Study of Dynamic Response of Doubly Fed Induction Generator during Grid Interconnection & Fault Condition

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***Abstract*—In the recent times, due to environmental concerns, there is rapid growth of wind power in the electric power systems. Power system planners and operators are facing many difficulties while integrating wind power because of its inherent characteristics. To solve these difficulties there is need for various studies and models of wind turbines. Doubly Fed Induction Generator (DFIG) based Wind Turbine (WT) is one of the most popular configurations being adapted. In this paper a dynamic model of DFIG based WT is developed in EMTDC/PSCAD and the results of various dynamic studies have been presented.**

Keywords— Doubly fed induction generator, Grid Side Converter (GSC), RSC (Rotor Side Converter), Crowbar protection.

I. INTRODUCTION

Due to environmental concerns caused by excessive exploitation of conventional resources, now the focus is diverted to non renewable resources especially solar & wind as these are environmentally clean and eco-friendly. With the modern technology incorporated in the wind turbines, wind power generation limits have been uplifted to considerable level in the grid. Hence penetration level of wind power has become more significant and is leading to more complex, sophisticated and reliable interconnection requirements.

According to the requirements, dynamic behavior of grid should not get affected by operation of wind farm. But when grid is attributed to fault and voltage dips, the disconnection of the wind farm creates shedding of loads resulting in unreliable power supply. Therefore according to the magnitude of voltage at point of interconnection, the fault ride through capability is specified to withstand voltage dips without load shedding. Some more areas in which constraints need to be incorporated in study are power quality problems, protection of hardware equipments and ancillary services [1]. To study these issues, dynamic model of WT has been developed. For the present study DFIG WT is considered. This WT is connected to grid through step up transformer. The Grid Side Converter and Rotor Side Converter are connected back to back to control generator output parameters in both normal & abnormal conditions. The Rotor Side Converter is current controlled & Grid Side Converter is voltage controlled. Both control schemes are based on per unit system. In these schemes, stationary frame is converted to synchronous frame and vice-versa. In synchronous frame, steady state or DC values are compared to desired references to achieve required output in synchronous frame. Apart from this crowbar protection circuit is also added so as to control over-current phenomenon in Rotor Side Converter which may arise in fault conditions.

II. COMPONENTS AND OPERATING MODES OF DFIG

The main components of DFIG are wound rotor induction generator, aerodynamic system with gear box, Rotor side converter, Grid side converter, coupling transformer, filter & protection system. The rotor shaft is connected to drive train system of WT and stator terminal is connected to grid.

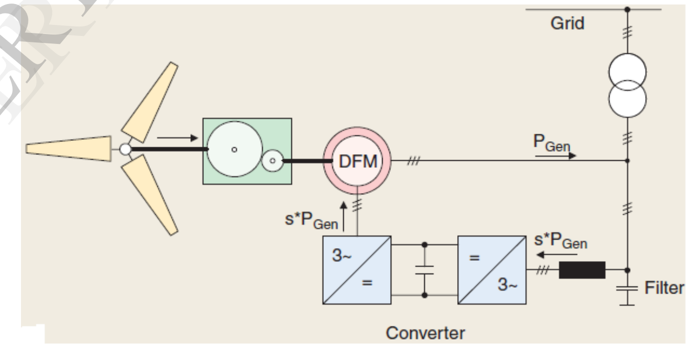

Fig. 1 Components of DFIG-based WECS [2]

The rotor terminals are connected to back to back dc link connected converter system. It is capable to transmit 25-30% of rated power supplied to grid. Protection system provides safe operation of converters. The converter system is bidirectional so DFIG can be operated in sub-synchronous and super-synchronous mode.

III. MODELLING AND CONTROL SCHEMES OF RSC & GSC

A. Wind park modelling:

The terms which relate wind speed to developed power are as follows:

1) Power in air flow:

$P_{air}=0.5\rho A v^3$ also $C_P = P_{wind\ turbine} / P_{air}$, on substituting we get $P_{wind\ turbine} = 0.5\rho A v^3 C_P$

2) Tip speed ratio: $\lambda=\omega r/v$

3) Beta Limit:

The maximum power extraction limit of wind turbine is 59.3% of wind power. Here the value of C_P is 0.28 in model. [3]

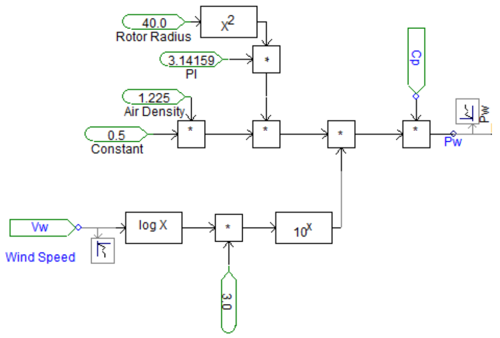

Fig. 2 Model of Wind Park

B. Current Reference – PWM control RSC

The DFIM is controlled in synchronous *dq* reference frame with d-axis aligned to rotor flux vector position [4]. The i_d component refers to magnitude of rotor flux in air gap aligned in direction to stator flux vector; whereas i_q component produces quadrature flux vector. The developed torque is vectoring cross product of i_d & i_q vectors, and hence contributes to developed power. The i_d component controls magnitude of reactive power entering DFIM. The i_d and i_q can be controlled so as to control real and reactive power flow [5]. In stator-flux orientation, the torque and the *dq* axis voltages, currents and fluxes are related as: [6]

$$V^*_{dr} = R_r I_{dr} + \sigma L_r\, dI_{dr}/dt - \omega_{slip}\sigma L_r I_{qr}$$
$$V^*_{qr} = R_r I_{qr} + \sigma L_r\, dI_{qr}/dt + \omega_{slip}(L_m I_{ms} + \sigma L_r I_{dr})$$
$$T_e = -3p\, L_m I_{ms} I_{qr}/2$$
$$\omega_{slip} = \omega_e - \omega_r$$

The $\omega_{slip}\sigma L_r I_{qr}$ component is neglected from expression of V_{dr}. By this approximation, rotor excitation current I_{dr} is controlled using V_{dr}. The d-axis reference is Reactive power reference Q_g* in model instead of I_{dr}*. Assuming that all reactive power to the machine is supplied by the stator, Reactive power reference Q_g* or I_{dr}* is set to zero. The approximated expression for d- axis reduces to

$$V^*_{dr} = V'_{dr} = R_r I_{dr} + \sigma L_r\, dI_{dr}/dt$$

Similarly the $\omega_{slip}(L_m I_{ms} + \sigma L_r I_{dr})$ is neglected from expression of V_{qr}. By this approximation, the torque is proportional to I_{qr} and I_{qr} can be regulated using V_{qr}.

The reference q-axis rotor current can be obtained either from outer speed-control loop or from a reference torque imposed on the machine.

These two options may be termed a speed-control mode or torque-control mode for the generator. In this model, first speed control mode is applied for 0 to 0.5 seconds and then torque control mode is enabled.

The q-axis reference W_{ref} is considered in model instead of I_{qr}. The approximated expression for d- axis comes to be:

$$V^*_{qr} = V'_{qr} = R_r I_{qr} + \sigma L_r\, dI_{qr}/dt$$

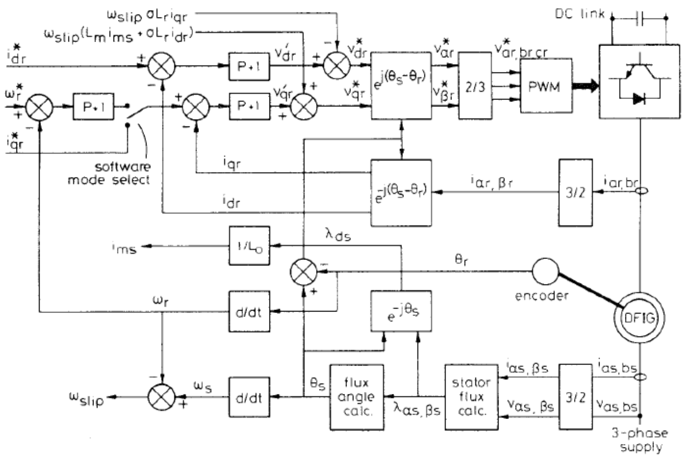

Fig. 3 Block diagram of rotor side converter control scheme [6]

In the model, the current reference PWM control scheme is applied. Therefore rotor current is split into two orthogonal components *d* and *q*. The voltage V^*_{dr} (or V'_{dr}) and (V^*_{qr}) or V'_{qr} of block diagram are replaced & modeled as I_{rd} and I_{rq}. The reactive power controls the voltage magnitude and power factor at the grid within limits, the reactive powers are taken to be input to comparator. They both are compared and after PI controller defines the accurate instantaneous value of I_{rd}, which controls reactive power Q_g.

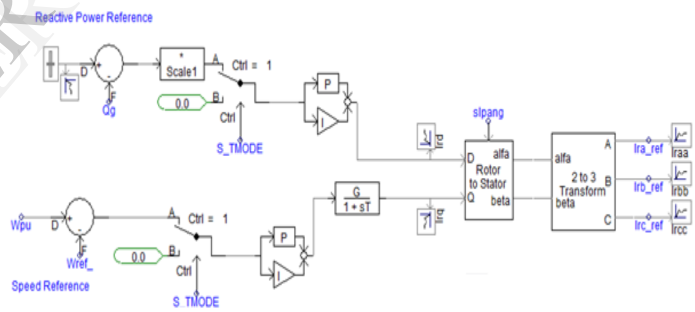

Fig. 4 Model of generation of reference currents in RSC

Here *q* component of the current is used to regulate the torque. The torque controller in the loop modifies magnitude of electromagnetic torque in accordance to the variation to wind speed and produce reference active power operating point.

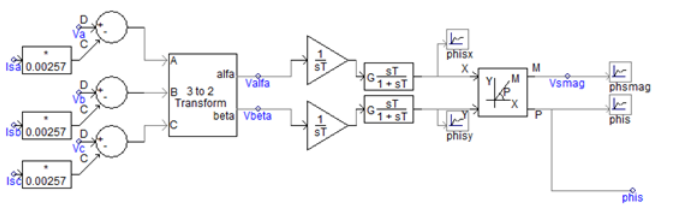

Fig. 5 Determination of location of stator flux

The reference torque calculation includes the rotor speed ω_r magnitude and is inferred from MPPT WT characteristics. Further q-axis reference current I_{rq} is decided by manipulating torque magnitude [3].

The present location of stator flux (ϕ_s) or *phis* is determined in order to convert *dq* variables from synchronous frame to stationary. The *phis* ϕ_s can be determined by transforming stationary stator voltages to rotating axis components or α-β components using Clarke transformation. The α and β components are orthogonal and denoted by λ_α and λ_β, the stator flux angle ϕ_s is expressed as.

$$|\lambda| = \sqrt{\lambda_\alpha^{\,2} + \lambda_\beta^{\,2}}, \quad \phi_s = \tan^{-1}(\lambda_\beta / \lambda_\alpha)$$

In this model, ϕ_r is measured by the induction generator itself. The other parameters measured by it are T_m T_e and $W_{p.u.}$. Now consider rotor is rotating and having instant location at an angle ϕ_r and reference frame is with respect to rotor, then stator magnetic field vector location is expressed as ϕ_s- ϕ_r, which we refer to the "slip angle" ϕ_{slip} .

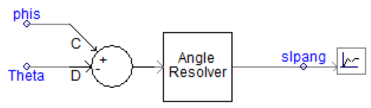

Fig. 6 Model of determination of slip angle

Once the reference currents are determined, the actual current are compared with them and the current-reference pulse width modulation output obtained are used as firing pulses to RSC in order to get desired phase current waveforms.

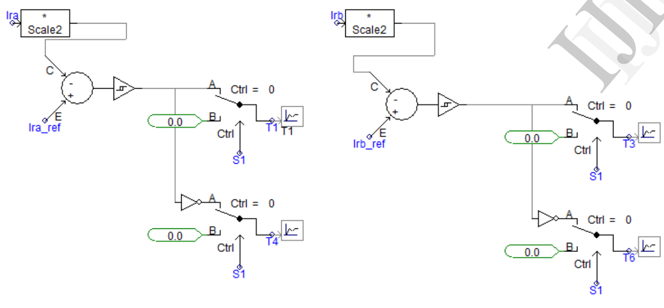

Fig. 7 Model of Rotor Side Converter PWM

In this way the desired *Ira*, *Irb* and *Irc* are synthesized. More the precise waveform of *Ira*, *Irb*, *Irc* are obtained, better will be controlling of reactive power and rotor speed and hence determines the status of stability.

C. Voltage oriented control –GSC control

Here VOC is implemented at grid side converter system and oriented along synchronous reference frame, all variables are in steady state i.e. DC magnitudes. For realization of VOC, the grid voltage needs to be measured and grid angle θ_g is to be detected. The grid angle θ_g is used for grid voltage transformation from stationary 3 phase to *dq* synchronous frame and vice versa. Let us consider V_a ,V_b ,V_c are 3-phase balanced sinusoidal voltages and V_{alpha} & V_{beta} are rotating voltages. V_{alpha} & V_{beta} are determined through Clarke's transformation obtained from 3-phase balanced voltages; then grid angle θ_g can be expressed as

$$\theta_g = tan^{-} (V_{beta} / V_{alpha})$$

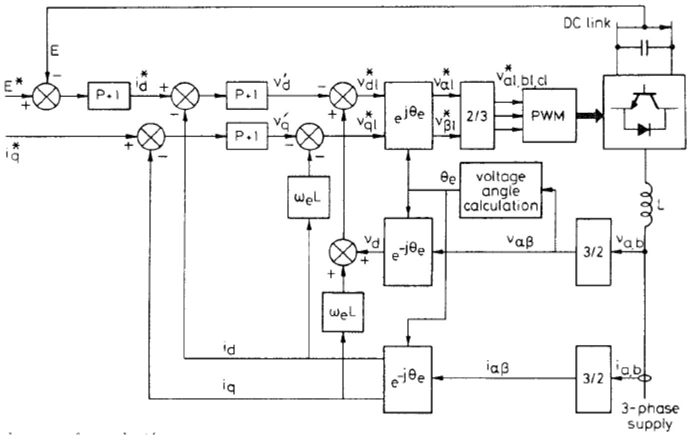

Fig. 8 Block diagram of Grid Side Converter control scheme [6]

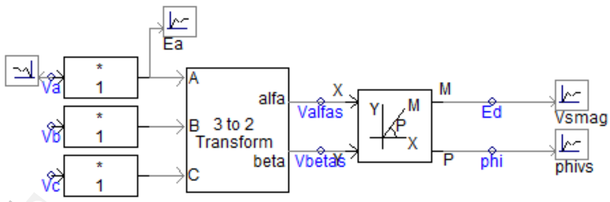

Fig. 9 Determination of stator phase angle in GSC

The VOC scheme has three feedback control loops; two of them are inner control loops for controlling of *dq* current components i_{1d} and i_{1q} and third feedback loop is DC voltage loop and this is to control capacitor /DC link voltage E_{cap} to maintain constant magnitude. In this scheme, 3-phase line currents i_{1a}, i_{1b}, and i_{1c} of stationary frame are transformed to *dq* synchronous frame and these *dq* components i_{1d} and i_{1q} are responsible for active and reactive components of 3-phase line currents. These i_{1d} and i_{1q} components are controlled independently so as to control active and reactive power respectively and provide better control of DFIM system.

In order to achieve VOC control scheme, *d*-axis of synchronous frame is oriented to grid voltage vector V_{dg}, or V_{dg} = V_g and remaining *q*-axis grid voltage V_{qg} is equal to zero as inferred by the following expression

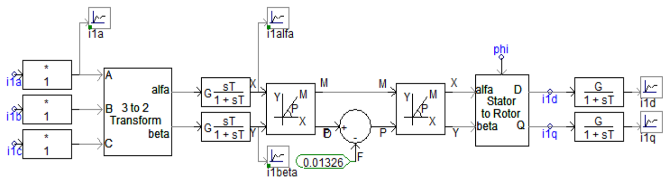

Fig. 10 Determination of *dq* stator current

$$P_g = 3/2\ [V_{dg} * i_{1d} - V_{qg} * i_{1q}];$$

$$P_g = 3/2\ [V_{dg} * i_{1d}]$$

$$Q_g = 3/2\ [V_{qg} * i_{1d} - V_{dg} * i_{1q}]\ ;$$

$$Q_g = 3/2\ [- V_{dg} * i_{1q}] \qquad \text{for } V_{qg} = 0$$

Similarly the *q*-axis reference current $i_{qref}*$ can be expressed as

$$i_{qref}* = Q_g* / (-1.5* V_{dg})$$

Here Q_g* stands for reference reactive power, its magnitude is zero due to unity power factor operation. The DC link voltage of capacitor E_{cap} is kept constant as its reference voltage E_{capref} is maintained at constant magnitude. Therefore magnitude of *d*-axis current generated i_{dg*} is in accordance to the operating conditions and it is generated through proper tuning of PI controller. If the losses in the inverter operation is neglected, then DC power of dc link will be equal to the magnitude of active power produced on AC side mathematically, this condition can be expressed as

$$P_g = 3/2\ [V_{dg} * i_{1d}] = E_{cap} * i_{1d}$$

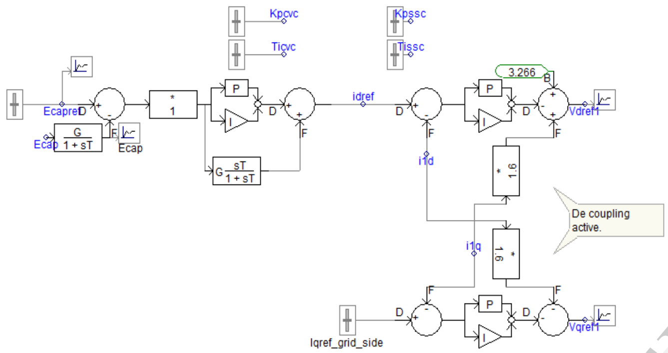

Fig. 11 Model of generation of reference *dq* voltages

In effect, the Grid side converter is supplying the real power demands of the rotor side converter. It is possible to control the *d* axis current by controlling the *d*-component of the SPWM output waveform and the *q* axis current via the *q* component. However, this leads to a poor control system response, because attempting to change i_d also causes i_q to change transiently. Hence, modifications have to be made to decoupled response. The PI controller makes the decoupled control design more convenient and makes the system output more accurate, precise and stabilized [7]. If these reference voltages Vd_{ref1} and Vq_{ref1} are applied at the secondary of the transformer, the desired currents *idref* and *iqref* will flow in the circuit.

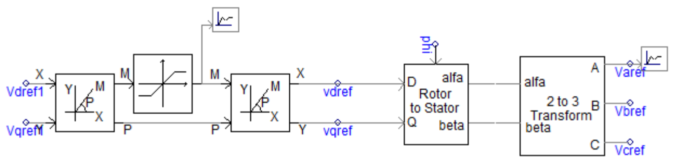

Fig. 12 Generation of voltage reference

The remaining parts of the controls are standard PWM controls in which each of the phase voltages is compared with a high frequency triangle wave to determine the firing pulse patterns.

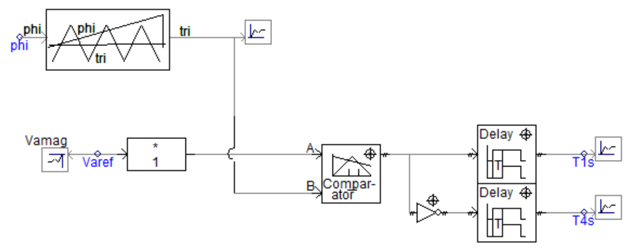

Fig. 13 Model of generation of firing pulses by PWM

D. Crowbar Protection

For the hardware protection in converters, the crowbar protection is used frequently. This is installed between RSC and rotor terminals. These are specially used for overvoltage condition created due to malfunctioning or damage of converters. In this case heavy current is passed through RSC to rotor terminals. The crowbar circuit provides alternate path and reduce the magnitude of over current spikes and bring it to normal magnitudes to provide stable operation in abnormal conditions. The crowbar can also provide LVRT capability i.e. eliminating short circuit conditions without disconnecting turbine from grid. [4]

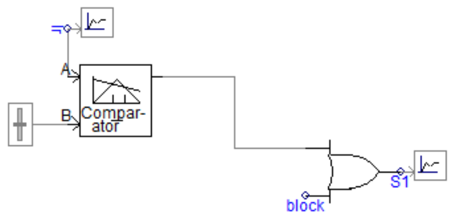

Fig. 14 Crowbar Protection for RSC

Ir is rotor current which is compared with threshold value. When it becomes greater than that value, *S1* operates & crowbar becomes active.

IV. RESULTS AND DISCUSSIONS

The single line diagram in the model is as follows

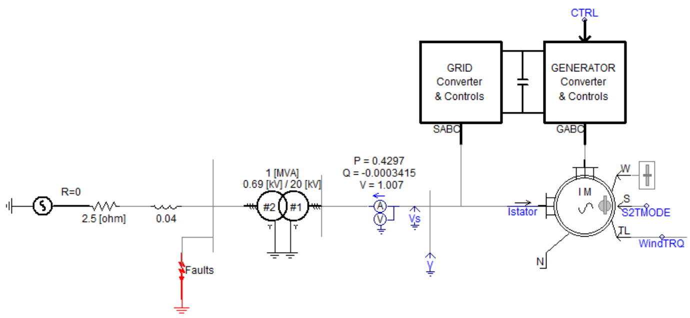

Fig. 15 Single line diagram of grid interconnection

It consists of induction generator, Wind Park, grid side & rotor side converter, step up transformer, transmission line and grid. The base MVA is 1 p.u. and the generated voltage is set to 0.69 KV, which is fed to grid via step up transformer. In the model, wind park, converter and induction generator are modeled is based on p.u. values. At the secondary side of transformer, symmetrical fault is modeled.

The Induction Machine is made to operate on speed control mode from $0 < t < 0.5$ second and then mode is changed to torque control mode. Until this time ($t=0.5$ *sec*), the machine will rotate at $W = 0.55$ *p.u*. At $t = 3$ second fault occurs, the dynamic variation of active power, reactive power, Mechanical torque and rotor speed is analyzed for stability aspects. Also the induction machine is subjected to the step change in the wind speed at $t = 8$ second. The induction machine is made to operate in super synchronous mode. ($Wref = 1.054$ *p.u*.)

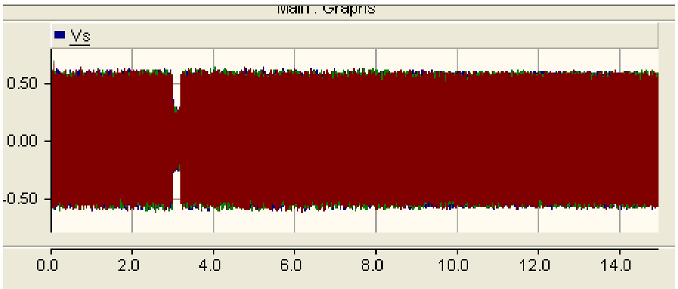

Fig. 16 Voltage magnitude (in p.u.)

When Fault occurs, voltage magnitude dips to 0.38 p.u. from 0.69 p.u.

During grid connectivity, rotor speed dips up to 1.05 p.u. from 1.054 p.u. In case of fault, rotor speed rises and oscillates.

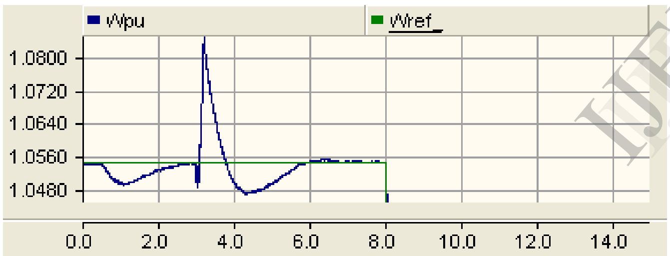

Fig. 17 Actual & Reference rotor speed (in p.u.)

The wind speed changes to 10.5 m/sec from 11.5 m/sec. at $t = 8$ second. The rotor speed *Wp.u*. decreases as *Wref* decrease.

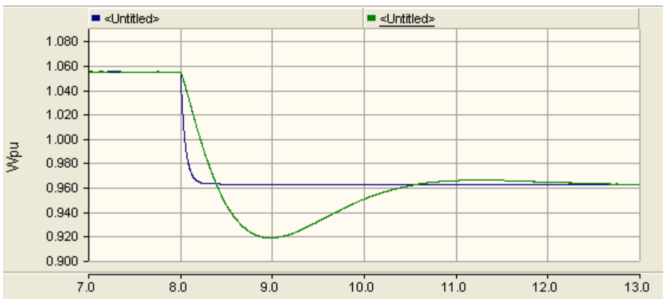

Fig. 18 Actual & Reference rotor speed (in p.u.)

The stator side voltage and current at the time of prefault, fault & postfault are shown in figure. At prefault condition, the voltage and current waveform maintains outphase relation (180 degree) approximately [8]. So the active power supplied is almost constant. But in fault duration, voltage dips and current spikes, hence active power dips and occurs oscillations in reactive power.

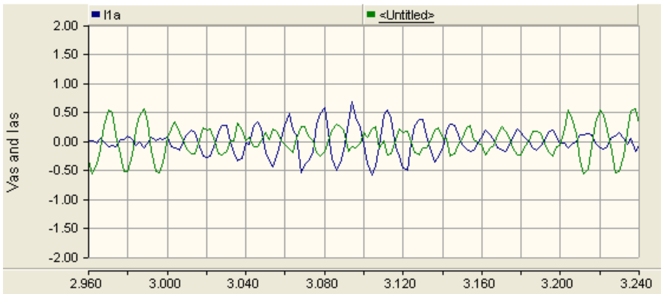

Fig. 19 Stator voltage & stator current

At last the power gets decrease due to drop in wind speed.

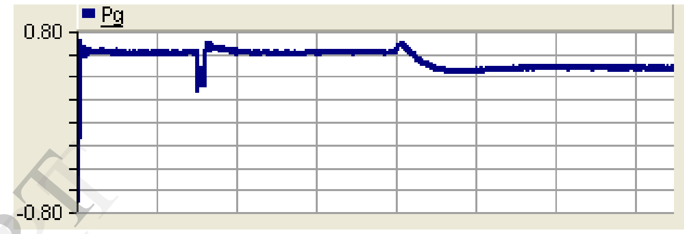

Fig. 20 Active power supplied to grid (in p.u.)

Similarly the reactive power is supplied at the time of fault or grid interconnection.

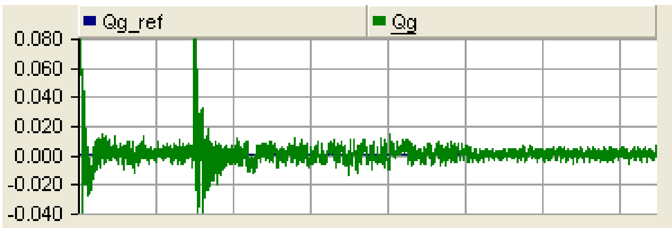

Fig. 21 Reactive power supplied to grid (in p.u.)

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A. Rotor side Converter (Current Reference PWM):

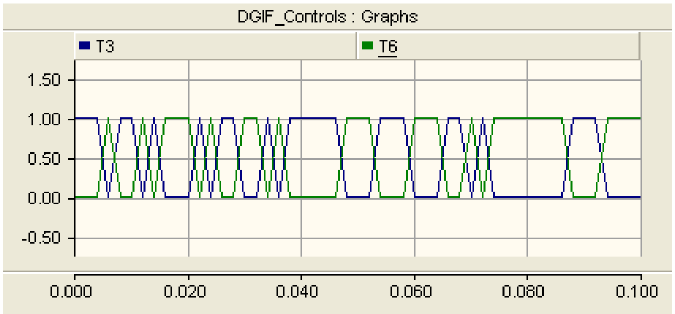

Fig. 22 Generation of firing pulses (RSC)

The *T3* and *T6* are fired in consecutive in order to control the tracking of I_{rb_ref}. Similarly I_{ra} and I_{rc} are also synthesized.

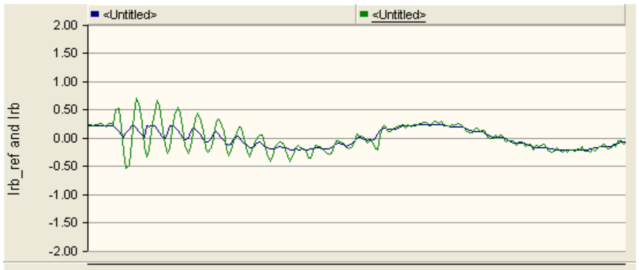

Fig. 23 Stator current chasing reference current of b-phase

B. Grid side Converter (Voltage oriented Control)

As the model is run at super synchronous mode the direction of active power will be RSC to GSC. The magnitude of active power at normal conditions

$P_g = E_{cap} * i_{1d} = 0.8*(-0.772) = -0.62$ p.u

The negative sign indicates that the power is generated not absorbed.

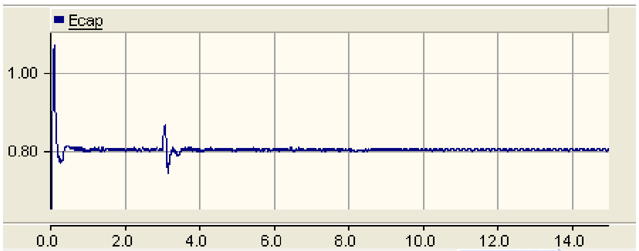

Fig. 24 Actual & Reference Capacitor voltage of DC link

$Q_g = 3/2\ [- V_{dg} * i_{1q}]$, i_{1q}

Oscillates are at zero magnitude in graph, so reactive power is just oscillating as that of i_{1q}.

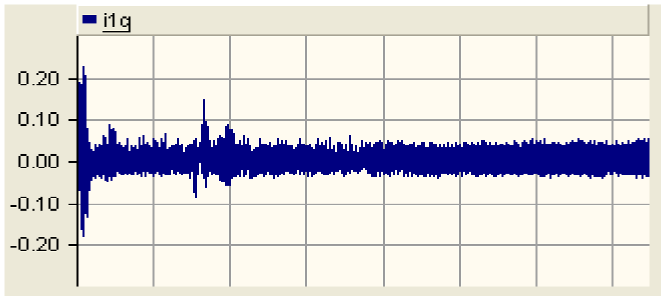

Fig. 25 q axis current in GSC Scheme

C. Crowbar Protection

The rotor current *Ir* has constant magnitude in normal conditions. At the condition of fault, it spikes to 0.7 p.u. but it is below the threshold value. So the switch *S1* remains at off state i.e. at 0.

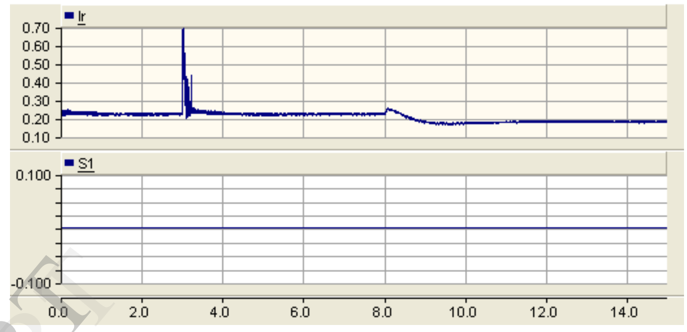

Fig. 26 Rotor current & Status of crowbar switch

V. CONCLUSION

The PSCAD simulation results verify that the control schemes used in the RSC and GSC increases the fault ride through capability of DFIG as compared to conventional protection schemes. The transient characteristics of voltage at faulty condition recovered in a very short time due to adequate supply of reactive power to grid. This ensures better power quality status at the abnormal conditions. Also variation in rotor speed is controlled effectively to ensure stability aspects. The active & reactive power flow is made independent by the decoupling method resulting in better control & performance of DFIG. Hence the operation of hardware protection is not frequent.

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