GRID CONNECTION OF DOUBLY FED INDUCTION GENERATOR WIND TURBINES: A SURVEY

I. MARTINEZ DE ALEGRIA[1], J.L. VILLATE[2], J. ANDREU[1] , I. GABIOLA[2], P. IBAÑEZ[2],

(1) :UPV-EHU , Urkixo Zumarkalea, 48013
Bilbao, Spain,
jtpmamai@bi.ehu.es
Tél : + 34 (0) 94 601 4147, Fax : + 34 (0) 94 601 4259

(2) : ROBOTIKER , Parque Tecnológico Edif. 202 48170
Zamudio (Bizkaia), Spain.
joseluis@robotiker.es
Tél : + 34 94 600 22 66, Fax : + 34 94 600 22 99

ABSTRACT: The suitability of Wind Turbines with Doubly Fed Induction Generator for new grid operator norms that require Ride Through operation is analysed. New grid codes require that the wind turbines remain connected during voltage dips in the grid. A survey of the problems associated with voltage dips and methods for Ride Through operation of this type of system are presented. Different alternatives for Low Voltage Ride Through are described. Simulation results of Power Error Vector Control method for the Voltage Source Inverter connected to the rotor during a voltage dip are shown. The simulated results show that this type of control may eliminate the need for a crowbar, or at least a great reduction in the rotor currents is obtained and activation of crowbar may be limited to very extreme cases when very strong wind gusts and very deep voltage dips take place at the same time.

Keywords: Doubly-Fed induction Generator, Low Voltage Ride Trough, Voltage Dip

1 INTRODUCTION

The increasing penetration of wind energy in the power system is reshaping the way wind farms are operated. Denmark maintains a 15% yearly average of the total power generated by wind farms, and during certain periods of high wind and low consumption, most of the power is generated by the wind. Other countries may face a similar situation in a short time. The share of wind power in relation to the strength of electricity grids and other power plants is reaching levels where they may cause problems to system operators such as voltage variations, grid output unbalance and grid instability. Wind farms can no longer be considered as a simple energy source, VAR neutral or consumer, shutting down when system faults occur and with local control of regulation. Now they must operate as power plants, they must be able to provide reactive power, remain connected during system faults and adapt their control to the needs of the system.

System Operators in Denmark and Germany [1][2] have been the first countries adapting their grid codes to this new scenario. Many other countries have followed the example, and others are still adapting their grid codes. A good review of new grid codes adapted for wind farm integration is shown in [3][4].

Wind farms may easily contribute to grid frequency control by modifying active power control strategies. Voltage control can also be implemented because most wind power farms can control reactive power, so by adapting the reactive power control strategy Voltage control is achieved.

The most demanding requisite for wind farms, specially with Doubly Fed Induction Generators (DFIG) is the Fault Ride Through capability. Wind farms connected to high voltage (usually above 100kV) transmission system must stay connected when a voltage dip occurs in the grid, otherwise, the sudden disconnection of a great amount of wind power may contribute to the voltage dip, with terrible consequences. Wind farms must remain connected when the voltage dip profile is above the line shown in figure 1 under the E.ON regulation [2]. The per unit voltage at the point of connection to the grid is shown in the vertical axes and the duration (seconds) of the fault in the horizontal axes. This code requires Fault Ride-Through (FRT) capability during voltage drops in Transmission System (110kV and above) of 15% of nominal voltage during 300 ms with recovery up to 80% of nominal voltage after 3 s, with the slope shown in figure 1. Other grid codes propose similar profiles, adapted to the regions fault statistics.

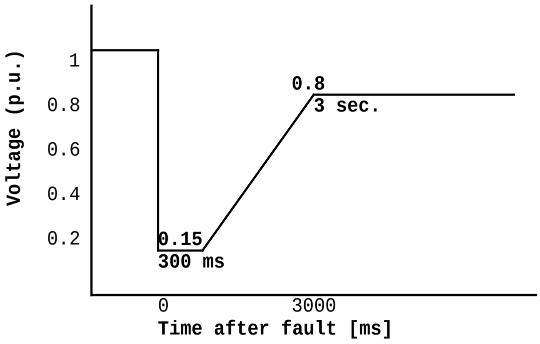

Figure 1. E.ON Fault Ride Through Voltage limiting curve

Actual grid codes in vigour only mention depth and duration for balanced voltage dips. The effect of such a voltage dip in the wind turbine is different for different wind turbine system technologies. Directly coupled synchronous generators and squirrel cage asynchronous generators with full power back-to-back converters may cope with the voltage dip readapting their controls and power ratings. On the other hand Doubly Fed Induction Generators (DFIG) with the power converters connected to the rotor must be disconnected from the grid unless additional protection systems are provided. This may become a serious drawback for the wind turbine industry because most of the wind turbines manufactured actually use Doubly-Fed Induction Generators.

2 DFIG LOW VOLTAGE RIDE THROUGH PROBLEM DESCRIPTION

Experience of wind farm developers and research studies have demonstrated that grid faults negatively affect wind farms. The different types of faults that may affect a wind farm are summarized in [5] and are mainly classified as symmetrical and non-symmetrical faults. Actual grid codes only specify symmetrical faults, because they affect more severely the grid stability. On the other hand, non-symmetrical faults are more difficult to deal with DFIG generators.

The stator flux of the DFIG machine is determined by the following expression:

$$\overline{\psi}_S = \overline{\psi}_{S0} + \int_0^t \left(\overline{V}_S - R_S \overline{I}_S\right) dt \qquad (1)$$

The problem with a DFIG when a voltage dip occurs is that the stator flux cannot follow the sudden change in stator voltage and a DC component in the stator flux appears, because the integral term is reduced and the stator flux vector becomes almost stationary. The rotor keeps turning and high slip is generated, which tends to introduce over-voltage and over-current in the rotor circuits due to the effect of speed-voltage. Non-symmetrical faults create higher over-currents and over-voltages in the rotor because a negative sequence component exists in the stator voltage, and the slip of this negative sequence is very high [6].

The excess current may damage the power converter, and the over-voltage may damage the rotor of the generator. In order to protect the power converter connected to the rotor from this over-voltage and over-currents a protection mechanism is necessary.

A vast amount of research projects are being carried away in order to determine the behaviour of DFIG wind turbines under voltage dip conditions [6] [7] [10] [11] [12] [13] [14] [15] [16] [17][26]. All of them demonstrate that over-current in the rotor takes place at the voltage dip. Also, the excess current in the rotor increases the voltage in the DC bus [26]. Oscillations take place in the currents, active and reactive power of the machine [7].

A simulation study of the Spanish grid has been presented in [8]. Actually Spanish grid code requires all wind generation to disconnect from the grid if the voltage falls below 85% of the rated voltage [9], though this is likely to change in the next months. The simulations shows that a voltage dip spread through the Spanish network might trip all the 3650 MW wind generation. Similar results are obtained in simulations of a voltage dip in the Irish grid.

Unlike Danish and German grid codes, Red Eléctrica Española contemplates to introduce the requirement of Fault Ride Through even under unbalanced voltage dips in its upcoming new grid code. DFIG wind turbine commercial systems may ride through balanced voltage dips. Balanced or symmetrical voltage dips are the most dangerous for grid stability. On the other hand, DFIG wind turbine systems are unable to cope with unbalanced faults, even if this type of faults are less severe for the grid. Unless Red Eléctrica Española drops down the idea of requiring unbalanced voltage dip ride through, Spain, the second wind power market in the world, will become a very tough market for DFIG wind turbines.

An interesting conclusion of all research being carried away is that reduced order models of the DFIG are useful for the study of power system stability [18], but they are inaccurate to determine the real currents in the power converters [19]. In order to study the DFIG behavior during a voltage dip, the complete 5th order model should be used.

A problem that has not been described in detail in the literature is the response of wind turbines with DFIG generator under unbalanced Voltage Dips in the grid.

Another problem that remains to be studied, is the effect of saturation. Voltage dips may cause saturation, but most of the models used for DFIG simulation do not include saturation effects. [20] shows the behaviour of a squirrel cage asynchronous machine under voltage dip and saturation. This results in higher currents and torque. This may accelerate the ageing of the machine. Similar effects are expected in a DFIG.

3 SURVEY OF DFIG FAULT RIDE THROUGH SOLUTIONS

The usual approach to the problem of voltage dips has been to place a crowbar circuit connected to the rotor of the wind turbine. The crowbar shortcircuits the rotor when a voltage dip is detected and the power converter connected to the rotor is protected [12].

Crowbar circuits may be antiparallel thyristor crowbar, diode bridge crowbar or other more unusual configurations (Fig. 2). The diode bridge crowbar is usually preferred to the antiparallel thyristor and the rest of configurations because it uses less thyristors and it is controlled more easily.

Either when the voltage at the DC bus reaches its maximum value or when the limit rotor current is exceeded, the crowbar is activated, the rotor converter is disconnected from the rotor, and the rotor windings are short-circuited by the crowbar. The crowbar remains connected to the rotor until stator is disconnected from the grid and the rotor currents disappear because there is no control on the turning off of thyristors. This is no longer acceptable under the new grid codes. New grid codes require that the wind farm remains connected to the grid during the voltage dip.

New solutions for Low Voltage Ride Through in Wind turbines with DFIG

-Active Crowbar

In order to remove the crowbar short as fast as possible, the crowbar thyristors are substituted with fully controlable switches, namely IGBTs [12]. The stator of the machine is not disconnected from the grid when the crowbar actuates, and the crowbar action is disabled as soon as possible in order to regain control on the machine. During the crowbar active time, the rotor side converter is disconnected and there is no control on the generator. When the crowbar is deactivated and the converter regains control, high current transients may take place and sometimes the crowbar is reactivated.

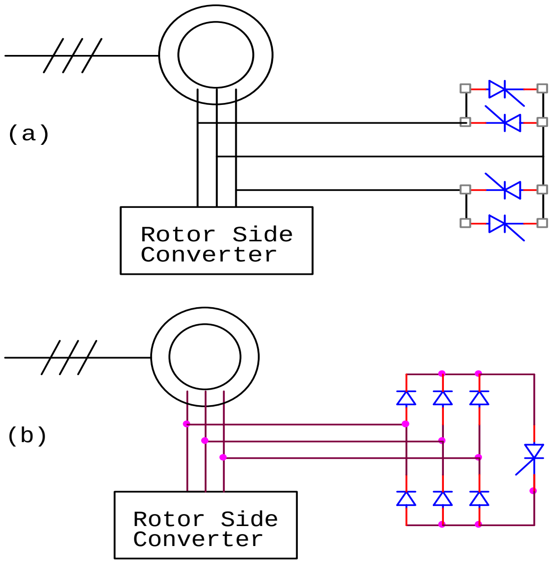

**Figure 2. Typical Crowbar circuits.
a) antiparallel thyristor crowbar
b) diode bridge crowbar**

-Series antiparallel thyristors

In [11] a new LVRT system is proposed. The power rating of the IGBTs in the converter connected to the rotor are dimensioned for higher current ratings, and anti-parallel thyristors are placed as in figure 3, just like a conventional soft-starter. When the grid voltage recovers, high transient currents appear in the stator. This high currents are controlled with the anti-parallel thyristors by increasing the stator voltage in a controlled manner. During normal operation the thyristors are kept on. The problem with this configuration is that the efficiency decreases due to the conduction losses in the thyristors during normal operation. This could be avoided by bypassing the thyristors with commutators, but the switching time of the commutators may be too slow and the system may not respond fast enough to a voltage dip. The higher ratings of the IGBT-s will increase the cost of the power converter, but this high currents only take place during very short periods of time, and the cooling system doesn´t need un upgrade.

-Static Series Compensator (SSC)

The ideal solution for a DFIG wind turbine during a voltage dip would be a system that would isolate the wind turbine from the voltage dip. This can be achieved through a Static Series Compensator (SSC) also called Dynamic Voltage Restorer (DVR) [21]. The SSC is a voltage source converter connected in series on the connection between the grid and the load (in this case the wind turbine), whose voltage adds to the grid voltage to obtain the desired load voltage (Fig. 4). The load in the figure would be either a wind turbine or the whole wind farm. Depending on the type of control, the SSC may also correct voltage unbalance, perform voltage regulation and cancel low-order harmonics. This type of converter may be placed individually for each wind turbine or a high power SSC may be installed at the connection of the wind farm to the grid. This would depend mainly in the accessibility, required maintenance, evaluation of losses and other factors that influence the cost of each solution. Different SSC topologies for the power converter have been proposed. Multimode Static Series Compensator has been proposed in [22], where the trasformers are substituted by series conexion of power cells. A Static Voltage Regulator,a variation of the load tap changer without storage elements, has been proposed in [23].

The disadvantage of this methods is that the additional cost of the added power converters may override the advantage of the lower price of DFIG wind turbines.

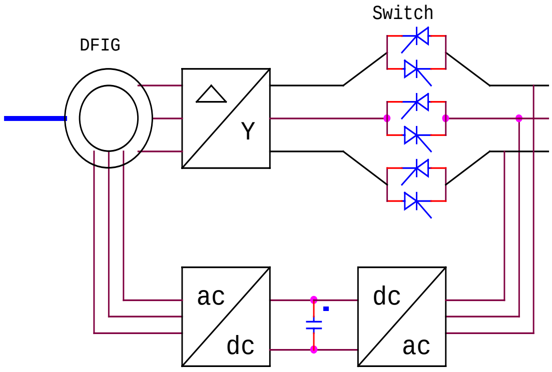

Figure 3. Series antiparallel thyristors for LVRT

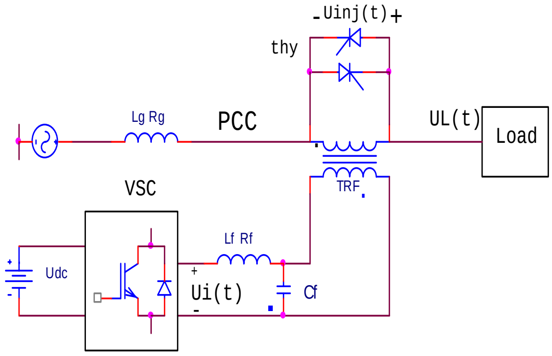

Figure 4. Static Series Compensator

-STATCOM

Some authors have mentioned the possibility of using the grid connected Voltage Source Inverter as a STATCOM. A STATCOM controls the reactive power in the point where it is connected, in order to sustain the voltage. In opinion of the authors of this paper, the low power rating of the Voltage Source Converter does not allow to compensate the voltage dip at all, so this is not a viable solution. It could be useful to compensate for voltage unbalances under steady state operating conditions [24], but even then, the stator reactive power control capability is of more importance.

-HVDC

The use of HVDC in Offshore wind farms may be helpful for LVRT. Even Onshore wind farms could benefit from HVDC if the cost of HVDC stations would drop. HVDC schemes provide additional benefits when compared to a conventional AC connection for LVRT:

- RPC and ACVC at the grid connection
- Fully defined and controllable power flow
- Sending end and receiving end frequencies are independent
- Offshore network is isolated from mainland disturbances which provides for a ride through capability for the wind turbines during AC system faults at the receiving end.
- Low cable power losses compared with AC
- Fewer cables provide both environmental benefits and reduced civil works

-Commercial systems

Different manufacturers are adapting their DFIG designs in order to comply with the new regulations. General Electric calls it system *LVRT*, Neg mICON offers *Grid+*^{TM}, REpower calls its system *Extended grid compatibility package*, Alstom, ABB offers the *Fold-back control concept*, Enercon´s system is called Infeed Inverter and so on. All this Ride Through systems are a mixture of crowbar (active or non-active) activation, power limitation, pitch control and variations in control strategies. Anyway manufacturers are obviously not willing to describe their system and the details of their LVRT systems are not public.

-Proposed LVRT method: Power Error Vector Control

It would be very helpful if only by using the control capabilities of the rotor converter, and without the use of additional converters, such as SSC, a wind turbine with DFIG could ride through the voltage dips. Fuzzy control has been used instead of conventional PI controllers [25], and slight current reductions may be obtained, but the current reduction is limited.

The increase in the stator and rotor currents is generated because of the sudden stop of stator flux. If the rotor flux could be controlled in order to de-magnetize and re-magnetize rapidly the magnetic circuit of the machine according to the stator flux, this current increase could be limited.

A controller that controls rotor flux, and not rotor currents, called Power Error Vector Control (PEVC), is patent pending [27]. In addition to the use of PEVC, the stator active and reactive power references are reduced during the voltage dip, in order to limit the current. The reactive power reference is maintained at zero value after voltage recovery. By doing so, the DFIG does not consume reactive power when the voltage recovers, wich might provoke a second voltage dip.

In PEVC control, the voltage of the rotor converter is obtained from the following expression

$$\overline{V_r} = \frac{1}{K \cdot T_m} \cdot \left(\Delta Q_S , \Delta P_S\right) \qquad (2)$$

where

$$\frac{1}{K} = \frac{1}{V} \frac{L_r L_s - L_m^2}{L_m} \qquad (3)$$

and $\Delta Q_S , \Delta P_S$ are the errors in the stsator active and reactive power.

By doing so, the rotor voltage corrects the rotor flux in order to obtain the desired stator active and reactive power [26]. The reason is that the rotor flux error of the machine and the stator active and reactive power error are linked by the following expression

$$\Delta \overline{\psi}_r^e = \frac{1}{K} \left(\Delta Q_S , \Delta P_S\right) \qquad (4)$$

Simulations of PEVC controller under symmetrical voltage dip conditions, without crowbar activation, are shown in figure 5. The voltage dip lasts 300 ms and drops down to a 15% of the nominal voltage (figure 5 a). As soon as the voltage dip disappears total control of the system is regained almost instantaneously. A delay of 1ms for active and reactive power reference reduction has been simulated. The time needed for the detection of the presence of a voltage dip plays a fundamental role in reducing the rotor current increase. Simulations show that the rotor current peak is kept very low at the start of the dip, almost at its nominal value, and a high but very short current peak is observed at voltage recovery (figure 5 d). The crowbar becomes unnecessary in this case, as the rotor currents are kept under control. Stator and rotor currents suffer a sudden increase just as the voltage dip starts and when the voltage recovers, but their duration is less than 100ms, and it does not affect the machine (figure 5 c). Thus, crowbar action may be limited to very extreme voltage dips, when grid codes allow disconnection from the grid.

As the stator power reference is reduced, the excess power of the system is stored as kinetic energy in the rotor, thus increasing the rotor speed. The increase in the speed is shown in (figure 5 b). The increase in speed is acceptable for the application, but pitch controlled wind turbines may avoid the speed acceleration.

4 CONCLUSIONS

Low Voltage Ride Through for Wind Turbines with DFIG is a challenge that all manufacturers must solve. Most manufacturers have already implemented LVRT systems, but compliance of the different grid codes is still a problem that has not been totally solved. New LVRT systems must comply grid codes without penalizing the system cost. The ideal solution is the utilization of low cost additional hardware (active crowbar) and adaptation of control strategies. The present paper shows that the use of Power Error Vector Control and active and reactive power reference reduction during voltage dips may be a good solution for LVRT.

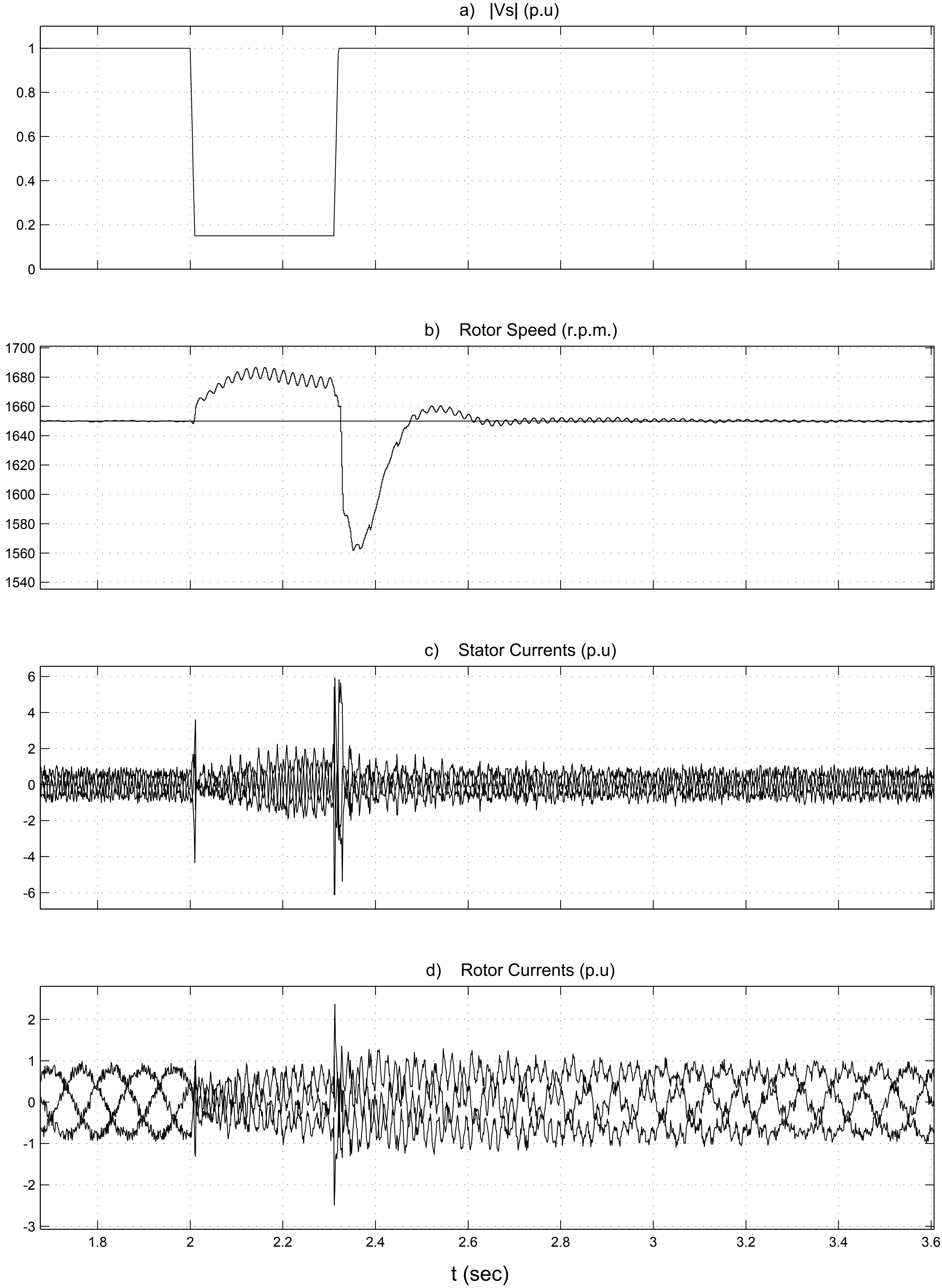

Figure 5. LVRT behaviour with PEVC control of DFIG machine

5 REFERENCES

[1] ELTRA, "Specificatons for connecting wind farms to the transmission network", 2000.

[2] E.on Netz, "Ergänzede netzansschlussregeln für windenergieanlagen". Technical report E.on Netz, 2001.

[3] J. Matevosyan, T. Ackermann, S. Bolik, L.Söder "Comparison of International Regulations for Connection of Wind Turbines to the Network" Nordic Wind Power Conference, 1-2 march, 2004

[4] C. Jauch, P. Sørensen, B. Bak-Jensen "International Review of Grid Connection Requirements for Wind Turbines" Nordic Wind Power Conference, 1-2 march, 2004

[5] M.H.J. Bollen , G. Olguin, M. Martins, "Voltage Dips at the Terminals of Wind Power Installations" Nordic Wind Power Conference, march 1-2, 2004

[6] J. Niiranen "Voltage Dip Ride Through of a doubly-fed system" World Wide Energy Conference, 2004

[7] T. Thiringer, A. Petersson, T. Petru, "Grid disturbance response of wind turbines equipped with induction generator and doubly-fed induction generator", Power engineering society annual meeting, Toronto, Canada july, 2003

[8] J. M. Rodriguez, J. L Fernandez, D. Beato, R. Iturbe, J. Usaola, P. Ledesma, j. R. Wilhelmi, "Incidence on power system dynamics of high penetration of fixed speed and doubly fed wind energy systems: study of the Spanish case", IEEE Trans. in Power Systems., vol. 17,nº 4 pp. 1089–1095, November 2002.

[9] "Administrative and technical specifications for grid connection and required performance of hydraulic power plants up to 5000 kVA and electrical sel generation", Tech. Rep. Ministerio de Industria y Energía, B.O.E. 219, 2002.

[10] S. Seman, J. Niiranen, S. Kanerva, A. Arkkio, "Analysis of a 1.7 MVA Doubly Fed Wind-Power Induction Generator during Power Systems Disturbances", Nordic Workshop on Power and Industrial Electronics, Trondheim, 2004

[11] A. Petersson, S. Lundberg, T. Thiringer "A DFIG wind-turbine ride through system influence on energy production", Nordic Wind Power Conference, march 1-2, 2004

[12] J. Niiranen, "Voltage ride through of a doubly-fed generator equiped with an active crowbar", Nordic Wind Power Conference, march 1-2, 2004

[13] J. Niiranen, "Simulation of doubly fed induction generator wind turbine with an active crowbar", EPE-PEMC 2004, Riga, Latvia.

[14] R.J. Koessler, S. Pillutla, , L.H. Trinh, D.L. Dickmander, "Integration of Large Wind Farms into Utility Grids (Part 1 - Modeling of DFIG)" Proc. of the IEEE PES , Dallas U.S.A., September 2003

[15] J. Fortmann "Validation of DFIG model using 1.5 MW turbine for the analysis of its behaviour during voltage drops in the 110 kV grid" Fourth International Workshop on Large-Scale Integration of Wind Power and Transmission Networks for Offshore Wind farms, october 20-21, 2003, Billund, Denmark

[16] P. Van Meirhaghe "Double fed induction machine: a EUROSTAG model" Tractebel Engineering, http://www.eurostag.be/

[17] M.V.A. Nunes, J.A. Pecas Lopes, H.H. Zürn, U.H. Bezerra, R.G. Almeida "Influence of the variable-speed wind generators in transient stability margin of the conventional generatos integrated in electrical grids" IEEE Transactions on Energy Conversion, vol , nº, pp 2004.

[18] M.A. Pöller "Doubly-Fed induction machine models for stability assesment of wind farms" World Wide Energy Conference, Cape Town, South Africa 2003

[19] F. Koch, F. Shewarega, I. Erlich "Alternative models of the Doubly-Fed Induction Machine for power system dynamic analysis" International Conference on New and Renewable Energy Technologies for Sustainable Development, Evora, Portugal, 28 June-1 July 2004

[20] F. Carlsson "Saturation in Asynchronous Machines due to Voltage Sags", Proceedings of the European Conference on Power Electronics and Applications, EPE´03, Toulouse, France, September 2003

[21] H. Awad, J. Svensson, M. Bollen, "Mitigation of unbalanced voltage dips using Static Series Compensator", IEEE Trans. Pow. Elec., vol.19, pp. 837–846, (May 2004).

[22] H. Okayama, T. Fujii, S. Tamai, S. Jochi, M. Takeda, R. Hellested, G. Reed, "Applicaton and development concepts for a new transformer-less FACTS device – the Multimode Static Series Compensator", Proc. of the IEEE PES , Dallas U.S.A., September 2003

[23] E. Alegría, A. Khan, J. Rajda, S. Dewan, "Static Voltage Regulator (SVR) – Ride Through Support for semiconductor Facilities", Power Quality Conference, Powersystems World´98, Santa Clara, California, november 1998.

[24] B. I. Næss T. M. Undeland T. Gjengedal "Methods for Reduction of Voltage Unbalance in Weak Grids Connected to Wind Plants" Wind Power and the Impacts on Power Systems, IEEE Workshop, Oslo 17 - 18 junie2002

[25] R.G. de Almeida, J.A. Lopes, J.A.L. Barreiros, "Improving power system dynamics behavior though Doubly-Fed Induction Machines controlled by Static Converter using Fuzzy control" IEEE Transations on Power Systems, vol. 19, nº 4, pp 1942-1950, november 2004

[26] T. Sun, Z. Chen, F. Blaabjerg, "Voltage recovery of grid-connected wind turbines after a short-circuit fault" Proc. of 29th Conference of IEEE Industrial Electronics Society, Roanoke, Virginia, 2003.

[27] I. Martinez de Alegria, J. Andreu, J.L. Martin, J.L. Villate, I. Gabiola "Método y dispositivo para el control de potencia activa y reactiva de máquinas asíncronas doblemente alimentadas" Spanish Patent Register nº P200402665.