Performance Evaluation of New Series Connected Grid-Side Converter of Doubly-Fed Induction Generator

Bharat Singh, V. Emmoji, S. N. Singh, *Senior Member, IEEE*, and I. Erlich, *Senior Member, IEEE*

***Abstract*—Increasing penetration of the large wind farm in the system has forced the power system policy makers to develop new electricity grid codes which are required for the wind power generator to fulfill the same requirements as conventional power plants. In this paper, a series connected grid side converters with conventional Doubly-fed Induction Generator (DFIG) scheme is explored to suit the Grid Code Requirements (GCRs) during static and dynamic conditions. A dynamic model and control structure for the series architecture are developed and the performance of the system along with the controller is analyzed for voltage sag condition. Reactive power support capability of series converter during steady state condition is also demonstrated.**

***Index Terms*--DFIG, Series Grid-Side Converter, Performance evaluation, Reactive power compensation**

I. INTRODUCTION

RECENTLY, there has been a growing interest in the use of wind energy due environmental and rising fossil fuel prices. In spite of this growth, more technological advances are needed to make wind energy competitive with many other energy supply methods. It is capital-intensive but has low operating costs. Wind is an innovative, clean, modular, and intermittent technology. Wind farms are becoming an increasingly offshore and onshore site. At the end of 2007, the wind installed capacity stands at over 94,112 MW, worldwide, which is more than 20,000 MW from the capacity in 2006. [1]. Wind projects, today, are large enough to have a significant effect on transmission network security, operation, and planning. Rapid installation growth, increased turbine size, and large-scale wind farm development, worldwide, demand an integration of large-scale wind projects with generation and transmission planning, to ensure generation adequacy and secure grid operation [2].

Harnessing wind energy for electric power generation is an area of research interest and at present, the emphasis is given to the cost-effective utilization of this energy resource for quality and reliable power supply. In the past, when the wind power generation penetration was not high, the wind turbines were treated largely as embedded generators, which were not to control the power system control and therefore requirements for wind turbines were focused primary on protection of the turbines themselves and did not consider the impact of these on the power systems.

However, with increased penetration of wind turbines connected directly to the high voltage grid, the loss of a considerable part of the wind generators cannot be accepted. Hence, according to the present requirements, wind turbines should remain connected and actively support to the grid during system disturbances. If the entire wind farm is suddenly disconnected from the grid, a large frequency and voltage drop will occur and possibly followed by complete outage, if system does not have sufficient spinning reserve. Therefore, the new generation of wind turbines is required to be able to 'Fault-Ride-Through capability" (FRT) during disturbances and faults to avoid total disconnection from the grid. In order to keep system stable, it is necessary to ensure that the wind turbine restores normal operation in an appropriate way and within appropriate time [3]. Several countries issue stringent Grid Code Requirements (GCR) for interconnection of wind farms [4].

Through, different types of variable speed wind power generation became popular in the market. The Doubly Fed Induction Generator (DFIG) is mainly used in variable speed windmills due to its many advantages such as the improved power quality, high-energy efficiency and controllability, reduced power converter rating, etc. If a DFIG is used, it is possible to control the generator by accessing the rotor circuits. According to new trends, DFIG is the most successful for variable speed wind power generation with more than 45% market share [5].

A major drawback of wind turbines with DFIG is their operation during abnormal conditions like grid faults and voltage sags, which cause voltage dip at the Point of Common Coupling (PCC). The dip in the grid voltage will result in an increase of the current in the stator windings of the DFIG. Because of the magnetic coupling between stator and rotor, this current will also flow in the rotor circuit and the power-electronic converter. This can lead to the damage of the converter. It is possible to limit the current by current-control on the rotor side of the converter; however, this will lead to

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high voltages at the converter terminals, which might also lead to the failure of the converter.

A possible solution suggested in literature is to limit the high current in the rotor to protect the converter and to provide a bypass for this current via a set of resistors that are connected to the rotor windings so called crowbar [6] during the faults without disconnecting the turbine from the grid. During period of operation of crowbar the control action of the converter is trimmed to shut down and allow the DFIG to operate as a conventional slip-ring induction machine. Another solution, in which one Grid Side Converter (GSC) is connected in series with the stator winding of the DFIG, is presented in [7], but its control scheme and performance is not fully explored.

In conventional DFIG system, the grid side converter is connected to the grid in shunt configuration. This means that the grid side converter injects current in to the grid. However, if the converter is connected in series with the grid instead, a voltage is introduced in series with the stator voltage. The basic idea is to inject a voltage between the PCC and the stator of DFIG at desired amplitude, frequency and phase, in order to control the stator flux of DFIG and to prevent the high rotor currents, which may result in disconnection of wind generator from the grid, during abnormal conditions sharing common DC bus voltage with conventional DFIG scheme.

In this paper, a Series Architecture (SA) of DFIG is explored, which utilizes a Series GSC (SGSC). It will introduce a voltage in series with the line to maintain the DC link voltage. During, normal and abnormal conditions, the SGSC facilitate the normal power processing capabilities for both, sub-synchronous and super-synchronous modes of operation of DFIG. Performance of the DFIG with SGSC is analyzed and dynamic performances are demonstrated for voltage sag ride through capability of modified DFIG. Results are also shown for step change in reactive power injection from SGSC.

II. SYSTEM ARCHITECTURE

A conventional DFIG connected to grid is shown in Fig. 2. The DFIG exchanges power with the grid as well as rotor windings. The major portion of real power flows from the stator to grid and only fraction of power (approximately slip times stator power) flows from rotor to grid, as shown in Fig. 3. The rotor power is fed back to the grid through the two back-to-back PWM converters. The Machine Side Converter (MSC) is used to convert the rotor frequency power to DC power and then feedback to the AC system using GSC, which converts DC power to AC system frequency. The GSC is connected in shunt and injects the shunt current in to the grid.

It is possible to connect the grid side converter in series with the line, as shown in Fig. 4. The idea of SGSC is to have a controlled series voltage with the stator and grid. In this configuration, SGSC is connected via a series transformer, as shown in Fig.4. This configuration is similar to that used in Dynamic Voltage Restorer (DVR). Normally, an LC filter is connected to reduce the voltage and current harmonics generated from the voltage source inverter. In order to avoid magnetic saturation, series injection transformer must be rated to handle twice the nominal flux. SGSC will provide series compensation that is used to achieve balanced voltage in the stator of the machine, avoiding torque oscillations and high currents due to the grid voltage unbalance.

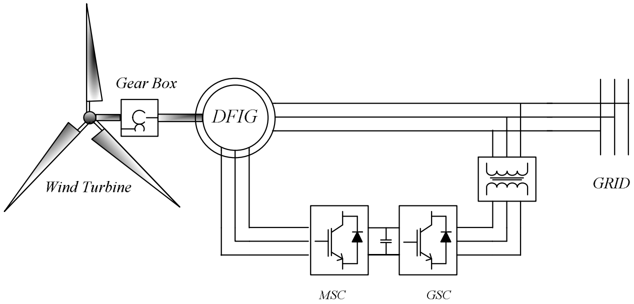


Fig. 2. DFIG with Back-to-Back PWM voltage source converters.

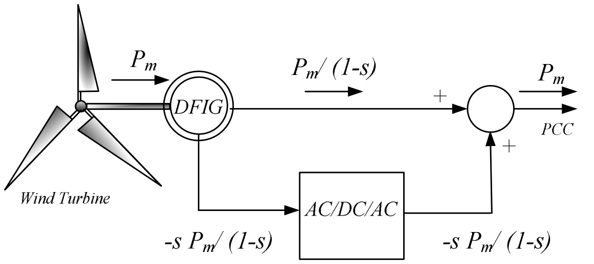


Fig. 3. Power flow of a lossless DFIG system.

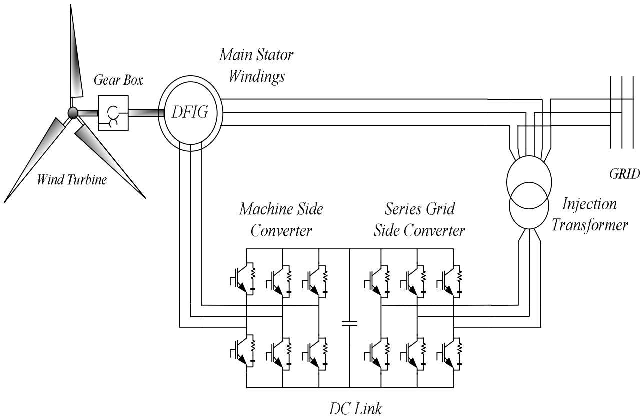


Fig. 4. Transformer interfaced SGSC.

III. CONTROL STRUCTURE

The control objectives of the DFIG with series connected GSC includes the regulation of stator active power and reactive power, DC link voltage and the control of stator flux during voltage sag conditions. The stator active and reactive powers are controlled by the MSC, similar to a conventional DFIG. The SGSC regulates the DC link voltage and controls the stator flux of the machine during abnormal condition. In this case, the series GSC has to provide certain amount of real power in the line. The stator voltage of the DFIG is the sum of the PCC voltage and series injected voltage.

SGSC is a bidirectional active power converter and it controls the DC bus voltage during both sub- and super-synchronous modes. A hierarchal block diagram of system controller is presented in Fig. 5.

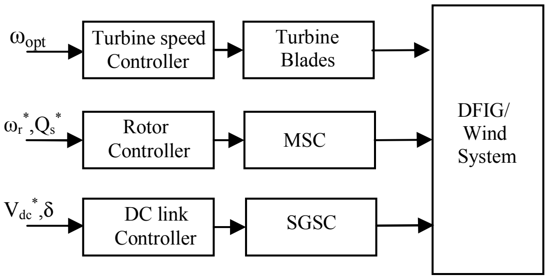


Fig. 5. Controller Structure for Unified Architecture.

A. Turbine Speed Controller

The turbine rotor speed is controlled by throttling the mechanical torque through pitching of the turbine blades. The command rotor speed is set to the optimum value. The rotor speed error drives a PI regulator to command the appropriate pitch angle. Saturation blocks prevent blade pitch actuation unless the rotor speed error is positive.

B. MSC Control Scheme

The control of MSC is similar to the conventional DFIG scheme presented in various papers [8-11]. Usually, the field-oriented approach is employed for controlling MSC that allows the control of active and reactive powers independently, of the stator side. MSC is used to convert the rotor frequency power to DC power and then feed back to AC system using GSC, which converts DC power to AC power at system frequency. Inner control loop of the MSC regulates the rotor current and MSC current commands are generated from field oriented torque control and farm collector reactive power control loops.

C. SGSC Control Scheme

The objective of the SGSC converter is to keep the DC link voltage constant irrespective of the direction of rotor power flow and to control the stator flux during abnormal conditions. Decoupled control of active and reactive powers flowing between rotor and grid is done by using stator current vector oriented control.

The DC link dynamics of the back to back converter can be given as

$$\frac{1}{2} C \frac{d}{dt} V_{dc}{}^2 = -P_g - P_r \tag{1}$$

$$P_g = V_{dg} i_{ds} + V_{qg} i_{qs} \tag{2}$$

$$P_r = V_{dr} i_{dr} + V_{qr} i_{qr} \tag{3}$$

where, V_{dg} and V_{qg} are the d-q axis voltages of SGSC; P_g is the active power delivered by the grid side converter; and P_r is the active power delivered to the rotor.

The SGSC d-q axis voltage components, V_{dg} and V_{qg}, can be expressed in terms of modulation index of the grid side converter and DC link voltage as:

$$\begin{aligned} V_{dg} &= m\, k\, V_{dc} \cos\delta = k\, m_d\, V_{dc} \\ V_{qg} &= m\, k\, V_{dc} \sin\delta = k\, m_q\, V_{dc} \end{aligned} \tag{4}$$

where, m is the magnitude of modulation index of the grid side converter; k is the constant which depends on control strategy; δ is phase angle of the SGSC voltage and is given by

$$\delta = \tan^{-1}\left(\frac{V_{qinj}}{V_{dinj}}\right) \tag{5}$$

In stator current reference frame

$$i_{ds} = |\, i_s \,| \text{ and } i_{qs} = 0 \tag{6}$$

By substituting (6) and (4) in (2), we get

$$P_g = m\, k\, V_{dc} \cos\delta\, i_{ds} \tag{7}$$

Substituting (7) in (1), we get

$$\frac{d}{dt} V_{dc} = -\frac{m}{C_{dc}} k \cos\delta\, i_{ds} - \frac{P_r}{C_{dc} V_{dc}} \tag{8}$$

Here, the control variables are ‘m’ and ‘δ’. For ease of control, one variable is fixed and another variable is controlled. The main objective of SGSC is to control the DC link voltage. DC link voltage can be regulated by the real power flow of SGSC. Hence, δ is fixed to zero ensuring that series injected voltage has only real power component. In this work ‘m’ is controlled to regulate the DC link voltage.

By equating δ to zero (8) results in

$$\frac{d}{dt} V_{dc} = -\frac{m}{C_{dc}} k\, |\, i_s \,| - D \tag{9}$$

where, D is the disturbance term.

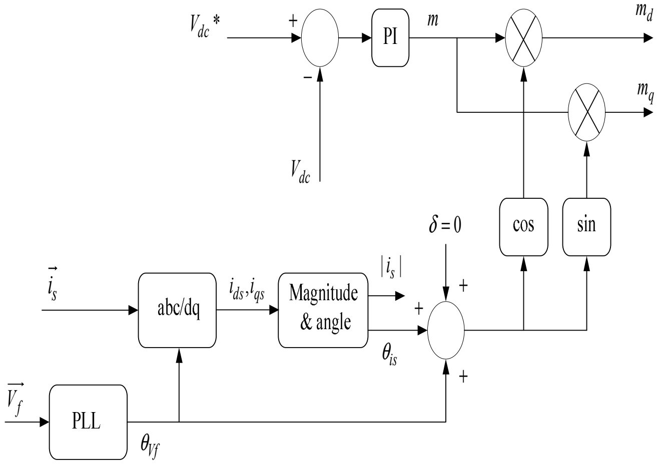


Fig. 6. SGSC control scheme with reactive power injection.

The control scheme uses a PI controller to obtain the magnitude of modulation index (m) from the DC link voltage error. Fig. 6 shows the complete DC-link voltage control loop of series GSC. The reference DC link voltage and measured DC link voltage are compared and the error is passed through a PI controller that produces modulation index ‘m’. The voltage at PCC, V_f, is used to calculate the reference angle (θ_{vf}). The stator current is decomposed into I_d and I_q using the PLL angle. The amplitude | i_s | and relative angle θ_{is} of the stator current with respect to PLL angle are calculated. As said earlier, the injected component has only real power component. Hence, the phase angle of the series injected voltage (δ) with respect to the stator current is set to zero. At lower slips, only some part of the GSC capability is used. The remaining capability can be used to inject/absorb the reactive power to the grid in order to maintain the stator voltage at its nominal value. This can be done by controlling the ‘δ’.

The other objective of the SGSC is to control the stator flux during abnormal conditions. SGSC controls the stator flux using a synchronous frame proportional controller aligned in stator current reference frame. Complete block diagram of the stator flux control scheme is shown in Fig. 7.

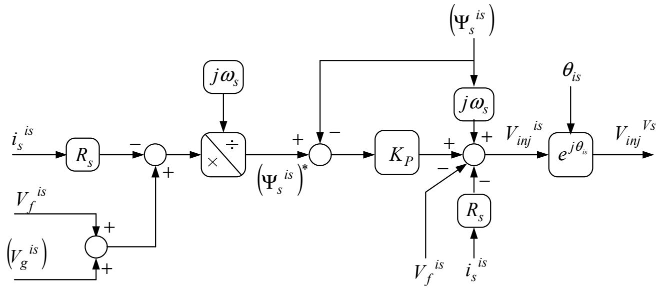


Fig. 7. Controller structure for modified architecture.

The reference stator flux command can be derived from the stator voltage equation by making the stator flux gradient to zero and can be given as

$$\overrightarrow{\Psi_s^{is*}} = \frac{\overrightarrow{V_f^{is}} + \overrightarrow{V_g^{is}} - R_s \overrightarrow{i_s^{is}}}{j\omega_s} \qquad (10)$$

where, V_g^{is} is the output voltage of DC link voltage control loop. Measured stator current, farm voltage and estimated stator flux are further added to improve performance of the controller. In order to meet the power flow requirements of DFIG, the SGSC output voltage in steady state will be approximately given by [12]:

$$V_{dg} = |V_g| = \frac{s|V_f|}{(1-s)} \qquad (11)$$

The phasor diagram for the DFIG with series connected GSC for unity power factor operation is shown in Fig. 8. As seen in the phasor diagrams, the stator of the DFIG with series connected GSC gets under excited during super synchronous operation and gets over excited during sub synchronous operation due to the series injection voltage to meet power flow requirements. It is undesirable to operate the DFIG with stator flux greater than 1 pu, as this leads to magnetic saturation of the iron in the machine. Magnetic saturation results in very large magnetizing currents and increased core losses. Even the under excitation of the stator is also not desirable, because it makes the DFIG to operate at low flux levels and causing the under rated operation of DFIG [12].

The reactive power support of the SGSC can be used to regulate the stator voltage of DFIG to nominal value. As earlier said, the reactive power flow of SGSC can be controlled by controlling δ. The DFIG stator voltage error can be used to obtain the value of δ. During high slip conditions, the deviation of stator voltage is large.

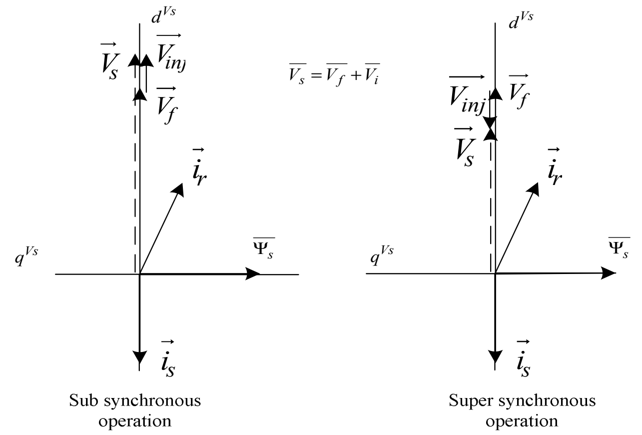


Fig. 8. Phasor diagram of DFIG with SGSC for unity power factor operation.

IV. PERFORMANCE EVALUATION AND DISCUSSIONS

The performance of the proposed control scheme has been tested on a 1.5 MW wind generator connected to the grid. The parameters of the DFIG have been given in appendix. Simulation studies are performed on the conventional and modified DFIG in MATLAB/SIMULINK. All the controllers are built in continuous time domain.

The impact of voltage sag on conventional DFIG and proposed series architecture of DFIG are shown in Figs. 9-11. The responses to voltage sag of 0.5 pu magnitude introduced at 10.0 s for 150 ms duration (i.e. 9 cycles at 60 Hz). For sub-synchronous speed condition the wind speed is set to 10 m/s and for the case of super-synchronous speed the wind speed is set to 14 m/s. During voltage sag condition, series injected voltage by SGSC is shown in Fig. 9 for sub and super synchronous speed operations. Simulation responses of stator voltage, stator flux, stator power, DC link voltage, rotor speed and torque for conventional and modified DFIG are shown in Figs. 10 and 11 for sub and super synchronous speed operation, respectively. Turns ratio of the series injection transformer is set to unity. The magnetic saturation of the iron core of machine is neglected and the B-H curve is assumed to be linear. Hence, the stator flux is proportionally varied with the stator voltage.

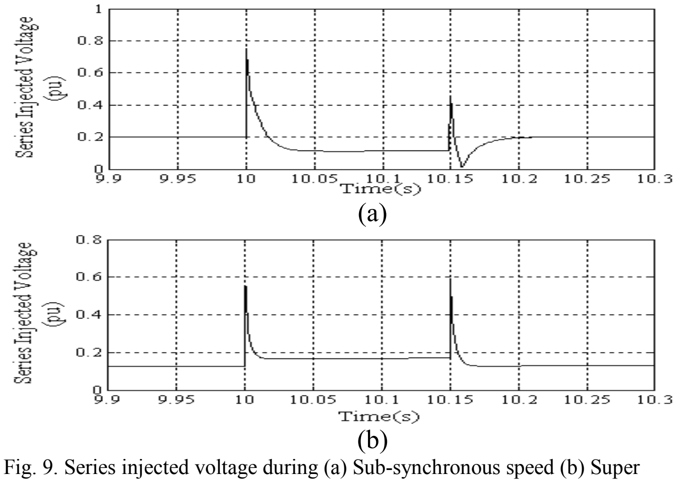
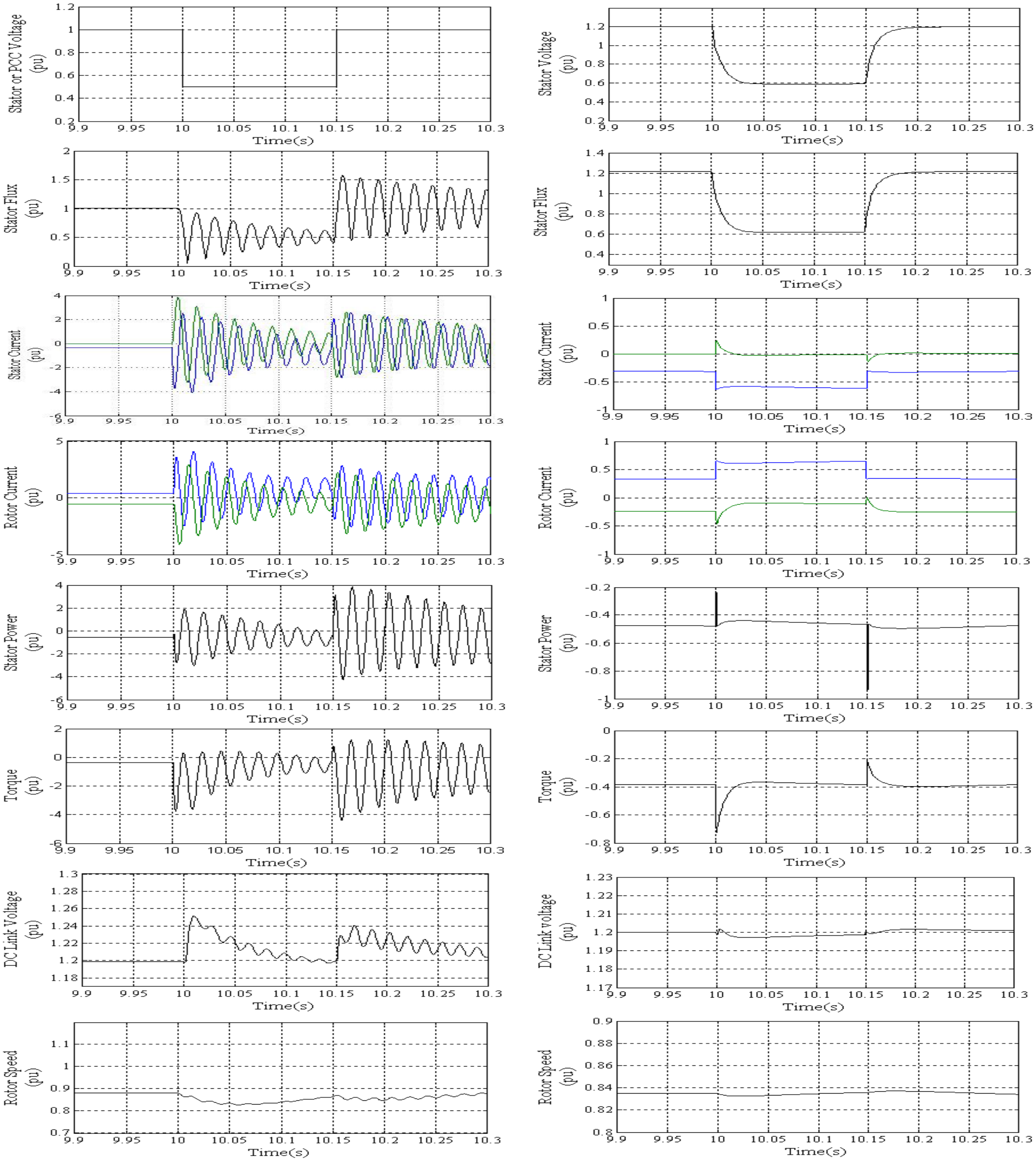


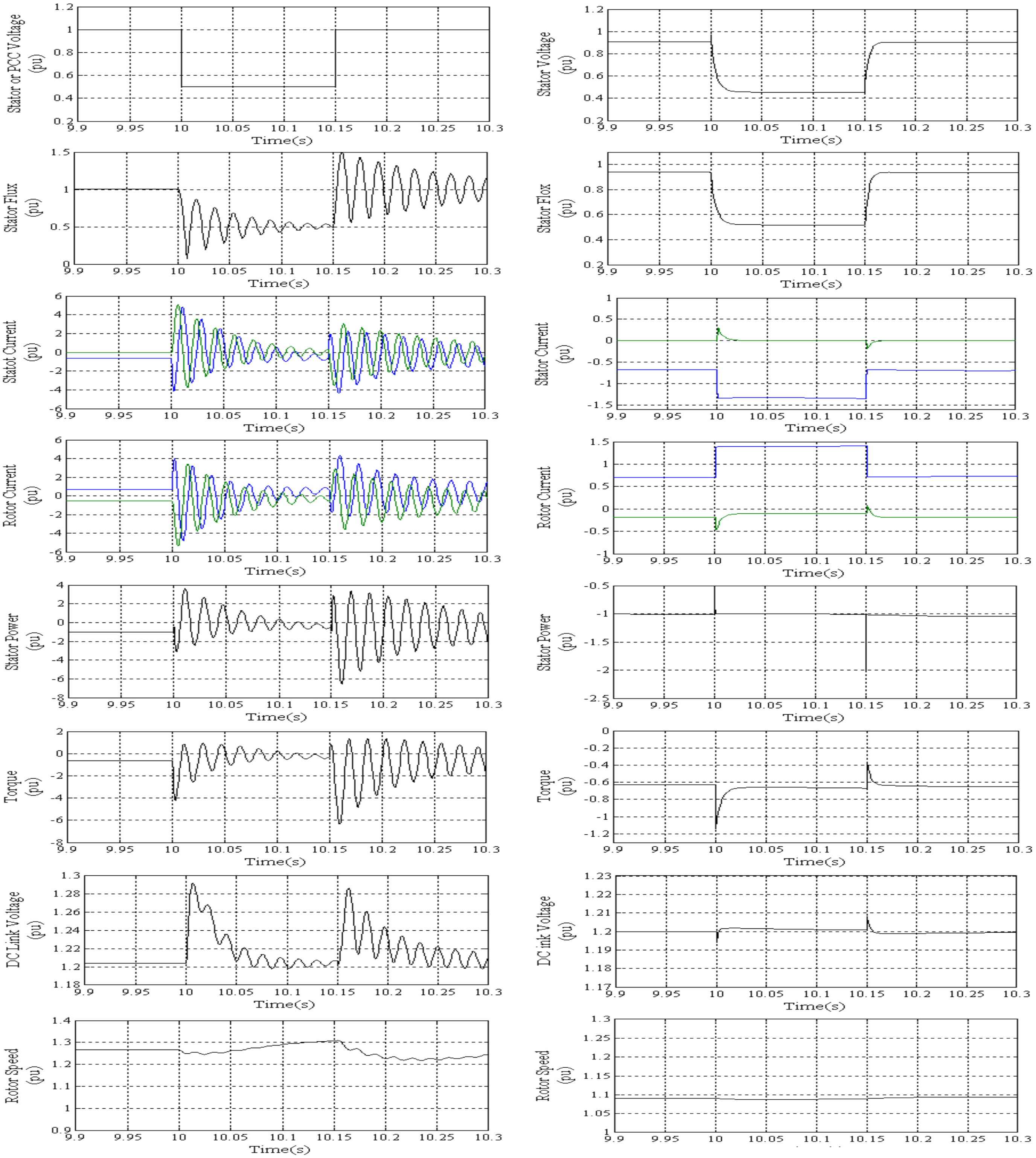
Fig. 9. Series injected voltage during (a) Sub-synchronous speed (b) Super Synchronous speed.



(a) Conventional DFIG

(b) Series Connected DFIG

Fig. 10. Dynamic response during voltage sag of 50 % condition at sub-synchronous speed.



(a) Conventional DFIG

(b) Series Connected DFIG

Fig. 11. Dynamic response during voltage sag of 50 % condition at super-synchronous speed.

Because of the proportional regulation and command scaling, the stator flux exhibits properties of a well-damped dynamic system. The stator flux magnitude exponentially reaches its post-sag steady state value without any oscillations. The MSC rotor current regulator maintains regulation of the rotor currents, and the electromagnetic torque reaches its new steady state value. The wind turbine speed regulator increases the blade pitch to keep the rotor speed within safe bounds. The stator terminals remain connected to the PCC and continue to supply current to the grid during the voltage sag. Fluctuations in DC link voltage are significantly reduced.

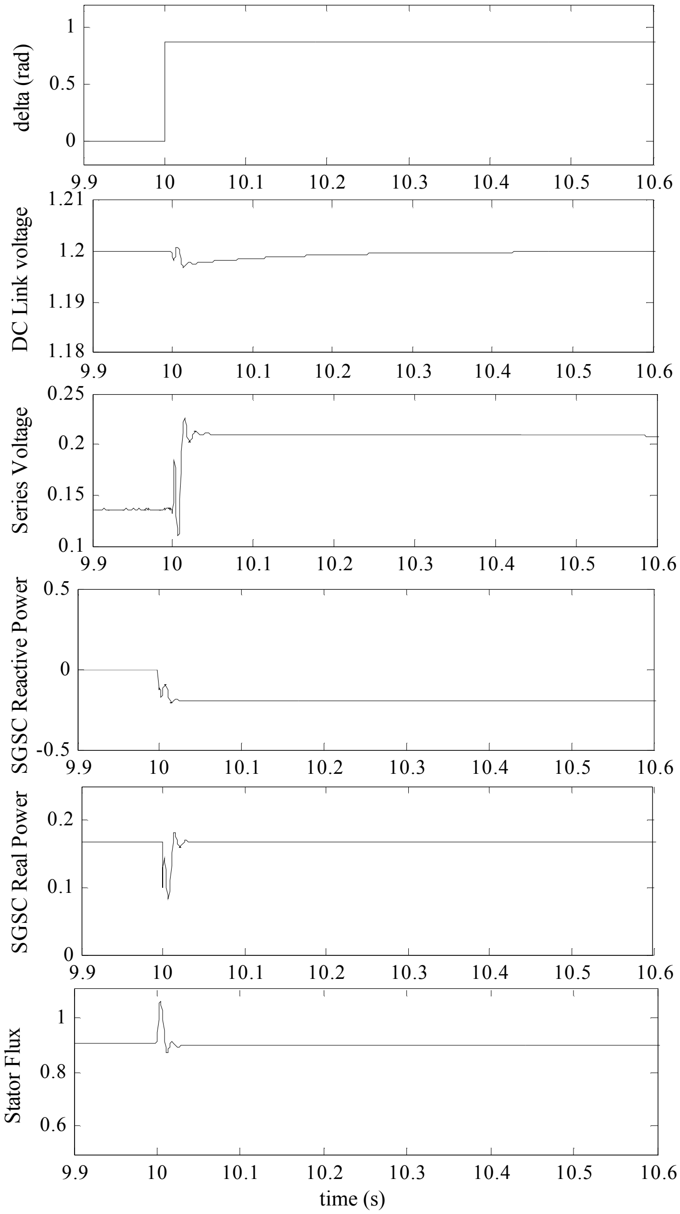


Fig. 12. Dynamic response during step change in reactive power command.

The stator flux of the conventional DFIG is poorly damped and has oscillations at line frequency. The stator flux response of DFIG with SGSC is smooth and its oscillations are well damped out during voltage sag condition. DC link voltage is within safe bounds and fluctuations are significantly reduced. The proposed architecture and controls give excellent performance in regulating the stator flux during voltage sags condition.

To show the effectiveness of the proposed control scheme of series connected grid side converter of DFIG, the transient response with a step change in reactive power injection i.e. (δ) from 0 to 0.9 rad, at 10 s instant, during normal operation is shown in Fig. 12. It is observed that series reactive power (Q_{SGSC}) settles within 0.04 s, showing very fast dynamic response. Stator injected active power remains at 0 p.u. Series injected voltage is increased from 0.15 p.u. to 0.21 p.u. Stator terminal (and stator flux) remains constant which is in reasonable limit. Stator terminal voltage will always be the addition of grid voltage and series injected voltage.

V. CONCLUSIONS

In the new grid code requirements, the wind power generators must be capable of supporting to the network during the steady and abnormal conditions. In this paper, new Series Grid-Side Converter (SGSC) topology is explored. The dynamic performance with a proposed controller is investigated using voltage sag and step response to reactive power injection. It has been shown that dynamic performance of modified DFIG is well damped and far better than conventional DFIG. During the abnormal conditions, the modified DFIG out performs with the proposed controllers. It is shown that during steady state the series converter can be utilized to provide reactive power capability.

VI. APPENDIX

TABLE A
PARAMETERS OF SIMULATED DFIG

Rated Power	1.5 MW
Stator Voltage	575V
Rs	0.0071 p.u.
Rr	0.005 p.u. (referred to stator)
Ls	0.171p.u.
Lr	0.156 p.u. (referred to stator)
Lm	2.9 p.u.
Number of Pole Pairs	3
Inertia Constant	5.04

VII. ACKNOWLEDGEMENT

Financial support obtained by Central Power Research Institute (CPRI), Bangalore, India vide project no. CPRI/EE/20070101 is gratefully acknowledged.

VIII. REFERENCES

[1] Global Wind Energy Council. [Online] Available: http://www.gwec.net
[2] Santiago Grijalva, Scott R. Dahman, Kollin J. Patten, and Anthony M. Visnesky, "Large-Scale Integration of Wind Generation Including Network Temporal Security Analysis," *IEEE Transactions on Energy Conversion*, vol. 22, No. 1, pp. 181–188, March 2007.
[3] B.S. Rajpurohit, S.N. Singh and I. Erlich, "Wind Power in Electricity Markets: Key Issues and Challenges", *International Journal of Energy Technology and Policy (IJETP),* Vol. 6, No.3, pp. 196-211, 2008.
[4] Erlich I., Winter W. and Dittrich A., "Advanced grid requirements for the integration of wind turbines into the German transmission system", *IEEE PES General Meeting*, June 18-22 2006, Montreal, Canada.
[5] Hansen AD, Iov F, Blaabjerg F and Hansen LH. "Review of contemporary wind turbine concepts and their market penetration", *Wind Engineering,* pp. 247-263, Vol. 28*,* May 2004.
[6] J Morren and Sjoerd W.H. de Haan, "Ridethrough of Wind Turbines with Doubly-Fed Induction Generator During a Voltage Dip", *IEEE Transaction on Energy Conversion*, Vol. 20, No. 2, pp. 435-441, June 2005.
[7] A. Peterson, "Analysis Modeling and Control of Doubly-Fed Induction Generators for Wind Turbines", Ph.D. Thesis, Chalmers University of Technology, Goteborg, Sweden, 2005.
[8] R. Pena, J.C. Clare and G.M. Asher , "Doubly Fed Induction Generator Using Back-to-Back PWM converters and its Application to Variable-Speed Wind-Energy Generation," IEE Proc. Electric Power Applications, Vol. 143, pp. 231- 241, May 1996.

[9] R. Datta and V. T. Ranganathan, “Direct power control of grid-connected wound rotor induction machine without rotor position sensors,” *IEEE Trans. Power Electronics*, vol. 16, pp. 390–399, May 2001.

[10] Lie Xu and Phillip Cartwright, “Direct Active and Reactive Power Control of DFIG for Wind Energy Generation,” *IEEE Transactions on Energy Conversion*, vol. 21, No. 3, pp. 750–758, Sept. 2006.

[11] B. Hopfensperger, D. Atkinson and R. Lakin, “Statot-flux oriented control of a doubly-fed induction machine with an without position encoder ”, IEE Proc. of Electrical Power Application , Vol. 147, No. 4, pp. 241-250, July 2000.

[12] P. Flannery and G. Venkataramanan, “A Unified Architecture for Doubly Fed Induction Generator Wind Turbines using a Parallel Grid Side Rectifier and Series Grid Side Converter” Power Conversion Conference PCC 07, April 2-5 2007, pp. 1442-1449, Nagoya.

IX. BIOGRAPHIES

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Istvan Erlich (SM’06) received his Dipl.-Ing. degree in electrical engineering from the University of Dresden/Germany in 1976. After his studies, he worked in Hungary in the field of electrical distribution networks. From 1979 to 1991, he joined the Department of Electrical Power Systems of the University of Dresden again, where he received his PhD degree in 1983. In the period of 1991 to 1998, he worked with the consulting company EAB in Berlin and the Fraunhofer Institute IITB Dresden respectively. During this time, he also had a teaching assignment at the University of Dresden. Since 1998, he is Professor and head of the Institute of Electrical Power Systems at the University of Duisburg-Essen/Germany. His major scientific interest is focused on power system stability and control, modelling and simulation of power system dynamics including intelligent system applications. He is a member of VDE and senior member of IEEE.