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Modeling and Analysis of DFIG Based Wind Power System Using Instantaneous Power Components

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Abstract**—**As per the statistical data, the Doubly-fed Induction Generator (DFIG) based wind turbine with variable speed and variable pitch control is the most common wind turbine in the growing wind market. This machine is usually used on the grid connected wind energy conversion system to satisfy grid code requirements such as grid stability, Fault Ride Through (FRT), power quality improvement, grid synchronization and power control etc. Though the requirements are not fulfilled directly by the machine, the control strategy is used in both the stator as well as rotor side along with power electronic converters to fulfil the requirements stated above. To satisfy the grid code requirements of wind turbine, usually grid side converter is playing a major role. So in order to improve the operation capacity of wind turbine under critical situation, the intensive study of both machine side converter control and grid side converter control is necessary In this paper DFIG is modeled using power components as variables and the performance of the DFIG system is analysed under grid voltage fluctuations. The voltage fluctuations are made by lowering and raising the voltage values in the utility grid intentionally for the purpose of simulation keeping in view of different grid disturbances.

Keywords**—**DFIG, dynamic modeling, DPC, sag, swell, voltage fluctuations, FRT.

I. INTRODUCTION

ENERGY supply plays an important role in the social and economic development of nations. With increases in energy consumption, scarcity and cost of basic energy resources have become a worldwide challenge. While coal remains apparently an abundant resource, oil and natural gas supply have concerns of declining in the long run [1]. Further, using conventional carbon-based energy resources will have harmful environmental impacts including global warming and climate change. As a result, to develop an ecologically sustainable energy supply, much attention is focused on utilizing renewable energy resources such as wind, photovoltaic, small hydro, wave, tidal, biomass and geothermal. In addition to the traditional use of hydro power, there is an immense potential for solar energy in its various manifestations such as wind, biomass, etc. However, they are subjected to the vagaries of nature. Conversion systems required to exploit these energy sources are still in various stages of development for large scale technical application. As of now, wind power is the most advanced and least expensive renewable resource for grid integrated electrical power generation [2].

Traditionally, power systems were designed with large centrally dispatched power plants delivering power to consumers through transmission and distribution networks. With high penetration of wind power into power distribution and transmission networks, technical concerns such as fault current contribution, protection coordination, voltage control and stability, power quality, reliability and control issues will affect the performance of the overall power system [4].

Modelling wind farms will facilitate the understanding of their operation and impacts on the overall power system [6]. Various approaches have been used to model the wind turbine, generator, transformers and control and protection systems [2]. Detailed modelling aspects of induction generators based on power components or voltage components and current components are discussed in Section II. In Section III modelling of DFIG based on instantaneous real and reactive power components is discussed. In this paper Matlab/ Simulink/SimPowerSystems is used for the modelling and simulation studies.

Understanding the behaviour of wind farms under faulted conditions is very important for designing the system from interconnection point to the generator. Further, selecting switchgear, control gear and protective gear is done based on the prospective fault levels [3]. In section IV Different types of faults from balanced to unbalanced and the use of symmetrical components in analysing unbalanced faults are included in the discussion.

The purpose of this paper is to study the fault dynamics of wind farms (employing Doubly Fed Induction Generators, DFIG). In order to analyse the DFIG performance during transient conditions, control and modelling of DFIG are important and they are also discussed.

II. CONTROL SCHEMES OF DFIG

Squirrel cage induction machines are simple and rugged and are considered to be the workhorses of industry. However, the control structure of an induction motor is complicated since the stator field is revolving, and further complications arises due to the fact that the rotor currents or rotor flux of a squirrel cage induction motor cannot be directly monitored [5].

The mechanism of torque production in an AC machine and in a DC machine is similar. Unfortunately this similarity was not emphasized before the 1970s, and this is one of the reasons why the technique of vector control did not emerge earlier. The formulae given in literature of the machine theory have also implied that, for the monitoring of the instantaneous

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electromagnetic torque of an induction machine, it is also necessary to monitor the rotor currents and the rotor position [6], [16]. However by using fundamental physical laws or space vector theory, it is easy to show that, similar to the expression of the electromagnetic torque of a separately exited dc machine, the instantaneous electromagnetic torque of an induction motor can be expressed as the product of a flux producing current and a torque producing current, if a special flux oriented reference is used.

Modelling and control of DFIGs have been widely investigated based on well-established vector control (VC) schemes in a stator field-oriented frame of [9]. The vector control is a fast method for independent control of the real/reactive power of a machine. Direct torque control (DTC) and direct power control schemes (DPC) have been presented as alternative methods which directly control machine flux and torque by selection of suitable vectors [11]. In the following sections vector control, DTC and DPC are well explained for controlling of the grid side converter as well as rotor side converter [10]. In the following phrases basic idea of VC, DTC and DPC are presented.

A. Vector Control Scheme (VC)

The standard voltage oriented vector control strategy is used for the machine side converter to implement control action. Here the real axis of the stator voltage is chosen as the d-axis [15]. Since the stator is connected to the utility grid and the influence of stator resistance is small, the stator magnetizing current i_m can be considered as constant. Under voltage orientation the relationship between the torque and the dq axis voltages, currents and fluxes can be written as follows.

The main objective of the grid side converter is to maintain dc-link voltage constant for the necessary action. The voltage oriented vector control technique is approached to solve this issue [8]. The control scheme utilizes current control loops for id and i_q with the id demand being derived from the dc-link voltage error through a standard PI controller. The i_q demand determines the displacement factor on the grid side of the choke. The i_q demand is set to zero to ensure unit power factor. The control design uses two loops, i.e. inner current loop and outer voltage loop to provide necessary control action. The plant for the current loop is decided by the line resistance and reactance, whereas dc link capacitor is taken as the plant for the voltage loop.

B. Direct Torque Control

The Direct Torque Control (DTC) method is an alternative to vector control for DFIG based wind power generation. Variable switching frequency and high torque ripple are the main limitations of hysteresis based DTC. To address these limitations, a new DTC method wherein rotor voltage vector is generated in polar form, with space vector modulation based on synchronous reference frame transformation, predictive control and deadbeat control are implemented. Hence, the implementation of DTC using space vector modulation becomes simple compared to above mentioned methods. The method is also capable of independent control of torque and reactive power

C. Direct Power Control

From the previous researches it has been shown that DPC is a more efficient approach compared to modified DTC [12]. The main drawback of the vector control system is that its performance depends greatly on accurate machine parameters pertaining to the stator, rotor resistances, and inductances. Thus, the performance degrades when the actual machine parameters depart from the values used in the control system. Direct power control (DPC) abandons the rotor current control philosophy, which is the characteristic of FOC. Also, DPC achieves active and reactive power control by the modulation of the rotor voltage in accordance with the active and reactive power errors. DPC is characterized by its fast dynamic response, simple structure and robust response against parameter variations

It does not utilize a rotor current controller and SVM. One drawback of a basic DPC is that it displays large current, active and reactive power ripple, resulting in vibration and acoustic noise. Another drawback of DPC is a converter switching frequency variation that significantly complicates the design of the power circuit. In order to obtain a smooth operation and at a fixed switching frequency, direct power control is combined with a SVM strategy based on the principles of the DPC method [13], [14].

III. MODELING OF DFIG USING INSTANTANEOUS POWER COMPONENTS

In the above section it has been shown that DPC is a more efficient approach than the other two methods. In this section the parameters of DFIG are modeled using instantaneous real and reactive powers as variables. The schematic diagram of DFIG wind turbine is shown in Fig. 1. The back to back power converter consists of rotor side converter which controls speed of the generator and grid side converter to inject reactive power to the system [18].

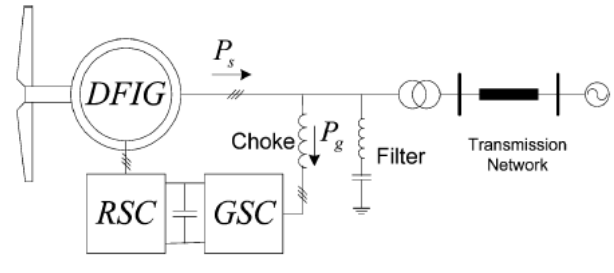

Fig. 1 Schematic diagram of DFIG based wind generator system.

From Fig. 1 the instantaneous real and reactive power components of the grid side converter $p_g(t)$ and $q_g(t)$ in the synchronous dq reference frame are

$$\begin{bmatrix} p_g(t) \\ q_g(t) \end{bmatrix} = \frac{3}{2}\begin{bmatrix} v_{sd} & v_{sq} \\ v_{sq} & -v_{sd} \end{bmatrix}\begin{bmatrix} i_{gd} \\ i_{gq} \end{bmatrix} \tag{1}$$

Solving (1) for i_{gd},i_{gq}

$$\begin{bmatrix} i_{gd} \\ i_{gq} \end{bmatrix} = -\frac{2}{3|v_s|^2}\begin{bmatrix} v_{sd} & v_{sq} \\ v_{sq} & -v_{sd} \end{bmatrix}\begin{bmatrix} p_g(t) \\ q_g(t) \end{bmatrix} \quad (2)$$

where

$$|v_s| = \sqrt{v_{sq}^2 + v_{sd}^2}\text{, let } \frac{2}{3|v_s|^2}\begin{bmatrix} v_{sd} & v_{sq} \\ v_{sq} & -v_{sd} \end{bmatrix} = k_{pq}$$

Similarly the instantaneous real $p_s(t)$ and reactive powers $q_s(t)$ of DFIG can be obtained in terms of stator currents as

$$\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} = \frac{2}{3|v_s|^2}\begin{bmatrix} v_{sd} & v_{sq} \\ v_{sq} & -v_{sd} \end{bmatrix}\begin{bmatrix} p_s(t) \\ q_s(t) \end{bmatrix} \quad (3)$$

The exact dynamic model of an induction machine is conventionally expressed by voltage and torque equations [5].

Here, we develop a simplified model for DFIG-based wind turbine of Fig. 1 by substituting currents in the exact model in terms of instantaneous real and reactive power. The main assumption to simplify the model is assuming an approximately constant stator voltage for DFIG. Using this assumption, k_{pq} is approximately constant with this derivatives of currents will be proportional to the derivatives of power based on (2) and (3). DFIG systems and induction machines are different only in one condition. In DFIG the rotor is also fed hence the name DFIG, whereas in general Induction machine only stator is fed with the power supply. So DFIG can be modelled as induction machine [7].

Three phase stator and rotor windings of an induction machine can be represented by two sets of fictitious orthogonal coils, which are located along direct (*d*) and quadrature (*q*) axes. As in the case of synchronous machines, rotor reference frame is selected.

Now the voltage and flux equations of a doubly fed induction machine in the stator voltage synchronous reference can be represented as

$$v_{sd} = r_s i_{sd} + jw_e \psi_{sd} + \frac{d\psi_{sd}}{dt} \quad (4)$$

$$v_{sq} = r_s i_{sq} + jw_e \psi_{sq} + \frac{d\psi_{sq}}{dt} \quad (5)$$

$$v_{rd} = r_r i_{rd} + jw_e \psi_{rd} + \frac{d\psi_{rd}}{dt} \quad (6)$$

$$v_{rq} = r_r i_{rq} + jw_e \psi_{rq} + \frac{d\psi_{rq}}{dt} \quad (7)$$

$$\psi_{sd} = L_s i_{sd} + L_m i_{rd} \quad (8)$$

$$\psi_{sq} = L_s i_{sq} + L_m i_{rq} \quad (9)$$

$$\psi_{rd} = L_m i_{sd} + L_r i_{rd} \quad (10)$$

$$\psi_{rd} = L_m i_{sq} + L_r i_{rq} \quad (11)$$

where w_e represents synchronous frequency, r represents resistance, L represents inductance and suffixes s,r,m represents stator, rotor and mutual quantities respectively. Now the stator voltages and rotor voltage quantities can be rewritten as

$$V_{sdq} = v_{sd} + jv_{sq} \quad (12)$$

$$V_{rdq} = v_{rd} + jv_{rq} \quad (13)$$

$$I_{sdq} = i_{sd} + ji_{sq} \quad (14)$$

$$I_{rdq} = i_{rd} + ji_{rq} \quad (15)$$

$$\psi_{sdq} = \psi_{sd} + j\psi_{sq} \quad (16)$$

From (8) and (9) i_{rd} and i_{rq} values can be written as

$$i_{rd} = \frac{\psi_{sd} - L_s i_{sd}}{L_m}\ i_{rq} = \frac{\psi_{sq} - L_s i_{sq}}{L_m} \quad (17)$$

Substituting these values in (10), (11) yields

$$\psi_{rd} = L_m i_{sd} + L_r\left[\frac{\psi_{sd}}{L_m} - \frac{L_s}{L_m} i_{sd}\right] \quad (18)$$

$$\psi_{rq} = L_m i_{sq} + L_r\left[\frac{\psi_{sq}}{L_m} - \frac{L_s}{L_m} i_{sq}\right] \quad (19)$$

Rearranging the terms in (15) and (16) yields

$$\psi_{rd} = \frac{L_r}{L_m}[\psi_{sd} - L_{se} i_{sd}] \quad (20)$$

$$\psi_{rq} = \frac{L_r}{L_m}[\psi_{sq} - L_{se} i_{sq}] \quad (21)$$

where

$$L_{se} = \left[1 - \frac{L_m^2}{L_s L_r}\right] \quad (22)$$

Now substituting (17), (20) and (21) in (6) and solving for i_{sd}&i_{sd} we can get

$$\frac{di_{sd}}{dt} = \frac{1}{L_{se}} v_{sd} - \frac{L_m}{L_s L_r} v_{rd} + \left[\frac{r_r - j\omega_r L_r}{L_{se} L_r}\right]\psi_{sd} - \left[\frac{r_r L_s + r_s L_r}{L_{se} L_r} + j\omega_{sl}\right] i_{sd} \quad (23)$$

$$\frac{di_{sq}}{dt} = \frac{1}{L_{se}} v_{sq} - \frac{L_m}{L_s L_r} v_{rq} + \left[\frac{r_r - j\omega_r L_r}{L_{se} L_r}\right]\psi_{sq} - \left[\frac{r_r L_s + r_s L_r}{L_{se} L_r} + j\omega_{sl}\right] i_{sq} \quad (24)$$

Using (1), (3) replacing i_{sd},i_{sq} with p_s&q_s and rearranging the terms yields

$$\frac{dp_s}{dt} = -\frac{r_s L_r + L_s r_s}{L_{se} L_r} p_s - \omega_{sl} q_s - \frac{3}{2}\left[\frac{r_r v_{sd} - L_r \omega_r v_{sq}}{L_{se} L_r}\right]\psi_{sd} - \frac{3}{2}\left[\frac{r_r v_{sq} + L_r \omega_r v_{sd}}{L_{se} L_r}\right]\psi_{sq} + \frac{3L_m v_{sd}}{2L_r L_{se}} v_{rd} + \frac{3L_m v_{sq}}{2L_r L_{se}} v_{rq} - \frac{3|v_s|^2}{2L_{se}} \quad (25)$$

$$\frac{dq_s}{dt} = -\frac{r_s L_r + L_s r_s}{L_{se} L_r} q_s + \omega_{sl} p_s - \frac{3}{2}\left[\frac{r_r v_{sd} - L_r \omega_r v_{sq}}{L_{se} L_r}\right]\psi_{sq} + \frac{3}{2}\left[\frac{r_r v_{sq} + L_r \omega_r v_{sd}}{L_{se} L_r}\right]\psi_{sd} + \frac{3L_m v_{sd}}{2L_r L_{se}} v_{rq} + \frac{3L_m v_{sq}}{2L_r L_{se}} v_{rd} \quad (26)$$

Stator flux state equation can be obtained by substituting i_{sd} and i_{sq} in (8) and (9) and upon solving we get

$$\frac{d\psi_{sd}}{dt} = v_{sd} + \psi_{sq}\omega_e + \frac{2r_s}{3|v_s|^2}(v_{sd} p_s + v_{sq} q_s) \quad (27)$$

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$$\frac{d\psi_{sq}}{dt} = v_{sq} - \psi_{sd}\omega_e + \frac{2r_s}{3|v_s|^2}(v_{sq}p_s - v_{sd}q_s) \quad (28)$$

The electromechanical dynamic model of the machine is presented in [18] as

$$\frac{d\omega_r}{dt} = \frac{P}{H}(T_e - T_m)$$

where p= number of poles; H=inertia of the rotor; T_m=mechanical torque of the machine; T_e=electromechanical torque

$$\tau_e = \frac{-3}{2}P(\psi_{sd}i_{sq} - \psi_{sq}i_{sd})$$

Now based on (27), (26) can be expressed in terms of instantaneous real and reactive power components

$$\frac{d\omega_r}{dt} = -\frac{P^2P_s}{h|v_s|^2}(\psi_{sq}v_{sd} - \psi_{sd}v_{sq}) + \frac{P^2q_s}{h|v_s|^2}(\psi_{sd}v_{rd} - \psi_{sq}v_{sq}) - \frac{P}{h}\tau_m$$

IV. CONTROL SYSTEM DESIGN FOR GRID SIDE AND MACHINE SIDE CONVERTERS

The purpose of the rotor side converter is to control the rotor currents such that the rotor flux position is optimally oriented with respect to stator flux in order that the desired torque is developed at the shaft of the machine [15], [16]. The grid side converter aims to regulate the voltage of the dc bus capacitor. Moreover, it is allowed to generate or absorb reactive power for voltage support requirements [17]. In this scheme the control inputs of the system are U_{rd}, Urq to control real/reactive power of the rotor and U_{gd}, Ugqto adjust the dc-link voltage and injected reactive power to the system.

The decoupled voltages of grid side converter and rotor side converter in dq reference frame values are given by

$$v_{rd}^* = \frac{k_1U_{rd}+k_1U_{rd}-3kk_1}{k_2^2+k_1^2} \quad (29)$$

$$v_{rq}^* = \frac{k_2U_{rd}-k_1U_{rq}-3kk_2}{k_2^2-k_1^2} \quad (30)$$

$$v_{gd}^* = -\left(\frac{c_1U_{gd}+c_2U_{gd}-kh_1}{h_2^2+h_1^2}\right) \quad (31)$$

$$v_{gq}^* = -\left(\frac{c_2U_{gd}-c_1U_{gq}-kh_1}{h_2^2+h_1^2}\right) \quad (32)$$

where

$$k_1 = \frac{3L_mv_{sd}}{2L_rL_{se}}k_2 = \frac{3L_mv_{sq}}{2L_rL_{se}}\ k = \frac{3|v_s|^2}{2L_{se}}$$

$$c_1 = \frac{3}{2L_f}v_{sd}c_2 = \frac{3}{2L_f}v_{sq}$$

Now using the reference frame transformer grid side variable voltages and rotor side variable voltages can be changed to three phase abc reference frame from dq reference frame. Since the dq components are not physically available, the calculation of these components uses a PLL to determine the synchronous angle, which is obtained by synchronizing the grid with the DFIG machine.

V. RESULTS AND DISCUSSIONS

In this section the performance of DFIG based wind farm modeled using MATLAB/SIMULINK under different wind speeds and different dynamic conditions (sag and swell). Here instantaneous power components are used in control theory for pulses to the converters are generated using reference active and reactive power for rotor side controller and reactive power of grid , DC link voltage references are used for Grid side controller [10]. Different dynamic conditions are introduced and stator active power, stator reactive power and dc link voltage is observed for a 1.5 KW DFIG. The parameters of the study system are given in Table I. Since the Dynamic model of DFIG contains several parameters, harmonics and integrators, for convenience the Simulink model is evaluated in discrete mode.

TABLE I
PARAMETERS OF THE INDUCTION MACHINE

Rated Power	1.5/0.9 Mw
Stator Voltage	415V
Rs(Stator Resistance)	0.00706 pu
Rr(Rotor Resistance)	0.005 pu
Ls	3.071 pu
Lm	2.9 pu (Referred to the rotor)
Lr (Rotor inductance)	3.056pu(Referred to the rotor)
Poles	6
Rated speed	1100 rpm
DC link Voltage	850V
f Frequency	60 Hz
h Inertia of rotor	5.04 s

A. Simulation under Balanced Grid Condition

The characteristic waveforms of DFIG under Balanced grid condition are shown in Figs. 2-4. It is observed that the active and reactive powers supplied by the utility grid are decoupled and dc link voltage is maintained constant due to the control strategy made in the grid side converter. It has also seen that the rotor runs with a constant speed.

B. Simulation Results under Voltage Sag Condition

The simulation results under the voltage sag are shown in Figs. 2-4. 80% of rated voltage is applied in the faulted period. The DFIG system produces active power of 1.4 MW which corresponds to maximum mechanical turbine output minus electrical losses in generator. When the grid voltage changes suddenly from its rated value i.e.415V the stator current as well as rotor current increases and the active power P suddenly oscillates between 0.8 MW to 1.4 MW. The reference reactive power is set at 0KVAr but when voltage decreases the reactive power suddenly increases then it settles to 0KVAr as per the control strategy made in the rotor side converter. The dc link voltage is set at 800V by the grid side converter and the rotor speed is also maintained constant to its rated (1100rpm) while the wind speed is kept constant at 12m/s. The rotor output is same as the converter output.

C. Simulation Result under Voltage Swell Condition

Simulation results under voltage swell is shown in Fig. 3. When the grid voltage increases up to 120% of its rated value the stator current as well as rotor current decreases and the reactive power Q decreases suddenly and then settles to 0kVAr. In Fig. 4 the behaviour of the generator is observed from 0.11s when the voltage rises to 120% of its rated Value.

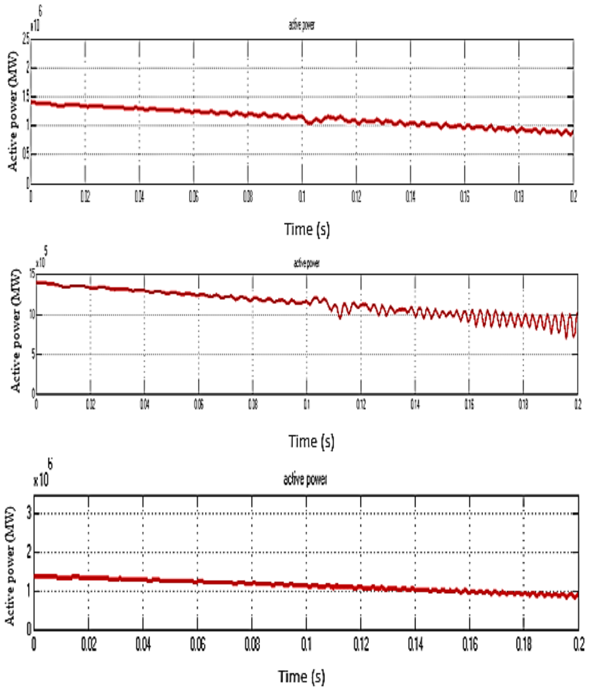

Fig. 2 Active power during balanced grid, voltage sag and voltage swell conditions

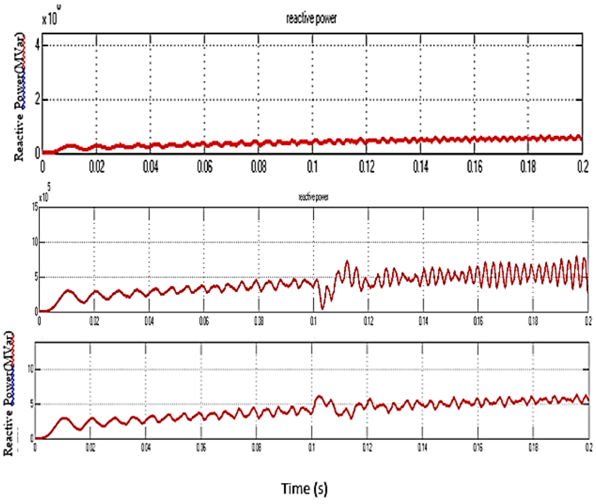

Fig. 3 Reactive power of DFIG during Balanced Condition, Voltage Sag and Voltage Swell Conditions

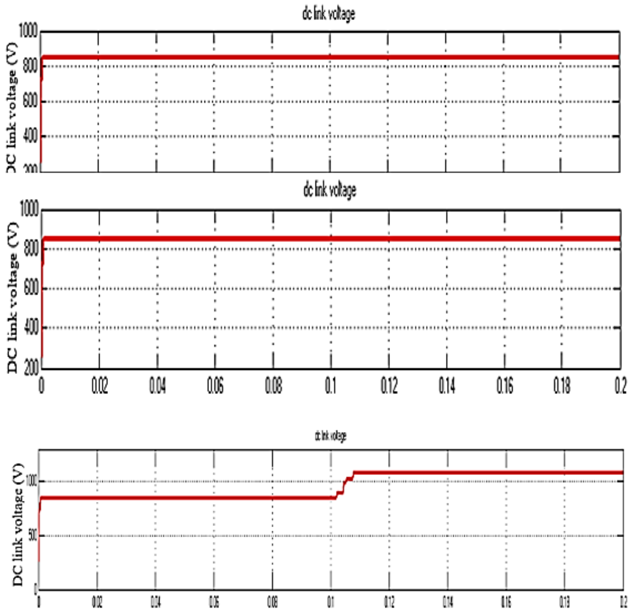

Fig. 4 DC Link Voltage during Balanced Condition, Voltage Sag and Voltage Swell Conditions

VI. CONCLUSION

This paper presented modelling of DFIG using power components as variables and the performance of the DFIG system is analysed under grid voltage fluctuations. The active and reactive power is controlled independently using the vector control strategy. The main drawback of the vector control system is that its performance depends greatly on accurate machine parameters pertaining to the stator, rotor resistances, and inductances. On the other hand direct power control has fast dynamic response, simple structure and robust response against variations. It has been shown that Direct power control is a more efficient approach compared to modified Direct torque control and Vector Control .The main aim of the controlling technique is maintaining the DC link voltage constant which is achievedduring voltage sag and swell conditions.

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