

# Enhancement of Reactive Power Capability of DFIG using Grid Side Converter

V. Sumitha<sup>1</sup>R. Gnanadass<sup>2</sup>

**Abstract** - In the new electricity grid code, reactive power generation by wind farms, which must operate similarly to other conventional power plants, is a major concern during both steady-state and fault conditions. This article presents the reactive power capability of a doubly-fed induction generator (DFIG) through the use of performance capability curves. The real and reactive power capability of conventional DFIG, the Unified Architecture (UA) is analyzed for various firing angles and modulation indexes ( $\mu$ ) of the grid side converters (GSC). The performance of both the DFIG models are compared and the enhanced reactive power capability is illustrated. The simulation is carried out in simulink based MATLAB environment.

**Keywords** - DFIG, GSC, UA, capability curve, reactive power capability.

## I. INTRODUCTION

Wind power, which has been proved to be a potential source for generation of electricity with minimal environmental impact, is the fastest-growing source for electric power generation, and it is expected to remain so in the future. At the end of 2007, the wind- installed capacity stands at over 94,112 MW worldwide, which is more than 20 GW from the capacity in 2006 [1]. With the advancement of aerodynamic designs, wind turbines can capture several megawatts of power, and this substantial amount of wind power can supplement the base power demand when such wind energy conversion systems (WECS) are integrated into the grid.

Due to large penetration and matured technology, wind farms must fulfill almost the same requirements as conventional power plants. According to new grid codes, wind farms have to supply not only active power, but also to supply/consume the reactive power to/from the grid. The requirements are defined with respect to the power factor as a function of the voltage at the point of common coupling (PCC) with the main grid. Thus, the reactive power management becomes an integral issue in the grid-connected wind farms.

The DFIG is commonly used in variable-speed large wind turbines. The DFIG has the ability to provide precise speed control and good power factor with a converter that is rated as low as 25% of the machine power rating. Due to its many advantages, such as improved power quality, high energy efficiency and controllability, reduced power converter rating, etc., the variable-speed wind turbine using a DFIG is becoming popular for large power generation from wind.

In order to determine the technical viability of the DFIG for a wind generator application, the capabilities of the DFIG need to be determined. Recently, some research has given attention to the steady-state P-Q curve of a DFIG [2–4]. Tapia et al.(2003) derived P-Q curves by imposing only rotor current limitation for different operating temperatures. Similarly, [3] presents P-Q curves of a DFIG for different terminal voltages by considering only rotor current limits. Lund et al. [4] derived P-Q curves of a DFIG by imposing rotor current, stator current, and rotor voltage limits. But none of these authors considered the reactive power capability of a grid-side converter (GSC). Considering the GSC reactive power capability will substantially change the operating range and operation of a DFIG. Peterson [5] proposed a new unified architecture (UA) of a DFIG using three converters; using a third converter drastically changed the reactive capability.

The reactive power capability of a conventional DFIG and a unified DFIG has been obtained by extending the analysis of steady-state model of operation of a DFIG with a power grid through the use of performance capability curves. First, three steady-state models of DFIGs are derived in terms of (i) stator and rotor voltage ( $V_s$  and  $V_r$ ), (ii) stator voltage and rotor current ( $V_s$  and  $I_r$ ), and (iii) stator voltage and stator current ( $V_s$  and  $I_s$ ) to derive the limitations in reactive power production, caused by the rotor voltage, the rotor current, and the stator current, respectively. Second, reactive power capability from the GSC is derived and included. Finally, a complete P-Q diagram of a DFIG is developed by optimization of rotor speed employing the maximum power point tracking (MPPT) algorithm. The effect of stator voltage variation on capability curves is also demonstrated [6].

This paper presents simulation results of a Grid-connected DFIG. The carrier-based Sinusoidal PWM modulation for grid-side converters have been proposed in this paper. Firing angle control has been developed to control the converters to provide independent control of active and reactive power and keep the DC-link voltage constant.

To enhance the reactive capability of the DFIG machine one more grid side converter is added in series with already existing grid side converter. Hence, named as series grid side converter (SGSC) and the former named as parallel grid side converter (PGSC). This newly proposed architecture is named as unified architecture (UA) of a DFIG using three converters by Peterson[5]. Both the configurations i.e. conventional DFIG and UA are simulated, the performance are compared and graphs are plotted. The effect of variation of the modulation index is also discussed and the plots are shown.

The paper first received 11 Mar 2010 and in revised form 1 July 2010.  
Digital Ref: A170801269

<sup>1</sup> EEE Department, Pondicherry Engineering College, Pondicherry – 605 014, E-mail: sumivaithi@yahoo.co.in

<sup>2</sup> EEE Department, Pondicherry Engineering College, Pondicherry – 605 014

In this paper the firing angle control limitation is proposed to vary the reactive power of the DFIG by varying the firing angle of the rotor side converter. The rotor side converter (RSC) is designed such that the output dc voltage is controlled by changing the firing angle of the converter. This dc output voltage is fed to the dc link capacitor. This dc link capacitor is the source of the grid side converter (inverter). This inverter synchronizes the low frequency ac voltage to the grid frequency ac voltage. Hence this system is called the power conditioning system (PCS).

### II. MODELLING OF DFIG

The DFIG is a wound rotor induction generator having three-phase windings on the rotor and stator. The stator is directly connected to the grid, and the rotor power is fed by variable frequency power electronic converters, as given in Fig.1. The power electronic converter system consists of two back-to-back pulse width modulated (PWM) voltage-fed current-regulated converters, namely, the rotor or machine-side converter (MSC) and GSC, which are controlled independently. The MSC is used to convert the rotor frequency power to DC power and then feed back to the AC system using the GSC, which converts DC power to AC power at the system frequency. The rotor voltage induced by the MSC in the rotor circuit is a complex quantity that represents two control variables. Usually, the field-oriented approach is employed for controlling the MSC, which allows the control of active and reactive powers, independently, of the stator side. The fundamental steady-state equations for the DFIG are given by Eqs. (1) – (4) [7] at the fundamental frequency. Higher harmonics, losses in core and windings, and losses in the converter are neglected for simplification.

Voltage equations:

$$V_S = j\omega_s \Psi_S \tag{1}$$

$$V_R = R_R I_R + j(\omega_s - \omega_r) \Psi_R \tag{2}$$

Flux equations:

$$\Psi_S = L_S I_S + L_M I_R \tag{3}$$

$$\Psi_R = L_R I_R + L_M I_S \tag{4}$$

where  $L_S = L_{O_S} + L_M$  and  $L_R = L_{O_R} + L_M$ .

Eliminating flux linkages using Eqs. (3) and (4), we have

$$V_S = j\omega_s (L_S I_S + L_M I_R) \tag{5}$$

$$V_R = R_R I_R + j s \omega_s (L_R I_R + L_M I_S) \tag{6}$$

The equivalent circuit corresponding to Eqs. (5) and (6) is illustrated in Fig. 2.

### III. NEW SERIES GSC DFIG ARCHITECTURE

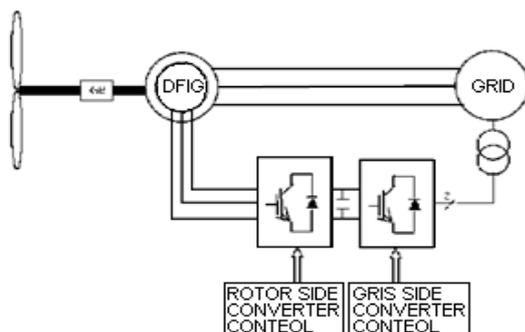


Fig. 1: DFIG with back-to-back PWM voltage source converters (conventional DFIG).

The conventional DFIG architecture in which the GSC is connected in parallel with the grid performs very well at power processing. Utilizing a series grid-side converter (SGSC) in addition to the GSC, which shares the same DC bus as the MSC and is connected in series with the stator winding of the DFIG, it is possible to inject series voltage and phase angle into the grid, similar to the unified power flow controller (UPFC), which has several benefits and provides necessary compensation during abnormal conditions.

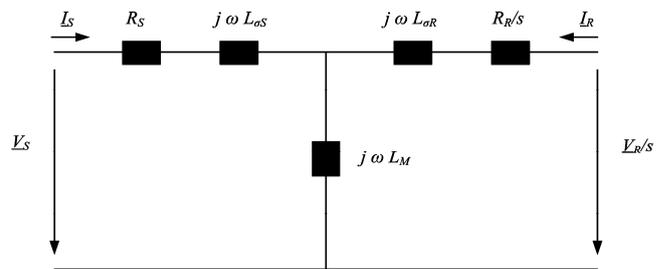


Fig. 2: Steady-state per phase equivalent circuit of DFIG.

This configuration is termed Unified Architecture (UA) and is given in Fig. 3. During normal and abnormal conditions, the GSC (termed as parallel GSC [PGSC]) facilitates the normal power processing capabilities for sub-synchronous and super-synchronous modes of operation of the DFIG. During normal operating conditions, the SGSC facilitates only reactive power capability, and during abnormal conditions, the SGSC injects series voltage and phase angle for necessary compensation required for secure and stable operation. In both normal and extreme conditions, the SGSC provides reactive power injection to the grid [8, 9]. The cost of the converter depends on the rating. Hence, the rating of the SGSC must be chosen wisely for economical operation. The rating of the SGSC is taken as 15% of the DFIG stator rating in this work.

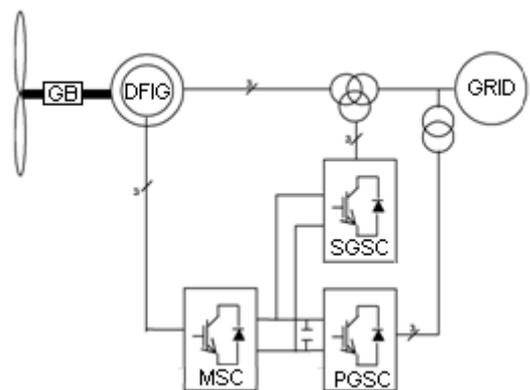


Fig. 3: Unified architecture (UA)

In this section, only static performance, such as injection/absorption of reactive power to/from grid during abnormal/normal conditions, is discussed. For reactive power support, the injection of series voltage must be in phase quadrant with the stator (or line) current. Hence, the injection of series voltage will not change the stator terminal voltage substantially. Stator terminal voltage will always be the addition of grid voltage and series injected voltage. The capability curve for UA, as given in Fig. 3,

can be obtained by adding the reactive power from the SGSC.

IV. SINUSOIDAL PWM TECHNIQUE USED IN THE GSC

The sinusoidal reference wave  $V_{ref}$  is created, a modulation method to commutate the switches is required. There are many methods to modulate the reference wave, with the most well known the so-called sinusoidal pulse width modulation (SPWM), which uses a triangular carrier to generate the PWM as illustrated in Fig. 4.

In this method, there are two important parameters to define: the amplitude modulation ratio, or modulation index  $\mu$ , and the frequency modulation ratio  $p$ . Definitions are given by

$$\mu = V_{ref\ max} / V_{tri\ max} \tag{7}$$

$$p = f_T / f_S \tag{8}$$

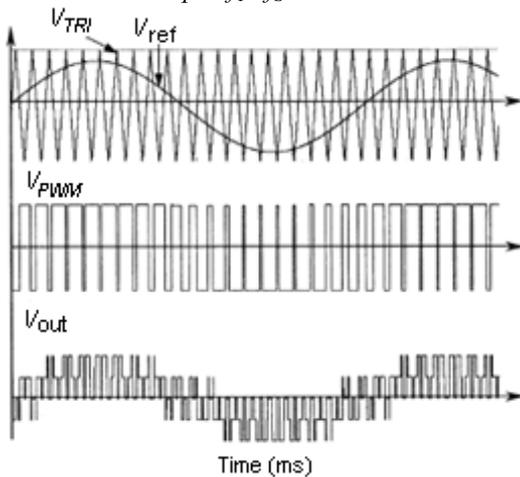


Fig. 4: Sinusoidal PWM technique.

where  $V_{ref\ max}$  and  $V_{tri\ max}$  are the amplitudes of the  $V_{ref}$  and  $V_{tri}$  respectively. On the other hand,  $f_S$  is the frequency of the main supply and  $f_T$  the frequency of the triangular carrier. The modulation method described in Fig. 4. has a harmonic content that changes with  $p$  and  $\mu$ . Furthermore, to avoid sub harmonics, it is also desired that  $p$  be an integer. If  $p$  is an odd number, even harmonics will be eliminated. If  $p$  is a multiple of three, then the PWM modulation of the three phases will be identical. When  $\mu$  increases, the amplitude of the fundamental voltage increases proportionally, but some harmonics decreases. This method is used in this paper for the grid side converters (GSCs) [10].

V. SIMULINK DIAGRAM

For the analysis of real and reactive power capability of the DFIG model, simulation is carried out in SIMULINK block set of MATLAB. The performance of the DFIG models are analyzed for various firing angles and modulation indexes of the grid side converters (GSCs). The DFIG model connected to grid system and P-Q load is given in Fig. 5.

The conventional DFIG with the parallel grid side converter (PGSC) is given in Fig. 6. This consists of an asynchronous machine from which rotor winding are tapped and connected to low frequency converter called rotor side converter (RSC). This delivers dc voltage to the DC link capacitor, the capacitor acts as the source to the inverter called the grid side converter (GSC) which synchronize the voltage from the rotor to the grid. DFIG with both parallel grid side converter (PGSC) and series grid side converter (SGCS) is given in is given in Fig. 7.

The only modification is the “addition of one more inverter” in series with converter-inverter circuit. This also takes the input from the DC link capacitor.

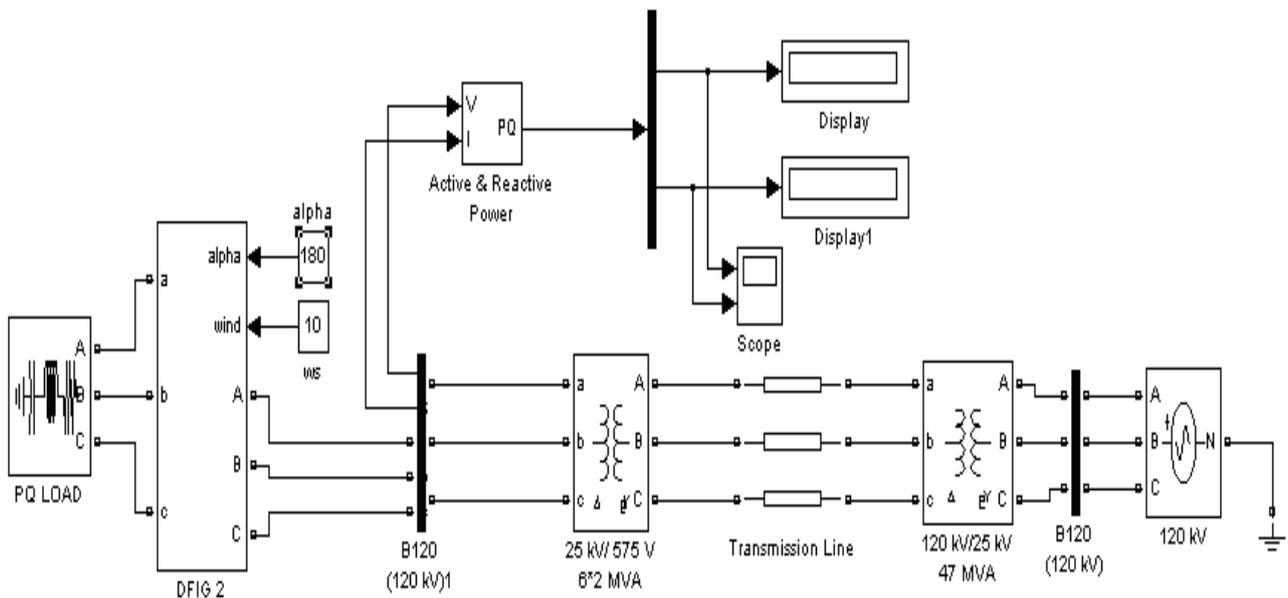


Fig. 5: Simulink model of DFIG

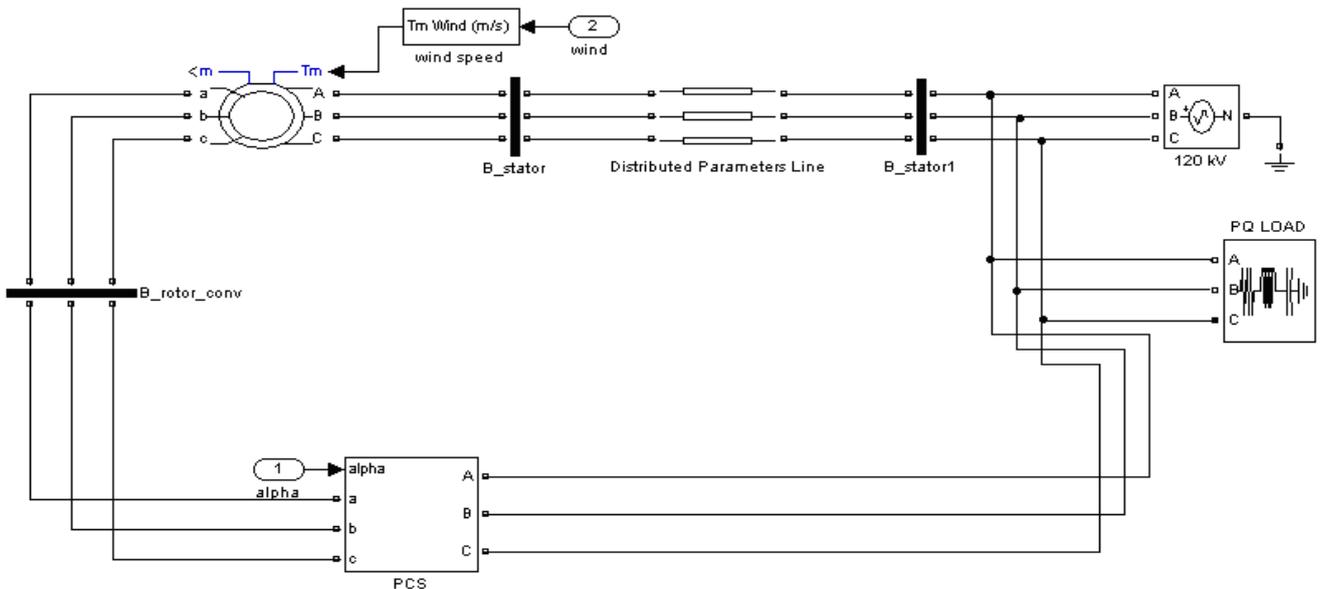


Fig. 6: DFIG with PGSC (conventional DFIG)

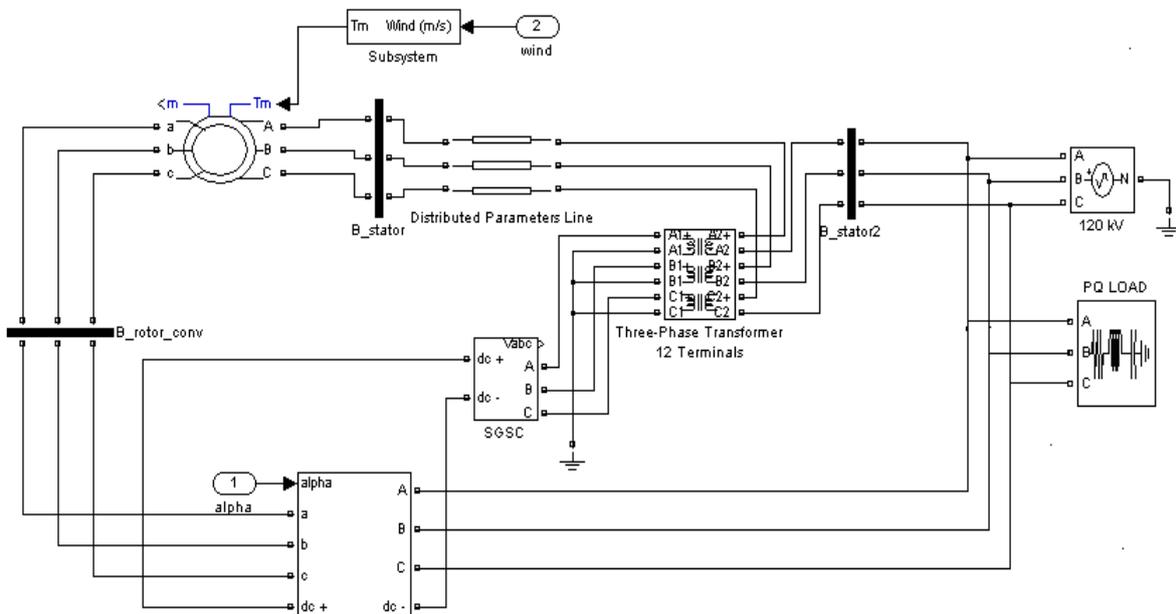


Fig. 7: DFIG with PGSC and SGSC (Unified Architecture)

## VI. SIMULATION RESULTS

The DFIG was modeled in simulink to analyze the power system parameters such as real power and reactive power. The firing angle of the rotor side converter (RSC) is controlled to vary the real and reactive power of the DFIG models. The case study for the reactive power capability of DFIG models is illustrated.

Case 1: The DFIG with parallel grid side converter (conventional DFIG).

Case 2: The DFIG with parallel and series grid side converter (UA). For various modulation index ( $\mu$ ) of the both PGSC and SGSC. The comparison of both the DFIG models is illustrated.

### Case 1: Conventional DFIG

The real power variation is almost constant for the firing angle ( $\alpha$ ) between  $10^\circ$  to  $80^\circ$  and the real power

increases as  $\alpha$  is varied from  $90^\circ$  to  $180^\circ$  (operating region). The variation of the real power with firing angle ( $\alpha$ ) is plotted in Fig. 8a. The reactive power is almost constant for the firing angle between  $10^\circ$  to  $80^\circ$  and starts increasing in negative direction from  $90^\circ$  to  $180^\circ$ . The variation of reactive power with  $\alpha$  is given in Fig. 8b. The reactive power varies as the load to the system is varied. According to the load added the reactive power supply to grid is varied. The variation of reactive power with load is traced in Fig. 8c. The reactive power does not drastically vary with wind velocity. It is almost constant throughout the operating region. So we can take it as fixed speed operating system. The variation of reactive power with wind velocity is as in the Fig. 8d. The plot between the real and reactive power for variation of  $\alpha$  is known as the capability curve (P-Q curve) of the DFIG machine. The capability curve of the DFIG is shown in Fig. 8e. The 3D view of the variation of real and reactive power of the DFIG machine with firing angle  $\alpha$  is presented in Fig. 8f.

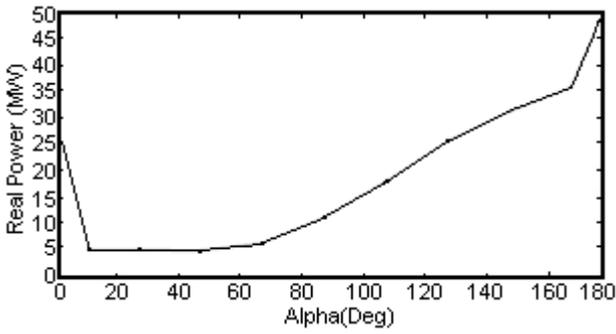


Fig. 8 a: Alpha Vs. real power

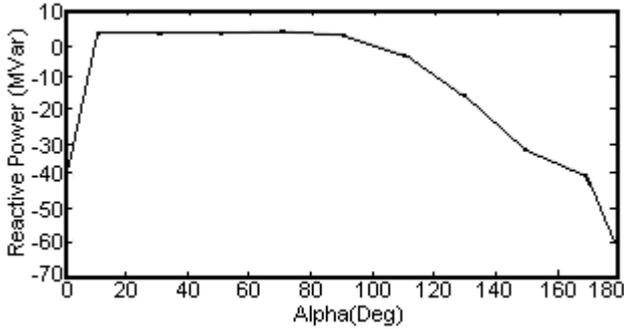


Fig.8 b: Alpha Vs. Reactive power

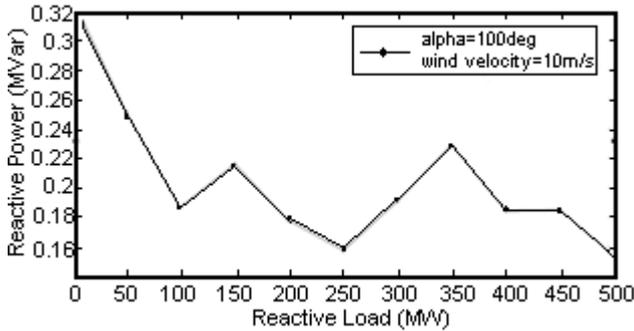


Fig. 8c: Reactive power Vs. load

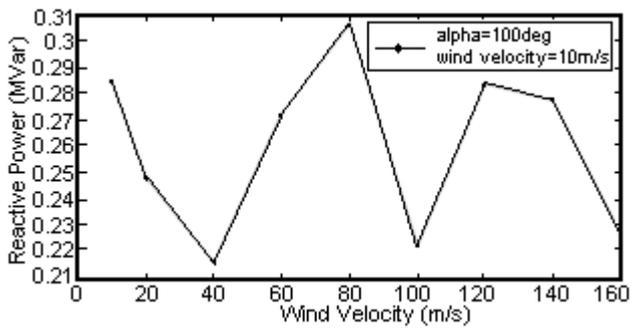


Fig. 8d: Reactive power Vs. wind velocity

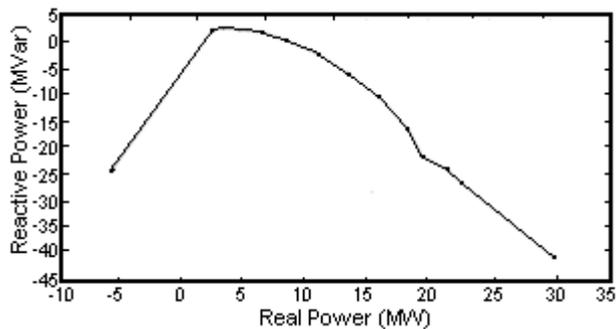


Fig. 8e: P-Q curve

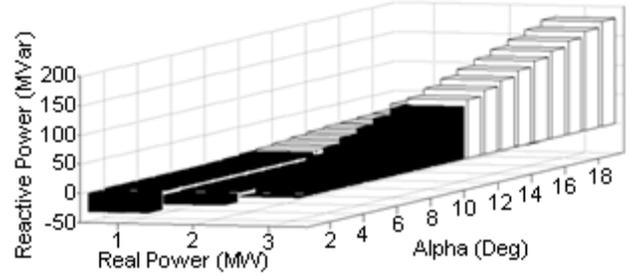


Fig. 8f: 3D view of real and reactive power Vs. Alpha

Case 2: Unified Architecture (UA)

The real power variation is almost similar to that of the conventional DFIG. The variation of the real power with firing angle (alpha) is plotted in Fig. 9a. The reactive power production trace as shown in Fig. 9b, is similar to as the conventional DFIG, but the reactive power production is higher then compared to the conventional DFIG. The reactive power varies as the load to the system is varied. As shown in Fig. 9c, when the load is added to the system the reactive power supply to grid is varied. The reactive power does not vary too much with wind velocity in the operating region as in the Fig. 9d. The capability curve of the DFIG is shown in Fig. 9e. The 3D view of the variation of real and reactive power of the DFIG machine with firing angle alpha is dissipated in Fig. 9f.

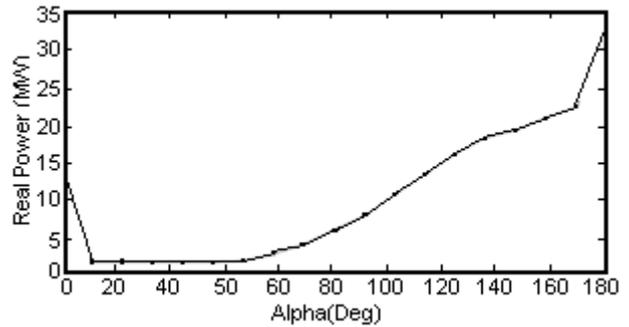


Fig. 9a: Alpha Vs. real power,

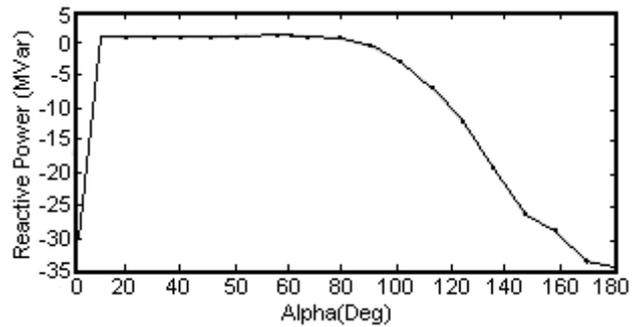


Fig. 9b: Alpha Vs. Reactive power

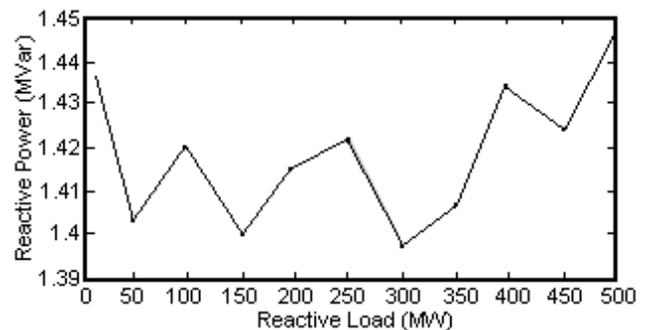


Fig. 9c: Reactive power Vs. load

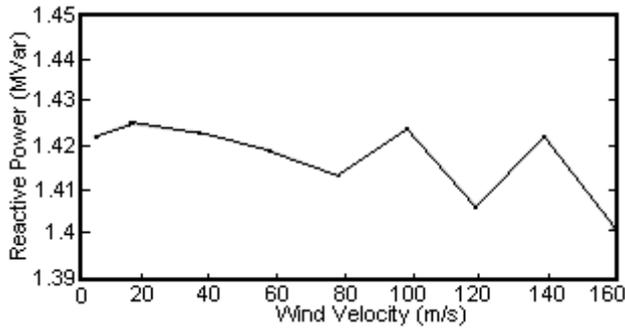


Fig. 9d: Reactive power Vs. wind velocity

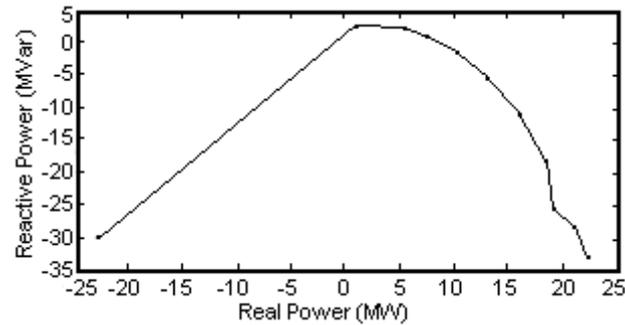


Fig. 9e: P-Q curve

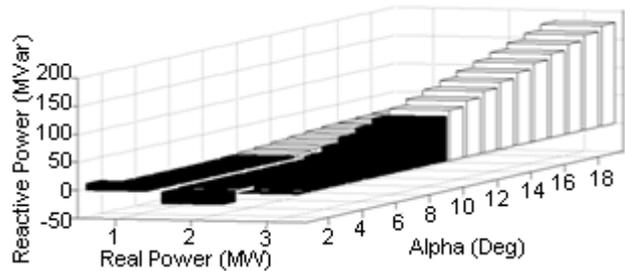


Fig. 9f: 3D view of real and reactive power Vs. Alpha

*A. Enhancement of reactive power capability*

In this case study the variation of reactive power capability of UA is demonstrated with variable modulation index ( $\mu$ ). The reactive power capability of UA is observed by keeping the modulation index ( $\mu$ ) of SGSC at constant value (for a value of 0.8) and the modulation index ( $\mu$ ) of PGSC is varied from 0.7 to 0.9, the graph is illustrated in Fig. 10. The reactive power capability of the DFIG increases as the modulation index ( $\mu$ ) of the PGSC increases.

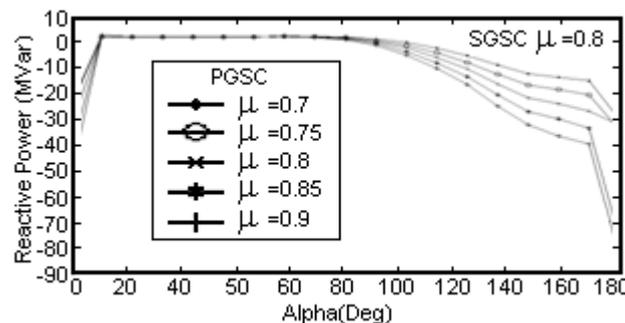


Fig. 10: Reactive Power Vs Alpha for Various  $\mu$  of PGSC

There is no considerable increase in the reactive power capability of the UA, when the modulation index ( $\mu$ ) of SGSC is varied from 0.7 to 0.9. So it is enough that the modulation index ( $\mu$ ) of the PGSC is varied, the reactive power capability of the UA is varied.

When we compare the performance of the DFIG models, the real power delivery of both the machines are the same in the operating region. The reactive power delivery of the UA is more than conventional DFIG in the operating region. The capability curve (P-Q curve) is extended for UA than conventional DFIG. The plots are shown in Fig. 11a, Fig. 11b, and Fig. 11c.

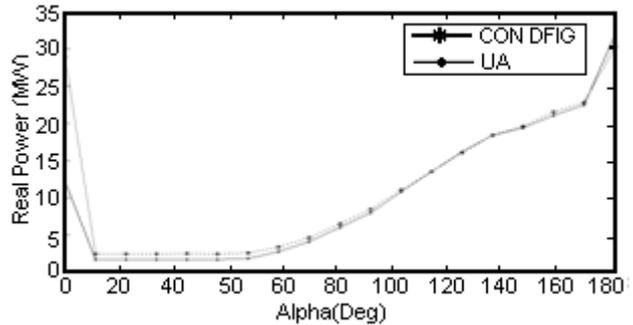


Fig. 11a: Alpha Vs Real Power

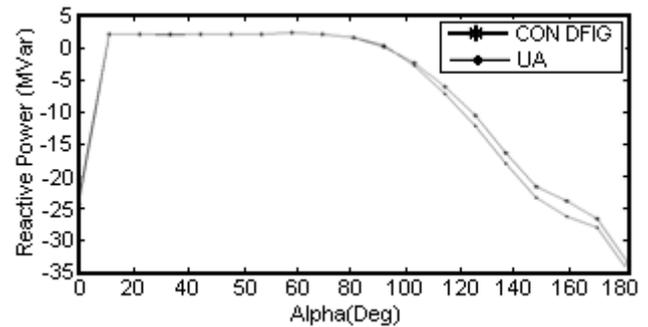


Fig. 11b: Alpha Vs Reactive Power

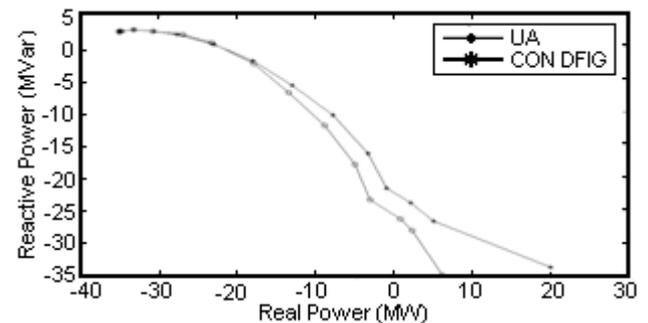


Fig. 11c: P-Q curve

VII. CONCLUSION

The real and reactive power capability of the DFIG model is analyzed for various firing angles and modulation indexes of the grid side converters (GSCs). The reactive power production is improved as the modulation index is increased. The simulation demonstrates the enhanced reactive power capability of the UA.

## VIII. APPENDIX

Parameters of simulated DFIG	
Rated power	1.5 MW
Stator Voltage	575 V
Rs (stator resistance)	0.0071 p.u
Rr (rotor resistance)	0.005 p.u (referred to stator)
Ls (stator inductance)	0.171 p.u
Lr (rotor inductance)	0.156 p.u. (referred to stator)
L <sub>m</sub> (magnetizing inductance)	2.9 p.u.
Number of pole pairs	3
Inertia constant	5.04

## VII. REFERENCES

- [1] Global Wind Energy Council, available at: <http://www.gwec.net>.
- [2] A. Tapia, G. Tapia, J.X. Ostolaza and J.R. Saenz, "Modeling and control of a wind turbine driven doubly fed induction generator", IEEE Trans. Energy Conversion, Vol. 18, No. 2, June 2003, pp. 194–204.
- [3] K. Mustafa and J. V. Milanovic, "Reactive power control strategies for DFIG-based plants", IEEE Trans. Energy Conversion, Vol. 22, No. 2, June 2007, pp. 389–396.
- [4] T. Lund, P. Sørensen and J. Eek, "Reactive power capability of a wind turbine with doubly fed induction generator", Wind Energy, Vol. 10, No. 4, July/August 2007, pp. 379–394.
- [5] A. Peterson, "Analysis Modeling and Control of Doubly-Fed Induction Generators for Wind Turbines", Ph.D. Thesis, Chalmers University of Technology, Goteborg, Sweden, 2005.

- [6] Bharat Singh and S. N. Singh "Reactive Capability Limitations of Doubly-fed induction generator", Electric Power Components and Systems, Vol. 37, No. 4, 2009, pp. 427 – 440.
- [7] Boldea, "Variable Speed Generators, Boca Raton", FL: CRC Press, 2006.
- [8] Singh, V. Emmoji and S. N. Singh, "Performance evaluation of series and parallel connected grid side converters of DFIG", IEEE PES General Meeting 2008, Pittsburgh, PA, 20–24 July 2008.
- [9] Akhmatov "Variable-speed wind turbines with doubly-fed induction generator part 1: Modelling in Dynamic Simulation Tools", Wind Eng., Vol. 26, No. 2, March 2002, pp.85-108.
- [10] Muhammad h. Rashid, "Power Electronics Handbook", University of Florida, 2003.

## BIOGRAPHIES

**V. Sumitha** received the Undergraduate Degree in Electrical Engineering Pondicherry engineering college in 2003 and pursuing her M.Tech in the same college. Her field of interest is power systems, enhancement of reactive power of DFIG.

**R. Gnanadass** received the Undergraduate Degree in Electrical Engineering and the Masters degree in Power Systems Engineering with Distinction in 1991 and 1993, respectively. He has obtained the Ph.D. degree in the Department of Electrical & Electronics Engineering, Pondicherry Engineering College, Pondicherry, India in July 2005. He is working as a teaching faculty in Pondicherry Engineering College since 1996. He was with the Department of Electrical and Computer Engineering, Iowa State University, Ames, USA from March 2007 to March 2008 to carry out his Postdoctoral studies under BOYSCAST fellowship sponsored by Department of Science and Technology, Government of India. He published 30 research articles in the journals. His field of interest is power system privatization, reactive power pricing and management, voltage stability, concepts of power system restructuring and optimization problems.