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EVALUATION & PERFORMANCE ANALYSIS OF DFIG WIND TURBINE WITH CROWBAR PROTECTION UNDER SHORT CIRCUIT & VOLTAGE DIP CONDITION

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Abstract: Wind energy is the fastest and most promising energy source. Due to many advantages such as the improved power quality, high energy efficiency and controllability, etc. the variable speed wind turbine using a doubly fed induction generator (DFIG) is becoming a popular concept. This paper also presents a model through which steady-state and transient behavior of a DFIG can be analyzed. The machine used was a doubly fed induction generator (DFIG). Two fault ride through situations were investigated. As protection against short circuit transients, the dump resistor and the crowbar protection were modelled. The challenge that DFIG poses is its behavior during transient condition of the systems, especially voltage dips. During system faults the stator and rotor currents become very high which may damage back-to-back connected power electronic converters in the rotor circuit. For this reason the usual practice is to disconnect the DFIG in case of a fault. In this work crowbar or dump protection is employed. In\ this paper, the impacts of different types of faults a grid system on the DFIG transient response is presented. The paper also includes the study of Low Voltage Ride Through (LVRT). The simplified crowbar and dump resistormodels were compared tosimulations constructed with MATLAB – Simulink.

I. INTRODUCTION

The search for a polluting and non-polluting sustainable source of energy calls for intense research to tap energy from renewable sources. Wind energy conversion system offers one of such option. The use of wind generator for electricity began in twentieth century. At present conventional energy sources (Coal, Oil and Natural gases) comprises a major share, about 87%, of the total electrical energy generated. In the recent years, people have become more conscious of reducing greenhouse gas emissions for environmental reasons. As a result, there is an emphasis on generation from renewable energy sources like wind, photovoltaic, tidal, biomass etc. The kinetic energy associated with the wind is converted to electrical energy using wind energy conversion system. DFIG had gain more popularity as compared to Synchronous Generator (SG) because DFIG requires only 25-30% of the total nominal power rating of the generator, to operate control functions. So the control equipment rating is also small and which makes it more economical as compared to SG which requires power electronics control equipment of same rating as that of generator nominal power rating. A wind turbine can be designed for a constant speed or variable speed operation. Variable speed wind turbines can produce 8% to 15% more energy output as compared to their constant speed wind turbines. The doubly fed induction generator (DFIG) with rotor side control forms one of the best alternatives for variable speed constant frequency system. The power converter is now connected between the rotor of wind turbine directly, offers high reliability, low maintenance, and possibly low cost for certain turbines.

II. WIND ENERGY CONVERSION

Wind energy is basically the kinetic energy of air moving over the earth's surface. When the sun strikes the earth, it heats the soil near the surface that in turn warms the air lying above it. Warm air is less dense than the cool air, therefore warm air rises in the atmosphere and cool air flows into take its place and is itself heated. The rising warm air eventually cools and falls back to earth. This cycle is continuous. Normally winds are stronger along the shores of large lake, along the costs and mountain valley because of differential heating. It is very important to make maximum use of available energy resources. A wind turbine is a machine that converts kinetic energy of the moving air into mechanical energy which in turns is converted into electrical energy by a generator. The blades of the wind turbine receive this kinetic energy. It is then transformed to mechanical and electrical forms. The kinetic energy E_{ke} of a stream of air with mass m and moving with a velocity V_w is given by the equation,

$$E_{ke} = \frac{1}{2} m V_w^{\ 2} \qquad 1$$

If a wind turbine rotor of cross sectional area A is exposed to this wind, kinetic energy available can be expressed as shown by equation,

$$E_{ke} = \frac{1}{2} \rho v V_w^{\ 2} \qquad 2$$

Where ρ = Density of air (kg/m^3),
$v =$ Volume of parcel available to rotor (m^3),
V_w = wind velocity (m/s).

The air parcel interacting with the rotor per unit has a cross-sectional area equal to that of the rotor and thickness equal to wind velocity. Therefore, the power can be expressed (energy per unit time) by equation,

$$P = \frac{1}{2}\rho A V_w{}^3 \quad 3$$

Where $P =$ Power generated $(watt)$, $A =$ Cross sectional area of the rotor (m^2)

The density of air depends on factors like temperature, atmospheric pressure, elevation and constituents in air. A wind turbine cannot extract power completely from the wind. A part of the kinetic energy is transferred to the rotor and remaining energy is carried away by the air leaving the turbine. Therefore equation (3) can now be expressed as shown by equation,

$$P = \frac{1}{2} C_p(\lambda, \beta)\rho A V_w{}^3 \quad 4$$

Where, $C_p(\lambda,\beta) =$ Co-efficient of power

Pw – Power captured from wind (Watts)

λ –Tip speed ratio (vtVw)

β - pitch angle of the blades (deg)

Ar– area swept by the rotor blades (m2)

Vw – Wind speed (m/s)

The co-efficient of power is given by the ratio of power extracted to the power available. Its theoretical maximum limit is 59% set by Betz's law which means that under ideal conditions only 59% of the wind power could be extracted. Power co-efficient (C_p) is a function of the tip speed ratio of the wind turbine and depends on the blade dynamics. The tip speed ratio is given by equation,

$$\lambda_t = \frac{\omega_r r_r}{V_w} \text{ or,}$$

$$w_r = \frac{V_w \lambda_t}{r_r}$$

Where, 5

ω_r = Rotational speed of rotor (rpm) at any given speed, r_r = Radius of the rotor blade (m). A simplified aerodynamic model is normally used when the electrical behavior of the wind turbine is the main interest of the study. The aerodynamic torque, which is the ratio of rotor power and rotor speed is given by equation,

$$T = \frac{Power}{\omega_r} = \frac{1}{2}\frac{\pi R_r{}^2 V_w{}^3 \rho C_p}{\omega_r}$$

$$T = \frac{1}{2}\pi r_r^3 V_w^2 \rho C_t \quad 6$$

Where, C_t =Torque co-efficient and is related to the power co-efficient by, $C_t = \frac{C_p}{\lambda_t}$.

The relations between power, power co-efficient and tip speed ratio indicate that the mechanical power available from the wind is the maximum for a specified wind speed, which corresponds to optimal Cp. Below the cut-in speed (minimum speed needed for the turbine to generate power), there is no generation of power and when the speed limit is reached, a constant speed characteristic up to the rated power is adopted. It can be observed that maximum power co-efficient is obtained at about wind velocity of 12 m/s.

$$Cp(\lambda,\beta) = C1(\frac{C2}{\lambda i} - C3\lambda - C4)e * (\frac{-C5}{\lambda i}) + C_6$$

$$with,$$

$$\lambda i = \frac{1}{\frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta * 3 + 1}} \quad 7$$

Where C1 = 0.5176, C2 = 116, C3= 0.4, C4 = 5, C5= 21, C6 =0.0068.

III. WIND ENERGY SYSTEM

The three most important currently applied wind turbine concept are:

- A constant (fixed) speed wind turbine [figure 1], which consists of a directly grid coupled squirrel cage induction generator. The wind turbine rotor is coupled to the generator through a gearbox. The power extracted from the wind is limited using the stall effect. This means that the rotor is designed in such a way that its efficiency decreases in high wind speeds, thus preventing the mechanical power extracted from the wind to become too large. In most cases, no active control systems are used to this end.
- A variable speed wind turbine with doubly fed (wound rotor) induction generator [figure 2]. The rotor winding is fed using a back-to-back voltage source converter. Like in first concept, the wind turbine rotor is coupled to the generator through a gearbox. In high wind speeds, the power extracted from the wind can be limited by pitching the rotor blades.
- A variable speed wind turbine with a direct drive synchronous generator [figure 3]. The synchronous generator can have a wound rotor or be excited using permanent magnets. It is grid coupled through a back-to-back voltage source converter or a diode rectifier and voltage source converter. The synchronous generator is a low speed multi pole generator, therefore no gearbox is needed. Like in the second concept, the power extracted from the wind is limited by pitching the rotor blades in high wind speeds.

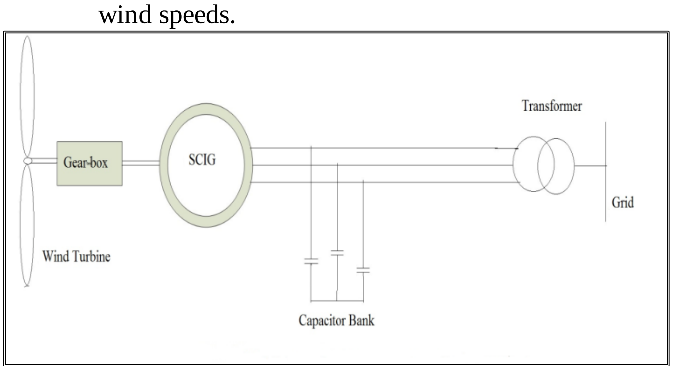


Figure1: Fixed Speed Induction Generator [5]

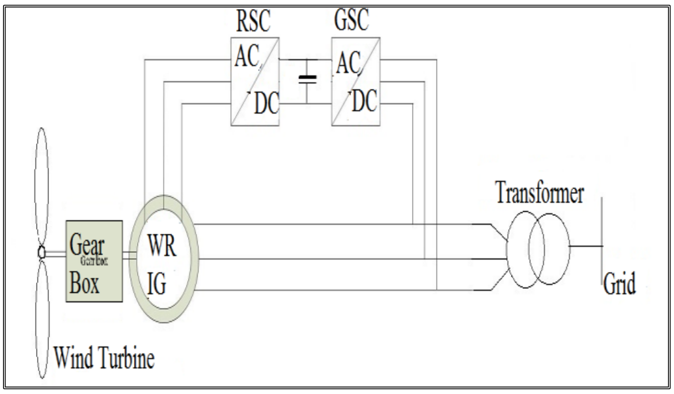


Figure 2: Variable Speed Induction Generator [5]

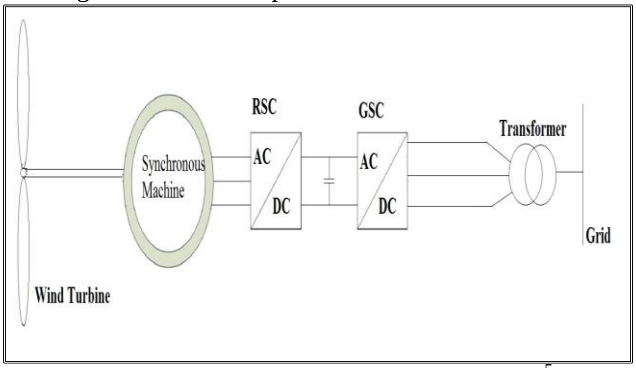


Figure3: Multipole Synchronous Machine [5]

A. Proposed structure of DFIG

In figure 4 the basic normal duty diagram for the wind turbine is presented. Tw represents the driving torque produce by the wind. From the blade and shaft, the rotor of the generator receives the torque. The energy is fed to the grid through the back-to-back inverter system and the three phase transformer. The initial model of the transmission line consisted of a pi diagram containing the parasitic elements of the conduction cable. According to lines under 100 km are considered short lines and may be modeled as an inductance. The grid was modeled as a three phase voltage source.

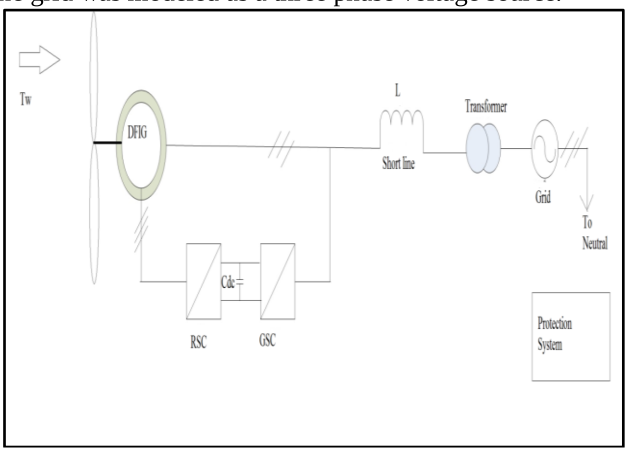


Figure 4: Basic Normal Duty Diagram [8]

IV. NORMAL DUTY

Normal duty connection diagram of the generator system is shown in figure 5. The rotor of the generator is connected to the rotor side converter through switch K. In the actual setup, K is a switch converter. The crowbar protection is also depicted in figure 5. By switch K, the resistor bank may be connected to the rotor windings. This is activated when a fault occurs and transients are so high that the generator must be protected by short-circuiting the rotor. Rdump is used as an alternative fault protection. If the dump resistor is connected into the circuit the rotor converter is disconnected from the circuit. For charging/discharging the dc link capacitor Cdc a dedicated circuit is used. The grid side converter is connected to the transmission line through a three-phase step down transformer. The grid is modeled as a three-phase voltage source.

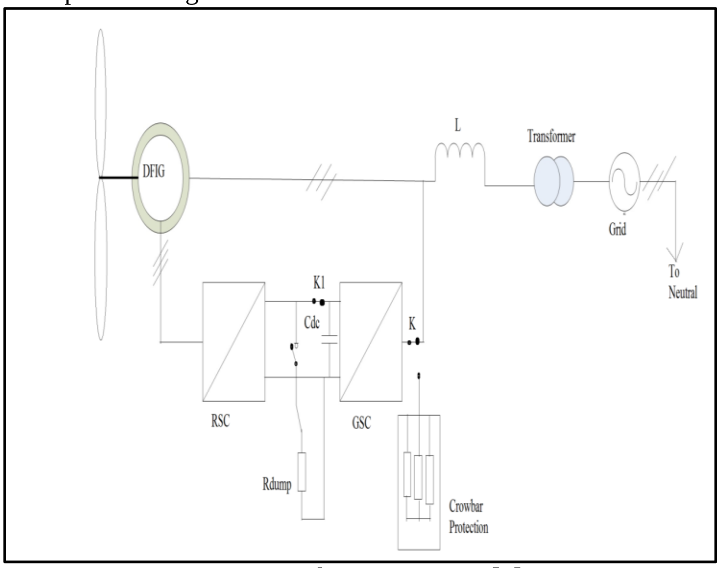


Figure 5: Normal Duty Diagram [8]

In order to simplify the equivalent circuit and consequently the mathematical model derived from it, a set of simplifying assumptions were considered. Arguments are provided for each assumption to show their validity.

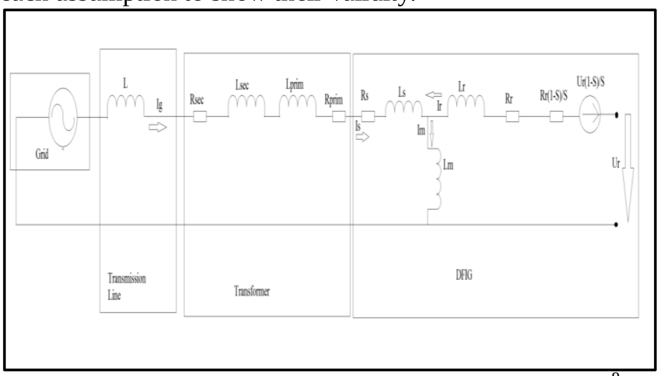


Figure 6: Normal Duty Simplified Equivalent Circuit [8]

Equations derived from, figure 6 is presented in the following:

The first circuit loop comprising the grid voltage Ug the equivalent inductance Lech and resistance Rech. By omitting the magnetizing of the transformer, the primary and secondary elements being connected in series may be reduced to equivalent components below.

$$U_g = R_{ech} i_g + \frac{dL_{ech}}{dt} i_g \frac{dL_m}{dt} i_m \qquad 8$$

The detailed formulas for the equivalent resistance and inductance are presented in the Following

$$R_{ech} = R_{\sec} + R_{prim} + R_s \quad 9$$

$$L_{ech} = L_{\sec} + L_{prim} + L_{line} + L_s \quad 10$$

Where

$R_{\sec}$ resistance of the secondary side of the transformer

R_{prim} resistance of the primary side of the transformer

R_s stator resistance of the machine

$L_{\sec}$ inductance of the secondary side of the transformer

L_{prim} inductance of the primary side of the transformer

L_{line} line parasitic inductance

L_s stator inductance

The second circuit loop equation comprises the rotor voltage and the slip dependent Elements

$$U_r = R_a i_r + \frac{d\psi_r}{dt} - \frac{Ur(1-S)}{S} \quad 11$$

Where,

Rarotor equivalent resistor

S slip

Ψr rotor flux

$$R_a = R_r + \frac{Rr(1-S)}{S} \quad 12$$

The rotor flux is,

$$\psi_r = L_r i_r + L_m i_s \quad 13$$

If the slip is considered constant, the rotor resistor value would incorporate the slip value component for a given slip.

V. SIMULATION MODELING AND RESULTS

A. Simulink model of DFIG with Crowbar Protection

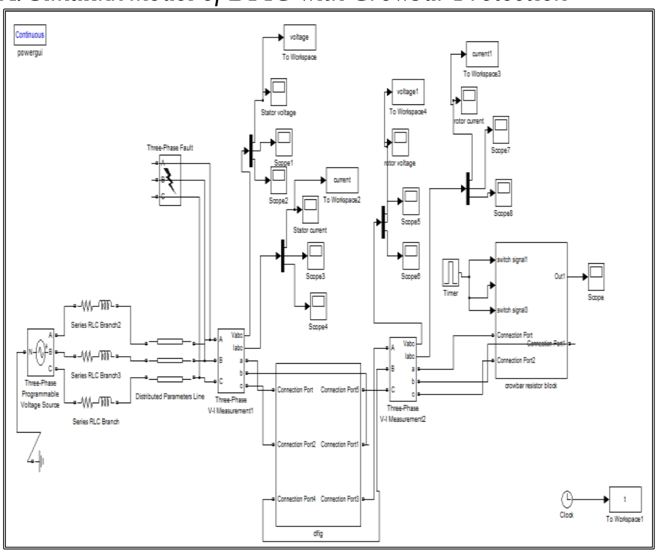


Figure 7 Main Simulation Diagram of DFIG with Crowbar Protection

In th main simulation diagram, two subsystem are designed, and those sub system are DFIG equivalent and dump protection sub systems. Alternative solution of the crowbar protective system of the DFIG is dump protection. Simulation block is same as the dump protection, only difference that instead of dump protection block crowbar protection block is emplyoed,

B. Simulation Results of DFIG with Dump and crowbar protection Protection

In the simulation, the 3 phase fault was applied between 0.2 to 0.6 second by setting fault block to generate short-circuit between all 3 phases. The protection is switched on during 0.4 to 0.6s. And result is taken with both types of protective system. Simulation results for stator input voltage, stator input current, rotor voltage, rotor current with crowbar protection shown by figure 8 (a) to 11(a) and with dump protection shown by fig 8 (b) to 11 (b).

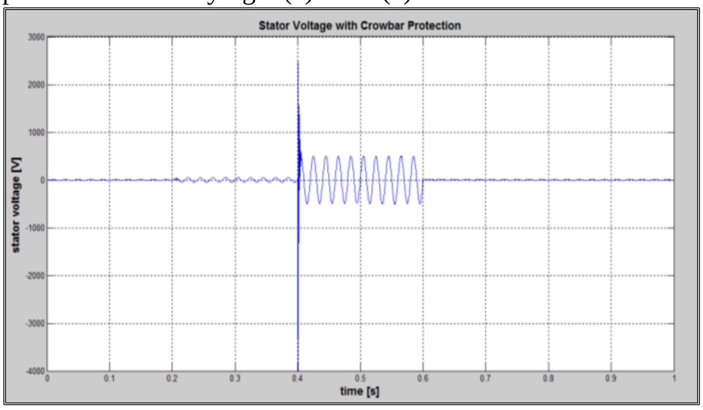


Figure 8 (a) Stator I/P Voltage

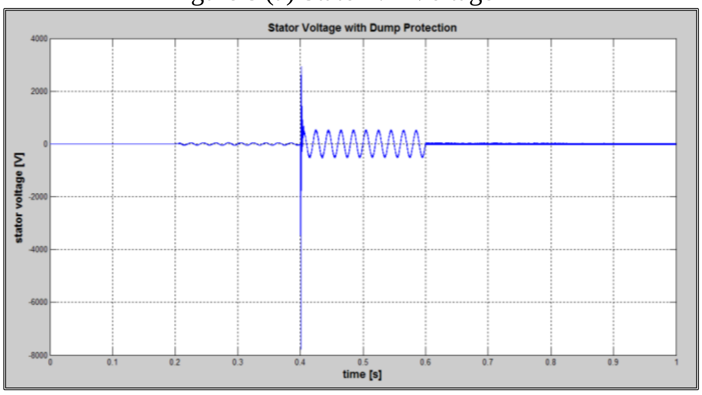


Figure 8 (b) Stator I/P Voltage

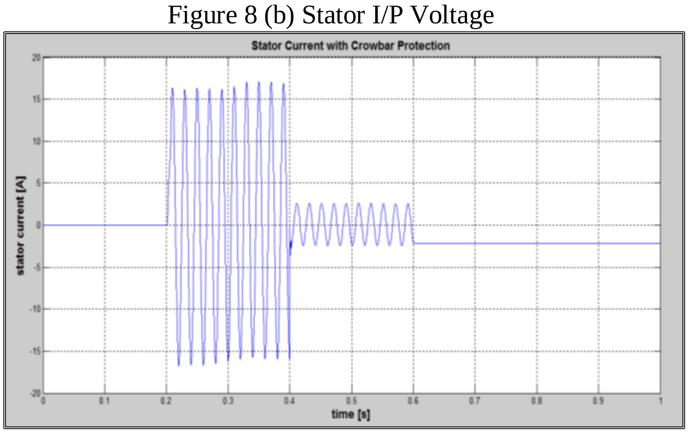


Figure 9 (a) Stator I/P Current

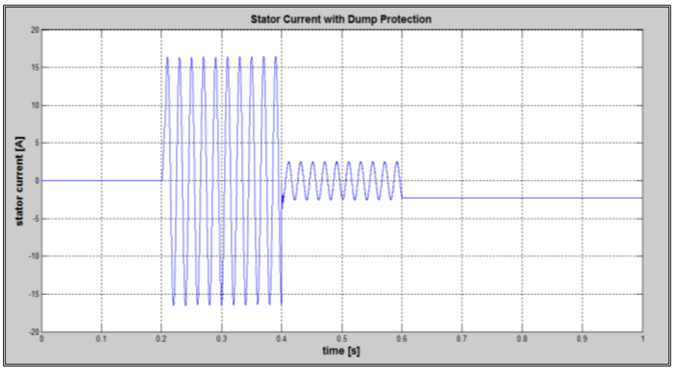


Figure 9 (b) Stator I/P Current

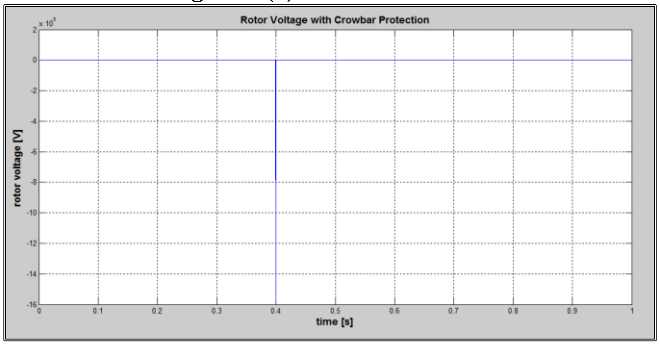


Figure 10 (a) Rotor Voltage

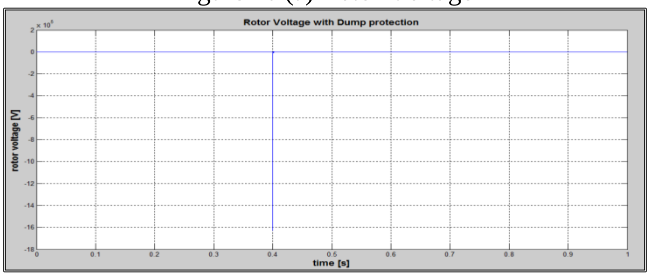


Figure 10 (b) Rotor Voltage

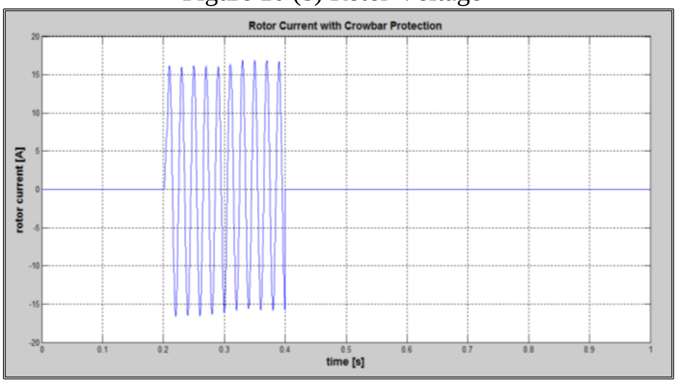


Figure 11 (a) Rotor Current

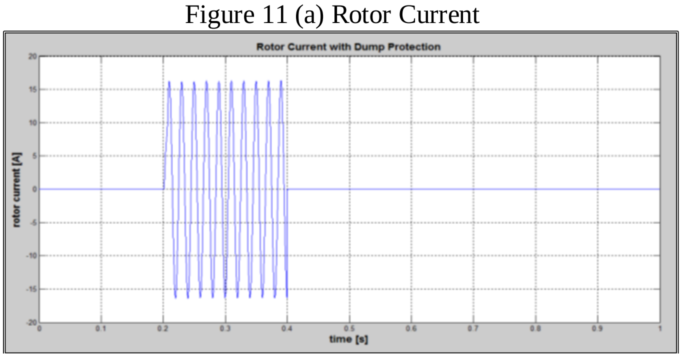


Figure 11 (b) Rotor Current

VI. DFIG MACHINE MODEL IN FIELD CO-ORDINATES

The rotor side control is exerted on the doubly fed induction generator. The presence of power electronic converter makes possible to assume a controllable current source in the rotor. So the rotor currents are taken as inputs in the model [2]. The stator is grid connected .Hence the voltage impressed will be having constant voltage and constant frequency.

$V_S=R_Si_S+ (1+s)L_o d/dt(i_s) + L_o d/dt(i_r e^{je})$

14

$V_S=R_Si_S+ L_o d/dt [(1+\sigma_s) i_s + i_r e^{je}]$

15

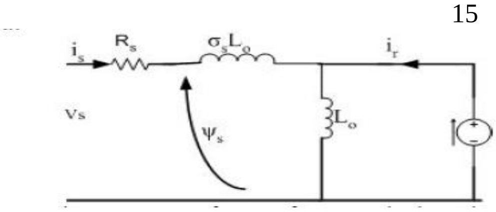


Fig 12 Stator reference frame equivalent circuit [9]

The stator flux magnetizing current (i_{ms}) can be defined from the expression of stator flux as

$\Psi_S= L_o i_{ms}= i_s 6_s L_o+ i_s L_o+ i_r e^{je} L_o$

16

Therefor $i_{ms}=(1+\sigma_s) i_s + i_r e^{je}$

17

e^{je} rotates the vector i_r in the clockwise direction ,implying rotor currents are represented in stator reference frame.

The stator voltage can be now expressed as

$V_S= R_S i_s+ L_o d(i_{ms})/dt$

18

Substituting for stator currents in terms of rotor currents,

$V_s = R_s [i_{ms} - i_r e^{je}/ 1+ \sigma_s] + L_o di_{ms}/dt$

19

Rearranging,

$I_{ms}+ L_o (1+\sigma_s / R_s) di_{ms}/dt = (1+\sigma_s / R_s)/ V_s +i_r e^{je}$

20

Let $T_s= L_o (1+\sigma_s) /R_s = L_s/R_s$

21

All the above equations are in stator reference frame. These can be converted to field reference frame by representing the vectors in polar form as

$I_{ms}=I_{ms}e^{j\mu`}$

22

Where i_{ms}represents vector and i_{ms} represents the instantaneous values. μ represents the instantaneous angle of the field axis with stator axis. The positions of vectors are depicted in the vector diagram

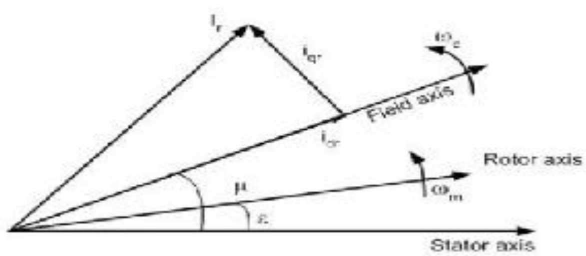


Fig 13 .Position of vectors of doubly fed induction machine [9]

The equation can now be expressed as

$T_S\, d/dt(i_{ms}e^{je}) + i_{ms}e^{j\mu} = (1+\sigma_s/ R_s)V_s + i_r e^{je}$ 23

Expanding

$T_s(di_m/dt)e^{j\mu} + T_s i_{ms}(j\, d\mu/dt)\, e^{j\mu} + i_{ms}e^{j\mu} = (1+ \sigma_s)/ R_s\ v_s + i_r e^{je}$ 24

Simplifying by multiplying both the sides by $e^{-j\mu}$,

$T_s di_{ms}/dt + j\, T_s i_{ms} d\mu/dt + i_{ms} = (1+ \sigma_s)/ R_s\ v_s\, e^{-j\mu} + i_r e^{j(e-\mu)}$ 25

The stator voltage and rotor currents are also expressed in the field coordinates as

$V_s\, es^{-j\mu}=V_{ds}+ j\, V_{qs}$ 26

$I_r e^{j(e-\mu)}=i_{dr} + ji_{qr}$ 27

By separating the real and imaginary part of equation and equating with equation

$T_s di_{ms}/dt + i_{ms}= (1+ \sigma_s)/ R_s V_{ds}+ i_{dr}$ 28

$d\mu/dt= w_e=i/ T_s i_{ms}[1+\sigma_s / R_s*V_{qs} + i_{qr}]$ 29

The developed torque in the machine can be expressed in the field quantities.

$m_d= (2/3)(P/2)\, Imag\{i_s(i_r e^{je})^*\}$ 30

By substituting for stator currents in terms of rotor currents

$m_d= 2/3* p/2* L_o/(1+\sigma_s)\{(i_{ms}- i_r e^{je})\, i_r e^{je}\}$
$= -2/3 * p/2 *L_o/ (1+\sigma_s)\, i_{ms} i_{qr}$ 31

The speed of rotation neglecting friction losses follows the equation,

$J\, dw_m/dt = m_d - m$ 32

Where, m_l is the torque exerted by the wind at the generator terminals.

$de/dt=w_m$ 33

These equations are represented in the form of block diagram inthe below figure.

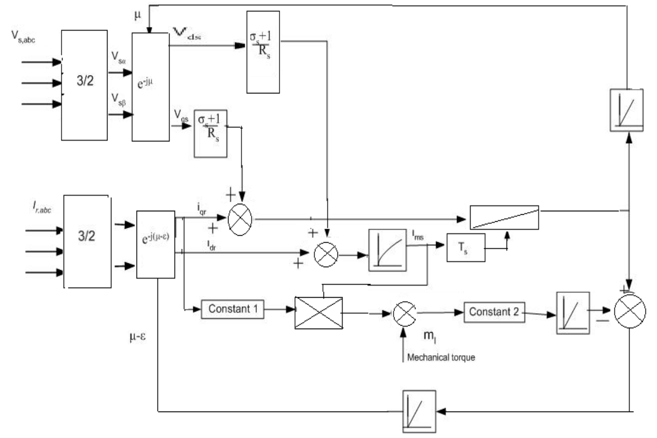


Fig 14 Block diagram of doubly fed induction machine in field coordinates [10]

From the simulation circuit of above block diagram, following simulation results for V_{abc} and I_{abc} are obtained. For phasor voltages and currents pure sinusoidal waveforms are generated.

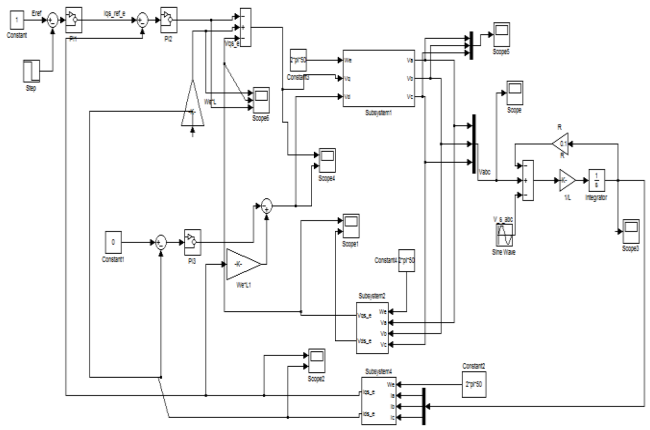


Fig 15 Simulation Circuit of Field Oriented Control of DFIG Machine Model

In the simulation diagram, by applying step signal and E_{ref} to PI controller, $I_{q\_ref\_e}$ is genearated and from some other close loop block $I_{\_qs\_e}$ is taken and it will be given to the PI controller, in that's way $I_{\_ref}$ is be generated.

V_a, V_b, V_c and V_d, V_q and I_a, I_b, I_c, I_d, I_q are generated through close loop.

To generate V_a, V_b, V_c from V_d, V_q 2 to 3 conversion is implemented and to generate V_d, V_q from V_a, V_b, V_c 3 to 2 conversion is implemented. In actual, I_{abc} is converted in to $I_{\_qs\_e}$ and $I_{\_ds\_e}$, and these two quantities are compared in PI controller to remove error by adjusting the gain value and it converted into I_{qs} and I_{ds}.

In a same way, I_{abc} is converted in to $V_{\_qs\_e}$ and $V_{\_ds\_e}$, and these two quantities are compared in PI controller to remove error by adjusting the gain valueand it converted into V_{qs} and V_{ds}. The waveforms of these individual voltage and current component isobtaind as shown in fig below.

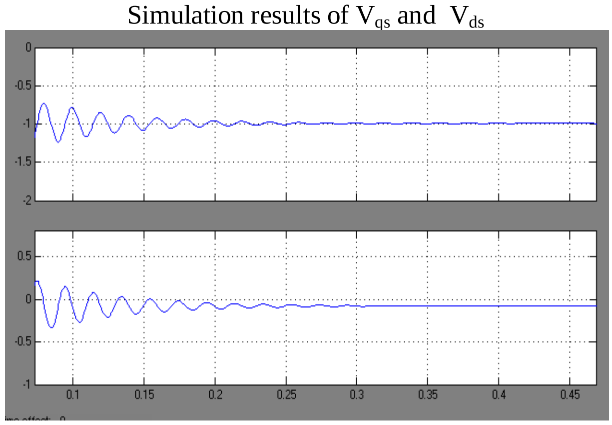
For phasor voltages and currents pure sinusoidal waveforms are generated.

V_{qs}, V_{ds} are in form of transients up to 0.2 s and after that they will reduces to zero.

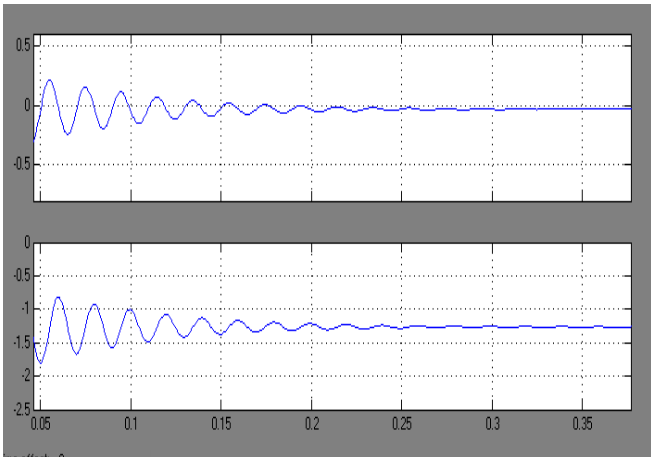
The simulations results for phasor voltages and phasorcureents and d-q axis voltages and currents are obtained. That are shown in the figure below

Fig 16 Simulation Results FOC diagram of DFIG

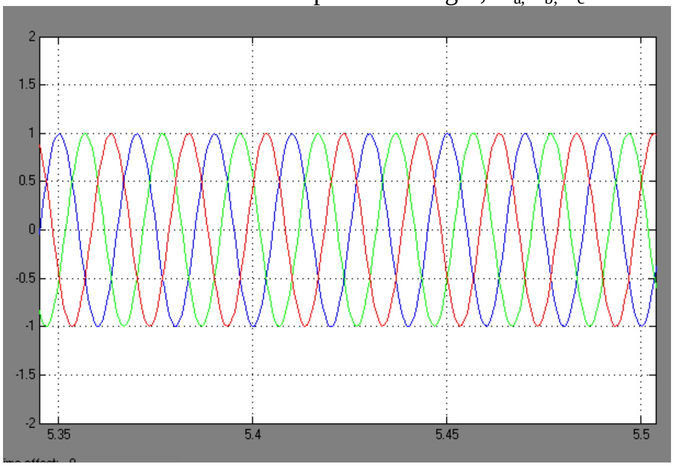
Simulation results of V_{qs} and V_{ds}



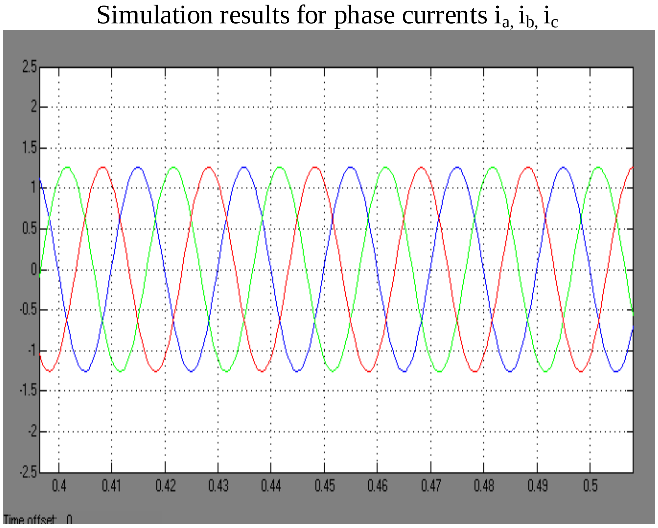
Simulation results for i_{ds} and i_{qs}



Simulation results for pharos voltages, V_a, V_b, V_c



Simulation results for phase currents i_a, i_b, i_c



VII. CONCLUSION

Major problem of the DFIG in faulty condition, rotor current is very high in rotor side converter. Applying bothtype of protective system, reduce the rotor current shown in figure 11 (a) & 11 (b) and protect the converter. Results of both protective systems are same see in figure 8 to 11. So, we can use any one of the protective system. Also compare the both protective system, the response of the crowbar system is more intense. Economic point of view crowbar protection is more beneficial than dump protection. Also analysis of results of DFIG with different fault.

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