Vector Control of DFIG

Ninad Kiran Gaikwad [#1]

[#] *Depatment of Electrical Engineering, Sardar Patel College Of Engineering (SPCE), Munshi Nagar, Andheri (W), Mumbai-400058, India*

[1] ninadkgaikwad@gmail.com

Abstract—**This paper describes the design and control of a doubly fed induction generator (DFIG), using a back-to-back SVPWM voltage-source converters in the rotor circuit. A vector-control scheme is utilised for the control of these back-to-back converters. The vector control of the grid-side converter results in an independent control of active and reactive power drawn from the supply and also maintains the dc-link voltage between the two converters at a constant value. The vector-control of the rotor-side converters provides for the independent control for the wide-range speed operation and reactive power supply to the stator circuit. Such behaviour of the DFIG system can be utilised for a better grid connection of wind farms.**

I. Introduction

The DFIG using an AC-AC converter in the rotor circuit (Scherbius Drive) has long been a standard drive option for high power application involving limited speed range. The power converter used in this configuration needs to be designed to handle only rotor power, which is almost one-third of the stator power. Moreover, the vector-control scheme employed to control the AC-AC converters results in independent control of torque and rotor excitation current as well as decoupled control of the active and reactive power drawn from the grid supply.

The natural application of the Scherbius DFIG system is in wind generation, since the speed range is restricted (from cut-off to rated wind velocity). Most Scherbius DFIG reported employ either a current-fed DC-Link converter or cycloconverter in the rotor circuit. But, the use of current-fed DC-Link has a number of disadvantages: the DC-Link choke is expensive, and an extra commutation circuit is required for operation at synchronous speed(which is the operational speed range) and this has resulted in poor performance at low slip speeds. In addition, such a converter draws rectangular current waveforms from the supply, hence introducing harmonics which are undesired. A vector-controlled Scherbius scheme with 6/3-pulse cycloconverter can be used to overcome the problem at synchronous speed. On the other hand, such a cycloconverter scheme has the disadvantage of requiring a transformer for voltage matching in addition to a naturally commutated DC-Link.

These above disadvantages of the cycloconverter schemes can be overcome using two PWM/SVPWM voltage-fed current-regulated inverters connected back-to-back in the rotor circuit. The typical characteristics of such a Scherbius scheme, in which both the converters are controlled, are as follows:

1.) Operation below, above and through synchronous speed with the speed range restricted only by the rotor-voltage ratings of the DFIG
2.) Operation at synchronous, with DC currents injected into the rotor with the inverter working in the chopping mode
3.) Low distortion stator, rotor and supply currents
4.) Independent control of the generator torque and rotor excitation
5.) Control of the displacement factor between the voltage and the current in the supply converter, and hence control over the system power factor

Thus, a DFIG with PWM/SVPWM voltage-fed current-regulated inverters connected back-to-back in the rotor circuit provide with a characteristic similar to a conventional generator and hence, such a wind generator can be effectively connected with the main grid.

II. DFIG Mechanical/Electrical systems and integrated controls

A DFIG wind turbine primarily consists of the following three parts:

A. A Wind Turbine Drive Train

In the wind turbine drive train, the rotor blades of the turine catch wind energy which is then transferred to the induction generator through the gearbox.

B. Generator

The induction generator is a standard, wound rotor induction machine with its stator windings directly connected to the grid and its rotor windings connected to the grid through a frequency converter.

C. Power Electronic Converter

The power electronic converter is a frequency converter built by two self-commutated voltage-source converters, the RSC (Rotor-Side Converter) and the GSC (Grid-Side Converter), with an intermediate dc voltage link.

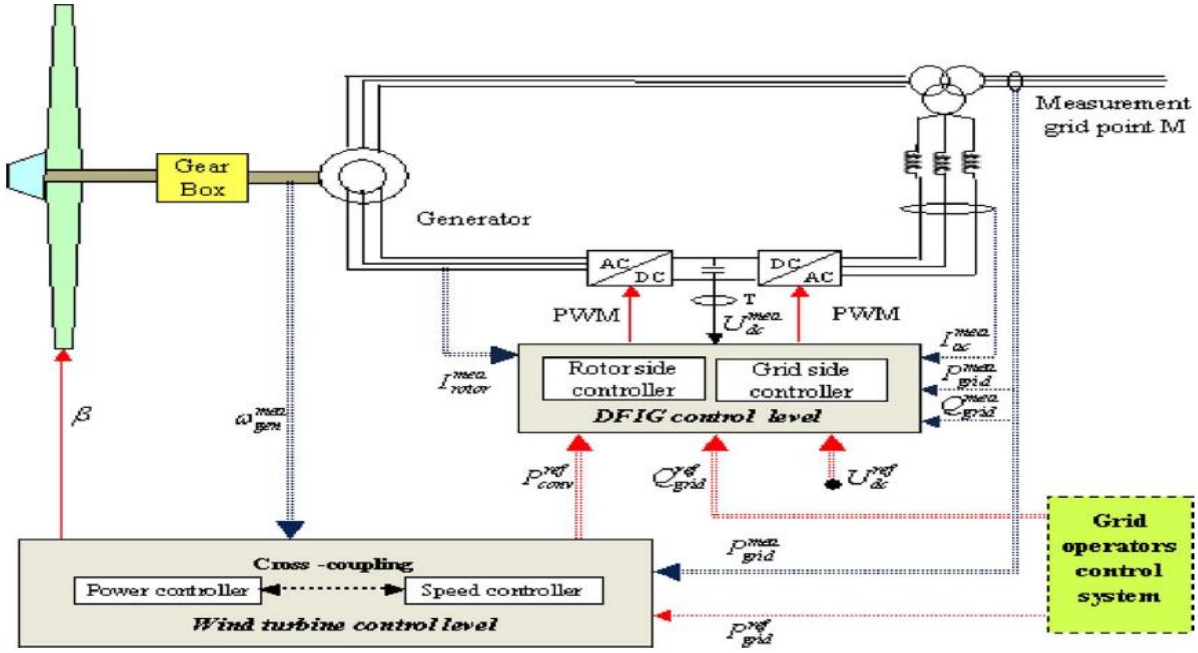

Figure.1. Configuration of DFIG System

The control in a DFIG wind power plant has following three levels:

A. Generator Level

At the generator level, the RSC controller regulates the DFIG to achieve maximum energy extraction from the wind or compliance with the wind plant control demand. The GSC controller maintains a constant dc-link voltage and adjusts reactive power absorbed from the grid by the GSC.

B. Turbine Level

At the turbine level, there is a speed controller and a power limitation controller. At a low wind speed, the speed controller gives a power reference to the RSC based on the principle of maximum energy extraction. At a high wind speed, the power limitation controller increases or decreases the pitch angle of the turbine blades to prevent the wind turbine from going over the rated power.

C. Wind Power Plant Level

At the wind power plant level, the power production of the entire plant is determined based on the grid requirement. The central control system sends out power references to eacj individual turbine, while the local turbine control system ensures that the power reference from the control level is reached.

III. CONTROL OF GRID-SIDE CONVERTER

The objective of the supply-side converter is to keep the dc-link voltage constant regardless of the magnitude and direction of the rotor power. A vector-control approach is used with a reference frame oriented along the stator (i.e. supply) voltage vector position. This enables independent control of the active and reactive power flowing between the supply and the GSC. The PWM converter is current regulated, with the direct axis current used to regulate the dc-link voltage and the quadrature axis current component used to regulate the reactive power. Schematic of the GSC is given below,

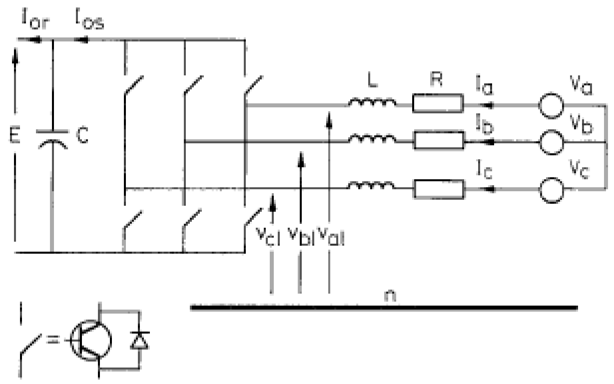

Fig.2. GSC Schematic

The KVL for above GSC circuit can be written as follows,

$$\begin{bmatrix} \nu_a \\ \nu_b \\ \nu_c \end{bmatrix} = R \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L \frac{\mathrm{d}}{\mathrm{d}t} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} \nu_{a1} \\ \nu_{b1} \\ \nu_{c1} \end{bmatrix} \qquad (2)$$

Where L and R are the line inductance and resistance, respectively. Using dq transformation in frame rotating at grid frequency we can transform eqn. 2, as follows,

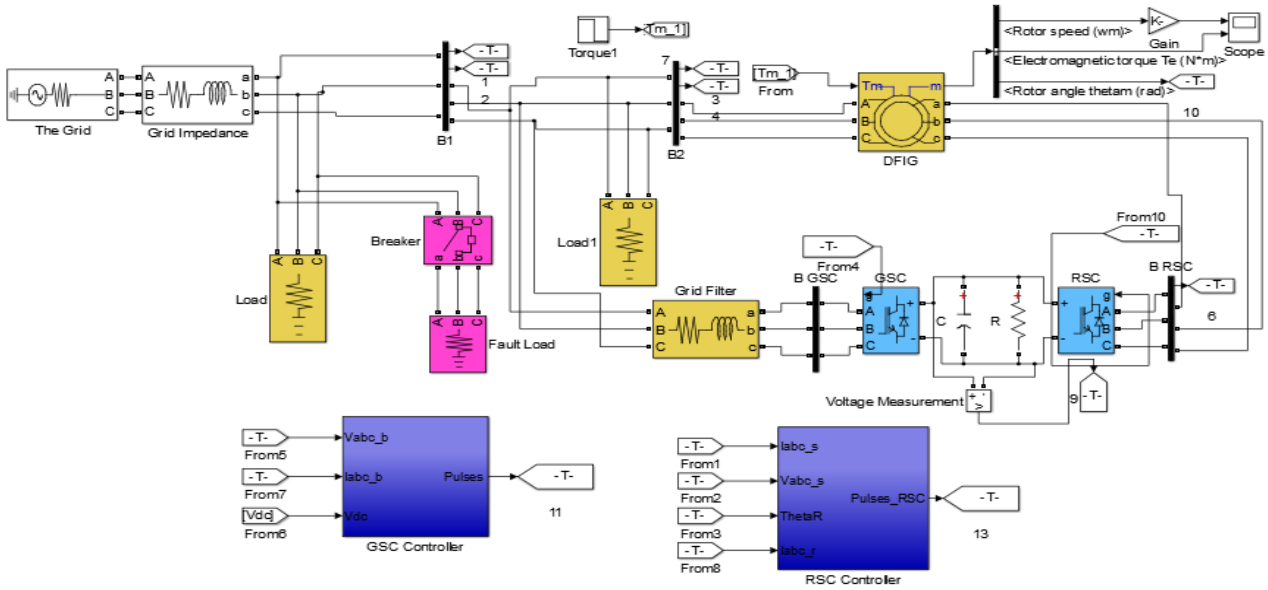

Fig.3 . DFIG System in Simulink

Active and reactive power flow in dq frame is given as follows,

$$P = 3(\nu_d i_d + \nu_q i_q) \\ Q = 3(\nu_d i_q + \nu_q i_d) \tag{4}$$

The angular position of the supply voltage vector is calculated as follows,

$$\theta_e = \int \omega_e \mathrm{d}t = \tan^{-1} \frac{\nu_\beta}{\nu\alpha} \tag{5}$$

Where v_α and v_β are the α, β (stationary 2-axis) stator voltage components.

Aligning the d-axis of the reference frame along the stator-voltage position results in the active and reactive powers to be proportional to d and q axis currents respectively.

$$\begin{aligned} E i_{os} &= 3\nu_d i_d \\ \nu_d &= \frac{m_1}{2\sqrt{2}} E \\ i_{os} &= \frac{3}{2\sqrt{2}} m_1 i_d \\ C\frac{\mathrm{d}E}{\mathrm{d}t} &= i_{os} - i_{or} \end{aligned} \tag{6}$$

The dc-link voltage can be controlled via i_q. The control scheme. The control scheme thus utilises current control loops for i_d and i_q, with the i_d demand being derived from the dc-link voltage error through a standard PI controller. The i_q demand determines the displacement factor on the supply-side of the inductors. The strategy is shown in Fig.3. From eqn 3, the plant for the current loops is given by,

$$F(s) = \frac{i_d(s)}{\nu'_d(s)} = \frac{i_q(s)}{\nu'_q(s)} = \frac{1}{Ls + R} \tag{7}$$

Where the reference voltages are given by,

$$\begin{aligned} \nu^*_{d1} &= -\nu'_d + (\omega_e L i_q + \nu_d) \\ \nu^*_{q1} &= -\nu'_q - (\omega_e L i_d) \end{aligned} \tag{8}$$

The current control loop is given in discrete form as follows,

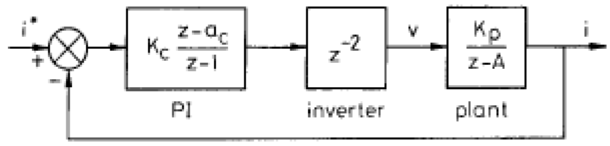

Fig.4. GSC Converter current loop

Where the plant is given as,

$$F(z) = \frac{(1-A)/R}{(z-A)} \qquad A = e^{-(R/L)T_s} \tag{9}$$

The dc link voltage controller is given in continuous domain as follows,

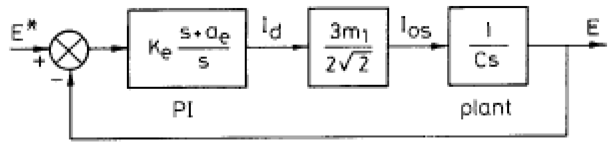

Fig.5. DC-Link voltage loop

Where the plant is given as,

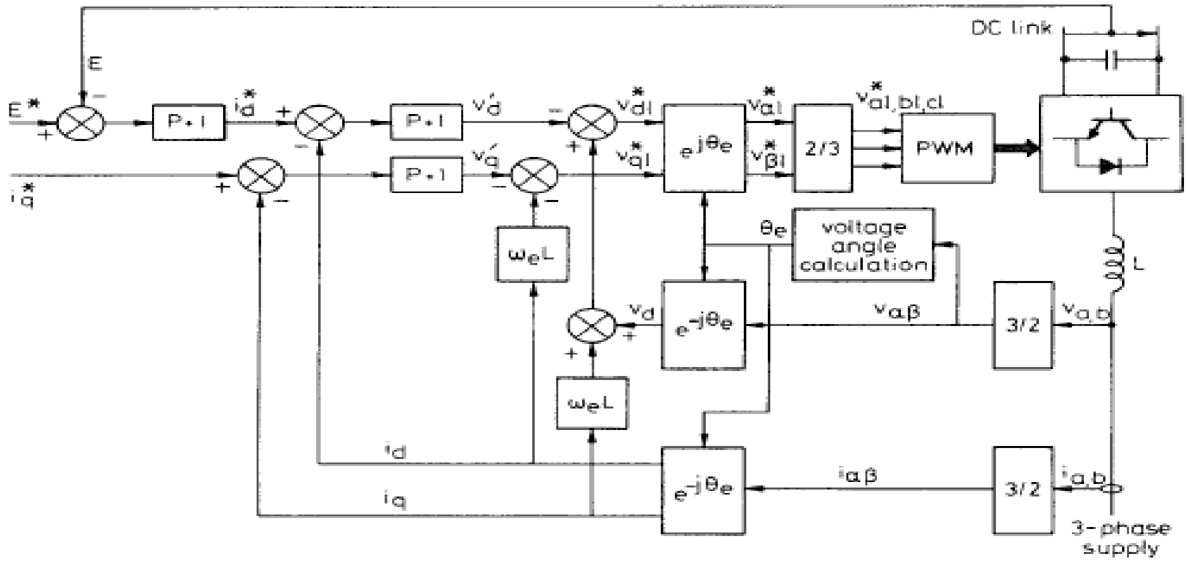

Fig.6. GSC Vector Control Scheme

$$\frac{E(s)}{i_d(s)} = \frac{3m_1}{2\sqrt{2}Cs} \tag{10}$$

IV. CONTROL OF ROTOR SIDE CONVERTER

The induction machine is controlled in a synchronously rotating dq axis frame, with the d-axis oriented along the stator-flux vector position. This gives rise to a decoupled control of the electrical torque and the rotor excitation current is obtained. The rotor-side PWM converter provides the actuation, and the control requires the measurement of the rotor and stator currents, stator voltage and the rotor position.

Under the stator-flux orientation, the relationship between torque and dq axes voltages, currents and fluxes can be written as;

$$\begin{aligned}
&\lambda_s = \lambda_{ds} = L_o i_{ms} = L_s i_{ds} + L_o i_{dr} \\
&\lambda_{dr} = \frac{L_o^2}{L_s} i_{ms} + \sigma L_r i_{dr} \\
&\lambda_{qr} = \sigma L_r i_{qr} \\
&i_{qs} = -\frac{L_o}{L_s} i_{qr} \\
&\nu_{dr} = R_r i_{dr} + \sigma L_r \frac{\mathrm{d}i_{dr}}{\mathrm{d}t} - \omega_{slip}\sigma L_r i_{qr} \\
&\nu_{qr} = R_r i_{qr} + \sigma L_r \frac{\mathrm{d}i_{qr}}{\mathrm{d}t} + \omega_{slip}(L_m i_{ms} + \sigma L_r i_{dr}) \\
&T_e = -3\frac{P}{2} L_m i_{ms} i_{qr} \\
&\omega_{slip} = \omega_e - \omega_r \\
&\sigma = 1 - \frac{L_o^2}{L_s L_r} \\
&L_m = \frac{L_o^2}{L_s}
\end{aligned} \tag{11}$$

The stator flux angle is calculated from,

$$\begin{aligned}
\lambda_{\alpha s} &= \int (v_{\alpha s} - R_s i_{\alpha s})\mathrm{d}t \\
\lambda_{\beta s} &= \int (v_{\beta s} - R_s i_{\beta s})\mathrm{d}t \\
\theta_s &= \tan^{-1}\frac{\lambda_{\beta s}}{\lambda_{\alpha s}}
\end{aligned} \tag{12}$$

Where the above angle gives the position of the stator-flux position. The torque is proportional to i_{qr} and can be regulated using v_{qr}. The rotor excitation current i_{dr} is controlled using v_{dr}. Assuming that all reactive power to the machine is supplied by the stator, the reference i_{dr} may set to zero.

The figure shows the schematic of the RSC control. The q-axis rotor current can be obtained either from a outer speed control loop or from a reference torque imposed on the machine. These two options may be termed as speed-control mode or torque-control mode for the generator.

An analysis of the rotor circuit similar to that done for the grid-side converter results in the following voltage equations,

$$\begin{aligned}
\nu'_{dr} &= R_r i_{dr} + \sigma L_r \frac{\mathrm{d}i_{dr}}{\mathrm{d}t} \\
\nu'_{qr} &= R_r i_{qr} + \sigma L_r \frac{\mathrm{d}i_{qr}}{\mathrm{d}t}
\end{aligned} \tag{13}$$

The i_{dr} and i_{qr} errors are processed by the PI controller to give v_{dr} and v_{qr} to obtain the following reference voltages,

$$\begin{aligned}
\nu^*_{dr} &= \nu'_{dr} - \omega_{slip}\sigma L_r I_{qr} \\
\nu^*_{qr} &= \nu'_{qr} + \omega_{slip}(L_m i_{ms} + \sigma L_r i_{dr})
\end{aligned} \tag{14}$$

Which are analogous to eqn. 8. Of the GSC

The plant for the current-control design is similar to the case of the supply-side converter current controller with the following variable substitutions,

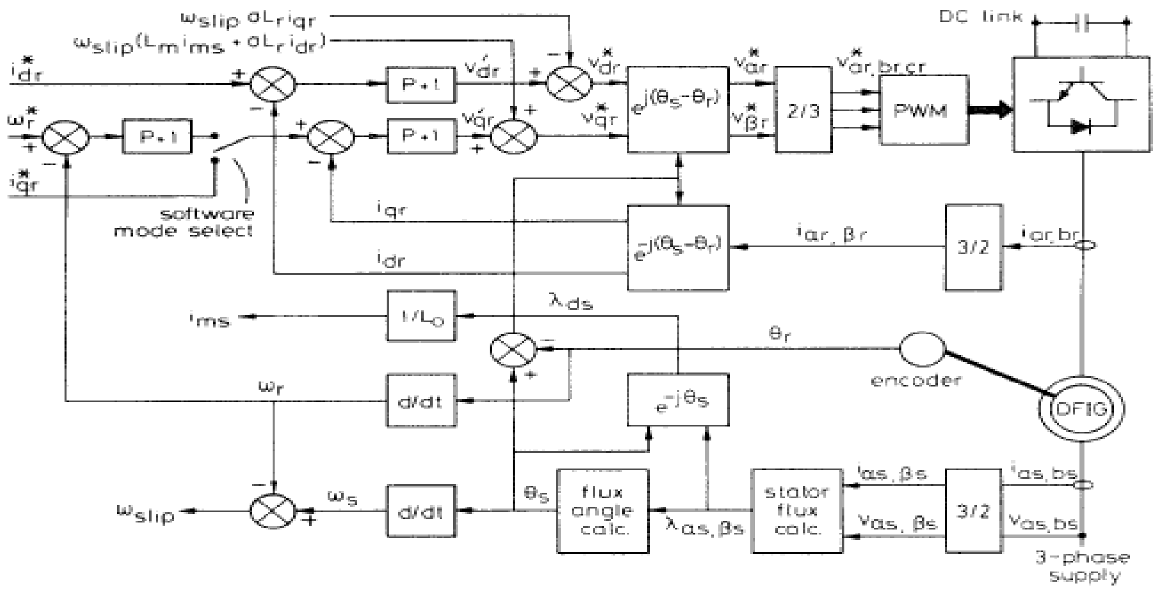

Fig.7. RSC Vector Control Scheme

$$i_d, i_q \to i_{dr}, i_{qr}$$
$$\nu'_d, \nu'_q \to \nu'_{dr}, \nu'_{qr}$$
$$R \to R_r$$
$$L \to \sigma L_r$$
$$K_c \to K_i$$
$$a_c \to a_i$$

A speed controller is required for machine operation in the speed-control mode. The design of the speed controllers done in the continuous domain, in a similar way to that of the GSC. The current controllers should faster than the speed controllers for ideal operation of the system. The variable substitutions made here are,

$$E \to \omega_r$$
$$i_d \to i_{qr}$$
$$\frac{3m_1}{2\sqrt{2}} \to \frac{-3p}{2} L_m i_{ms}$$
$$i_{os} \to T_e$$
$$\frac{1}{Cs} \to \frac{1}{Js + B}$$
$$K_e \to K_\omega$$
$$a_e \to a_\omega$$

The controllers have to be tuned properly to get the desired result.

V. RESULTS

A. Calculation of PI Controller Gains

PI controllers for both GSC and RSC were tuned in MATLAB, following are the results;

For GSC current controller; P= 8.37 , I= 0.0516

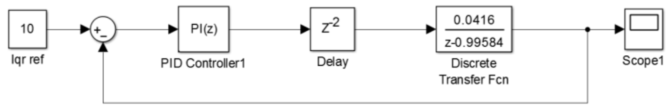

Fig.8. GSC Current Loop Controller in Simulink

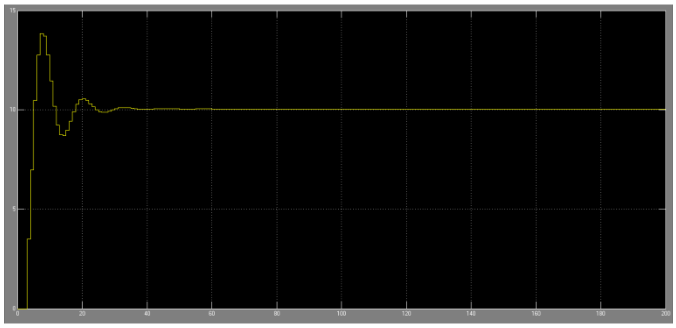

Fig.9. GSC Current Loop Controller in Simulink

For GSC outer loop DC voltage link controller; P= 0.0280 , I= 0.0618

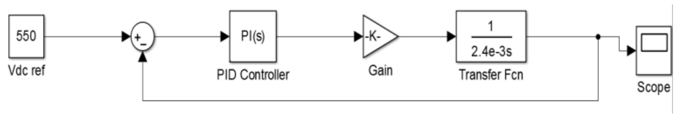

Fig.10. GSC Outer Vdc Loop Controller in Simulink

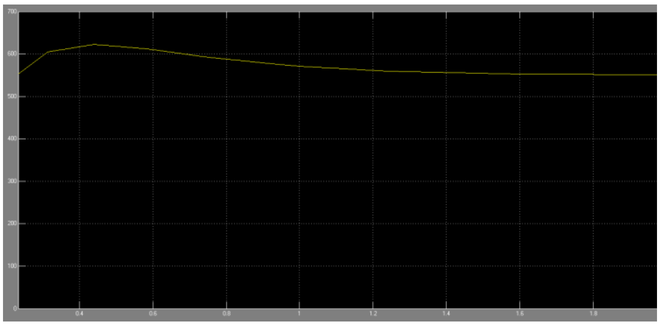

Fig.11. GSC Outer Vdc Loop Controller Graph

For RSC current controller; P= 8.37, I= 0.0658

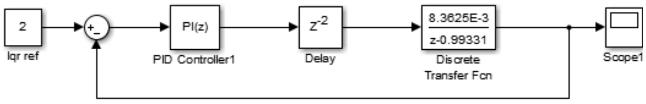

Fig.12. RSCCurrent Loop Controller in Simulink

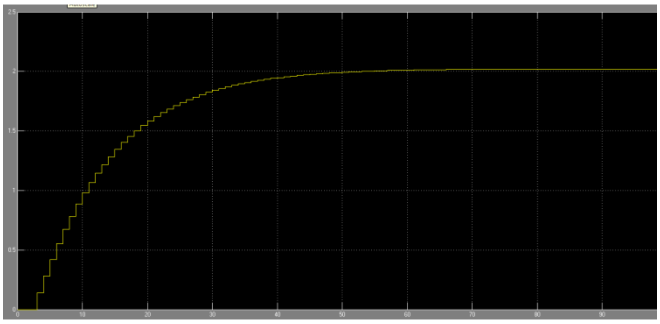

Fig.13. RSC Current Loop Controller Graph

For RSC outer loop speed controller; P= 35.08, I= 33.14

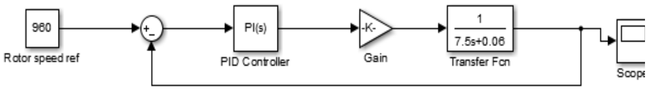

Fig.14. RSC Outer speed Loop Controller in Simulink

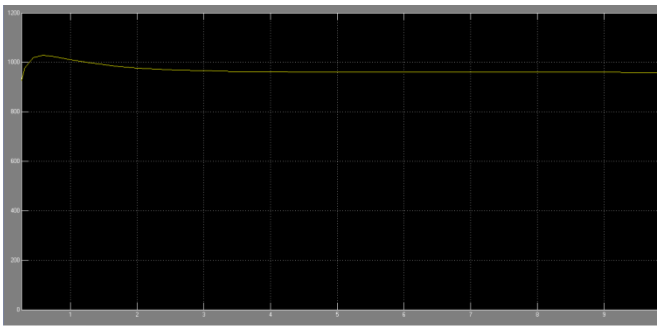

Fig.15. RSC Outer Speed Current Loop Controller Graph

The GSC Vector-Control Scheme in Simulink,

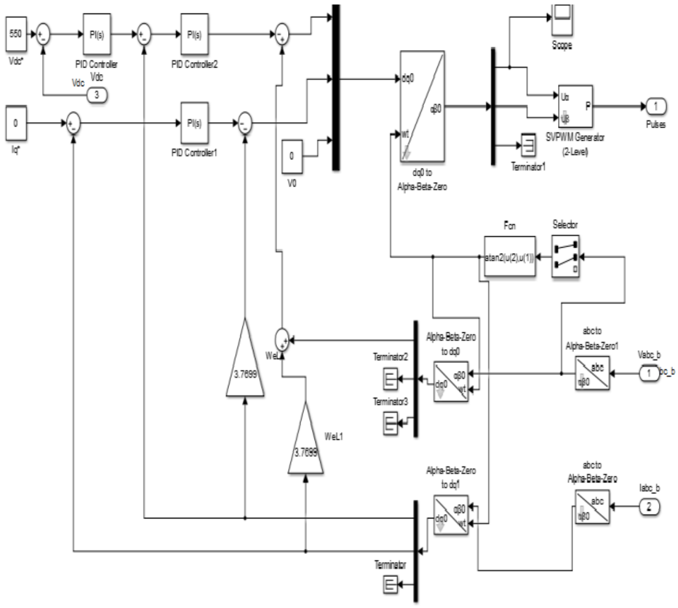

Fig.16. GSC Vector Control Scheme implemented in Simulink

The RSC Vector-Control Scheme in Simulink,

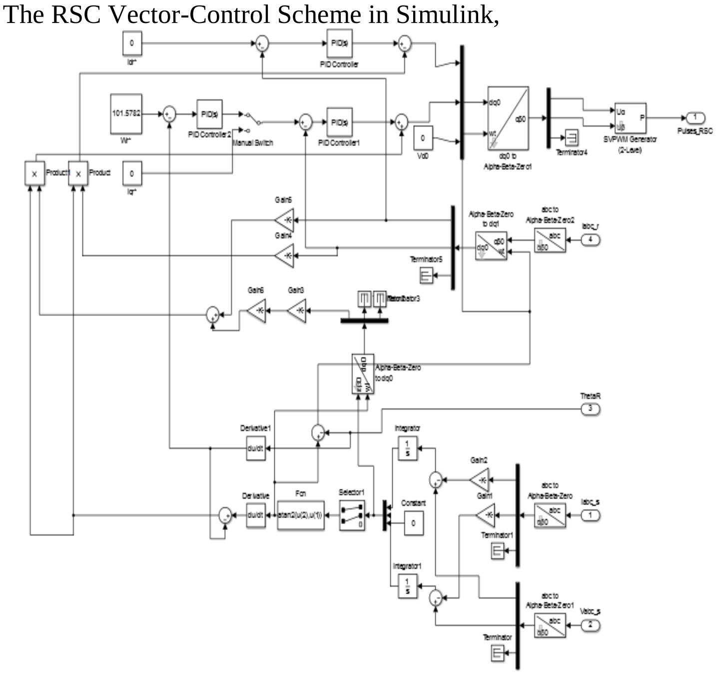

Fig.17. RSC Vector Control Scheme implemented in Simulink

Further results could not be verified due to a unsolvable algebraic loop face in the control structure during initilizaion in Simulink.

VI. CONCLUSION

A DFIG with a back-to-back voltage-fed current regulated SVPWM/PWM inverters is athe best possible wind energy generation system available. Moreover, with the vector control strategy the DFIG could be made to act like a conventional power plant with reduced uncertainties and a good grid connected behavior.Vector control gives a decoupled control over the electrical trque, rotor speed, active and reactive power supplied and absorbed by the DFIG. For more optimized performance better vector control strategies should be developed

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APPENDICES

Model information;

Inertia = 7.5Kgm^2
Gear box = 5.065
Friction coefficient = 0.06Nmsrad^{-1}

Wound rotor induction machine:

Power = 7.5kW
Stator voltage = 415V
Rotor voltage = 440V
Rated stator current = 19A
Rated rotor current = 11A
$R_s = 1.06\Omega$
$R_r = 0.80\Omega$
$L_s = 0.2065$H
$L_o = 0.0664$H (referred to the rotor)
$L_r = 0.0810$H (referred to the rotor)
$L_{ext} = 0.0320$H (referred to the rotor)
Pole pairs = 3
Rated speed = 970rpm
Stator-rotor turns ratio n = 1.7
Stator connection = delta
Rotor connection = star