Design and Control of the Brushless Doubly Fed Twin Induction Generator (BDFTIG)

A. Bensadeq, P. W. Lefley

Department of Electrical Engineering
Leicester University, University Road, Leicester LE1 7RH (United Kingdom)
Phone:+44 116 252 2559, fax:+44 116 252 2619, e-mail: ab320@leicester.ac.uk, pw13@leicester.ac.uk

1. Brief introduction

A Doubly Fed Induction Generator (DFIG) has a significant advantage in high power, variable speed generator applications, because independent control of active and reactive power can be achieved by using a power electronic converter connected to the rotor circuit, and it handles only a fraction of the total power [1].The main disadvantage of the DFIG is the slip rings, which reduce the life time of the machine and increases the maintenance costs. An alternative to overcome this drawback an alternative machine arrangement is proposed which is the Brushless Doubly Fed Induction Generator (BDFIG). Brass at al. published a direct torque control algorithm in Simulink for the BDFIG. This is believed to be the first control algorithm proposed for the BDFIG [2]. The BDFIG has been considered as a variable speed drive [3, 4]. The increase in the use of BDFIG has been driven by the need to expand the range and operation of wind turbines. A study has been successively conducted on the implementation and control of the BDFIG [5,6], but the BDFIG efficiency is worse than the DFIG at low speeds by 7% [7]. To combine the advantage of the DFIG with the advantage of a brushless machine, the Brushless Doubly Fed Twin Induction Generator (BDFTIG) is being investigated and considered for high power wind generators where variable-speed operation, high reliability and low maintenance are required. A number of studies have been conducted on the performance modelling of the BDFTIG; the results have been presented in simulation results only [8]. The aim of this research is to present a new brushless technique for the indirect vector control of a BDFTIG. This method is suitable for both stand-alone and grid-connected variable speed BDFTIGs. This paper presents the analysis and the simulated results using Simulink (in MATLAB) for control of the grid connected operation, where the power flow is controlled into the grid.

Key words: Wind power generator, doubly fed induction generator, machine simulation, and field-oriented vector control.

2 Equivalent Circuit Analysis of the BDFTIG

The BDFTIG consist of two separate wound rotor induction machines; the power and the control machines are connected mechanically and electrically see figure 1. The overall control of the twin machine is via the stator winding of the control machine, which can modify and control the rotor current, which is also being induced from the power machine stator winding. Therefore there is an electromagnetic cross-coupling effect between the two stator windings through the rotor. An appropriate BDFTIG model and flexible power flow control strategy for wind energy conversion is developed in the following sections.

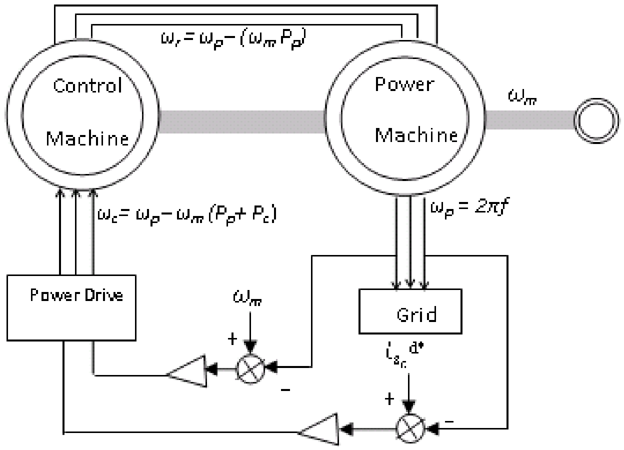

Fig 1- The BDFTIG Construction

Figure 2 shows the equivalent circuit of the BDFTIG from which the electrical system equations can be derived. As long as the equations are known, any control algorithm can be modelled in Simulink. From these equations the flux of the power and control machines can be derived.

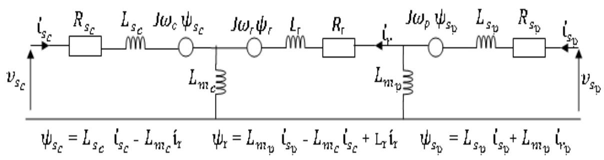

Fig 2- The equivalent circuit of the BDFTIG

To simplify the controller algorithm, the machine quantities should be expressed in the d-q frame by employing Park's transformation. Then starting with the power machine, the general form of the vector equations of the BDFTIG can be written as:

$$v_{s_p} = R_{s_p} i_{s_p} + L_{s_p} \frac{di_{s_p}}{dt} + j\omega_p L_{s_p} i_{s_p} + L_{m_p} \frac{di_{r_p}}{dt} + j\,\omega_p L_{m_p} i_{r_p}$$
$$v_{s_p} = R_{s_p} i_{s_p} + (L_{s_p} i_{s_p} + L_{m_p} i_{r_p})(s + j\,\omega_p)$$

The flux linkage current relations are:

$$\psi_{s_p} = L_{s_p} i_{s_p} + L_{m_p} i_{r_p}$$
$$\therefore v_{s_p} = R_{s_p} i_{s_p} + \frac{d\psi_{sp}}{dt} + j\,\omega_p \psi_{s_p} \qquad (1)$$

For the control machine:

$$v_{s_c} = R_{s_c} i_{s_c} + L_{s_c} \frac{di_{s_c}}{dt} + j\,\omega_c L_{s_c} i_{s_c} - L_{m_c} \frac{di_{r_c}}{dt} - j\,\omega_c L_{s_c} i_{s_c}$$

$v_{s_c} = R_{s_c}\ i_{s_c} + (L_{s_c}\, i_{s_c} - L_{m_c}\, i_{r_c})\ (s + j\,\omega_c)$

The flux linkage current relations are:

$$\psi_{s_c} = L_{s_c}\, i_{s_c} - L_{m_c}\, i_{r_c}$$
$$\therefore v_{s_c} = R_{s_c}\ i_{s_c} + \frac{d\psi_{s_c}}{dt} + j\,\omega_c\, \psi_{s_c} \qquad (2)$$

$$v_{r_p} = R_{r_p}\ i_{r_p} + L_{r_p}\frac{d i_{r_p}}{dt} + j\,\omega_r\, L_{r_p}\, i_{r_p} + L_{m_p}\frac{d i_{s_p}}{dt} + j\omega_r\, L_{m_p}\, i_{s_p}$$
$$v_{r_c} = R_{r_c}\ i_{r_c} + L_{r_c}\frac{d i_{r_c}}{dt} + j\,\omega_r\, L_{r_c}\ i_{r_c} + L_{m_c}\frac{d i_{s_c}}{dt} + j\omega_r\, L_{m_c}\, i_{s_c}$$

The rotors are mechanically connected and their windings are electrically interconnected so the rotors currents are in the opposite direction.

$$i_{r_p} = -\, i_{r_c} = i_r \qquad v_{r_p} = v_{r_c} \quad \therefore\ 0 = v_{r_p} - v_{r_c}$$
$$0 = R_{r_p}\, i_{r_p} + L_{r_p}\frac{d i_{rp}}{dt} + j\omega_r L_{r_p}\, i_{r_p} + L_{m_p}\frac{d i_{sp}}{dt} + j\,\omega_r L_{m_p}\, i_{s_p} -$$
$$[-(R_{rc}\, i_{r_p} + L_{r_c}\frac{d i_{rp}}{dt} + j\,\omega_r L_{r_c}\, i_{r_p}) + (L_{m_c}\frac{d i_{s_c}}{dt} + j\,\omega_r L_{m_c}\, i_{s_c})]$$
$$0 = (R_{r_p} + R_{r_c})\ i_{r_p} + (L_{r_p}\ i_{r_p} + L_{r_c}\, i_{r_p})(s + j\,\omega_r) + L_{m_p}\ i_{s_p}\ (s + j\,\omega_r) - (L_{m_c}\, i_{s_c})(s + j\,\omega_r)$$

Assume $L_r = L_{r_p} + L_{r_c}$ and $R_r = R_{r_p} + R_{r_c}$

$$\therefore 0 = R_r\, i_r + (L_r\, i_r + L_{m_p}\ i_{s_p} - L_{m_c}\, i_{s_c})\,(s + j\,\omega_r)$$

The flux linkage current relations are

$$\psi_r = L_r\, i_r + L_{m_p}\ i_{s_p} - L_{m_c}\, i_{s_c} \qquad (3)$$
$$\therefore 0 = R_r\, i_r + \frac{d\psi_r}{dt} + j\,\omega_r\, \psi_r$$

Rearranging the power machine stator flux and the rotor flux equations to obtain the power machine and rotor currents.

$$\because \psi_{s_p} = L_{s_p}\, i_{s_p} + L_{m_p}\, i_{r_p} \qquad \therefore i_{s_p} = \frac{\psi_{sp} - L_{m_p}\ i_r}{L_{sp}}$$
$$\because \psi_r = L_r\, i_r + \boldsymbol{L_{m_p}}\, i_{s_p} - \boldsymbol{L_{m_c}}\, i_{s_c} \qquad \therefore i_r = \frac{\boldsymbol{\psi_r - L_{m_p}\, i_{sp} + L_{m_c}\, i_{sc}}}{\boldsymbol{L_r}}$$

The equation for the rotor current, i_r; is substituted into the equation for the power machine stator current i_{s_p}:

$$i_{s_p} = \frac{L_r\,\psi_{s_p}}{L_{sp}\ L_r - L^2{}_{m_p}} - \frac{L_{m_p}\,\psi_r}{L_{sp}\ L_r - L^2{}_{m_p}} - \frac{L_{m_p}\, L_{m_c}\, i_{s_c}}{L_{s_p}\ L_r - L^2{}_{m_p}}$$

Because the reference frame is aligned with the d-component of ψ_{s_p}, the q-component always remains at zero.

$$i_{s_p}{}^{d} = \frac{L_r\,\psi_{sp}\,d}{L_{sp}\ L_r - L^2{}_{m_p}} - \frac{L_{m_p}\,\psi_r\, d}{L_{sp}\ L_r - L^2{}_{m_p}} - \frac{L_{m_p}\, L_{m_c}\, i_{s_c} d}{L_{sp}\ L_r - L^2{}_{m_p}}$$
$$i_{s_p}{}^{q} = -\frac{L_{m_p}}{L_{sp}\ L_r - L^2{}_{m_p}}\,\psi_r{}^{q} - \frac{L_{m_p}\, L_{m_c}}{L_{sp}\ L_r - L^2{}_{m_p}}\ i_{s_c}{}^{q}$$

Rearranging the last two equations will give the value of the rotor flux $\psi_r{}^{q}$ & $\psi_r{}^{d}$:

$$\psi_r{}^{d} = L_{m_p}\, i_{s_p}{}^{d} - \frac{L_{sp}\ L_r\ \boldsymbol{i_{sp}} d}{L_{m_p}} + \frac{L_r\,\psi_{sp}}{L_{m_p}} - L_{m_c}\ i_{s_c}{}^{d} \qquad (4)$$

$$\psi_r{}^{q} = L_{m_p}\ i_{s_p}{}^{q} - \frac{L_{sp}\ L_r\ \boldsymbol{i_{sp}} q}{L_{m_p}} - L_{m_c}\ i_{s_c}{}^{q} \qquad (5)$$

Eliminating i_r in the equation for the control machine stator flux ψ_{s_c} and using the rotor current equation and transformed into d-q frame:

$$\psi_{s_c}{}^{d} = L_{s_c} i_{s_c}{}^{d} - \frac{L_{m_c}\ \psi_r^{d}}{Lr} + \frac{L_{m_c}\, L_{m_p}\ i_{sp}\, d}{Lr} - \frac{L^2_{m_c} i_{sc}\, d}{Lr}$$
$$\psi_{s_c}{}^{q} = L_{s_c}\ i_{s_c}{}^{q} - \frac{L_{m_c}\ \psi_r^{q}}{Lr} + \frac{L_{m_c}\, L_{m_p}\ i_{sp}\, q}{Lr} - \frac{L^2_{m_c} i_{sc}\, q}{Lr}$$

Rearranging the control machine stator flux equations to obtain the control machine stator currents:

$$i_{s_c}{}^{d} = \frac{\psi_{s_c} d\ \ Lr + L_{m_c}\psi_r^{d} - L_{m_c}\ L_{m_p}\, i_{s_p} d}{(Lr\ L_{s_c} - L^2{}_{m_c})}$$
$$i_{s_c}{}^{q} = \frac{\psi_{s_c} q\ \ Lr + L_{m_c}\psi_r^{q} - L_{m_c}\ L_{m_p}\, i_{s_p} q}{(Lr\ L_{s_c} - L^2{}_{m_c})}$$

The active and reactive power flow equations for the power machine are:

$$P_p = \frac{3}{2}\,(v_{s_p}{}^{q}\ i_{s_p}{}^{q} + v_{s_p}{}^{d}\ i_{s_p}{}^{d})$$
$$Q_p = \frac{3}{2}\,(v_{s_p}{}^{q}\ i_{s_p}{}^{d} - v_{s_p}{}^{d}\ i_{s_p}{}^{q})$$

If the power machine winding resistance is neglected, the flux vector is perpendicular to the voltage vector. Consequently, the reactive power (Q_p), is controlled by d-axis current of the power machine ($i_{s_p}{}^{d}$), and the active power (P_p), is dominated by the q-axis current of power machine ($i_{s_p}{}^{q}$).

$$P_p = \frac{3}{2}\,(v_{s_p}{}^{q}\ i_{s_p}{}^{q}) \quad \& \quad Q_p = \frac{3}{2}\,(v_{s_p}{}^{q}\ i_{s_p}{}^{d})$$

Then substitute the current of the power machine $i_{s_p}{}^{q}$ equation into machine reactive power Q_p:

$$Q_p = \frac{-3}{2}\, v_{s_p}{}^{q}\Big[\frac{L_r\,\psi_{sp}\, d}{L_{sp}\ L_r - L^2{}_{m_p}} - \frac{L_{m_p}\,\psi_r\, d}{L_{sp}\ L_r - L^2{}_{m_p}} - \frac{L_{m_p}\, L_{m_c}\, i_{sc}\, d}{L_{sp}\ L_r - L^2{}_{m_p}}\Big]$$

The $i_{s_c}{}^{d}$ reference signal can be obtain directly from the last equation:

$$i_{s_c}{}^{d} = \Big[\frac{-2\, L_{sp}\ L_r - L^2{}_{m_p}}{3\, v_{sp}\, q\, L_{m_p}\ L_{m_c}} + \frac{L_r\,\psi_{sp}\, d}{L_{m_p}\ L_{m_c}\mathrm{Qp}} - \frac{L_{m_p}\,\psi_r\,\mathrm{d}}{L_{m_p}\ L_{m_c}\mathrm{Qp}}\Big]\frac{1}{Qp} \qquad (6)$$

$$\because\ \omega_c = \omega_p - \omega_m(p_p + p_c) \qquad \therefore\ \omega_p = \omega_c + \omega_m(p_p + p_c)$$

and $\omega_p = 2\pi f$ $\quad \therefore\ f = \dfrac{\boldsymbol{\omega_c + \omega_m(p_p + p_c)}}{\boldsymbol{2\Pi}}$ (7)

The total electric torque (T_e) for BDFTIG is the sum of both machines:

$$T_e = \frac{-3}{4}\big[P_p(\psi_{s_p}{}^{q}\, i_{s_p}{}^{d} - \psi_{s_p}{}^{d}\, i_{s_p}{}^{q}) + P_c\, L_{m_c}(i_{s_c}{}^{d}\, i_r{}^{q} - i_{s_c}{}^{q}\, i_r{}^{d})$$

The electric torque equation is defined by the friction and total inertia of the power and control machines:

$$T_e = T_L + (B_F{}^{P} + B_F{}^{c})\,\omega_m + (j_s{}^{p} + j_s{}^{c})\,\frac{\mathrm{d}\omega_m}{\mathrm{dt}} \qquad (8)$$

The shaft speed $\omega_m = \int \Big[\dfrac{T_e - T_L - \omega_m (B_F^{p} + B_F^{c})}{(j_s^{p} + j_s^{c})}\Big]dt$ (9)

3 The Control Design

When connected to the grid, the output voltage and frequency of the generator machine will be fixed. Therefore the indirect vector control scheme will control the power flow through the power machine (reactive power, Q_p and active power P_p) at any given operational condition of the wind turbine. The P_p and Q_p of the power machine stator can be controlled via the rotor circuit from the control machine stator by adjusting the phase, and magnitude of the stator current of the control machine. The P_p and Q_p are proportional to the $i_{s_c}{}^{q}$ and $i_{s_c}{}^{d}$, respectively. As shown in the control design, there are three control loops with PI controllers; a rotor speed loop and two currents loops. The q-component magnitude of the stator current of the control machine is derived from mechanical speed error. Speed control is also required for machine synchronisation to the grid upon start up [9].

The d-component magnitude of the stator current of the control machine is derived from equation (8).

The $i_{s_c}{}^{d}$ and $i_{s_c}{}^{q}$ errors are processed by PI current controllers to give the voltage of the control machine $v_{s_c}{}^{q}$ and $v_{s_c}{}^{d}$ respectively. The voltage compensation $v_{s_c}{}^{d'}$ and $v_{s_c}{}^{q'}$ are subtracted from the control machine voltages $v_{s_c}{}^{q}$ and $v_{s_c}{}^{d}$ to obtain reference voltage $v_{s_c}{}^{d*}$ and $v_{s_c}{}^{q*}$ respectively. The voltage compensation $v_{s_c}{}^{d'}$ and $v_{s_c}{}^{q'}$ are used to ensure good tracking of control machine stator current components and improves the performance of the d-q control loop, subtract $v_{s_c}{}^{d'}$ and $v_{s_c}{}^{q'}$ from $v_{s_c}{}^{d}$ and $v_{s_c}{}^{q}$ voltage to obtain voltage references $v_{s_c}{}^{d*}$ and $v_{s_c}{}^{q*}$ respectively [9].

$$v_{s_c}{}^{d'}=\frac{\omega c\, L_{m_c} L_{sp}\, \psi_r^q}{(Lr\, L_{sp}-L^2{}_{mp})}+\frac{\omega c\, L^2{}_{m_c}\, L_{sp} i_{s_c} q}{(Lr\, L_{sp}-L^2{}_{mp})}-\frac{\omega c\, L_r\, L_{sp}\, L_{s_c}\, i_{s_c} q}{(LrL_{sp}-L^2{}_{mp})}+\frac{\omega c\, L_{s_c} L^2{}_{mp}\, i_{s_c} q}{(Lr\, L_{sp}-L^2{}_{mp})}$$

$$v_{s_c}{}^{q'}=\frac{\omega c\, L_{m_c} L_{mp} \psi_{sp} d}{\left(L_r L_{sp}-L^2{}_{mp}\right)}-\frac{\omega c\, L_{m_c}\, L_{sp} \psi_r^d}{\left(L_r L_{sp}-L^2{}_{mp}\right)}+\frac{\omega c\, L_r\, L_{s_c}\, L_{sp}\, i_{s_c} d}{\left(L_r L_{sp}-L^2{}_{mp}\right)}-\frac{\omega c\, L^2{}_{mp} L_{s_c} i_{s_c} d}{(LrL_{sp}-L^2{}_{mp})}-\frac{\omega c\, L^2{}_{m_c} L_{sp} i_{s_c} d}{(LrL_{sp}-L^2{}_{mp})} \quad (10,11)$$

The reference voltage $v_{s_c}{}^{d*}$ and $v_{s_c}{}^{q*}$ are transformed to the α-β reference frame and later into three phase voltage reference frame. The shaft speed feedback to speed control is derived from equation (9).

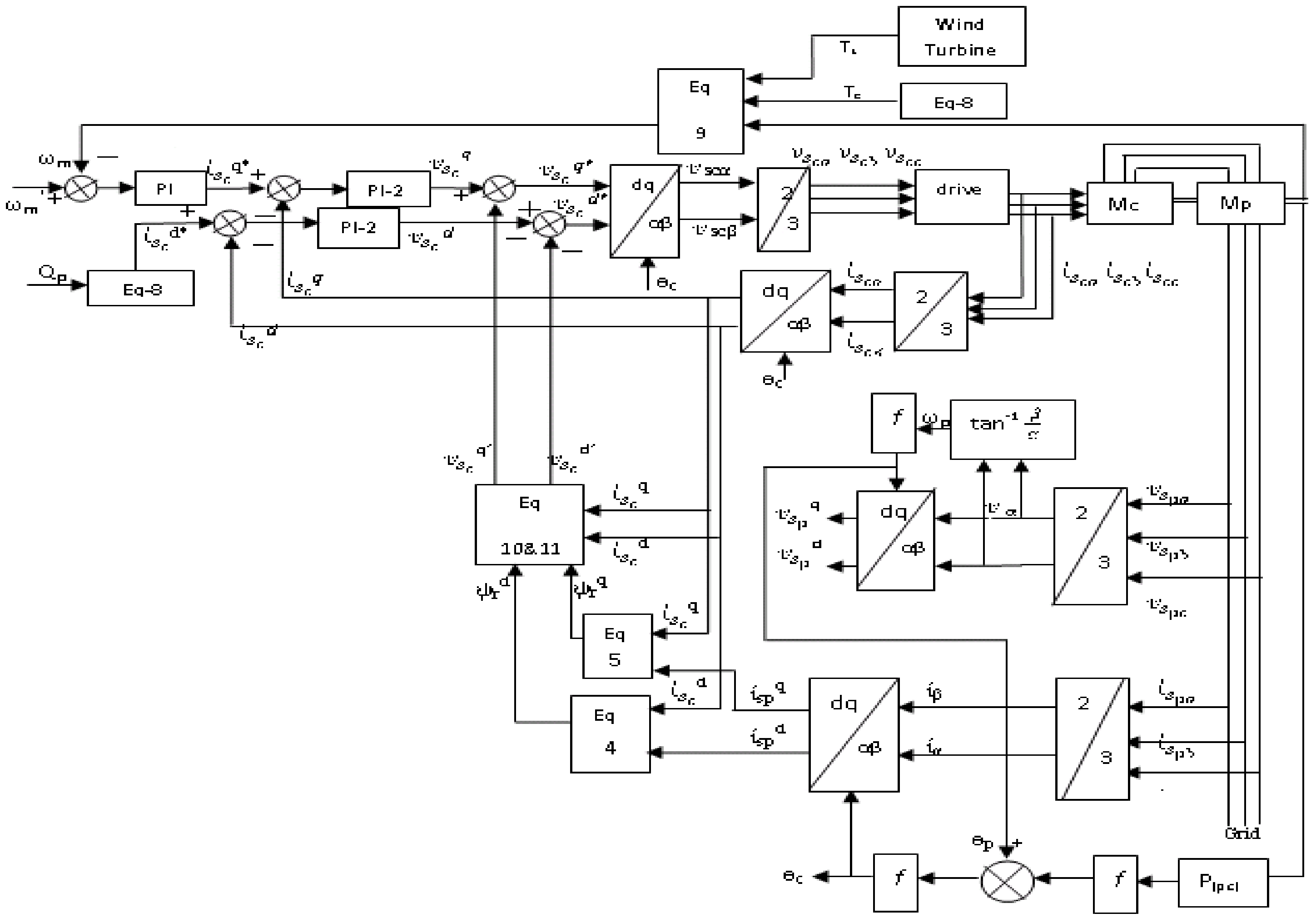

Fig 3- The Control System for a Grid Connected BDFTIG

4 Simulations Results

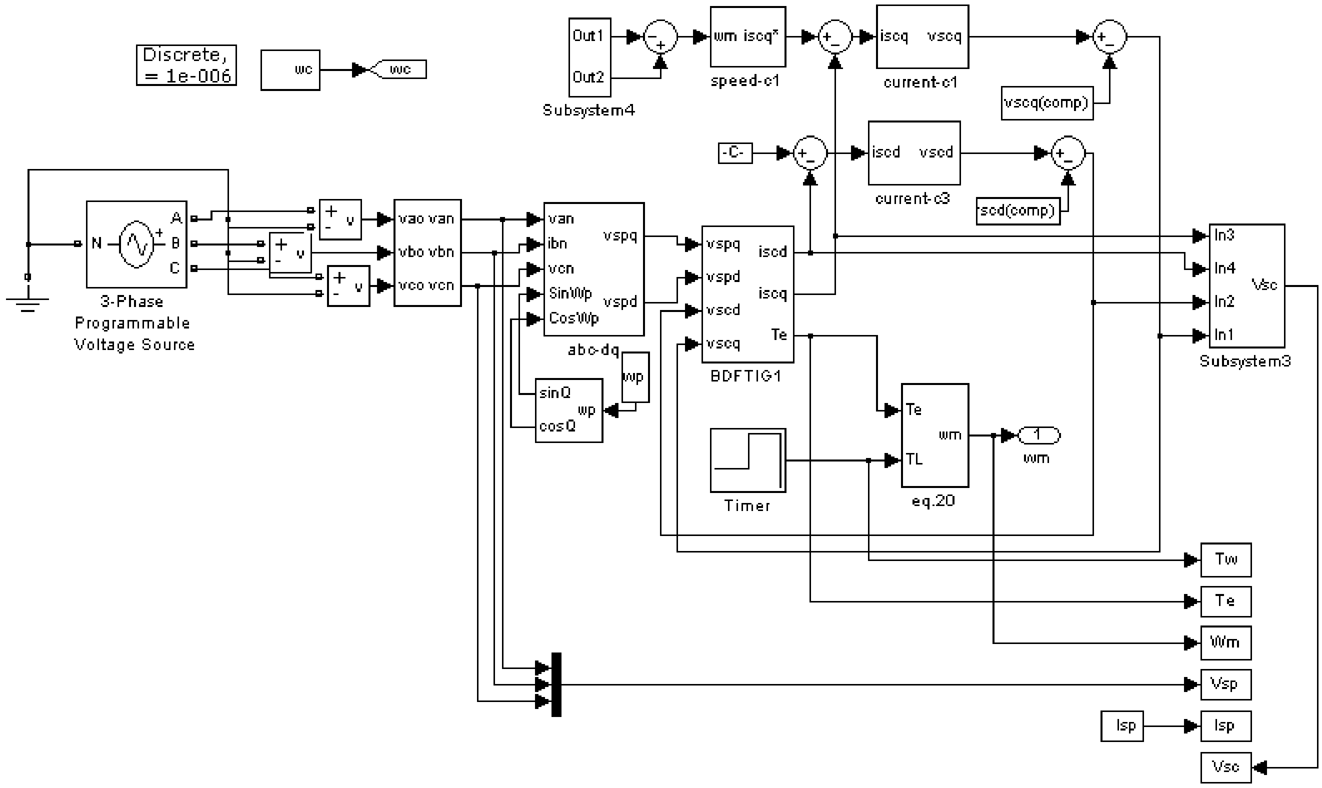

Fig 4- The Block Diagram of BDFTIG Simulation in MATLAB/Simulink

The BDFTIG system has been modelled using Matlab Simulink package as shown in Fig 4, the simulation results of indirect vector control are shown below.

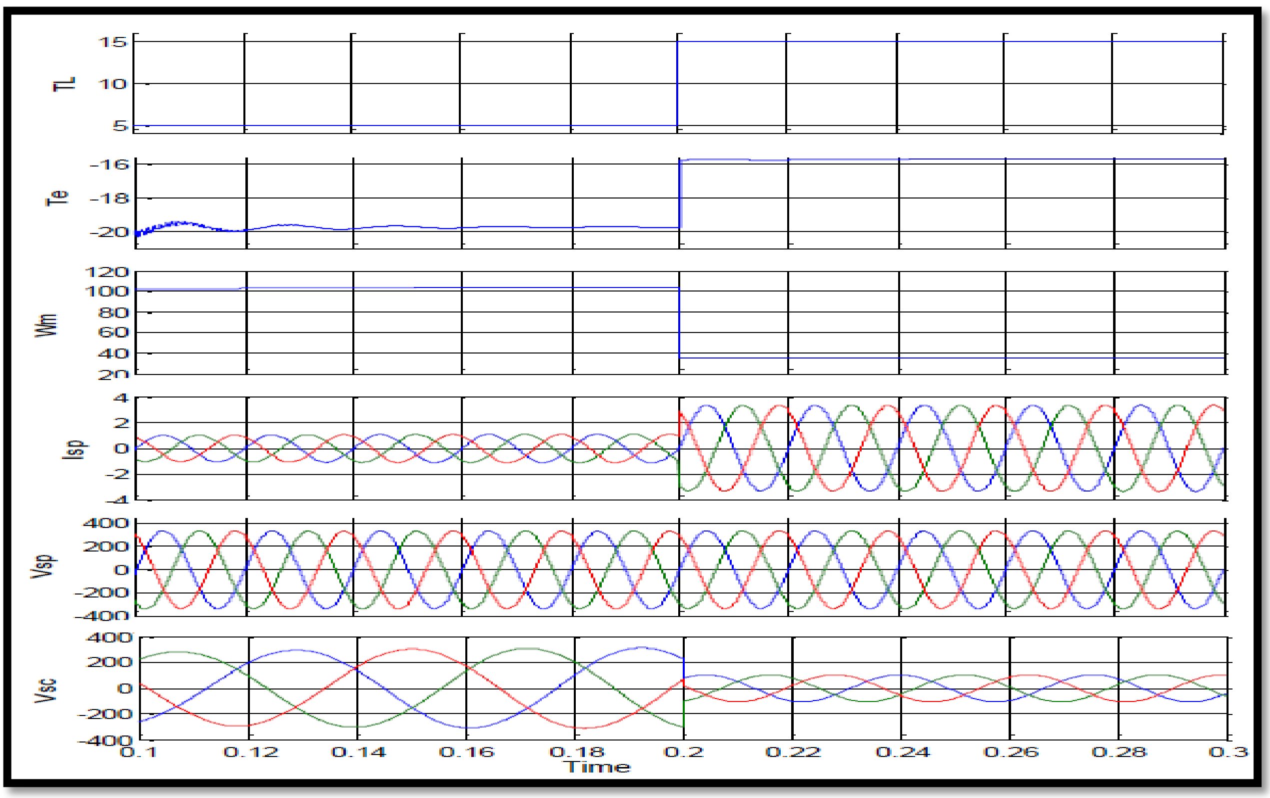

Fig 5- The Simulink Results: Torque Load, Electrical Torque, Mechanical Speed, O/P Current, O/P Voltage and Control Voltage

As appear in the results the indirect vector control scheme will control the power flow through the power machine (reactive power and active power), at any given operational condition of the wind turbine. Further, with the de-coupled control scheme. The speed is adjusted by the turbine pitch control to maximize the power generated. The machine representatives are based on the motor convention; consequently in the generator mode of operation, such as electrical torque is negative.

5 Conclusions

In this paper, a new control scheme has been presented for the BDFTIG which controls the power flow to the grid based on the direct control of the stator voltage of the control machine using a *d-q* model in the synchronous reference frame. A theoretical model and anexperimental control system have been described using field orientated control, and the fundamental operational advantages have been verified as shown. The MATLAB/ Simulink modelling package was used, to simulate the control scheme for the BDFTIG.

6 References

[1] R. Pena, J. Clare, and G. Asher, "*Doubly fed induction generator using back-to-back PWM converters and its applications to variable speed wind-energy generation*", Electrical Engineering, 1996, pp. 231-241.

[2[W. Brass, R. Spée, and T. Habetler. "*Direct torque control for brushless doubly-fed machines*". Applications Society Annual Meeting, *1992* pages 615.622. IEEE, Houston, TX, USA.

[3] N. Chilakapati, V. Ramsden, V. Ramaswamy, and J. Zhu, "*Comparison of Closed-loop Speed Control Schemes for a Doubly Fed Twin Stator Induction Motor Drive*", Proc. International Power Electronics and Motion Control Conference *(IPEMC), 2000*, pp.786-791.

[4] N. Chilakapati, V. Ramsden, V. Ramaswamy, and J. Zhu, "*Investigation of Doubly Fed Twin Stator Induction Motor as a Variable Speed Drive*", Proc. International Conference on Power Electronics Drives and Energy Systems for Industrial Growth, 1998, pp.160-165.

[5] N. Chayawatto, E. Ortohann and S. Condition, "*Dynamic Behaviour of a Doubly Fed Induction Machine with Generator-side Converter under Abnormal Condition*", Sustainable Energy and Environment, 2004.

[6] G. Iwanski and W. Koczara, "*Sensorless direct voltage control of the stand-alone slip-ring induction generator*," IEEE Trans. Ind. Electron, 2007, pp. 1237–1239.

[7] R. Carlson, H. Voltolini, F. Runcos, N. Sadowski and P. Kuo-Peng, "*A Performance Comparison between Brush and Brushless Doubly Fed Asynchronous Generators for Wind Power System*", Proc. IEEE Industry Applications Conference, pp. 2395-2402.

[8] F. Runcos, R. Carlson, A. Oliveira, P. Kuo-Pen, N. Sadowski, "*Performance Analysis of a Brushless Double Fed Cage Induction Generator*", Proc. Nordic Wind Power Conference, 2004, pp.1- 8.

[9] R. Pena, R. cardenas, J. Proboste, G. Asher and J. Clare, "*Sensorless Control of Doubly-Fed Induction Generators Using a Rotor-Current-Based MRAS Observer*", IEEE Trans. on Energy Conversion, 2008, pp.687-692.