Investigation of DFIG with Fault Ride-Through Capability in Weak Power Systems

C. Rahmann, H.-J. Haubrich, L. Vargas and M. B. C. Salles

***Abstract*--In this paper, the ability of doubly fed induction generators to provide voltage stability support in weak transmission networks is investigated. Specifically, the response of wind turbines to voltage dips at the point of common coupling and its effects on system stability are analyzed. A control strategy for the operation of the grid and rotor side converters is developed in order to support the grid voltage by injecting reactive power during and after grid fault events. The performance of the strategy is analyzed for different voltage dips at the point of common coupling of a wind farm and compared with the case when the converters do not provide any voltage support. Simulations are performed using a simplified model of the Chilean transmission network. This system is considered to be a good example of weak power system, because of its radial configuration.**

***Keywords*: doubly fed induction generator, fault ride-through, reactive power control.**

I. INTRODUCTION

IN last years, the trend in wind generation has been the installation of large and concentrated wind farms into electrical power networks. As a consequence, wind power has reached in some regions significant penetration levels imposing new challenges to the Transmission System Operators (TSO). This is the case for instance in Denmark, some regions of Spain and Northern Germany, where wind power injections are already exceeding local demand.

This situation has demanded the establishment of new grid requirements for wind generators in many countries around the world. Disconnection of wind turbines in case of disturbance is not admitted anymore, and voltage and transient stability support -during and after grid fault events- are required [1]-[2]. By this way, the risk of losing a significant fraction of wind generators during disturbances decreases and grid operators can guarantee a reliable and secure power system operation even by high wind power penetration levels.

Doubly Fed Induction Generators (DFIG) are the most common technology used in variable speed wind turbines, having 45% of the medium to large wind turbines installed in Europe in 2005 [3]. In normal grid conditions, the use of power converters enables DFIG to operate at optimal rotor speed and to maximize power generation by controlling the active and reactive power injected into the grid. In case of voltage dips close to the wind farm, high currents will pass through the stator winding, which will also flow through the rotor winding due to the magnetic coupling between stator and rotor. Such high currents could damage the converters and therefore, a protection system is required. The protection of the converter is usually achieved by short circuiting the generator rotor through a crowbar and thus blocking the rotor side converter [4]. Once the rotor side converter is blocked, the DFIG operates like a typical induction generator and therefore, the control of active and reactive power through the rotor is inactive.

The aim of this work is to provide insight and understanding about the effective Fault Ride-Through (FRT) capability of DFIG in weak transmission networks and its effects on system stability. A control strategy allowing the grid and rotor side converters to support the grid voltage by injecting reactive power during and after grid faults is developed. Simulations are performed using the Chilean transmission network, which can be considered a weak power system.

This paper is organized as follows. Section II presents the dynamic model and control system of the DFIG. Section III describes the dynamic simulations carried out in the study and Section IV presents the results. A brief discussion and the conclusions are presented in Section V and Section VI respectively.

II. MODELING AND CONTROL OF DFIG

A. *Wind Turbines with DFIG*

Many authors have described the modeling of wind turbines with DFIG [5]-[8], therefore, just the main issues will be presented here.

Figure 1 shows the arrangement of a DFIG. This concept uses a wound rotor induction generator whose stator windings are directly connected to the grid, while the rotor winding is

---

This work was partially supported by the German Academic Exchange Service (DAAD), the Institute of Complex Engineering Systems, Milenio, Chile, the German Research Foundation (DFG) and the Chilean Council of Scientific and Technological Research (CONICYT).

C. Rahmann is PhD student at the Institute of Power Systems and Power Economics (IAEW), RWTH Aachen University, Aachen, Germany (e-mail: ar@iaew.rwth-aachen.de).

H.-J. Haubrich is head of the Institute of Power Systems and Power Economics (IAEW), RWTH Aachen University, Aachen, Germany (e-mail: haubrich@iaew.rwth-aachen.de).

L. Vargas is professor of the Department of Electrical Engineering, University of Chile, Santiago, Chile (e-mail: lvargasd@ing.uchile.cl).

M. B. C. Salles is PhD student at the Laboratory of Applied Electromagnetism at the University of São Paulo, São Paulo, Brazil (e-mail: mausalles@pea.usp.br).

Paper submitted to the International Conference on Power Systems Transients (IPST2009) in Kyoto, Japan June 3-6, 2009

connected to the network via a back-to-back IGBT-based converter. The rotor side converter regulates the active and reactive power injected by the DFIG and the grid side converter controls the voltage at the DC link.

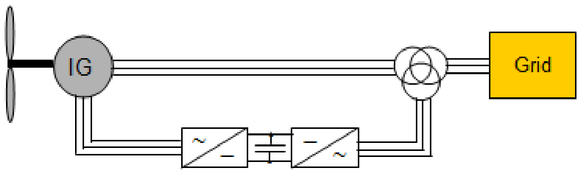

Fig. 1. Doubly fed induction generator.

The overall structure of the wind turbine model comprises the aerodynamic model, mechanical model and the electrical model for the generator. The well known actuator disc concept [7] is taken into account by the aerodynamic model under the assumption of constant wind velocity. The drive train is approximated by a two mass model considering one large mass to represent the turbine rotor inertia and one small mass representing the generator rotor. The two masses are connected by a flexible low speed shaft characterized by stiffness and damping [8]. As usual in fundamental frequency simulations, the generator is represented by a third order model, whose equations are simplified by neglecting the stator transients [9].

A pitch angle control is also implemented to limit the generator speed during grid disturbances and in normal operation under high wind speeds [5].

Finally, a protection system is included in order to block the rotor side converter when its safe operation is threatened. The protection system monitors the voltage at the point of common coupling (PCC), the magnitude of the rotor current and the generator rotor speed. When at least one of these variables exceed the range of their maximum and minimum values, the protection system blocks the rotor side converter by short circuiting the generator rotor through a crowbar.

B. *Rotor Side Converter*

The rotor side converter (RSC) controls independently the active and reactive power injected by the DFIG into the grid in a stator flux dq-reference frame. Figure 2 shows the control scheme of the RSC.

The q-axis current component is used to control the active power using a maximum power tracking (MPT) strategy to calculate the active power reference [10]. The reference value for the active power is compared with its actual value and the error is sent to a PI controller which generates the reference value for the q-axis current. This signal is compared to its actual value and the error is passed through a second PI controller determining the reference voltage for the q-axis component.

The d-axis is used to control the reactive power exchanged with the grid, which in normal operation is set to zero in order to operate with unity power factor. In case of disturbance, if the induced current in the rotor circuit is not high enough to trigger the over-current protection, the RSC is set to inject reactive power into the grid in order to support the voltage restoration. In such case, the actual voltage at the PCC is compared to its reference value and the error is passed through a PI controller to generate the reference signal for the reactive power of the DFIG. Similar to the control strategy of the q-component, the error between the reactive power reference and its actual value is passed through a PI controller to determine the reference value for the d-axis current. This signal is compared to the d-axis current value and the error is sent to a third PI controller which determines the reference voltage for the d-axis component. Finally, the dq-reference voltages are passed through the PWM module and the modulation indexes for the control of the RSC are determined.

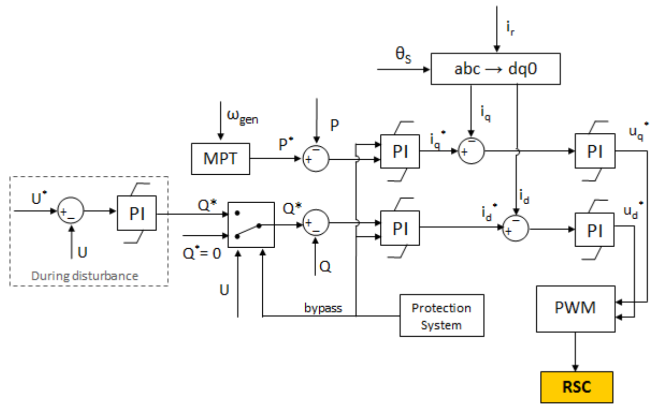

Fig. 2. Control diagram of the rotor side converter.

C. *Grid Side Converter*

The objective of the grid side converter (GSC) is to maintain the voltage at the DC link between both power converters. In normal operation, the RSC already controls the unity power factor operation and therefore the reference value for the exchanged reactive power between the GSC and the grid is set to zero. In case of disturbance, the GSC is set to inject reactive power into the grid, whether the RSC is blocked or is kept in operation. Figure 3 shows the control diagram of the GSC.

As for the RSC, the control of the GSC is performed using the dq- reference frame, but instead of rotating with the stator flux, the axis rotates with the grid voltage.

The actual voltage at the DC link is compared with its reference value and the error between both signals is passed through a PI controller which determines the reference signal for the d-axis current. This latter signal is subtracted with its current value and the error is sent to another PI controller to obtain the reference voltage for the d-axis component.

As for the q-axis current, its reference value depends whether the system operates in normal operation or during disturbance. In normal operation, the GSC is assumed reactive neutral by setting the reference value of the q-axis current to zero. In case of disturbance, the actual AC-side voltage of the GSC is compared with its reference value and the error is passed through a PI controller which generates the reference signal for the q-axis current. This reference signal is compared to its current value and the error is sent to a second PI controller which establishes the reference voltage for the q-axis component. Finally, both reference voltages in a dq-reference frame are sent to the PWM module which generates the modulation indexes for the control of the GSC.

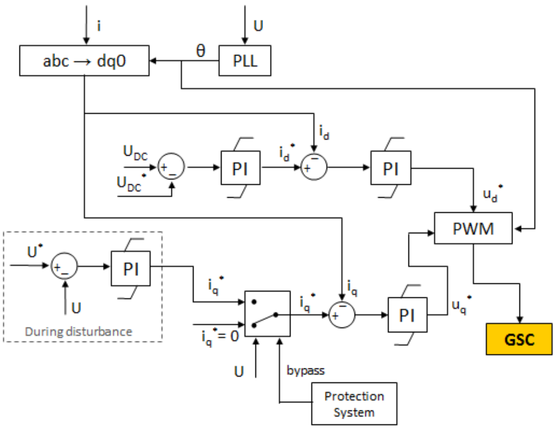

Fig. 3. Control diagram of the grid side converter.

The injection of active and reactive power by the GSC is limited by its nominal capacity represented by the following equation in per unit base:

$$|I_{conv}| = \sqrt{(I_q)^2 + (I_d)^2} \leq 1 \qquad (1)$$

The present work considers a strategy that prioritizes the injection of reactive power (q-axis current). The d-axis current is calculated based on equation (1). During normal operation, the strategy does not present limitations with the control of the DC link voltage since the q-axis current is set to zero and therefore the converter capacity is only used to control the DC link voltage.

III. Dynamic Simulations

The simulations performed in this work are based on the Chilean transmission system. The voltages in the bulk network are from 110 to 500 kV with nearly 750 busbars and 220 generators. The installed capacity of the system is about 10.000 MW for a peak load of 6.000 MW. The system is characterized by long distances between major load centers and generation plants and long transmission lines covering a total length of 2.200 km. In order to illustrate the structure of the network, a simplified diagram is shown in Figure 4.

For this work, a 150-busbar model of the Chilean transmission network is implemented in the power system simulation tool DIgSILENT Power Factory [11]. The model includes 150 synchronous generators representing the existing conventional power plants and around 100 consumption centers distributed throughout the system. The model considers only fundamental frequency components of currents and voltages, which allows a constant impedance representation of the network.

The ability of DFIG to provide voltage stability support in weak transmission networks and its effects on system stability are analyzed by including a 100 MW wind farm to the developed 150-busbar model of the Chilean transmission network (green circle in Figure 4). The wind park consists of 20 wind turbines of 5 MVA each. All of them are based on DFIG whose converter is about 40% of the generator capacity. The wind farm is represented by an aggregated model where the 20 wind turbines are modeled as one equivalent generator connected at a 220 kV busbar through two transformers.

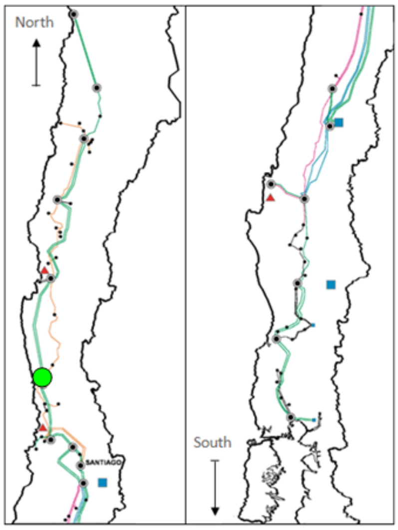

Fig. 4. Chilean bulk power network.

To analyze the ability of DFIG to provide voltage stability support, the control strategies presented in Section II.B and C are developed to allow the RSC and GSC to inject reactive power during and after grid fault events. The strategies are compared with the case when the converters do not provide any voltage stability support. The performance of the strategies is analyzed for two voltage dips with duration of 150 ms applied at the 220 kV busbar where the wind park is connected.

IV. Simulation Results

A. *Study Case I*

The first simulation considers a voltage dip of 90% applied at t=0.05 ms at the busbar connecting the wind park to the grid. Before the fault is applied, the active and reactive power output of the wind farm is 90 MW and 4 MVar respectively. The wind speed at the hub level is assumed to be 13 m/s.

Due to the high currents in the stator windings, the protection system acts by short circuiting the generator rotor through a crowbar and thus blocking the RSC. The reactive power injection of the GSC is activated when the fault is detected and ends when the RSC restarts (around t=0.6 ms). The evolution of the main variables regarding voltage support is shown in Figures 5, 6 and 7.

Figure 5 illustrates the effect of the reactive power injection by the GSC on the voltage at the PCC. It can be observed that the voltage level is slightly higher when the GSC injects reactive power during the fault (curve *"With voltage support"* in Figure 5). The voltage restoration to its nominal value after the fault clearing and before the crowbar disconnection is also faster when compared to the case which the GSC does not provide reactive power.

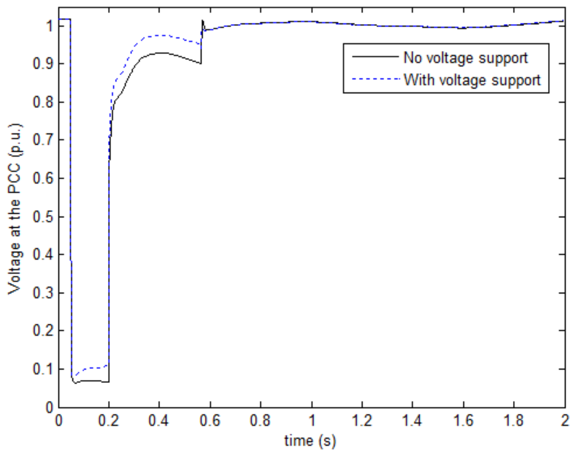

Fig. 5. Terminal voltage at the PCC (30 kV) for a voltage dip of 90%.

Figure 6 shows the reactive power injected by the GSC into the grid, which after the fault clearance reaches a value around 0.35 p.u. (in 100 MVA per unit base).

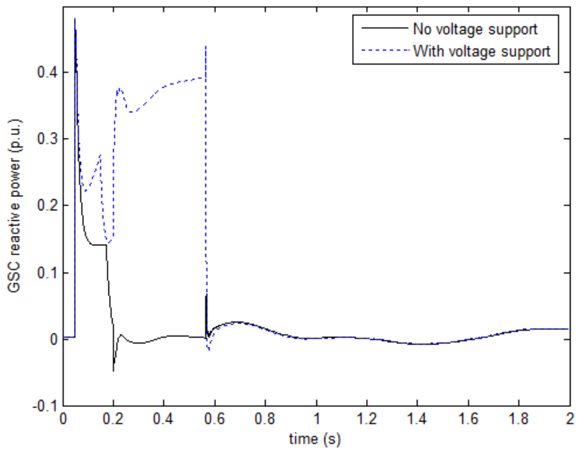

Fig. 6. Reactive power injected by the GSC.

The reactive power exchanged between the wind farm and the grid (in 100 MVA per unit base), is shown in Figure 7. It can be seen that in this case the reactive power injection by the wind farm into the grid is not possible. After the fault is cleared (at t=0.2 ms), the crowbar is still in operation and therefore the machine operates as a conventional induction generator absorbing a large amount of reactive power. The reactive power consumption of the DFIG is more than the reactive power that the GSC can feed (Figure 6), and therefore the generator takes this difference from the network (Figure 7). By this way, despite the reactive power injection of the GSC, the wind park does not inject reactive power at all.

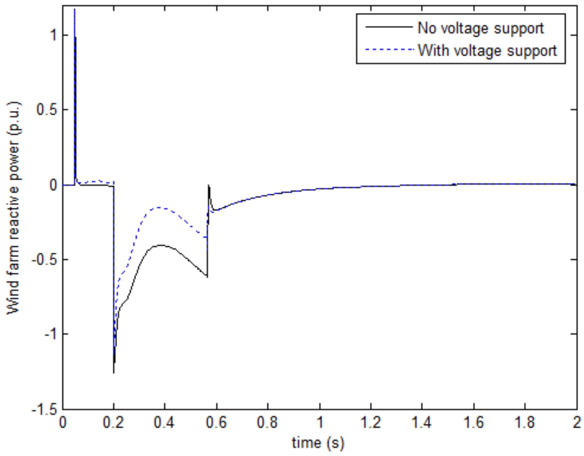

Fig. 7. Reactive power injected by the wind farm.

B. Study Case II

The second simulation considers a voltage dip of 70% at the PCC and the same operational conditions of Case I. In this case, the current induced in the rotor circuit is not high enough to activate the over-current protection, and therefore the RSC remains connected during the fault. Both converters are able to support the voltage restoration by injecting reactive power during the fault. The reactive power injection of the converters is activated when the fault is detected, and it ends when the voltage at the PCC reaches the interval of ±5% around its nominal value. The evolution of the main variables is shown in Figures 8, 9, 10, 11 and 12.

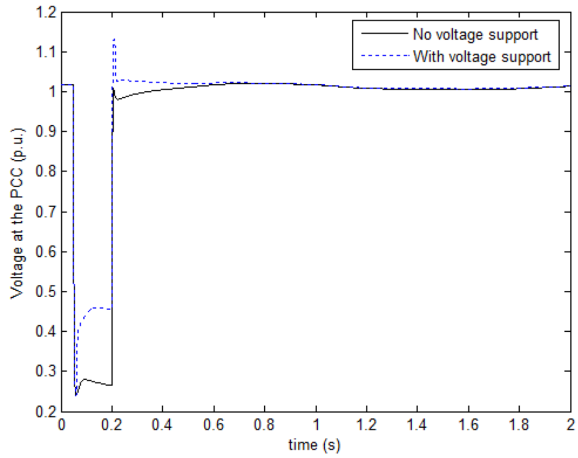

Fig. 8. Terminal voltage at the PCC (30 kV) for a voltage dip of 70%.

It can be seen from Figure 8 that the voltage at the PCC reaches a value around 0.45 p.u. showing a significant improvement when both converters are injecting reactive power during the fault. After the fault clearance, the wind park is also able to recover the voltage level at the PCC to its nominal value very fast.

The major difference comparing to the Case I is regarding to the reactive power injected by the wind park into the grid, which achieves around 60% of the wind farm rated power (Fig. 11). The additional reactive power injected by the RSC results to be quite significant.

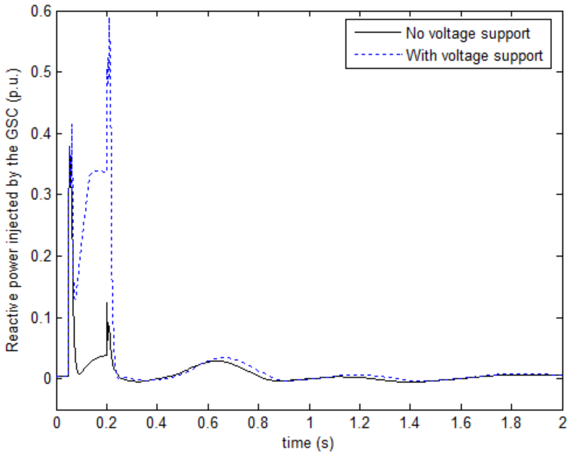

Fig. 9. Reactive power injected by the GSC.

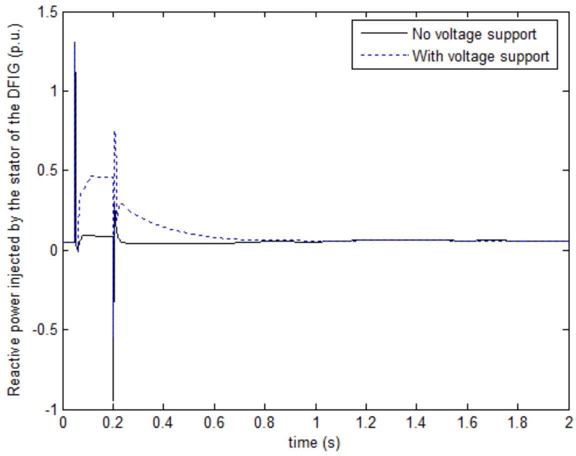

Fig. 10. Reactive power injected by the stator of the DFIG.

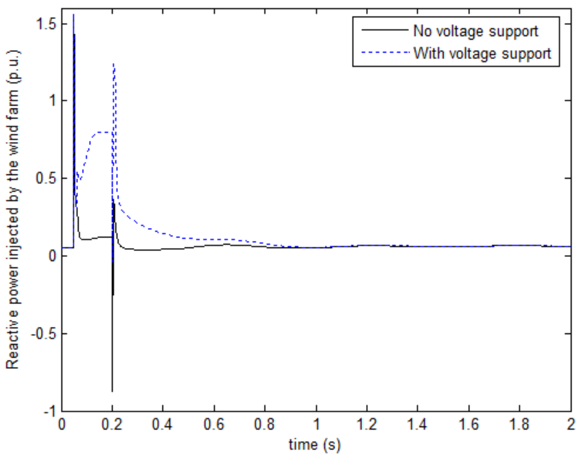

Fig. 11. Reactive power injected by the wind farm.

Figure 12 depicts the reactive current injected by the DFIG into the grid. A few milliseconds after applying the fault, the reactive current rises to 1 p.u of the generator nominal power. This fact contributes to a better voltage level during and after the fault (Figure 8).

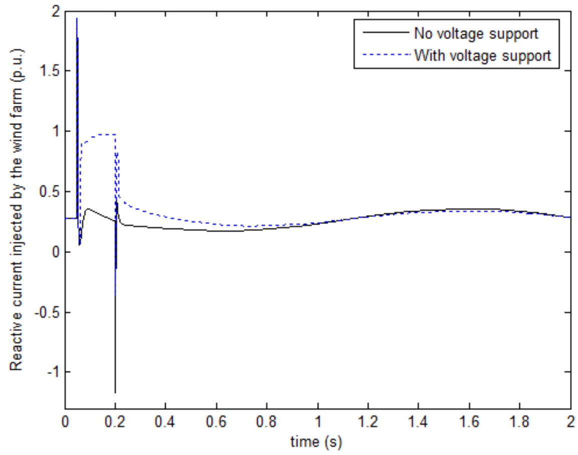

Fig. 12. Reactive current injected by the wind farm.

V. Discussion

The reactive current injected by the wind farm in Case II (Fig. 12), would be enough to accomplish new grid code requirements similar to the E.ON Netz (a German TSO). According to this code, wind turbines should be able to provide 100% of reactive current if the voltage at the PCC decreases to 0.5 p.u. or less. Furthermore, wind turbines must remain connected to the grid as long as the voltage at the PCC is above to the continuous line defined in Figure 13 [1].

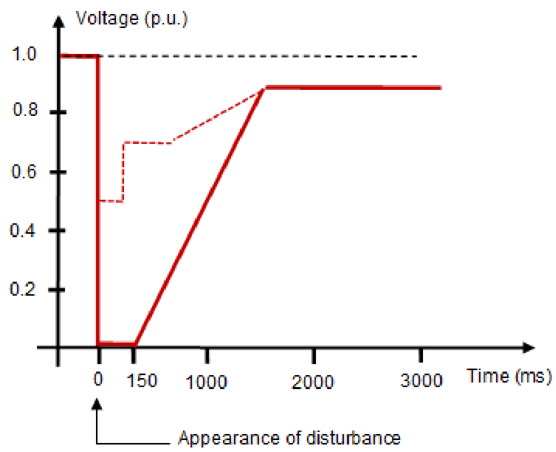

Fig. 13. E. ON voltage requirements at the PCC during a fault.

In case of more severe faults involving disconnection of the RSC (Case I), the current version of DFIG technology does not allow fulfilling the E.ON requirements. Additional investments in power electronics or in other reactive power support devices should be analyzed if such requirements have to be accomplished. However, restrictive FRT capability should only be required if they are technically necessary for a reliable and secure operation of the power system [12].

The challenge of how the FRT process is done, i.e., how the continuity of active and reactive power injections during disturbances is maintained depends strongly on the system to which the wind turbines are connected [13]. The establishment of general rules considering different power systems around the world is very complicated and probably would not be efficient as well. In this particular case, considering a weak power system, simulations have shown that without any extra investment the performance of the DFIG during disturbances can be improved depending on its control strategy and thus contributing positively to the system stability.

VI. Conclusions

This work has shown possibilities and limitations of DFIG concerning Fault Ride-Through capability during grid fault events. The main attention of the paper is focused on the control strategies of the grid- and rotor side converters to provide reactive power support in case of grid disturbances.

Simulations have shown that DFIG equipped with crowbar is able to ride through grid disturbances. In case of faults involving RSC disconnection, an appropriated control strategy of the GSC can improve the voltage level during the fault and also contribute to its re-establishment before the crowbar disconnection. However, the injected reactive current is not enough to accomplish restrictive grid code requirements similar to the E.ON Netz. For less severe faults, a control strategy allowing both converters to inject reactive power into the grid increases the performance of the DFIG supporting the network stability. In such cases the reactive current required by restrictive grid codes can be satisfied.

VII. Acknowledgment

The first author would like to acknowledge the contribution of Prof. Rodrigo Palma from the University of Chile for his valuable comments and advices during the realization of this work.

VIII. References

[1] Grid Code: High and Extra High Voltage, E.ON Netz GmbH Tech. Rep., 2006, Status: 1.

[2] Technical Requirements for the Connection of Generation Facilities to the Hydro-Québec Transmission System: Supplementary Requirements for Wind Generation, Hydro-Québec Tech. Rep., 2005.

[3] M. B. C. Salles, K. Hameyer, J. R. Cardoso and W. Freitas, "Dynamic Analysis of Wind Turbines Considering New Grid Requirements," IEEE International Conference on Electrical Machines, Portugal, Sept. 2008.

[4] A. D. Hansen, G. Michalke, "Fault Ride-Through Capability of DFIG Wind Turbines," Renewable Energy, vol. 32, No. 9, pp. 1594-1610, Jul. 2007.

[5] M. Poller "Doubly-Fed Induction Machine Models for Stability Assessment of Wind Farms," *in Proc. 2003 IEEE PowerTech Conference*, Bologna, 2003.

[6] V. Akhmatov, "Analysis of Dynamic Behavior of Electric Power SystemsWith Large Amount of Wind Power," Ph.D. dissertation, Technical Univ. Denmark, Denmark, 2003.

[7] T. Burton, D. Sharps, N. Jenkinsand E. Bossanyi, *Wind Energy Handbook*, Wiley, 2001.

[8] A.D. Hansen, P. Sørensen, F. Blaabjerg, J. Bech, "Dynamic modelling of wind farm grid interaction," *Wind Engineering*, vol. 26, No. 4, pp. 191-208, 2002.

[9] P. Kundur, Power System Stability and Control, Mc Graw Hill, 1994.

[10] Y. Lei, A. Mullane, G. Lightbody, and R. Yacamini, "Modeling of the wind turbine with a doubly fed induction generator for grid integration studies," *IEEE Trans. Energy Conversion*, vol. 21, pp. 257-264, March, 2006.

[11] DIgSILENT GmbH, web site: http://www.digsilent.de/

[12] F. Van Hulle, "Large Scale Integration of Wind Energy in the European Power Supply: Analysis, Issues and Recommendations," EWEA Tech Rep., 2005.

[13] N. Rahmat, T. Thiringer and D. Karlsson, "Voltage and Transient Stability Support by Wind Farms Complying with the E.ON Netz Grid Code," *IEEE Trans. Power Systems*, vol. 22, No. 4, pp. 1647-56, Nov. 2007.