



BEHAVIOUR ANALYSIS OF DOUBLY FED INDUCTION GENERATOR BASED WIND TURBINE SYSTEM DURING GRID DISTURBANCES

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Abstract: The fault response of doubly fed induction generator (DFIG) based wind turbine is analyzed and summarized with vector control scheme to show the influence on the dynamic behavior of the wind turbine system against this operation condition as fault ride through (FRT) enhancement. The theoretical fault simulations for voltage sag magnitude calculation are included utilizing Simulink, based on the SimPowerSystems toolbox, and also considering protection-systems modeling for sag duration calculation.

Keywords: DFIG, Voltage dip, Fault Ride- through (FRT).

تحليل اداء مولد حثي ثنائي التغذية باعتماد منظومة عتفة الريح خلال اضطرابات الشبكة الكهربائية

الخلاصة: تم تحليل استجابة الخطاء لاداء مولد حثي ثنائي التغذية باستخدام السيطرة الاتجاهية لغرض بيان الاداء الديناميكي لمنظومة عتفة ريح في ظروف عمل متعددة لغرض دعم خاصية عبور الخطأ و تم استخدام النمذجة.

1. Fault Ride- Through (FRT) in DFIG System

Doubly fed induction generator (DFIG) based wind turbines shown in figure (1) have certainly arisen as one of the leading technologies for wind turbine manufacturers, demonstrating that it is a cost effective, efficient, and reliable solution which attractive in both grid-connected and stand-alone operation. In this system, the rotor winding is connected to the grid via back-to-back power converter which for restricted speed range, with rated at a fraction of the machine rated power (typically 25-30% of nominal) [1].

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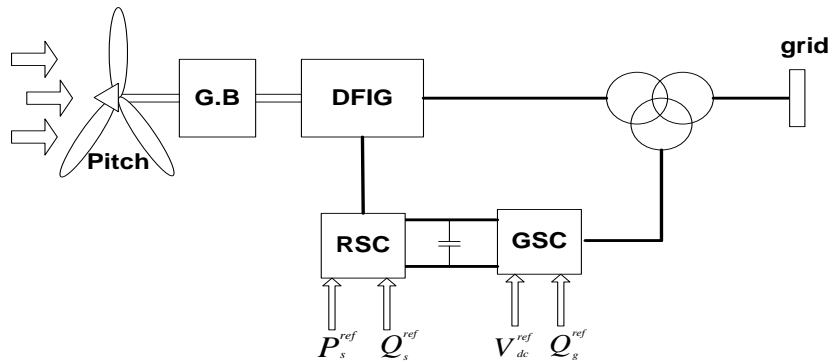


Figure (1) System construction of DFIG.

FRT is the ability of wind turbine (WT) to continues connected to the power grid even when the voltage across the point common coupling (PCC) drop to zero. This requirement is essential in the new grid code of power system in different countries since the isolated of the WT from the grid system at condition of sever voltage dips will lead to loss stability in power system. Grid code requirements vary considerably from region to region and from system to system. The grid codes in a certain country may only cover a part of the specific grid codes requirement.

The differences in requirements, besides local traditional practices, are caused by different wind power penetrations and by different degrees of power network robustness [2] [3]. The grid codes are put in place for all power generating plants transferring power to the grid, these are to increase the power transfer efficiency and decrease damage caused to grid-connected devices[4] [5].

According to new grid code requirements, one of the tasks of wind turbines that it must remain connected to the grid during grid disturbances.

Moreover, they must also contribute to voltage support during and after grid faults. Basically; the configuration of the DFIG has the stator circuit directly connected to the grid, while the rotor winding is connected to the grid via the back-to-back converter, and this is the reason for all efforts made to develop the FRT capability.

The case of power grid system faced the condition of voltage drop at the PCC; the stator voltage of the DFIG will immediately change and if it not suddenly varies the rotor voltage will be compensate the dropping in stator voltage and this will drive to oscillate the stator and rotor currents with high incremental in its values [6].

This disturbance in the stator and rotor currents will cause to damage the rotor converter and to increase the mechanical stress on the wind turbine as results of the transient in electromagnetic torque of the generator.

The wind energy conversion system (WECS) can only be disconnected from the grid during a fault condition which causes the a voltage drop exceeding the limit line, figure (2) depicted the ratio as a percentage of the actual voltage and normal voltage of the grid against time, during low voltage ride through (LVRT) the systems requires reactive power from the WECS this reduces the instabilities to the to the grid voltage. Therefore the wind farms are required to remain on line during voltage disturbances up to specified time periods and associated voltage levels.

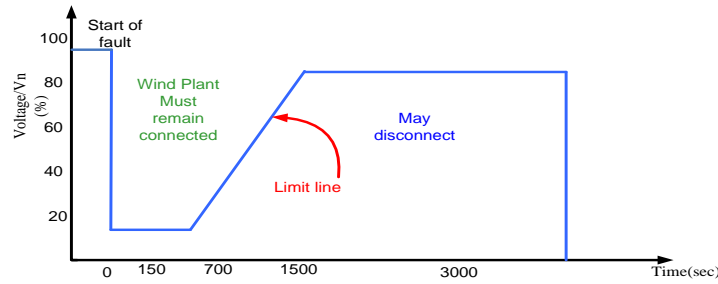


Figure (2): Typical voltage dip limit for LVRT [7] [3].

A key issue of concern regarding DFIG performance is that of fault ride-through. Network faults produce rapid voltage dips in any of the three phases connecting to a generating unit. The standard DFIG system is sensitive to such severe dips, inducing large transient currents in the stator and rotor circuits and risking overcurrent damage to the power electronic devices in the converters. Traditionally, to protect these devices the rotor circuit is typically shorted or ‘crowbarred’, resulting in a considerable demand of reactive power from the grid, exacerbating the voltage problem [8].

The crowbar protection system is one of the equipment uses to avoid the disconnection of the DFIG wind generators from the network during faults. The insertion of the crowbar in the rotor circuits for a short period of time to isolate the rotor side converter (RSC). As a general rule, the activation and the deactivation of the crowbar system is based only on the DC-link voltage level of the back-to-back converters [4] [5]. When faults occur and cause voltage dips, subsequently the current flowing through the power converter may be very high over-current. During this situation, it is common to block the converter to avoid any risk of damage, and then to disconnect the generator from the grid [9] [10].

The disadvantage of utilizing the crowbar is that the RSC has to be disable when the crowbar is activated and this mean the generator is start to consume reactive power leading to further deterioration of the grid voltage even some studies employ an active crowbar control scheme to enhanced the FRT ability but this modification not avoid the consumption of reactive power [11], [12]. The conventional scenarios of DFIG operation during normal and disturbance conditions explained in table (1).

Table (1): Summery of the conventional modes of DFIG based WT operation in normal and fault conditions

Normal Mode Operation	$V < \text{nominal}$	RSC	Tracking the Max Power
		GSC	Regulate the v_{dc}
		$\beta(\text{pitch blade angle})$	Set $\beta = 0$
	$V > \text{nominal}$	RSC	Limiting the Power capt.
		GSC	Regulate the v_{dc}
		$\beta(\text{pitch blade angle})$	Activated to limit power
Fault Mode Operation	Crowbar	Activated by inserted in series with the rotor windings	
	RSC	blocked	
	GSC	control reactive power	
	β	set to diminish the energy capture from the wind	
	crowbar	Removed after 100 ms	
	RSC	restarted	

2. Analysis of DFIG Performance During Voltage Dips

Based on the voltage and flux equations in stationary reference frame, the mathematical modeling of DFIG characterized by [13]:

$$v_s^s = r_s i_s^s + \frac{d}{dt} \lambda_s^s \quad (1)$$

$$v_r^s = r_r i_r^s + \frac{d}{dt} \lambda_r^s - j \omega_r \lambda_r^s \quad (2)$$

$$\lambda_s^s = L_s i_s^s + L_m i_r^s \quad (3)$$

$$\lambda_r^s = L_m i_s^s + L_r i_r^s \quad (4)$$

Where, $v_s^s, v_r^s, i_s^s, i_r^s, \lambda_s^s, \lambda_r^s$ are the stator and rotor voltages, currents, and flux vector; r_s, r_r represent the stator and rotor resistance; L_s, L_r the stator and rotor self-inductance; L_m the mutual inductance; ω_r the rotor angular speed. From equation (3); the stator current is:

$$i_s^s = \frac{1}{L_s} (\lambda_s^s - L_m i_r^s) \quad (5)$$

Then substitute (5) in (4) to eliminate the stator current from rotor flux:-

$$\lambda_r^s = \frac{L_m}{L_s} \lambda_s^s + L_r \sigma i_r^s \quad (6)$$

Where $\sigma = 1 - L_m^2/L_s + L_r$, the rotor voltage in equation (2) will have the following expression:

$$v_r^s = \frac{L_m}{L_s} \left(\frac{d}{dt} - j \omega_r \right) \lambda_s^s + (r_r + L_r \sigma) \left(\frac{d}{dt} - j \omega_r \right) i_r^s \quad (7)$$

Where the term $\left(\frac{L_m}{L_s} \left(\frac{d}{dt} - j \omega_r \right) \lambda_s^s = v_{ro}^s \right)$ is the rotor voltage at open circuit and it due to the stator flux of magnetic coupling and the later term in equation (7) is the voltage result from rotor side circuit (RSC) and crowbar.

In normal condition, the space vector of the stator voltage is:

$$v_s^s = v_s e^{j \omega_s t} \quad (8)$$

Where v_s is the constant amplitude, now sub (8) in (1), then:

$$v_s e^{j \omega_s t} = r_s i_s^s + \frac{d}{dt} \lambda_s^s \quad (9)$$

With neglect the stator resistance and take the integration for both sides of (9):

$$\frac{v_s}{j \omega_s} e^{j \omega_s t} = \lambda_s^s \quad (10)$$

Substitute (10) in the term of the rotor open circuit:

$$v_{ro}^s = \frac{S.L_m}{L_s} v_s e^{j\omega_s t} \quad (11)$$

Knowing that (s) in (11) is the slip. The maximum value of the rotor open circuit is:

$$v_{ro}^s = \frac{S.L_m}{L_s} v_s \quad (12)$$

Then the total value of rotor voltage will be:

$$v_r^s = \frac{S.L_m}{L_s} v_s + (r_r + L_r \sigma \left(\frac{d}{dt} - j\omega_r \right)) i_r^s \quad (13)$$

In condition of three phase voltage dips occurs and the DFIG performance under this operation can be investigate by define the limits and values of the voltage amplitude during the voltage dips ($v_0 > v_1$):

$$v_s^s = \begin{cases} v_0 e^{j\omega_s t} & \text{for } t < t_0 \\ v_1 e^{j\omega_s t} & \text{for } t > t_0 \end{cases} \quad (14)$$

By substitute (5) in (1) with assume the condition the open rotor circuit ($i_r^s = 0$):

$$v_s^s = \frac{r_s}{L_s} \lambda_s^s + \frac{d}{dt} \lambda_s^s \quad (15)$$

And by solve the differential equation, the stator flux in condition of voltage dips:

$$\lambda_s^s = \frac{v_1}{j\omega_s} e^{j\omega_s t} + \frac{v_0 - v_1}{j\omega_s} e^{-jt/\tau_s} \quad (16)$$

Where :

- $\frac{v_1}{j\omega_s} e^{j\omega_s t}$ (forced flux) is the rotation flux space vector corresponding to the grid during voltage dips
- $\frac{v_0 - v_1}{j\omega_s} e^{-jt/\tau_s}$ (nature flux) is the fixed flux of the stator which decreasing exponentially to zero by the stator time constant ($\tau_s = \frac{L_s}{r_s}$).

Substitute the stator flux (16) in the rotor open voltage equation:

$$v_{ro}^s = \frac{L_m}{L_s} (s \cdot v_1 e^{j\omega_s t} - (\frac{1}{\tau_s} + \omega_r) \frac{v_0 - v_1}{\omega_s} e^{-jt/\tau_s}) \quad (17)$$

With assume ($\frac{1}{\tau_s} \ll \omega_r$):

$$v_{ro}^s = \frac{L_m}{L_s} (s \cdot v_1 e^{j\omega_s t} - (1 - s)(v_0 - v_1) e^{-jt/\tau_s}) \quad (18)$$

And the then the maximum rotor voltage:

$$v_{ro}^s = \frac{L_m}{L_s} (|s|v_1 + (1-s)(v_0 - v_1)) \quad (19)$$

3. Improve the Control to Support the FRT Ability of DFIG

Different methods have been investigated to enhance the DFIG based wind turbine to ride through the severe voltage dips across the PCC without using the crowbar which all focuses on reducing the stator/ rotor overcurrent. These techniques of control have advantages upon the conventional FRT methods since it make full use of existing resources with the DFIG-WT without need of additional hardware components which costly and more complex to maintenance in addition the new strategies will erasure the back – to- back converter will continues connected to the DFIG even the grid suffer from the voltage drop. Firstly it needs to formulate the stator and rotor current in term of stator voltage to approximately describe the influence of voltage on these currents. The stator voltage and flux in synchronous reference frame formulated as:-

$$v_{ds} = r_s i_{ds} + j\omega_e \lambda_{ds} + \frac{d}{dt} \lambda_{qs} \quad (20)$$

$$v_{qs} = r_s i_{qs} + j\omega_e \lambda_{qs} + \frac{d}{dt} \lambda_{ds} \quad (21)$$

$$\lambda_{ds} = L_s i_{ds} + L_m i_{dr} \quad (22)$$

$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr} \quad (23)$$

Applying the Laplace transformation on equations (20) and (21) and after substitute (22) and (23) in (20) and (21), the stator currents can be formulated in term of stator voltages and rotor currents as following:

$$i_{ds} = \frac{(L_s S + r_s) v_{ds} + L_s \omega_s v_{qs}}{L_s^2 S^2 + 2L_s r_s S + r_s^2 + L_s^2 \omega_s^2} - \frac{(L_s S^2 + r_s S + L_s \omega_s^2) L_m i_{dr} - \omega_s L_m r_s i_{qr}}{L_s^2 S^2 + 2L_s r_s S + r_s^2 + L_s^2 \omega_s^2} \quad (24)$$

$$i_{qs} = \frac{(L_s S + r_s) v_{qs} - L_s \omega_s v_{ds}}{L_s^2 S^2 + 2L_s r_s S + r_s^2 + L_s^2 \omega_s^2} - \frac{(L_s S^2 + r_s S + L_s \omega_s^2) L_m i_{qr} + \omega_s L_m r_s i_{dr}}{L_s^2 S^2 + 2L_s r_s S + r_s^2 + L_s^2 \omega_s^2} \quad (25)$$

And with simplification (24) and (25) by assume $\lambda_{ds} = \lambda_s$, $\lambda_{qs} = 0$, $v_{ds} = 0$, $v_{qs} = v_s$, $L_m \ll L_s, L_r$, then:

$$i_{ds} = \frac{\omega_s v_{qs}}{L_s (S^2 + \frac{2r_s S}{L_s} + \omega_s^2)} - \frac{L_m i_{dr}}{L_s} \quad (26)$$

$$i_{qs} = \frac{(S + \frac{r_s}{L_s}) v_{qs}}{L_s (S^2 + \frac{2r_s S}{L_s} + \omega_s^2)} - \frac{L_m i_{qr}}{L_s} \quad (27)$$

In the configuration of Null the active and reactive power reference , as soon as the voltage dips detect, a switch will activated to switching the active and reactive stator reference power in the outer loop control in RSC will set to zero to limit the fluctuating

of stator and rotor currents as shown in figure(3). Thus the condition of this method is [2][13]:

$$P_s^{ref} = \frac{3}{2} v_{qs} \quad i_{qs} = 0 \quad (28)$$

$$Q_s^{ref} = -\frac{3}{2} v_{qs} \quad i_{ds} = 0 \quad (29)$$

Therefore the rotor currents will be:

$$i_{dr} = \frac{\omega_s v_{qs}}{L_m(S^2 + \frac{2r_s S}{L_s} + \omega_s^2)} \quad (30)$$

$$i_{qr} = \frac{(S + \frac{r_s}{L_s})v_{qs}}{L_m(S^2 + \frac{2r_s S}{L_s} + \omega_s^2)} \quad (31)$$

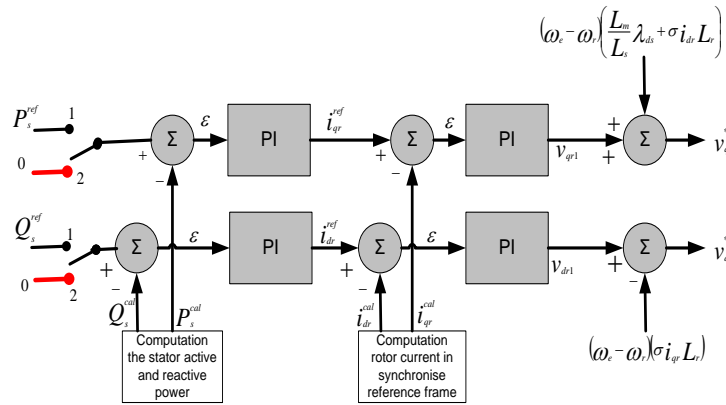


Figure (3). Null the active and reactive power reference set values method.

4. Simulation Results

This section include the simulation model of the DFIG based wind turbine which have been built in MATLAB/SIMULINK® platform as shown in appendix depending on the theoretical analysis with grid connected case.

The testing is applied on the DFIG system with sensed vector control and subject constant wind speed. The wind profile signal applied to drive the mechanical parts of the DFIG wind turbine system; this wind speed signal is utilized for a realistic, reliable and accurate simulation analysis. Two scenarios have been adopted normal and voltage dip condition respectively to evaluate the ability of PQ null method which used to enhance the DFIG based wind turbine FRT ability by run the generator.

Case study (1): Performance of DFIG System Grid Connected without Protection

In this investigation the DFIG is subjected to severe voltage dip with drop value 80% depth for a period (0.5-0.6 sec). The RSC and GSC both have been controlled using the vector control with assume the DFIG system produce zero reactive power and nominal rated active power injected to the grid during constant wind speed (4 m/sec) during this

simulation, when the reductions in the stator flux result from the voltage dip, the flux components (direct and quadrature) will fluctuate during the voltage dip and after the clearance of the fault. In addition, the q -axis stator flux cannot maintain to be zero due to the voltage dip.

As shown in figure (4) and figure (5) the voltage dip of 80% conducted to the terminal of the DFIG system have lead it to a transient overcurrents in both stator and rotor windings as illustrated in figures (6) - (9) with incremental about 2 pu then it will decay exponentially subjected to the RSC which cause a large stress upon it, in addition the step incremental clearly depicted in the total *rms* grid current in figure (10) as results of the sage condition.

On other hand the DC link voltage increase oscillatory during the voltage dip until it reach limit and then it will return to smooth regulate around the set value after fault remove as depicted in figure (11).

The stator active and reactive power tracking the reference set points shown in figure (12) and figure (13) highlights, that the severity of system during the voltage dip period that both active and reactive power varied and lose controllability where the active power nearly to zero while the reactive power absorbed by the machine. At voltage dip initiation, vector control of the rotor side converter was provisionally lost.

The brief surge in power output is associated with the rapid demagnetization of the DFIG associated with large, oscillatory power (active and reactive) as illustrated in figure (12) and figure (13).

After clearance, the power controller required 20ms to settle the highly oscillatory output which it ability of recovery depend on the magnitude of recovery voltage and the stabilize generator speed. The reactive power rose quickly after fault initiation to the same peak level as the active power, 0.1 MVAR, before oscillatory decaying. After fault clearance, the DFIG start re-magnetized. However, this effect lasted for less than one system cycle.

It should be noted that during the voltage sag, active power delivered to the grid is not balanced (voltage dip increases active and reactive powers continue to swing as rotor speed varies) with the mechanical power obtained from the wind turbine. This causes an acceleration of the generator speed that in any case will be dangerous due to the exceptional moment of inertia of the drive train itself to compensate the power drop due to the voltage drop.

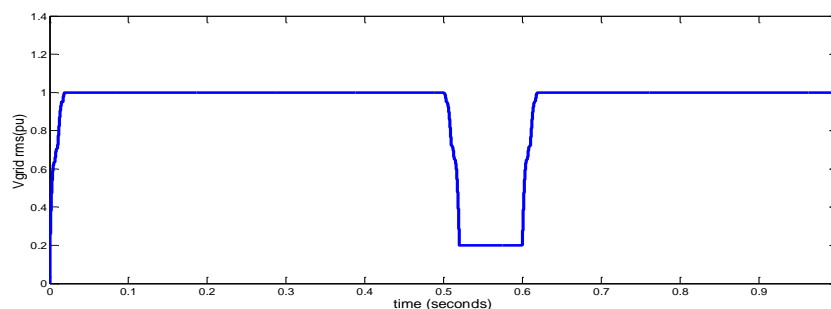


Figure (4): Instantaneous *rms* grid voltage

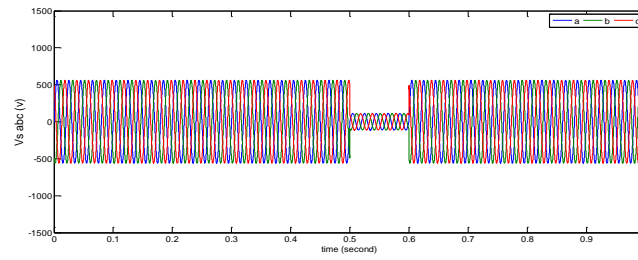


Figure (5): Instantaneous three phase stator voltage.

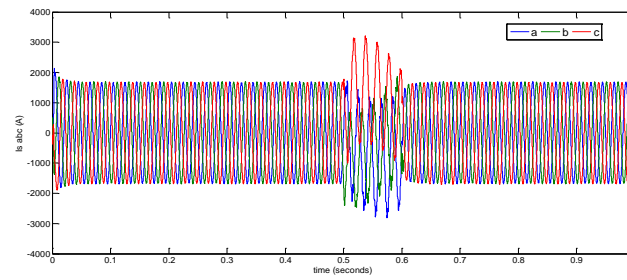


Figure (6): Instantaneous three phase stator current.

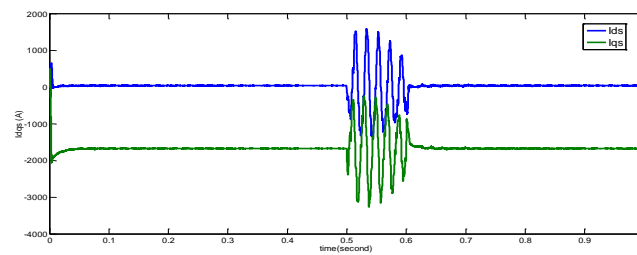


Figure (7): Instantaneous dq stator current.

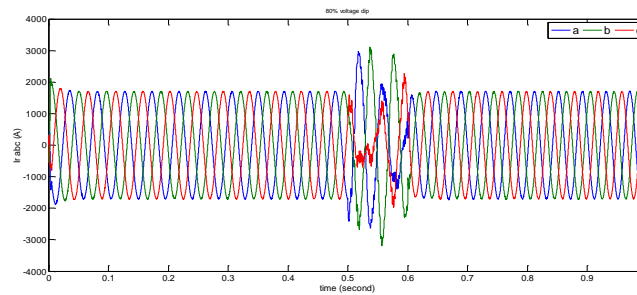


Figure (8): Instantaneous three phase rotor current.

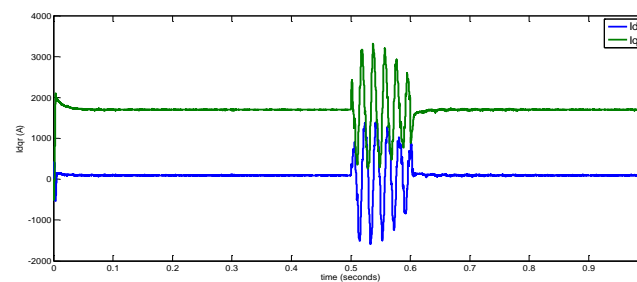


Figure (9): Instantaneous dq rotor current.

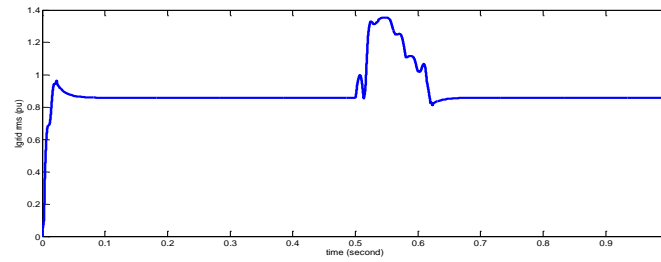


Figure (10): Instantaneous measurements of *rms* grid current.

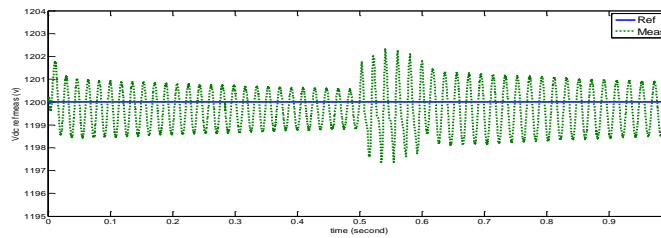


Figure (11): DC-link voltage regulator in the GSC.

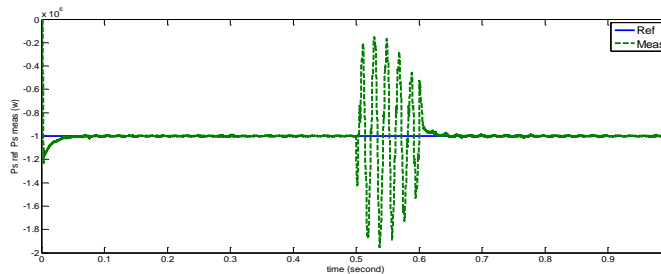


Figure (12): Instantaneous regulation of the stator active power in the RSC.

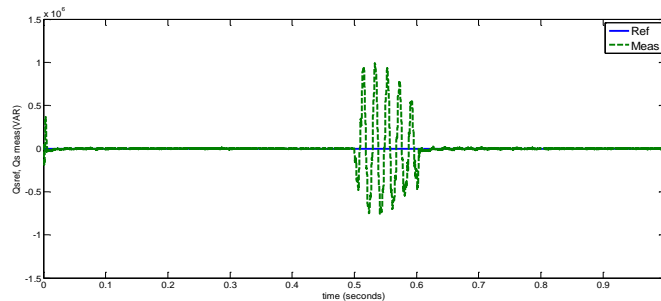


Figure (13): Instantaneous regulation of the stator reactive power in the RSC

Case study (2): Performance of DFIG System with *PQ* Null Modification during Disturbances

In order to study the validity of enhanced FRT by *PQ* null control strategy against voltage dips, a three-phase fault, which causes a voltage dip of about 80% depth and duration in range (0.5-0.6) second, at the stator terminal of the DFIG will be considered. With the constant wind speed (4 m/sec) in the grid fault calculation associated with *PQ* null method in the RSC. Immediately after the fault occurs at 0.5 second, the voltage at the wind turbine terminal drops, as it is shown in Figures (14) and figure (15). The DFIG reacts to the three phase voltage dip with dramatically incremental of stator currents and thus high rotor currents are induced in the rotor winding. At the moment when the stator voltage lower than the setting values in the detectors of faults, it will

directly activated the PQ null method by switch off the conventional power loop control and use the zero values as a reference sets to reduce over current of rotor/stator in parallel with regulate the DC bus voltage with acceptable fluctuation level as shown in figure(16), (19) and (24) where the PQ null prove its success to employed the available resources in stand of use the conventional protection devices. In Figure (16) and (19) the wind turbine system is protected by the PQ null solution and it's activated before the crowbar because it's very short voltage dip.

The stator and rotor currents are reduced. The stator currents decay slowly having a DC component. The RSC can stay in running and connected to the DFIG rotor windings. When the PQ null is activated the outer power control loops are disabled and thus active and reactive power controls are not achieved. The power control can be implemented to fulfill grid code requirements when the transients have decayed. After fault clearance the wind turbine system can continue with nominal operation.

Figures (16) - (25) illustrate the comparison response of this system vector control of to an 80% voltage dip. Rotor and stator currents begin to drop with the activation of the PQ null loop at the RSC without any crowbar engages at around 4m/s. Rotor and stator currents each approach with acceptable fluctuation around their pre-fault values. Voltage recovery allows sufficient control of the GSC currents to return the DC link voltage to the reference value. Figure (18) shows the response of the quadrature stator currents during the sag which oscillate around zero during sage duration, while the direct component exponentially fluctuated and then return to zero after end. When compare the reduction of rms value of grid current during the fault shown in figure (25) with condition of no protection. In figure (25), it's clear that the method with vector control successes to reduce the currents in the generator's windings during the fault.

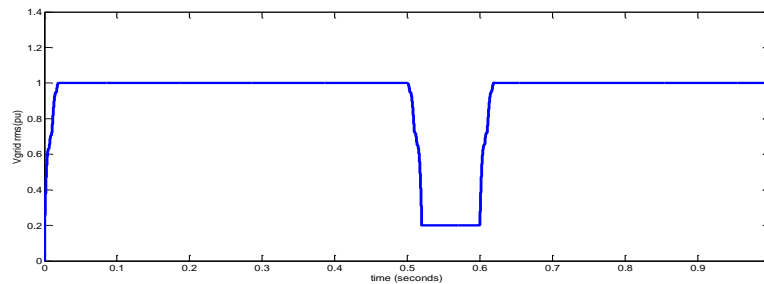


Figure (14): Instantaneous rms grid voltage.

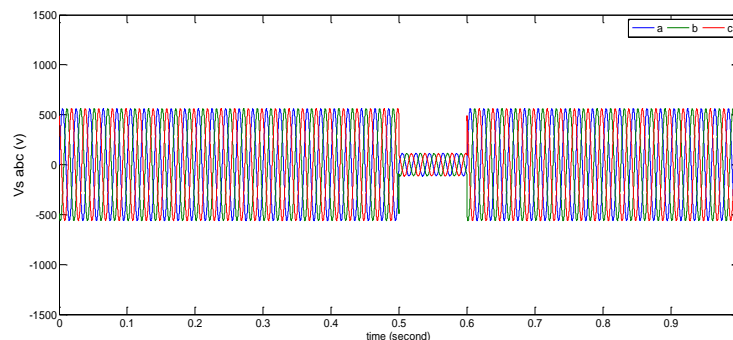


Figure (15): Instantaneous three phase stator voltage.

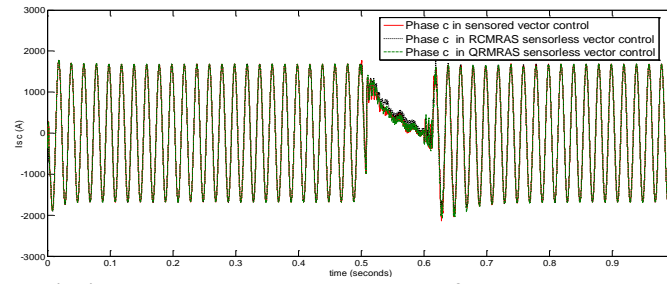


Figure (16): Instantaneous measurements of phase c stator current.

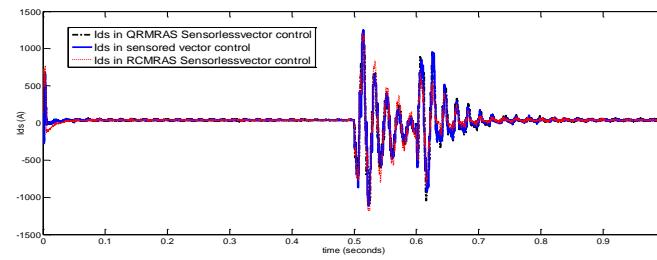


Figure (17): Instantaneous value of the d components stator current.

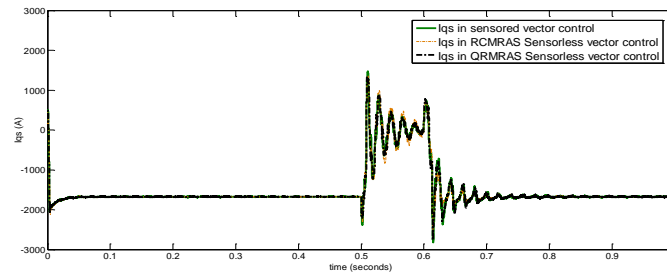


Figure (18): Instantaneous value of the q components stator current.

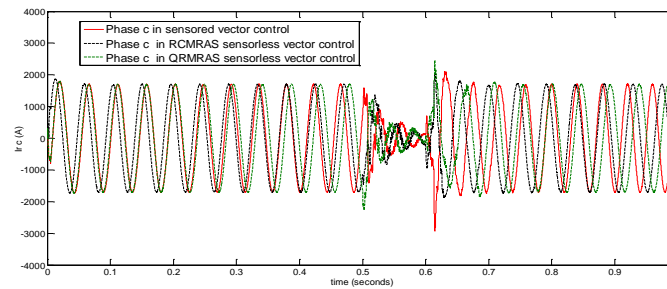


Figure (19): Instantaneous measurements of phase c rotor current.

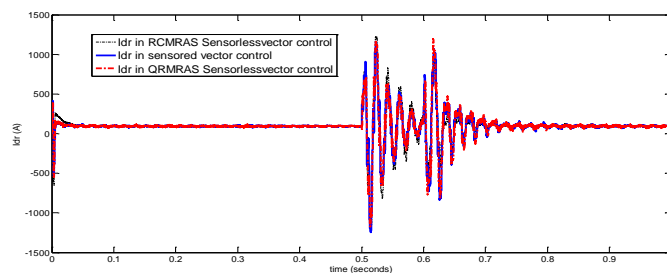


Figure (20): Instantaneous d -component rotor current.

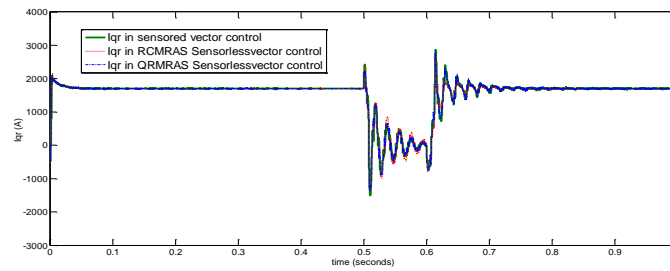


Figure (21): Instantaneous q -component rotor current.

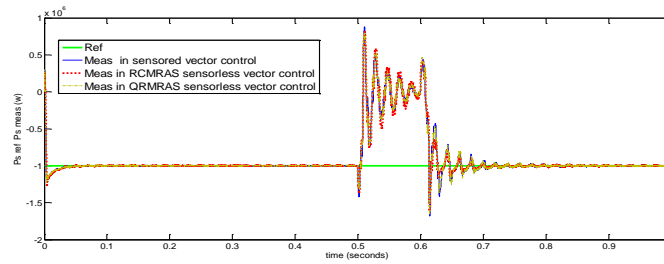


Figure (22): Instantaneous regulation of the stator active power in the RSC.

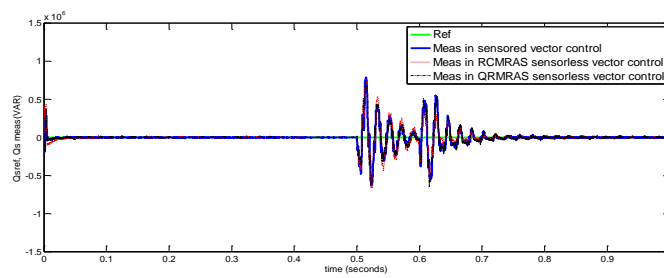


Figure (23): Instantaneous regulation of the stator reactive power in the RSC.

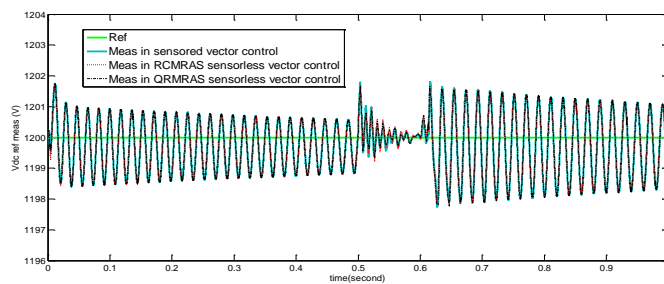


Figure (24): DC-link voltage regulator.

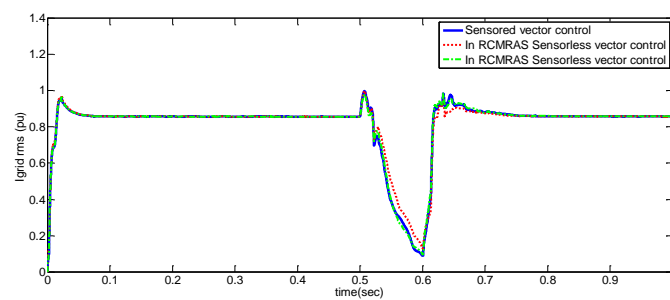


Figure (25): Instantaneous three phase grid current.

5. Conclusions

It is of great importance for new grid code requirements that the variable-speed wind turbines to remain connected to the grid network during severe grid voltage dips and contribute to voltage recovery in this condition. The necessities of fault ride through (FRT) have been explained and the requirements of the grid operators have been explained.

The fault ride through (FRT) ability of the DFIG based turbine is highly depending on the speed and the converter's ability to withstand heavy rotor current transients. The FRT behavior could thus be improved by over designing the electrical drive so that it can handle the big currents but this is limited by the commercial viability. Conventionally the crowbar system is utilized to isolate the rotor side converter (RSC) during voltage dips condition but this technique cause to isolate the RSC control, but with adopt a null the active and reactive reference power in the outer loop control of the RSC with full employing the available resource also it can be used as a back up to crowbar.

Abbreviations

General

C	Capacitance of the DC link
i	Current
L_r, L_s	Rotor and stator self-inductance
L_m	Magnetizing inductance
p	Pole pairs of induction machine
$P (Q)$	Active (reactive) power
v	Voltage
λ	Flux linkage
ω_r	Angular rotor speed (rev/s)
ω_e	Angular synchronous speed (rev/s)
θ_r	Rotor angular displacement position
σ	Total leakage coefficient, $\sigma = 1 - L_m^2 / L_s + L_r$

Superscripts

abc	Phase quantities
$\alpha\beta$	Stator fixed coordinates
dq	Synchronous rotating coordinates
r, s, m	Rotor, stator, magnetizing quantities

Subscripts

ref	Reference value
adb	Adaptive value

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Appendix – A

1) Induction Machine: Generated power=1.5 MW, Rated voltage (stator):398/690 V, rated voltage (rotor):225/389 V, nominal current: $I_n=1900$ A, Pair pole= 2, Rated

rotational speed=1450 rev/min, $r_r = 0.021 \Omega$, $r_s = 0.012 \Omega$, $L_s = 0.0137$ H, $L_r = 0.0136$ H, $L_m = 0.0135$ H, $f = 50$ Hz,

2) Wind Turbine: $R = 35.25$ m, Gear-box ratio= 90, $\rho = 1.255$, $J = 5679000$ kgm², $F_T = 0.0024$ N.m/s.

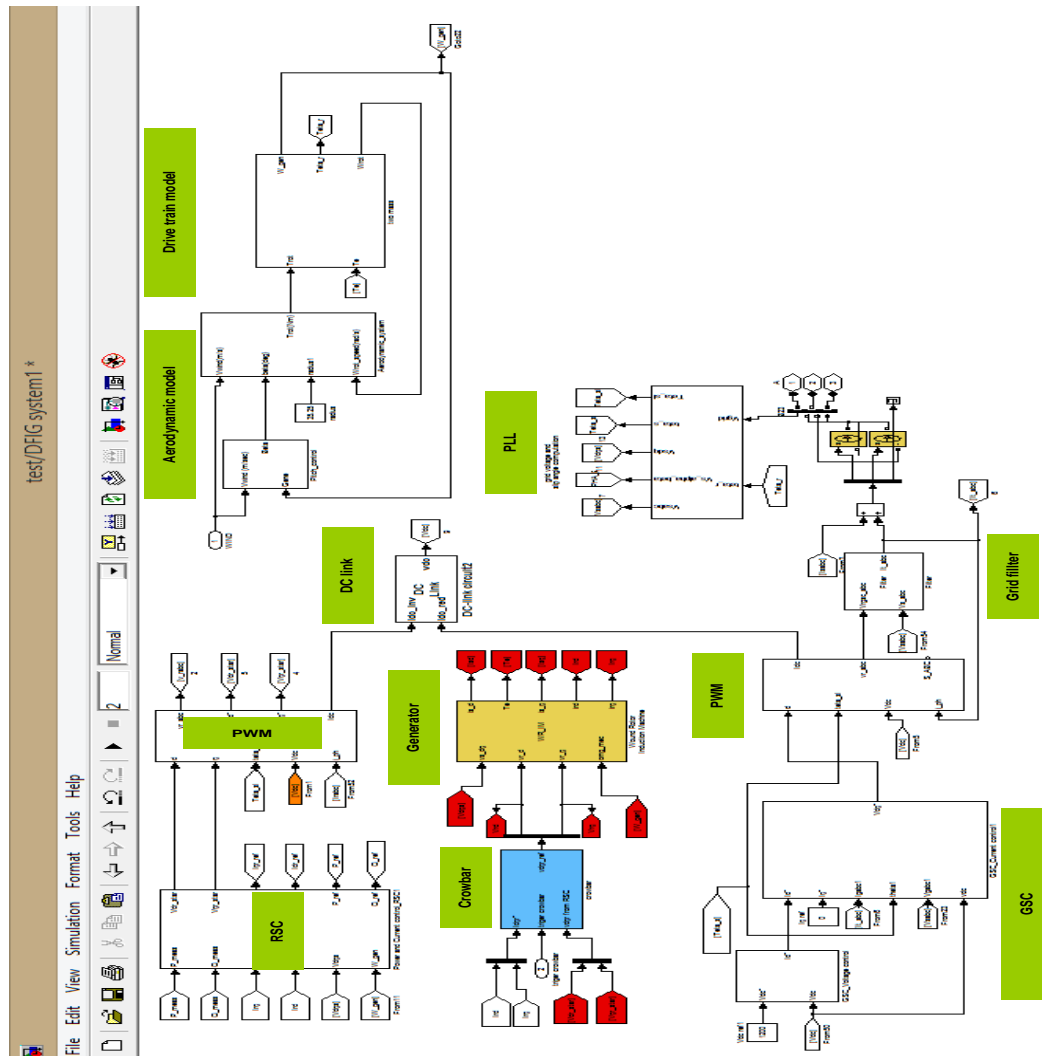


Figure (26): Screen-shot of DFIG system in the MATLAB/SIMULINK® model.