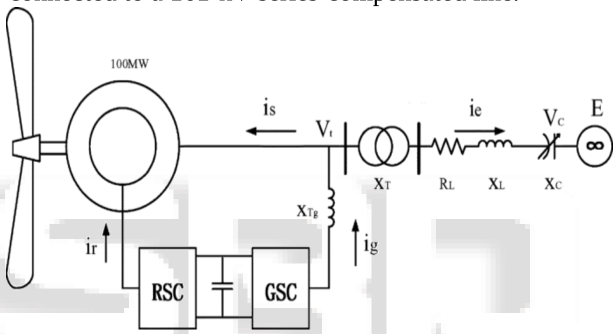

Fig. 2.1: Study system

The collective behaviour of a group of wind turbines is represented by an equivalent lumped machine. This assumption is supported by several recent studies that suggest that wind farm aggregation provides a reasonable approximation for system interconnection studies. When individual wind turbines are aggregated, the aggregated inertia is scaled up. However, the base power is also scaled up; therefore, the per unit value of the inertia does not change. The same also happens to other machine parameters such as impedances. Therefore, the parameters of a 2-MW DFIG in per unit values can continue to be used for the equivalent wind generator.

The DFIGs are wounded rotor asynchronous generators with two voltage source PWM converters namely Rotor Side Converter (RSC) and a Grid Side Converter (GSC). These converters are installed back-to-back in the rotor circuit, which connect the slip ring terminals to the AC supply system. A wind generator consists of the generator rotor, turbine shaft, gear box and blades.

Generally, the control system of the DFIG-based wind turbine generator consist of two separate parts: wind turbine control and the DFIG control. The wind turbine control aims to optimize the power extraction of the wind turbine with pitch angle control and also to avert the overrated power which is yielded in strong wind. The DFIG control includes the RSC and the GSC controller with a special objective.

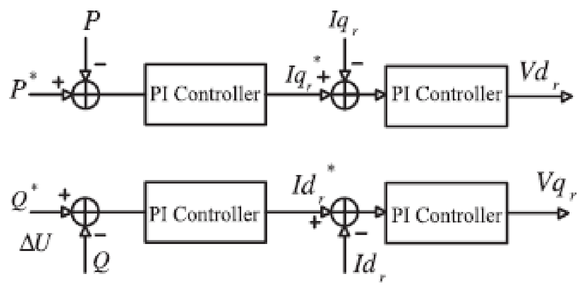

Fig. 2.2: The control structure of the DFIG rotor-side converter

The block diagram of the RSC controller is shown in Fig.2.2. The q axis loop is used to regulate the active power of the DFIG (P) and the d axis loop is utilized to control the reactive power of the DFIG stator (Q). The classical PI controllers are used for regulating both active and reactive controllers.

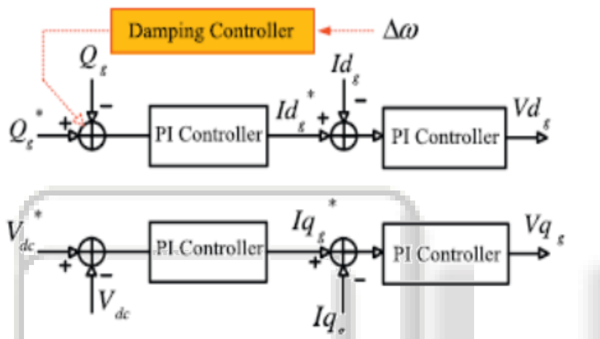

Fig. 2.3: The control structure of the DFIG grid-side converter

The GSC control loops which are shown in Fig. 2.3 have two objectives: (1) regulating the DC bus voltage of the DFIG with crossing the active power through the GSC and RSC and (2) regulating the reactive power of the DFIG GSC (Qg). Similar to the RSC, the classical PI controllers are used in both DC voltage control loop and Qg controller. So, because of these two separate controllers in RSC, additional functions can be carried out with supplementing the auxiliary controllers. If the auxiliary controller is added to the active power control loop of the RSC, the active power modulation will be achieved and if the damping controller is supplemented to the reactive power control loop of the RSC, the reactive power modulation will be achieved. Modeling of study system is shown below.

A. *Modeling Of Wind Turbine:*

The first part of the studied system is the wind turbine, which is used to conversion of wind kinetic energy to mechanical work. The kinetic energy produced by the wind linear speed v rotates the turbine with the speed ω_t which produces mechanical power P_m.

$$P_m = \frac{1}{2}\rho\pi R^2 C_p(\theta,\lambda)v^3 \qquad (2.1)$$

Where, ρ is the air density; Cp=f(θ, λ) is the efficiency coefficient and

$$\lambda = \frac{v}{\omega R} \qquad (2.2)$$

is the speed factor. For a known wind turbine, C_p can be determined by measurement but in some restrictive conditions can be approximated by exponential relations as follows:

$$C_p = c_1\left(\frac{c_2}{\lambda_t} - c_3\theta - c_4\right)e^{\frac{c_5}{\lambda_t}} + c_6\lambda \qquad (2.3)$$

$$\frac{1}{\lambda_t} = \frac{1}{\lambda^{-1} + g\theta} - \frac{h}{(l\theta)^3 + 1} \qquad (2.4)$$

B. *Modeling Of Drive Train:*

When studying the stability of DFIG wind turbine, the two-mass model of the drive train is important, as the wind turbine shaft is relatively softer than the typical steam turbine shaft in conventional power plants.

$$\frac{d\omega_r}{dt} = \frac{1}{2H_g}(T_{sh} - T_e - B\omega_r)$$

$$\frac{d\theta_t}{dt} = \omega_b(\omega_t - \omega_r)$$

$$\frac{d\omega_t}{dt} = \frac{1}{2H_t}(T_m - T_{sh})$$

Where ω_b, ω_r, ω_t and are the base, generator, and wind turbine speeds, respectively. H_g and H_t [SI unit(s)] are the generator and turbine inertias, respectively. θ_t is the shaft twist angle. The electromagnetic torque T_e, the shaft torque T_{sh}, and the mechanical torque T_m , which are the power input of the wind turbine, are as follows:

$$T_e = L_m(i_{ds}i_{qr} - i_{qs}i_{dr})$$

$$T_{sh} = K_{sh}\theta_t + D_{sh}\omega_b(\omega_t - \omega_r)$$

$$T_m = \frac{P_m}{\omega_t}$$

C. *Modeling Of Induction Generator:*

The modeling equations in flux linkage form are as follows:

$$\frac{d\psi_{qs}}{dt} = v_{qs} - R_s i_{qs} \qquad (2.11)$$

$$\frac{d\psi_{ds}}{dt} = v_{ds} - R_r i_{ds} \qquad (2.12)$$

$$\frac{d\psi_{dr}}{dt} = -\omega_r\psi_{qr} - R_r i_{rd} \qquad (2.13)$$

$$\frac{d\psi_{qr}}{dt} = \omega_r\psi_{dr} - R_r i_{qr} \qquad (2.14)$$

$$i_{ds} = \left(\frac{1}{L_s - L_m^2 L_r}\right)\left(\psi_{ds} - \psi_{dr}\frac{L_m}{L_r}\right) \qquad (2.15)$$

$$i_{qs} = \left(\frac{1}{L_s - L_m^2 L_r}\right)\left(\psi_{qs} - \psi_{qr}\frac{L_m}{L_r}\right) \qquad (2.16)$$

$$i_{dr} = \left(\frac{1}{L_r - L_m^2 L_s}\right)\left(\psi_{dr} - \psi_{ds}\frac{L_m}{L_s}\right) \qquad (2.17)$$

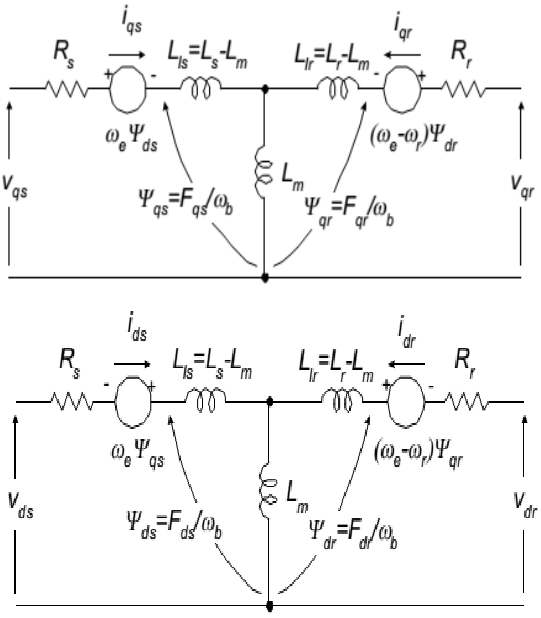

Fig. 2.4: Dynamic or d-q equavalent circuit of inductionmachine

$$i_{qr} = \left(\frac{1}{L_r - L_m^2 L_s}\right)\left(\psi_{qr} - \psi_{qs}\frac{L_m}{L_s}\right) \tag{2.18}$$

$$T_e = \frac{3}{2}\left(\frac{p}{2}\right)\frac{1}{\omega_r}\left(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}\right) \tag{2.19}$$

$$T_e - T_M = J\left(\frac{2}{p}\right)\frac{d\omega_r}{dt} \tag{2.20}$$

Where;
ψ_{ij}: the flux linkage,
v_{qs}, v_{ds}: q and d- axis stator voltages,
v_{qr}, v_{dr}: q and d- axis rotor voltages,
R_r: rotor resistances,
R_s: stator resistances,
L_s: stator inductance,
L_r: rotor inductance,
L_m: mutual inductance,
i_{qs}, i_{ds}: q and d- axis stator currents,
i_{qr}, i_{dr}: q and d- axis rotor currents,
P: number of poles,
J: moment of inertia,
T_e: electrical output torque,
T_m: mechanical torque,
ω_r: rotor angular speed.

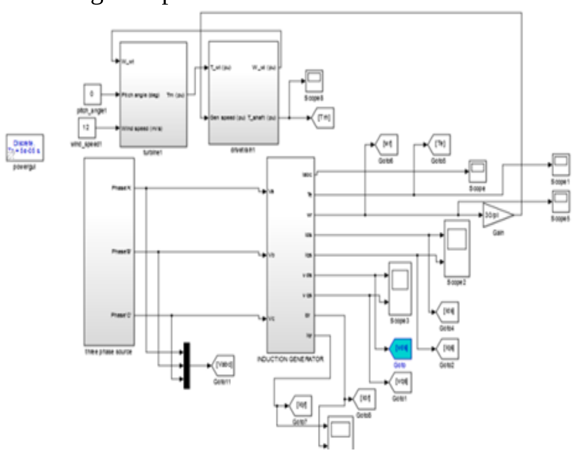

Fig. 2.5: Simulink model of induction generator with turbine and drive train

D. AC-DC-AC Converters:

For a variable-speed wind power system, the generator is connected to the grid through power electronic converters connected back-to-back. The converter is needed because the variable speed generator produces a variable frequency voltage that has to be converted to match the constant grid frequency.

The power converters are connected to the rotor in the DFIG configuration and need to carry only the slip power. The stator is directly connected to the grid while the rotor is connected to the grid through back to- back converters, rotor side and grid side converters.

Wind turbines use a doubly-fed induction generator (DFIG) consisting of a wound rotor induction generator and an AC/DC/AC IGBT-based PWM converter.

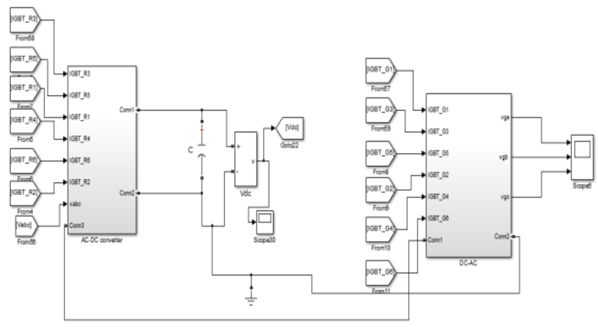

Fig. 2.6: Back-to-back PWM converter

Fig. 2.6 shows the three phase two level back-to-back PWM converter systems. This converter is connected to the induction generator.

III. SIMULATION & RESULT

The complete study system is shown in fig. 3.1. The performance of the system is first studied without any damping controller supplemented to the DFIG. The results shown are divided into two cases. The first case considered here is when there is no fault in the system and corresponding results are also shown. In the second case, the contingency simulated is a three phase to ground fault which will be applied in t = 2 s and will be removed after 0.07 s. The corresponding results are also shown. When the fault is removed, large fluctuations will be experienced between the different parts of the turbine generator shaft. It can be noted that after clearing the fault, oscillations will be increased and the system will be completely unstable.

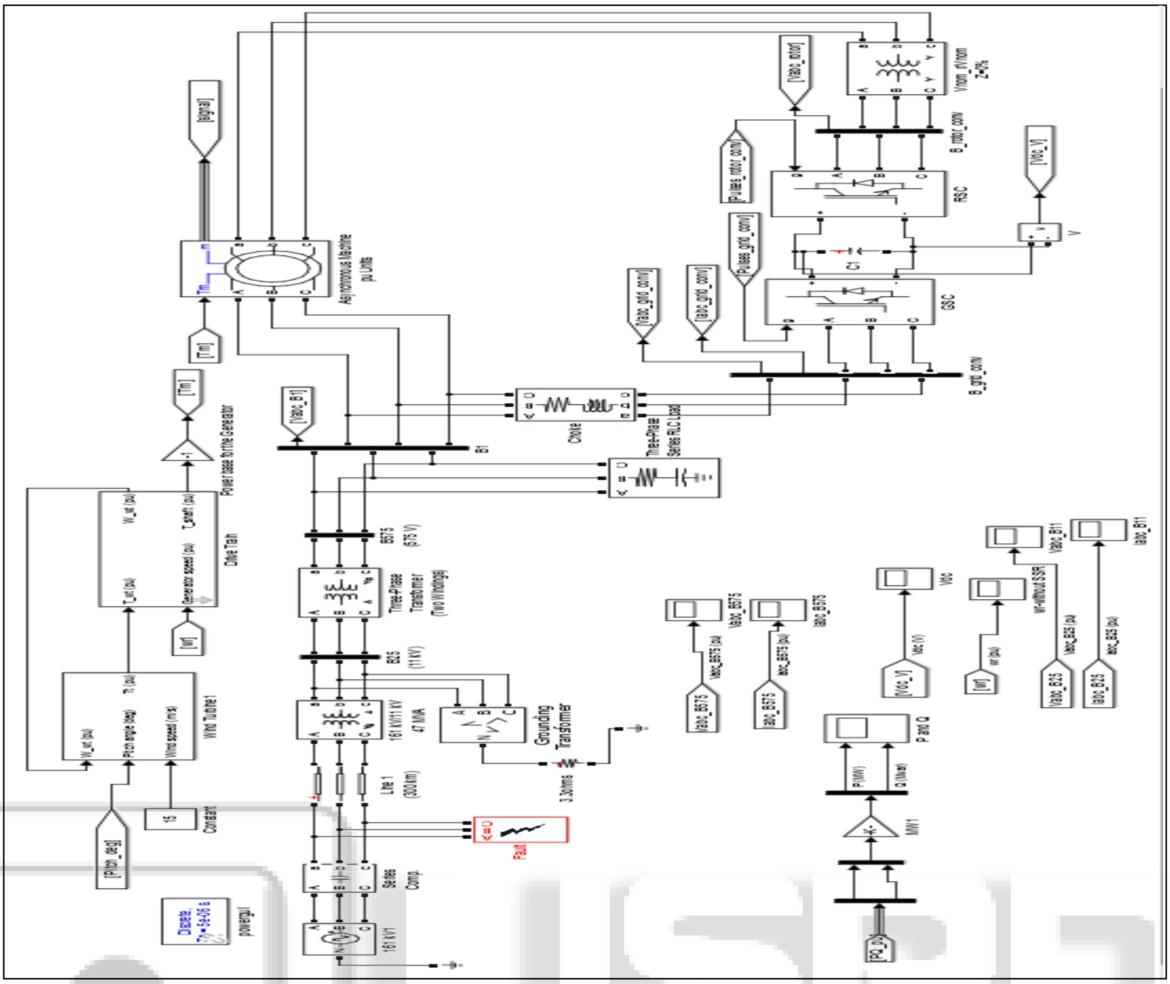

Fig. 3.1: The complete study system in MATLAB/Simulink

case A: Without fault

For this case, the waveforms of voltage, current, rotor speed, DC link capacitor voltage, active and reactive power are shown below.

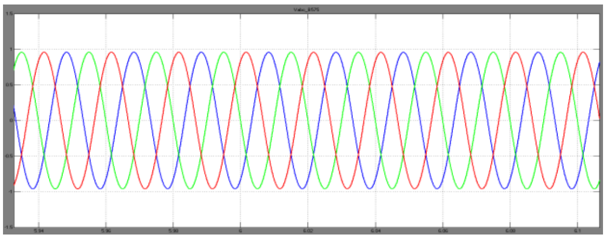

Fig. 3.1: Voltage at bus B575

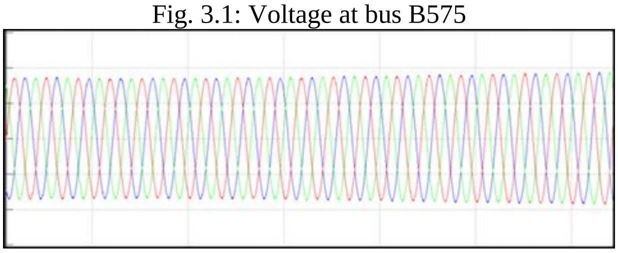

Fig. 3.2: Current at bus B575

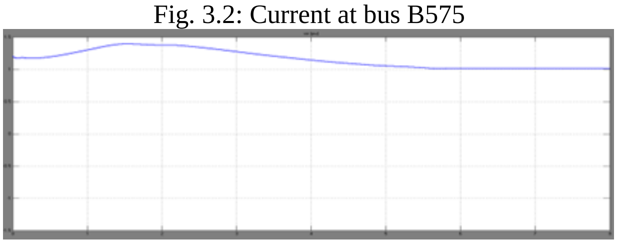

Fig. 3.3: Rotor speed

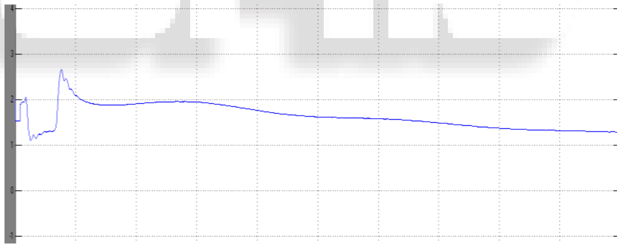

Fig. 3.4: Active power

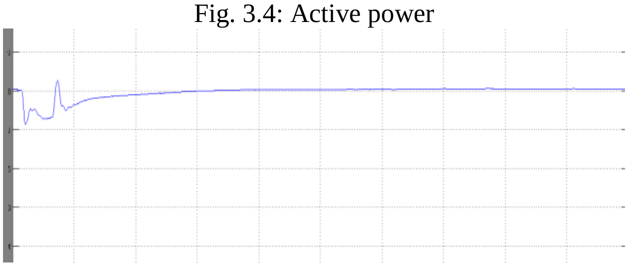

Fig. 3.5: Reactive power

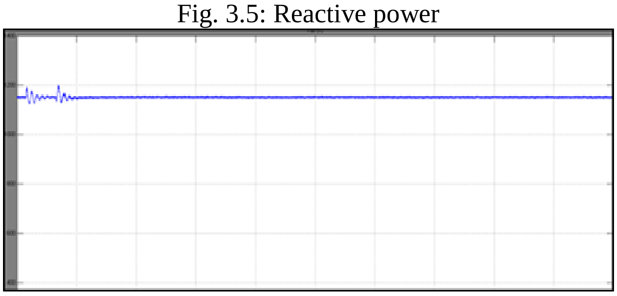

Fig. 3.6: DC link capacitor voltage

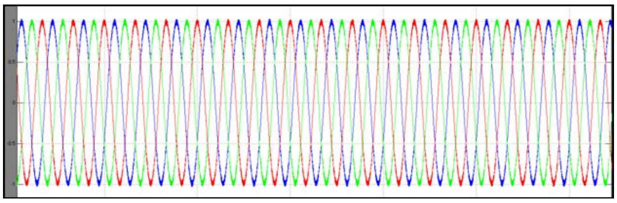
Fig. 3.7: Voltage at bus B25

case B: With fault

In this case, the contingency simulated is a three phase to ground fault which will be applied in t = 2 s and will be removed after 0.07 s. The waveforms of voltage, rotor speed, DC link capacitor voltage, active and reactive power are shown below. When the fault is removed, large fluctuations will be experienced between the different parts of the turbine generator shaft. It can be noted that after clearing the fault, oscillations will be increased and the system will be completely unstable.

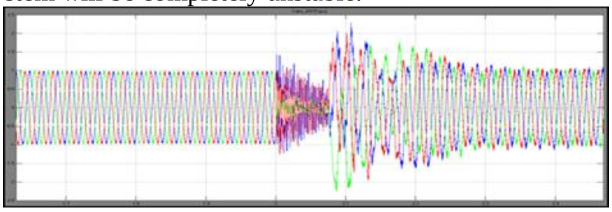
Fig. 3.8: Voltage at bus B575

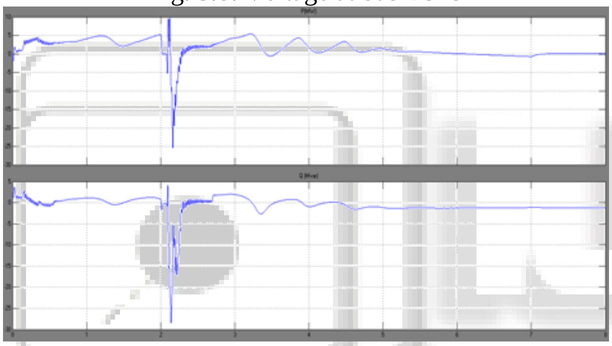
Fig. 3.9: Active and reactive power

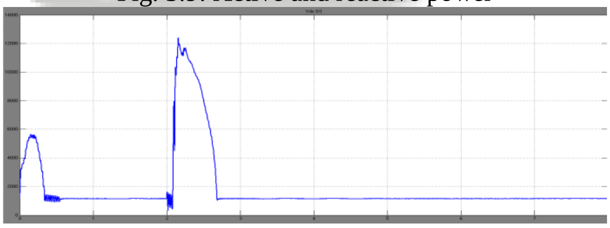
Fig. 3.10: DC link capacitor voltage

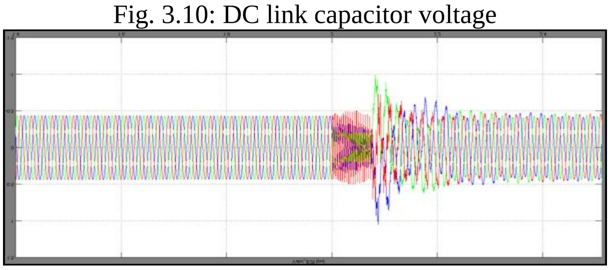
Fig. 3.11: Voltage at bus B25

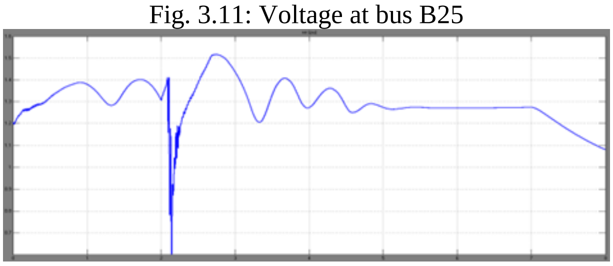
Fig. 3.12: Generator rotor speed

Percentage of compensation which means the proportion of the series capacitive reactance to the line reactance is set to 55% to entice the oscillatory modes of the generator rotor shaft. For obtaining the oscillatory modes of the rotor shaft and consequently the sub-synchronous mode, the FFT analysis is performed on the system which is shown in Fig. 3.13. It is founded by FFT analysis with MATLAB that, two modes exist in the rotor speed in this situation. To verify how unfavourable this dominant mode is, the FFT analysis of the generator rotor speed is performed in time interval 2 to 8 sec with the time division of 1.5 sec which is shown in fig. 3.14.

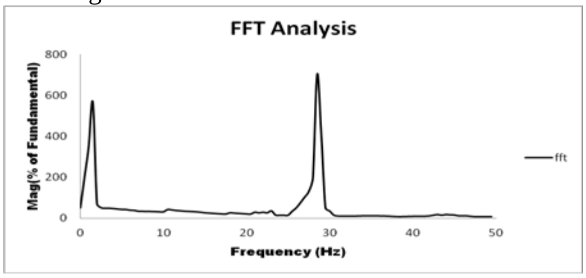

Fig. 3.13: FFT analysis of generator rotor speed

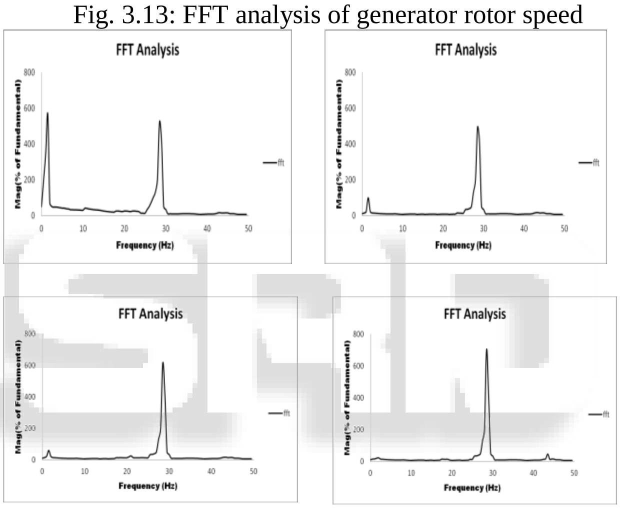

Fig. 3.14: FFT analysis of generator rotor speed in time interval of 1.5 s

IV. SSR DAMPING CONTROLLER

The SSR damping controller has been designed based on conventional lead-lag controllers. Conventional lead-lag controllers have been widely used in industry because of their simple structure, easy to design, robust performance in the linear system and low cost. In this investigation, the aim is to mitigate the SSR. The speed deviation of generator rotor has been utilized as input signal of SSR damping controller. As shown in Fig. 4.1, $\Delta\omega$ [p.u] has been implemented as an additional signal to mitigate the unstable modes.

The auxiliary SSR damping controller consists of five blocks: a washout filter, two phase compensator blocks, limiter block, and a gain block. The washout filter is used to prevent the controller from responding to the steady-state changes of the input signal. The phase compensator block presents the suitable lead-lag features so that to produce the damping torque. The limiter block tends to restrict the output of controller when it is going to decrease or increase from specific range. As shown in Fig.4.1, the output of the SSR damping controller is added to the DFIG's GSC controller loop. The parameters T_W and limiter parameters are set manual.

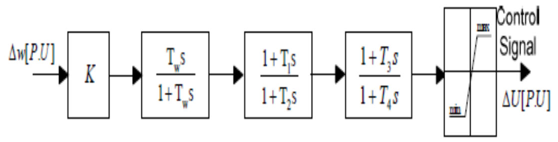

Fig. 4.1: Auxiliary SSR damping controller

The waveform of generator rotor speed is shown in the fig. 4.2 when the lead-lag type conventional damping controller is added to the controller loop of the grid side converter controller. In fig. 4.3 shows the FFT analysis of generator rotor speed with conventional damping controller in the time duration of 2 to 6 sec. From FFT analysis, it is clear that the SSR mode is diminishing as the time is going on.

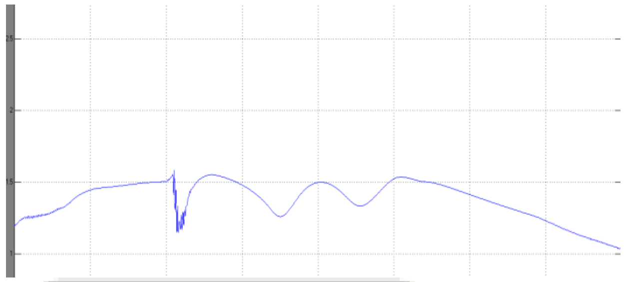

Fig. 4.2: Waveform of generator rotor speed when conventional damping controller is used

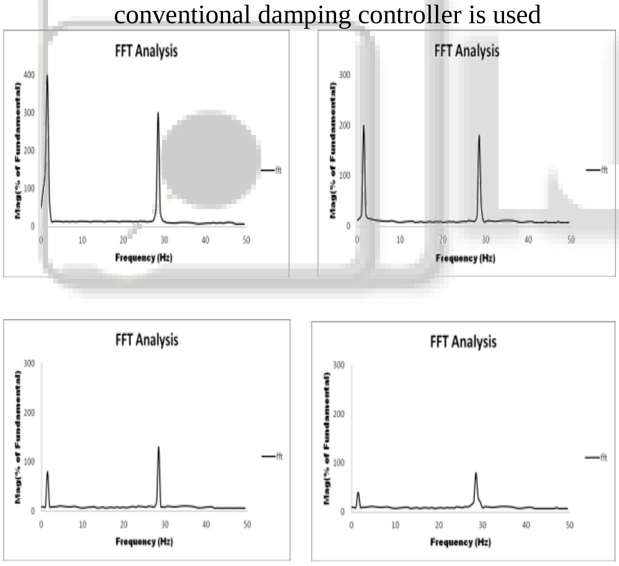

Fig. 4.3: FFT analysis of generator rotor speed with conventional damping controller

V. CONCLUSION

The objective of the project is to design a control scheme to effectively mitigate SSR in a DFIG-based wind farm interfaced with a series-compensated network. The control is realized not by additional FACTS controller but by DFIG's own converters. A supplementary SSR damping controller is designed on top of the GSC control. This damping controller employs the rotor speed as the input signal. Its output modulates the terminal voltage command signal. Stability analysis and time-domain simulations demonstrate the effectiveness of the control scheme.

VI. ACKNOWLEDGMENT

Success of any work depends upon the dedication, sincerity and hard work. It also requires some ingredients such as motivation, guidance, encouragement and time.

For that, I would like to thank Asst. Prof. Sweta Chauhan, Asst. Prof, Electrical Engineering Dept.,Parul Institute of Engineering & Technology who helped me for the successful completion of this work and for providing valuable guidance throughout the work.

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