ISSN 2229-5518

A Novel Approach For Damping Subsynchronous Resonance Oscillations In A Series Compensated Network Using Wind Turbine Driven Doubly Fed Induction Generator

Sathyanarayanan R, Dr. Kumar C

Abstract— This paper investigates the potential of variable speed wind turbine driven Doubly Fed Induction Generator (DFIG) in mitigating Subsynchronous Resonance (SSR) in a series compensated transmission network. The need for such analysis is that to get a physical insight of the capability of Doubly Fed Induction Generator in providing damping to Subsynchronous oscillations caused by series compensated transmission network. The analysis could be used for the mode of control of wind generation in the interconnected network by taking into account security and reliability of the network. Also, the design and optimal tuning of controllers can be evolved using this analysis. The system under study is Modified Second Benchmark Model (SBM) for computer simulation of subsynchronous resonance. The effect of DFIG supplementary control adopted in Grid Side Converter Controller (GSCC) which uses voltage across the series capacitor as control signal in damping Sub-synchronous resonance oscillations that occurs following a cleared three phase fault in the study system is clearly analyzed. The Simulations are carried out using MATLAB/SIMULINK R2012b.

Index Terms— Doubly Fed Induction Generator (DFIG), Grid Side Converter Controller (GSCC), Eigenvalues, Second Benchmark Model (SBM), Subsynchronous resonance (SSR), Subsynchronous oscillations, Supplementary Damping Controller.

1 INTRODUCTION

The demand for energy is never ending with increasing population and standard of living. Owing to excess emission of Green House Gases (GHG) by power generation using fossil fuels and also due to limited resources of fossil fuels has brought out means of non-degradable methods of power generation. By nature a large number of consistent system solutions exist. One of the robust technologies for bulk power generation with less environmental impact is wind power based electric power generation since it has the most favorable technical and economical prospects.

The electrical part of a wind turbine is becoming more and more important. The wind power generation technologies have been enriched with substantial development in power electronic industry offering high power handling capacity. Among the wind generation technologies variable speed wind turbine driven Doubly Fed Induction Generator have emerged out as dominant technology for wind power generation due to robust control capability by decoupling the active power and reactive power control and minimum cost of converters, as they requires only 30% of power rating of generator, comparing to that of other variable speed wind generation technologies.

Rapid wind power development has led to a shift from small generators to large generators and from single distributed units to large centralized clusters of generators commonly known as wind farms. Such wind farms are normally located far away from load centers. To bring in substantial amount of wind generation to the grid we normally employ power electronic controllers based compensators in improving steady state transfer capability of power transmission line connecting wind farms and main supply network. The problem with power electronic based compensators is that they tend to create detrimental interaction between generators and transmission system known as Subsynchronous and Supersynchronous Interactions. But subsynchronous Interactions are predominant phenomenon in interconnected system.

Subsynchronous Interactions (SSI) are a family of physical interactions which involve exchange of energy between a generator and a transmission system at AC frequencies below the system nominal frequency. They include Subsynchronous Resonance (SSR), Subsynchronous Torsional Interactions (SSTI), and Subsynchronous Control Interactions (SSCI). SSR tends to involve an interaction between a series compensated transmission system and a generator. SSTI involves an interaction between a generator and a power electronic controller such as would be found in an HVDC transmission system. SSCI involves an interaction between a series compensated transmission system and a power electronic control system.

In order to increase the steady state power transfer capabilities of transmission lines the series capacitor have been used . A major concern associated with fixed series capacitor is the sub-synchronous resonance (SSR) phenomenon which arises as a result of the interaction between the electrical oscillation modes of the series compensated network and the mechanical

- Sathyanarayananan R is currently pursuing masters degree program in power system engineering at S.K.P Engineering College, Thiruvannamalai, India. E-mail: rsn_edisnew@yahoo.com
- Dr C Kumar is Director-Academic at S.K.P Engineering College, Thiruvannamalai, India. E-mail: drchkumararima@gmail.com

oscillation modes of the turbine-generator group which may produce oscillating torsional torques on machine shaft causing their fatigue and damage.

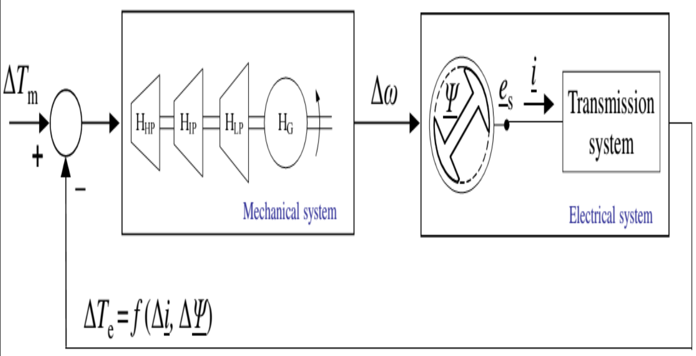

Fig. 1. Subsynchronous Resonance in power systems

In recent years, there has been many study have been conducted in damping the SSR. . The mitigation of SSR using FACTS devices in series compensated transmission line connected with wind power has been presented in the literature. A method to damp the SSR by STATCOM in IEEE First Benchmark Model (FBM) system is presented by Mohamed S. El-Moursi et al. [1]. In [2], Varma et al. explored TCSC and SVC's capability in SSR mitigation. Impacts of large-scale wind power integration on subsynchronous resonance have been analyzed by Tang Yi et al [3]. Lingling Fan et al. investigated control ability of back-to-back converters of DFIG in mitigating SSR [4]. The rotor speed has been used in SSR mitigation control [1], [2]. A preliminary study exploring the capability of the grid-side converters (GSCs) of a DFIG in mitigating SSR is presented in [5]. The major cause of SSR is the network resonant mode, measurements closely related to such a mode were chosen as control signals. But voltage across the series compensation as control signal found to be effective as discussed in [4].

The paper is organized as follows. Section 2 presents the study system. Section 3 presents the Modeling of DFIG converters for SSR mitigation. Section 4 presents the simulation results. Section 5 concludes the paper.

2 STUDY SYSTEM

The system under study is modified version of IEEE Second Benchmark Model (SBM) for sub-synchronous resonance studies. The Study sytem has DFIG based wind farm represented by a single machine connected at same bus where the synchronous generator is connected as shown in Fig. 2. It consists of a single generator (600 MVA/22kV/60 Hz/3600 rpm) connected to an infinite bus (3333 MVA/500kV/60 Hz) via two transmission lines, one of which is series-compensated. The mechanical system is modeled by 3-masses: mass 1 = generator; mass 2 = low pressure turbine (LP); mass 3 = high pressure turbine (HP).

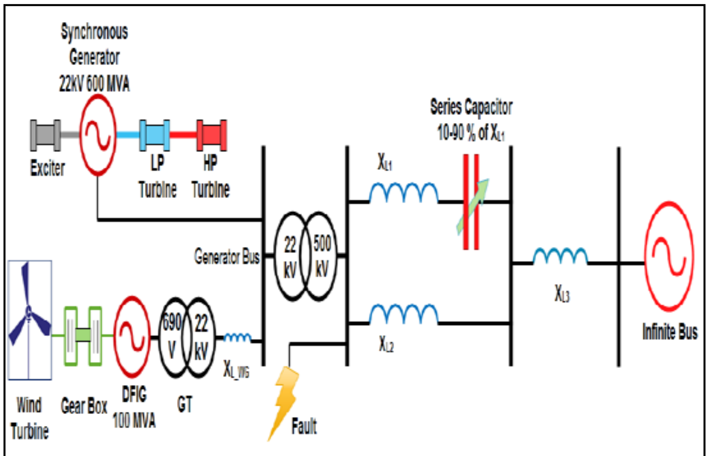

Fig. 2. Study system (Modified Second Benchmark model for subsynchronous resonance study)

The collective behavior of a group of wind turbines is represented by an equivalent lumped machine. Since the wind farm is made up of many identical machines, it is a reasonable approximation to parallel all the machines into a single equivalent large machine behind a single equivalent reactance. Many recent studies [6]–[9] revealed that this approximation quite resonable in interconnected system studies. In [10], [11] it is adjudged that simulations of bulk system dynamics using a single machine equivalent is adequate for most planning studies.

3 MODELING OF DFIG CONVERTERS FOR SSR DAMPING

The DFIG-based wind system includes the DFIG, the power electronic devices, and the drive trains. A 7th-order Doubly Fed Induction Generator model is used for this study. The model of DFIG converter control is one proposed in [12].

In this paper the method proposed in [4] using voltage across the series compensator as control signal for SSR damping is adopted. Here voltage across the series compensator is estimated using reduced order Luenberger Observer using local measurements of line current since the compensation capacitor are placed far away from generators.

3.1 Power Regulation and Voltage Regulation control

In RSC controller q-axis loop regulates the active power and d-axis loop regulates the reactive power but whereas in GSC control loop q-axis loop regulates the DC link voltage and d-axis loop regulates the terminal voltage as shown in figure 3 and 4 respectively. The proportional control is adopted in damping controller and control signal is the voltage across the series capacitor as it provides robust control. The dotted arrow shows the output of SSR damping controller and the injection point. The damping component injection can be at either terminal voltage (Vt) modulation or DC link voltage (V_{DC}) modulation can be used. Here the terminal voltage modulation is used.

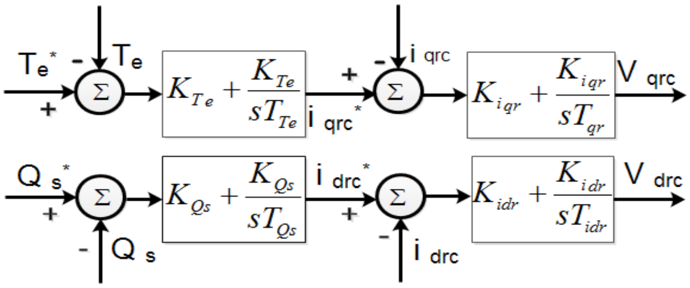

Fig. 3. RSC Control loop

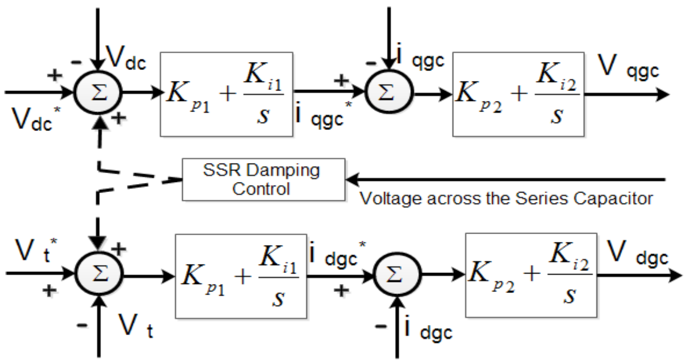

Fig. 4. GSC Control loop

3.2 Supplementary SSR Damping Control

The idea of utilizing Rotor Side Converter Controller for damping SSR has been identified in [4] and [13] and it revealed that the RSC control loop gains negatively impact the SSR network mode. Supplementary control for SSR damping is proposed in STATCOM control [14]. The proposal in [14] is extended to incorporate GSCC of DFIG since they are similar in terms of the topology. The difference between these two topologies for SSR mitigation is the consequent impact. So the idea of supplementary control adopted in STATCOM based SSR mitigation is inherited in the GSCC reactive power/voltage control loop for the d-axis to modulate the terminal voltage demand as shown in Fig. 4.

4 Simulation

The Simulation have been done retaining the same level of series compensation (55% on 3333 MVA base) and fault being initiated at 0.022th second and successfully cleared at 0.391th second in the uncompensated 500kV line section in all the three cases. It is noticed that subsynchronous resonant modes are initiated only after clearance of fault for all the three cases.

Case A – No DFIG connected and only Synchronous Generator with a capacity 0f 600MVA is connected to series compensated network.

Case B – DFIG with SSR damping controller connected at 22kV bus with a capacity of 100MVA and Synchronous Generator with a capacity of 500MVA. Controller , line, and machine parameters are given in appendix.

The plot in figure 5 indicates that subsynchronous resonance occuring at 27Hz and also phase shift occurs at that same instant. This is evident from eigenvalue analysis fig. 6 showing critical mode of interaction between machine and network.

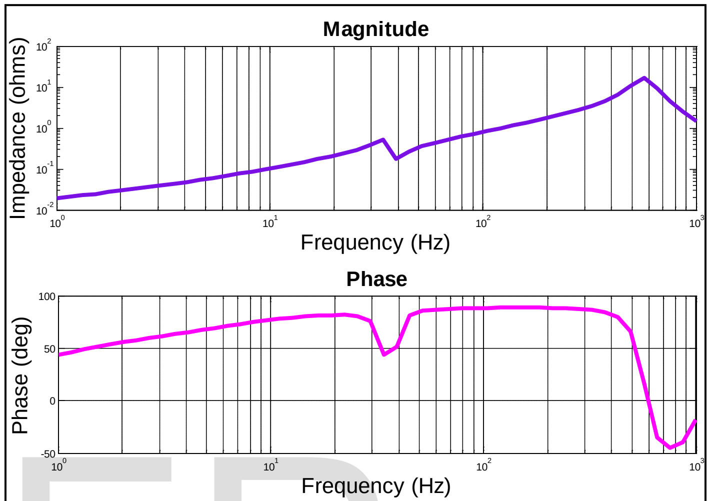

Fig. 5. Frequency Response of study system

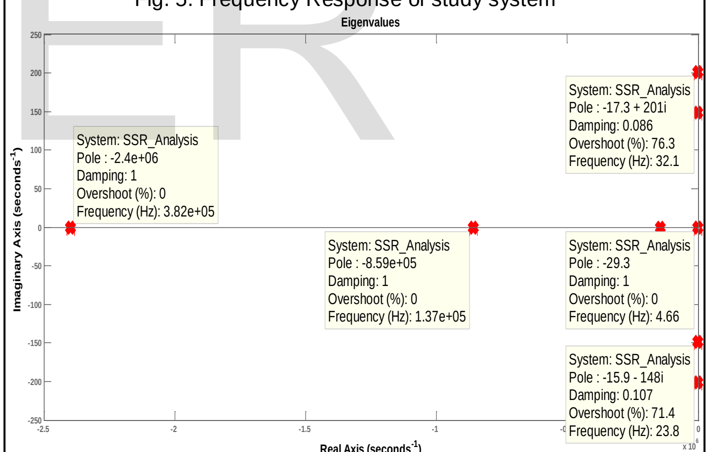

Fig. 6. Eigenvalues

4.1 Generator and Turbines Speed Oscillations

TABLE 1

NETWORK MODE EIGENVALUES OF THE STUDY SYSTEM

Eigenvalue	Damping ratio	Frequency In Hz
-17±201i	0.086	32.1
-15.9±148i	0.0107	23.8

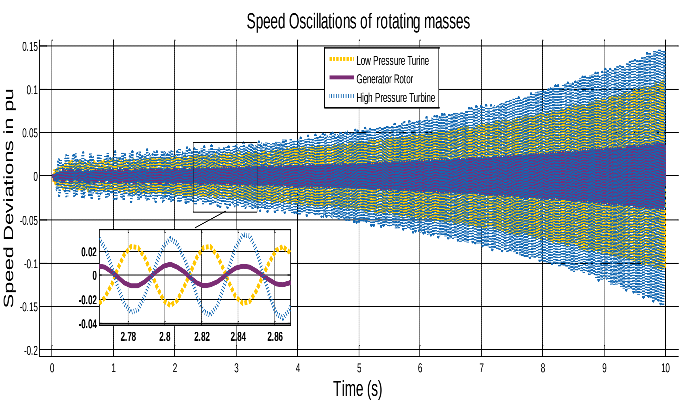

Fig. 7. Speed deviation caused by resonantory interaction between Synchronous Generator and compensated network for Case A i.e. without DFIG Damping Control.

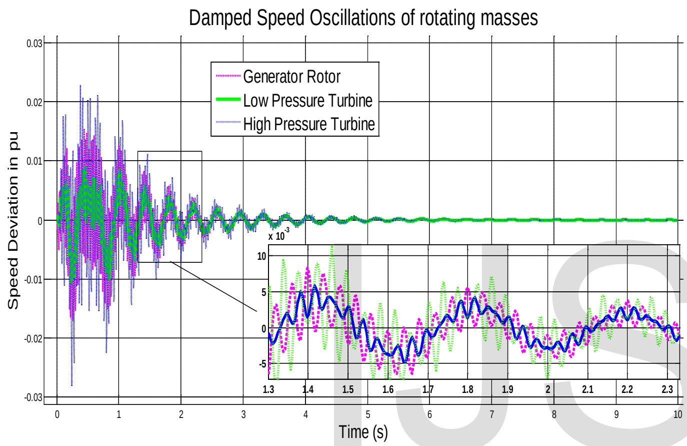

Fig. 8 Damped Speed Oscillations of the rotating masses for Case B

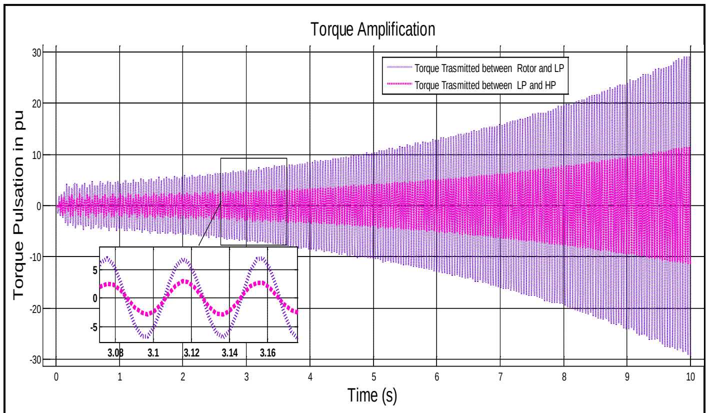

Fig. 9. Torque transmitted between multi-mass shaft system without DFIG Damping control

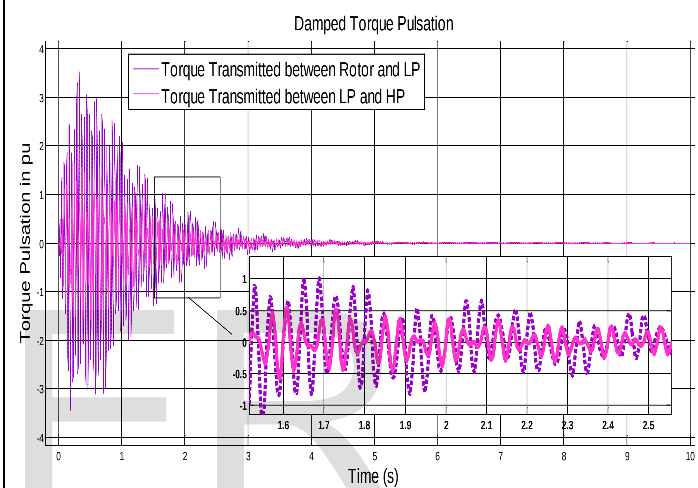

Fig. 10. Damped Torque Pulsations with DFIG Damping control

In Case A, second benchmark model is simulated with initial conditions of original SBM system. The oscillatory torsional modes of the multi-mass shaft indicates subsynchronous mode introduced by the series capacitor after a single cycle three-phase fault has been invoked and cleared successfully. Fig. 7 shows the deviation of synchronous generator rotor speed oscillation augmenting larger than 0.015 pu and continuing. Also the turbine speed deviation is also large for this case which can be seen too on figure 7. This is also because of network resonance which causes the synchronous machine to interact with transmission network reducing its damping torque contribution.

For Case B, DFIG with 100MVA capacity with additionally Grid Side Converter Controller designed to provide SSR damping control. The damping component provided by the grid side converter controller reduces the speed oscillations of rotor, low speed turbine and high speed turbine completely after 4 seconds from inception of fault. The simulation result of figure 7 shows the potential of damping provided by DFIG as counteract to SSR mode which is a promising result.

4.2 Torque Amplification

For Case A, it can be seen that the variations of torque of the mechanical system are severely unstable. The torque amplification phenomenon as can be observed from the simulation illustrating the network resonant mode introduced by series capacitor. The torque transmitted between Generator and low speed turbine reaches a peak of 10 pu after 5 seconds and grows continuosly which is very unlike situation as the shaft will be broken sooner or later. Also, the torque transmitted between low speed and high speed turbine oscillates and reaches a peak of 10 pu after 10 seconds which grows thereafter too. This is evident from figure 9.

For Case B with DFIG Damping Controller, the torque oscillations are completely damped out within 5 seconds without any presence of overshoot i.e. the damped torque components do not exceeding subsynchronous resonated torque value. Also the peak value is restricted to 3 pu initially for half a cycle which can be tolerated. This shows the impact of damping control at the grid side controller in mitigating SSR phenomenon. This is evident from figure 10.

4.3 Estimated and Actual Voltage Across The Series Capacitor

ISSN 2229-5518

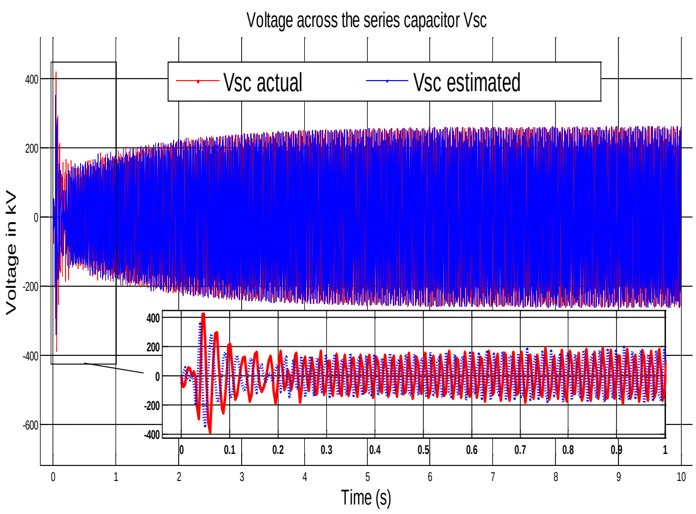

Fig. 11. Estimated and Actual Voltage across the Series Capacitor

From figure 11 it is clear that the estimated value of voltage across the series capacitor converges nearly to the actual value of voltage. This reveals the effectiveness of the reduced order observer used for estimating the voltage across the series capacitor using local measurement of line current.

4.4 DFIG's Response

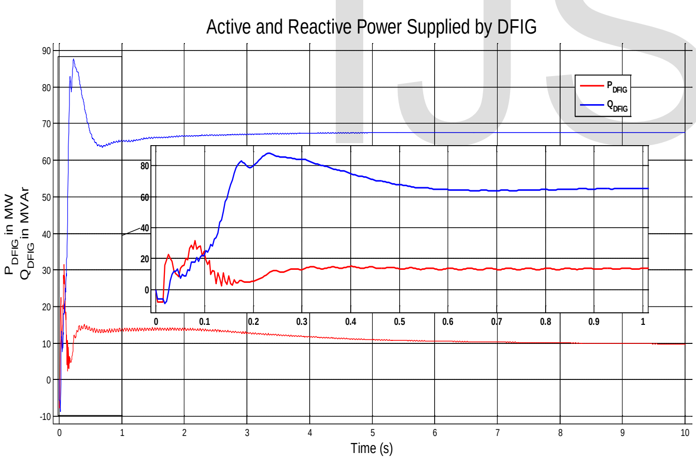

Fig. 12. Power Supplied by DFIG

4.4.1 Active and Reactive Power output of DFIG

Normally the Grid side converter controller is designed to exchange active power to and from the grid. Now as the system approaches subsynchronous conditions the reactive power output of DFIG tends to flow through Grid side converter as the damping controller introduced in the GSC modulates the terminal voltage to follow its reference and thereby the torsional interactions are alleviated. Also it favours situations arising to reestablish the votage collapse after a unfavourable voltage conditions like three phase faults etc. This contribution of DFIG makes it suitable for providing torsional oscillational damping contribution itself and the interconnected network. This is what the thing really happened down here.

The active power contribution of DFIG is such that when system demands reactive power the active power is modulated to inject the required reactive power. In this case as the system tends to SSR conditions the active power supplied is lowered to have adequate injection of reactive power which is clearly shown in figure 12.

4.4.2 DC link voltage

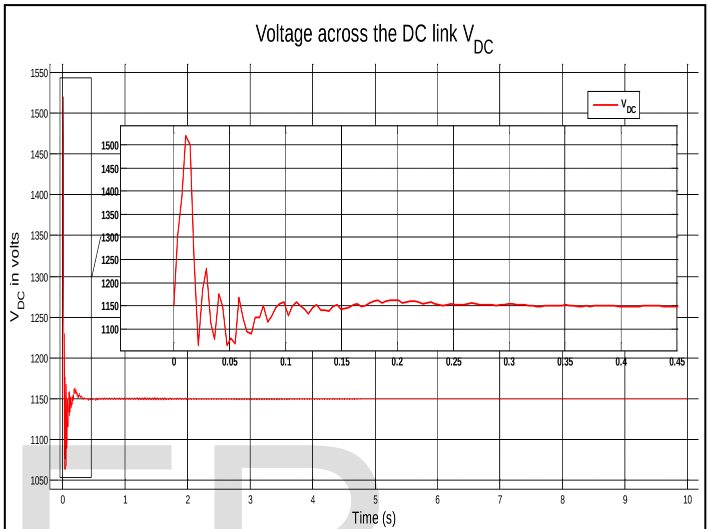

Fig. 13. DC link Voltage

The DC link votage reaches a peak of 1500v while the grid side converter based damping controller counteracts the subsynchronous resonanace mode and it attains it steady state nominal value 1150v after the subsynchronous oscillations are completely damped out.

4.4.3 Rotor Speed

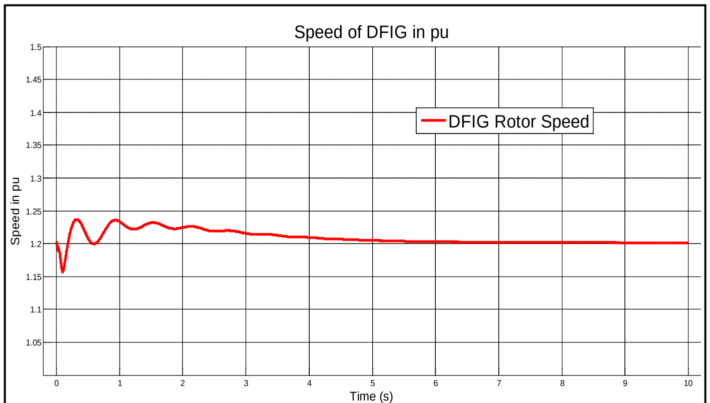

Fig. 14. DFIG rotor speed

The speed of rotor of DFIG changes with network mode torsional interaction in addition to wind speed changes. But the deviations are within the bound while the damping controller alleviates the SSR modes. The nominal value of 1.2 pu is attained and continued once the SSR oscillations are cleared out.

4.4.4 Electromagnetic Torque at DFIG's terminal

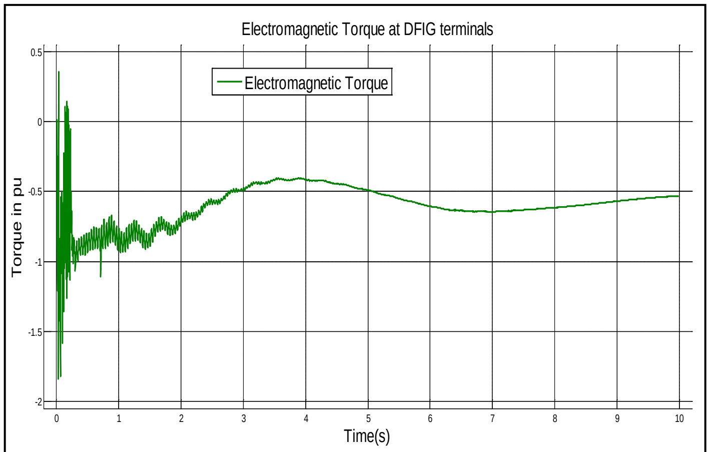

Fig. 15. Electromagnetic Torque

Initially the Electromagnetic torque at DFIG's terminals is oscillating but doesn't enter SSR mode. As the damping controller is initiated the torque slowly recovers nominal value of -0.5 pu and lies around it.

APPENDIX

Table 2

DFIG parameters	Values of a Single 1.66-MVA DFIG in study System
Rated power	1.66 MVA
Rated Voltage	575 V
Stator [Rs Lls]	[0.023 0.18] pu
Magnetizing inductance Lm	2.9 pu
Rotor [Rr Llr]	[0.016 0.16] pu
Generator Inertia constant H	0.685 s
Number of poles	3
Nominal DC bus voltage	1150 V
DC bus capacitor	10000 µF
Nominal mechanical output power	1.5e6 W
Wind speed at nominal speed and at Cp max	11 m/s
Wind turbine inertia constant H	4.32 s
DC bus voltage regulator gain [Kp Ki]	[8 400]
Grid-side converter current regulator gain [Kp Ki]	[0.83 5]
Q and V regulator gain [Ki_var Ki_volt]	[0.05 20]
Time Constant T_{id}	0.005 pu
T_{iq}	0.0025 pu
K_{iq}	0.01
K_{id}	0.01
K_{p3}	1.2
K_{i3}	105
K_{p4}	0.3
K_{i4}	0.12
K_{Te}	0.3

5 CONCLUSION

The mitigation of SSR using FACTS controllers seems to introduce SSCI, SSTI in the system. So, there is need of a system with eliminates the problem of above. For this system consisting of Doubly Fed Induction Generator with damping control is tested because torsional modes have a low frequency due to the low shaft stiffness of wind turbine drive trains which tends to avoid SSR at frequencies of network resonant modes. Thus from the Time Domain simulations of study system, it is clear that the capability of DFIG in damping SSR using supplementary control at its grid side controller using voltage across the series capacitor as the control signal seems to be promising.

So it is concluded that the idea of utilizing Doubly Fed Induction Generator with damping control in mitigating SSR in the series compensated network seems to work fine.

REFERENCES

[1] M.H. Abdel-Rahman, M.S. El-Moursi and B. Bak-Jensen, , "Novel STATCOM Controller for Mitigating SSR and Damping Power System Oscillations in a Series Compensated Wind Park", IEEE Transactions on Power Electronics, Vol. 25, No. 2, pp. 429-441, February 2010.

[1] R.K.Varma, S.Auddy,and Y.Semsedini, "Mitigation of subsynchronous resonance in a series-compensated wind farm using FACTS controllers,"IEEE Trans. Power Del., vol. 23, no. 3, pp. 1645–1654, Jul. 2008.

[2] T. Yi, Y. Rui-Qian, "Impacts of Large-Scale Wind Power Integration on Subsynchronous Resonance", Power and Energy Engineering Conference (APPEEC), Asia-Pacific, pp. 1-4, 2011.

[3] L. Fan, R. Kavasseri, Z.L. Miao, C. Zhu, "Modeling of DFIG-Based Wind Farms for SSR Analysis", IEEE Transactions on Power Delivery, Vol. 25, No. 4, pp. 2073-2082, October 2010.

[4] C. Zhu, L. Fan, and M. Hu, "Control and analysis of DFIG-based wind turbines in a series compensated network for SSR damping," in Proc. IEEE Power & Energy General Meeting, Minneapolis, MN, Jul. 2010.

[5] L. M. Fernandez, F. Jurado, and J. R. Saenz, "Aggregated dynamic model for wind farms with doubly fed induction generator wind turbines," Renewable Energy, vol. 33, pp. 129–140, 2008.

[6] J. T. Bialasiewics and E. Muljadi, The Wind Farm Aggregation Impact on Power Quality, National Renewable Energy Laboratory Report, Nov. 2006.

[7] E. Muljadi and B. Parsons, "Comparing single and multiple turbine representations in a wind farm simulation," in Proc. Eur. Wind Energy Conf., Athens, Greece, 2006.

[8] M. Poller and S. Acchilles, "Aggregated wind park models for analyzing power system dynamics," in Proc. 4th Int. Workshop on Large

ISSN 2229-5518
Scale Integration of Wind Power and Transmission Networks for Offshore Wind Farms, Billund, Denmark, 2003.

[9] N. W. Miller, W. W. Price, and J. J. Sanchez-Gasca, Dynamic Modeling of GE 1.5 and 3.6 Wind Turbine-Generators, GE-Power Systems Energy Consulting, General Electric International, Inc., Schenectady, NY, Oct. 2003.

[10] R. Piwko, N. Miller, J. Sanchez-Gasca, X. Yuan, R. Dai, and J.Lyons, "Integrating large wind farms into weak power grids with long transmission lines," in Proc. IEEE/PES Transmission and Distribution Conf. & Exhibition: Asia and Pacific, Dalian, China, 2005.

[11] F. Mei and B. C. Pal, "Modelling of dobuly-fed induction generator for power system stability study," in Proc. IEEE Power & Energy General Meeting 2008, Pittsburgh, PA, Jul. 2008.

[12] A. Ostadi, A. Yazdani, and R. Varma, "Modeling and stability analysis of a DFIG-based wind-power generator interfaced with a series-compensated line,"IEEE Trans. Power Del., vol. 24, no. 3, pp. 1504–1514,Jul. 2009

[13] K. Padiyar and N. Prabhu, "Design and performance evalution of subsynchronous damping controller with STATCOM,"IEEE Trans. Power Del., vol. 21, no. 3, pp. 1398–1405, Jul. 2006.