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Aparicio, N.; Chen, Zhe; Beltran, H.; Belenguer, E.

Publication date:
2007

Document Version
Publisher's PDF, also known as Version of record

Performance of Doubly-Fed Wind Power Generators During Voltage Dips

*N. Aparicio, **Z. Chen, *H. Beltran, *E. Belenguer

***Abstract*—The growing of wind generation in Spain has forced its Transmission System Operator (TSO) to release new requirements that establish the amount of reactive power that a wind turbine has to supply to the grid during a voltage dip. Wind turbines equipped with doubly-fed induction generators (DFIG) can regulate easily the reactive power generated in steady state. However, difficulties appear when reactive power has to be generated during voltage dips. Simulations have been carried out in order to check whether DFIG wind turbines can fulfill the reactive power requirements. Protection system commonly employed with DFIG in order to achieve ride-through capabilities including crowbar plays an important role to meet the requirements together with grid-side converter. Resistance associated with the crowbar and its connection duration are crucial at the beginning of the fault. Grid-side converter acting as STATCOM helps to improve the voltage profile sufficiently to permit rotor-side converter reconnection.**

***Index Terms*—grid requirements, reactive power consumption, renewable energy systems, voltage dips (sags), wind energy.**

I. Introduction

THE recent rapid growing of wind power connected to electrical networks has forced Transmission System Operators of different countries to develop specific grid requirements. Countries which experienced high penetration of wind energy earlier have already had their requirements such as Denmark [1] and Germany [2].

In the particular case of Spain the latest requirements have been announced on 24th October 2006 by Red Eléctrica de España (REE), the Spanish Transmission System Operator (TSO). The new Operational Procedure PO 12.3 "Requirements for wind installations behaviour against voltage dips" [3] establishes that a wind farm must remain connected when a voltage dip occurs in the grid, furthermore, it indicates with details, the amount of reactive power that wind turbines must generate during and after grid faults.

Previous requirements [4] (from 1985) established that wind turbines must disconnect instantaneously when voltage dropped below 85% of the nominal value. However, Spain has experienced one of the biggest growths in wind power installations. In 1999, the Spanish Renewable Energy Promotion Plan set a target for wind power of 8,974 MW by 2010. This has already been largely exceeded so a new objective of 20,155 MW by 2011 has been set by the Spanish government. In 2005, the Spanish capacity registered the third highest growth in the world with 1,764 MW that has raised the total capacity to 10,027 MW, the second biggest after Germany [5]. In certain moments of September 18th 2005 more than 30% of the electrical energy generated in Spain was wind energy.

These facts show the wind energy is no longer a small fraction of the total electrical energy generation with a negligible influence on the whole electrical system that can be switched off when a fault occurs. Now wind generators must remain connected and help the grid for voltage restoration.

Since the wind energy growing in Spain is very recent, most of its wind turbines are variable-speed equipped with doubly-fed induction generators (DFIG).

The stator of these generators is directly connected to the grid while the rotor is fed through a power-electronics converter. It provides these turbines several advantages compared with fixed-speed ones: higher power production, improvement of power quality, reduction of mechanical stresses and possibility of controlling torque and power pulsations.

In addition, DFIG can also control the reactive power generated/absorbed (i.e. power factor) during normal operation [6]. However, during grid faults this reactive power controllability disappears or it is very limited. This will be the main interest of this paper.

II. Spanish Requirements and Challenges

A. Requirements

New Spanish Operational Procedure requires wind farms to have fault ride-through capabilities similarly to other countries requirements. Fig. 1 shows the voltage limit curve above which wind turbines must remain connected to the network.

However, new requirements about reactive current differ considerately. While Danish requirements limit the reactive current that a wind farm can maximum take during a grid fault to 1.0 times the rated current, new Spanish Operation Procedure does not permit wind turbines to consume reactive power at the grid connection during both the fault period and voltage recovery period.

Moreover, in order to help voltage restoration, during these periods, wind turbines must feed the network with the maximum current possible (I_{total}) with a ratio of reactive current indicated on Fig. 2. This must be done before 150 ms

This work was supported in part by the Fundació Caixa Castelló-Bancaixa under Pla 2006 de promoció de la investigació de l'UJI.
*N. Aparicio, H. Beltran and E. Belenguer are with the Department of Industrial Engineering and Desing, Universitat Jaume I, Campus de Riu Sec, 12071 Castelló, SPAIN (e-mail: aparicio@esid.uji.es)
**Z. Chen is with the Institute of Energy Technology, Pontoppidanstraede 101, 9200 Aalborg, DENMARK (e-mail: zch@iet.aau.dk).

from the fault have past or, if the fault has been cleared before that time, from the clearance.

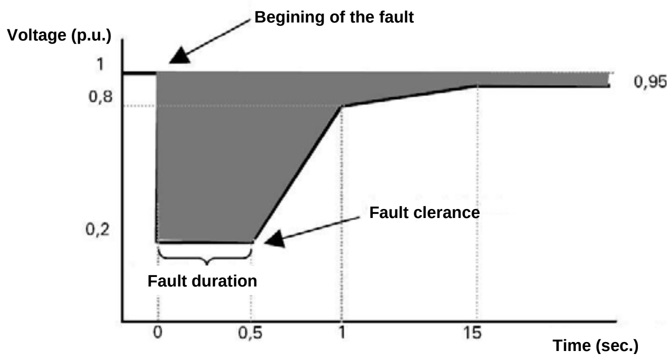

Fig. 1. Voltage limit above which wind turbines must remain connected to the network.

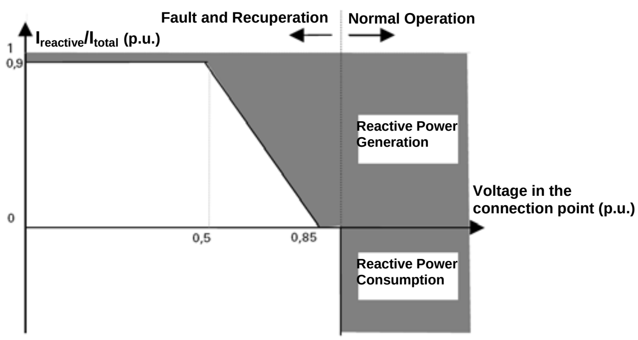

Fig. 2. Working area during fault and recuperation periods.

These requirements are very difficult to meet for the wind turbines installed in Spain since almost all of them are induction generators either squirrel cage or doubly-fed and as it has been pointed above that they have very limited reactive power controllability during voltages dips [7]. Hence, some exceptions are permitted.

1) During a 150 ms period from the beginning of the fault: specific reactive power consumption is only allowed if the net reactive power absorbed in each cycle (20 ms) does not exceed 60% of rated power.

2) During a 150 ms period from the fault clearance: specific reactive power consumption is only allowed if the net reactive power absorbed does not exceed 60% of rated power, and the incoming reactive current in each cycle (20 ms) does not exceed 1.5 times the rated current.

B. Challenges

New requirements present great challenge to the wind turbines that are going to be installed in Spain but it is also important for the already installed since they will have to accomplish the requirements sooner or later. Only DFIG wind turbines will be considered in the present paper since most of the wind turbines is Spain are equipped with this kind of generators.

III. Modeling of the DFIG Wind Turbine

The model of the DFIG wind turbine is shown in Fig. 3. All of the parts have been modeled in Matlab/Simulink software package. Those considered more important are described briefly in this section.

A. DFIG Model

In order to model the DFIG a standard wound-rotor induction machine component from the toolbox has been used. The synchronous *d–q* reference frame has been selected to perform all the simulations. When generator convention is used the following equations are obtained:

$$
\begin{aligned}
v_{ds} &= -R_s i_{ds} - \omega_s \psi_{qs} + \frac{d\psi_{ds}}{dt} \\
v_{qs} &= -R_s i_{qs} + \omega_s \psi_{ds} + \frac{d\psi_{qs}}{dt} \\
v_{dr} &= -R_r i_{dr} - \omega_r \psi_{qr} + \frac{d\psi_{dr}}{dt} \\
v_{qr} &= -R_r i_{qr} + \omega_r \psi_{dr} + \frac{d\psi_{qr}}{dt}
\end{aligned}
\quad (1)
$$

where v are voltages (V), i are currents(A), R are resistances (Ω), ψ are flux linkages (V·s). Indices d and q indicate direct and quadrature axis components respectively while s and r indicate stator and rotor quantities respectively. All quantities are referred to the stator.

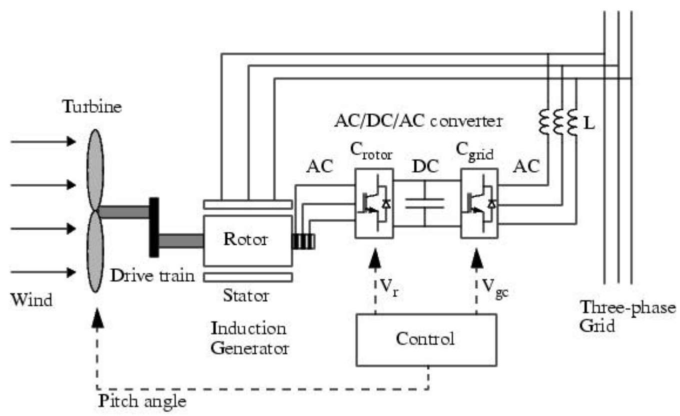

Fig. 3. DFIG wind turbine model in Simulink.

B. Rotor-Side Converter Model

The rotor-side converter is used to control the wind turbine output power and the voltage (or reactive power) measured at the grid terminal. The power is controlled in order to follow the tracking characteristics shown in Fig. 4. where the mechanical power characteristics of the turbine obtained at different wind speed is also shown. The tracking characteristic is defined by four points: A, B, C and D.

From zero speed to speed of point A the reference power is zero. Between point A and point B the tracking characteristic is a straight line, the speed of point B must be greater than the speed of point A. The line between B and C represents the optimal speed for maximal power generation. The tracking characteristic is a straight line between points C and D. The power at point D is one per unit (1 p.u.) and the speed of the point D must be greater than the speed of point C. Beyond point D the reference power is a constant equal to one per unit (1 p.u.).

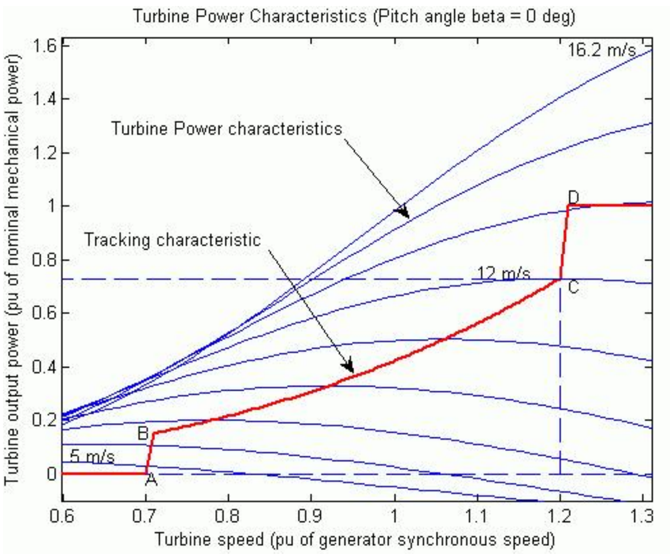

Fig. 4. Turbine power and tracking characteristics.

The actual speed of the turbine ω_r is measured and the corresponding mechanical power of the tracking characteristic is used as the reference power for the power control loop of Fig. 5.

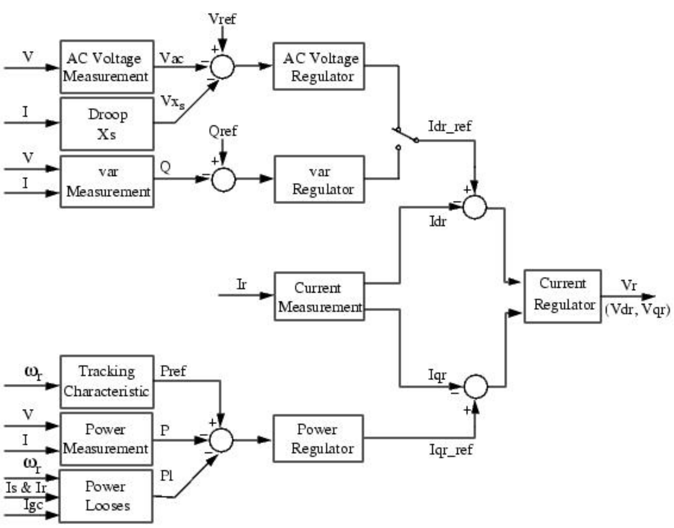

Fig. 5. Rotor-side converter control scheme considered in Simulink model.

C. Grid-Side Converter Model

The grid-side converter is used to regulate the voltage of the DC bus capacitor. The objective is to provide constant voltage to the rotor-side converter. In addition, this converter can also generate or absorb reactive power.

The control system, illustrated in Fig. 6 consists of: i) measurement systems measuring the *d* and *q* components of AC positive-sequence currents to be controlled as well as the DC voltage Vdc; ii) an outer regulation loop consisting of a DC voltage regulator. The output of the DC voltage regulator is the reference current Idgc_ref for the current regulator (Idgc = current in phase with grid voltage which controls active power flow); iii) an inner current regulation loop consisting of a current regulator. The current regulator controls the magnitude and phase of the voltage generated by converter Cgrid (Vgc) from the Idgc_ref produced by the DC voltage regulator and specified Iq_ref reference. The current regulator is assisted by feed forward terms which predict the Cgrid output voltage.

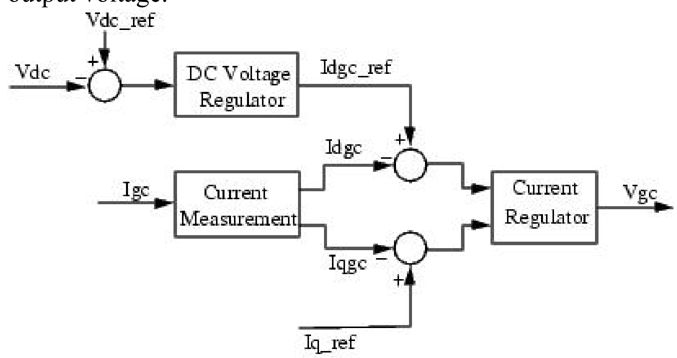

Fig. 6. Grid-side converter control scheme considered in Simulink model.

The magnitude of the reference grid converter current Igc_ref is equal to $\sqrt{Idcg\_ref^2 + Iq\_ref^2}$. The maximum value of this current is limited to a value defined by the converter maximum power at nominal voltage. When Idgc_ref and Iq_ref are such that the magnitude is higher than this maximum value the Iq_ref component is reduced in order to bring back the magnitude to its maximum value.

D. Pitch Angle Control Model

The pitch angle is kept constant when the power is lower than the rated value, i.e. wind speed lower than rated. Beyond these values the pitch angle varies with the speed deviation from the rated speed. The control system is shown in Fig 7. Before ride-though capabilities were required pitch control only took care of limit mechanical power. However, since harder requirements have been announced, the pith control is very important in both active power regulation and ride-though capabilities.

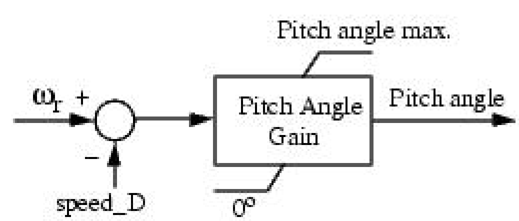

Fig. 7. Pitch angle control in Simulink model.

IV. Reactive Power Generation During Faults

The increasing number of wind turbines are connected to the network, most of them equipped with power electronics that offer enlarged control capabilities [8], has caused more demanding grid requirements. In a near future, wind turbines will have to share some of the duties carried out today by the conventional power plants, such as regulating both active and reactive power and having ride through capabilities. Firstly, the only goal was to avoid significant loss of wind generation in the event of grid faults [9]. The new Spanish grid code is a step forward because wind turbines not only have to remain connected but they also have to supply reactive power in order to support grid voltage restoration.

Grid faults are short enough to considerer that wind speed is constant during them. Consequently, the mechanical torque applied by the turbine may be considered constant too. A voltage drop will origin an electromagnetic torque reduction (quadratic dependent) that leads to the acceleration of the rotor. Moreover, the transfer of power to the grid with reduced voltage leads to an increase of stator currents. The magnetic coupling between stator and rotor will produce high induced currents in the rotor. This fact is very important in DFIGs because the power electronics converter is connected in series with the rotor winding and high current may damage it. Therefore, two kinds of protection measures are required for DFIG wind turbines during voltage dips.

In order to avoid overspeeding a reduction in mechanical torque is required. A pitch regulation as explained before is the most common in DFIG wind turbines

In order to avoid damages in power electronics the most common option is to block the rotor-side converter and short circuit the rotor winding by means the so-called crowbar [10], [11].

When the crowbar is triggered the DFIG becomes a squirrel cage induction generator (SCIG) directly connected to the grid with an increased rotor resistance [12]. During normal operation active and reactive power are controllable and the machine is magnetized by the rotor. However, while the rotor-side converter is disabled and bypassed, the controllability of active and reactive power gets lost and the magnetization is carried out by the stator, as a SCIG.

Reference [13] considers that resuming normal operation without transients when the fault is cleared is not properly feasible with crowbar protection. Other protection system consisting of by-pass resistors is then proposed. When a fault occurs the resistors are switched while the rotor-side converter remains connected. This permits that the synchronism of operation remains established during and after the fault and normal operation can be continued immediately after the fault has been cleared. The impedance of the resistor is important because it should be low enough to avoid high voltages on converter terminals and at the same time high enough to limit the current conveniently. Moreover, [13] considers that selection of a proper value is not critical and a range of them can be found.

The advantages found in DFIGs due to the use of power electronics in the rotor (rating only around 30% of the total generator power, i.e. reduced size and costs) become in a big disadvantage because of performance during voltage dips.

Due to the important presence of DFIGs in wind generation, some solutions have been proposed in the literature in order to achieve reactive power generation during voltage dips.

A. Reactive Power Generation with Blocked Converter

Systems that block the rotor the rotor-side converter and employ crowbar protection may use the grid-side converter as a STATCOM to produce reactive power (limited, however, by its rating) during faults [12]. This is possible because this converter is not directly coupled to the generator windings and it is not necessary to deactivate it too.

B. Reactive Power Generation with Connected Converter

Systems that keep the rotor-side converter connected employing by-pass resistors connected to the rotor windings may disconnect them when the dip duration is longer than a few hundred milliseconds [13]. The system can resume normal operation at reduced grid voltage and produce reactive power.

V. DFIG Wind Turbine Performance Analysis

In present paper, the presented DFIG model is connected to a simplified power system model. It is represented by the Thevenin equivalent as defined for turbine test by the Danish requirements [1]. The impedance of the power system has a phase angle of 84.3º (R/X = 0.1) with a short-circuit capacity 10 times the capacity of the wind turbine. The ratio between direct positive- and zero- sequence is 1/3.

Although single phase to ground faults are the most probable type, only symmetrical faults are considered since they are the most severe and, moreover, are often the only taken into account by grid requirements such as in the wind turbine test explained above.

A simply power system has been selected because the objective of the present paper is to check whether a DFIG could accomplish with the new Spanish requirements and produce the amount of reactive power that is required. The turbine test presented in the Danish requirements is considered good enough for this purpose.

The same starting conditions as in the test are considered: rated wind speed, nominal rotor speed, and reactive power compensation corresponding to the wind turbine, being neutral at the connection point.

These conditions are applied because if at nominal speed a fault occurs and the rotor-side converter is disabled the reactive power consumption by the generator will be maximum. Besides, the reactive power compensation corresponding to the turbine implies that there is no external compensation that could help during faults. This situation is then considered the worst case.

As the duration of all the simulations is less than one second a detailed model of power electronics IGBT converters has been considered with a switching frequency of 27 times the grid frequency (1350 Hz). The model must be discretized at a relatively small time step of 5 microseconds while the sample time used by the control system is 100 microseconds.

Several simulations have been carried out for a voltage dip of 0.6 pu (0.4 pu remaining) and 400 ms starting at 100 ms. The main aim is to find whether the wind turbine could accomplish the new requirements. As has been explained above, during a voltage dip some kind of protection has to be triggered. While the protection is triggered the generator behaves as a SCIG (i.e. absorbing reactive power). Reactive power consumption is only allowed during the first 150 ms so the protection system must be triggered less than this time in order to recover the reactive power controllability. In the simulations shown in Fig. 8 the rotor-side converter is blocked 10 ms after the fault occurs (detection time). At the same time the crowbar is triggered. This state only lasts 120 ms (130 ms after the fault occurs) because at this time the rotor-side converter is reconnected and the crowbar removed. This requires a fast reconnection of the rotor-side converter. In the selection of the crowbar resistance some considerations must be taken into account [14]

1) it should damp efficiently the rotor currents before rotor-side converter reconnects

2) its value should not be too much large to minimize the risk of excessive rotor currents transients when the crowbar is tripped to reconnect the rotor-side converter. Different values of resistance have been checked and the current transients after fast reconnection are always too high for the converter (above 2 pu) as shown in Fig. 8.

3) it influences the reactive power absorbed by the generator. As this consideration is the main interest of the present work the reactive consumption with different values has been simulated. The results are presented in Fig. 9.

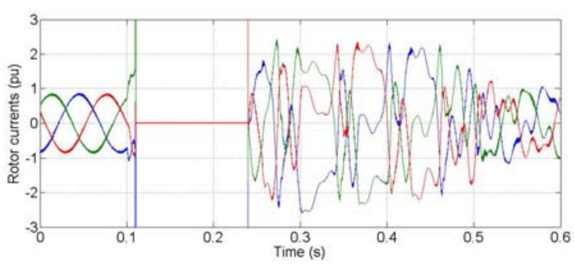

Fig. 8. Rotor currents after fast reconnection of rotor-side converter.

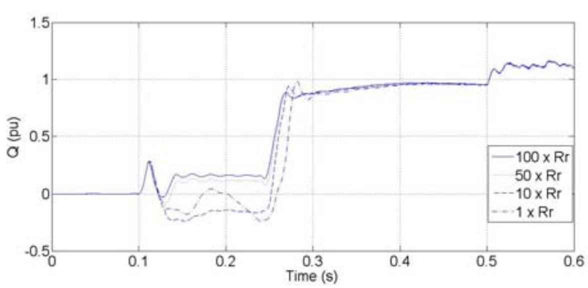

Fig. 9. Reactive power at generator terminal during a voltage dip with different values of crowbar resistance.

Reactive power must be generated 150 ms after the fault but the quantity that the grid-side converter could generate is not enough to meet the requirements and the rotor-side converter cannot be connected with the currents of Fig. 8. However, the grid-side converter acting as STATCOM could provide enough voltage recovery to reduce currents in stator and consequently rotor. The rotor-side converter reconnection at 150 ms may be acceptable (Fig. 10) although the currents are higher than 1 pu.

The limited reactive power generated by the grid-side converter is also enough to compensate the generator when rotor-side converter is blocked and it is working as SCIG with a crowbar resistance 100 times the rotor winding resistance (Fig. 9)

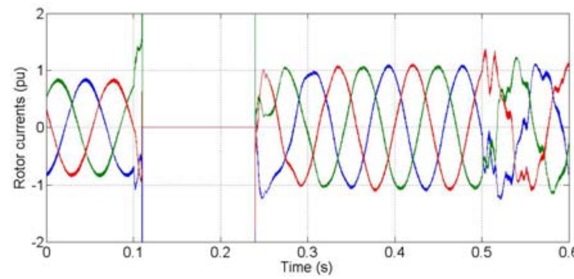

Fig. 10. Rotor currents after fast reconnection of rotor-side converter when the grid-side converter acts as STATCOM while

In Fig. 9 it can be also observed that higher values of crowbar resistance make accomplish the first of the two exceptions explained in section II (consumption of reactive allowed only during first 150 ms of voltage dip). With 100 and 50 Ω leading power factor (reactive power generation) is achieved at connection terminal at 250 ms (i.e. 150 ms after fault). That means that with these resistance values the reactive power generated by the grid-side converter is bigger than the absorbed by the generator. If it is desired to accomplish the exception with lower values of resistance earlier reconnection of rotor-side converter will be required in order to control the reactive power flow of the generator. This is difficult as it is already known due to the high rotor currents.

Once it has been checked that first exception is not overpassed the amount of reactive required in Fig. 2 has to be generated. With the magnitude of voltage dip considered the ratio between reactive current and total current must be 0.9.

The rotor-side converter takes care of the reactive power generated by a DFIG. Once it is fast reconnected the converter increases the q component of the current injected to the rotor in order to increase the reactive power generated. However, the response is not fast enough as can be seen in Fig. 11, for a crowbar resistance of 100 Ω. This behavior is obtained when the reactive power reference is set at the same time the rotor-side converter is reconnected.

Better performance can be obtained if the reactive power reference of the rotor-side converter is set to the maximum value at the moment the fault is detected even the converter is blocked.

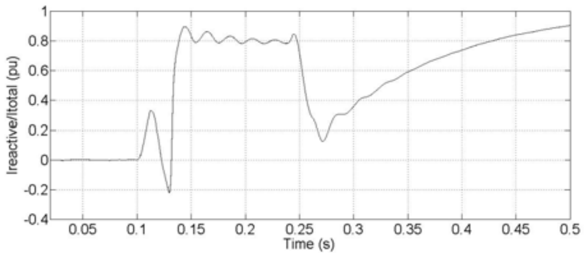

Fig. 11. Ratio between reactive and total current at connection terminal.

In Fig. 12, results with different values of resistances are shown. With lower values of crowbar resistance worst performance is obtained. With a value of 100 Ω the ratio is higher of 0.9 pu before 250 ms but little later goes down during a short time going up again till 1 pu and remaining at this value until the end of the simulation. Strictly, due to this short and small drop the requirements are not fulfilled.

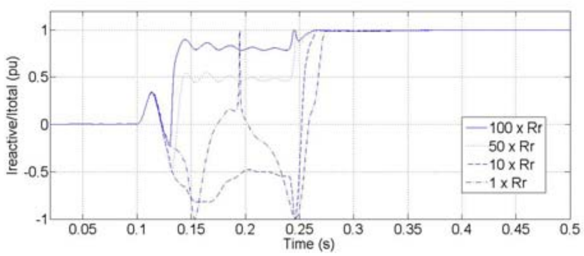

Fig. 11. Ratio between reactive current and total current generated by the DFIG with different values of crowbar resistance and maximum reactive power reference.

VI. Discussion

Although the requirements have not been completely fulfilled it is not so difficult as was thought before carrying out this study. First exception of the requirements is not overpassed since the DFIG working as SCIG by the action of crowbar protection absorbs less than 0.6 pu of reactive power.

In order to achieve the amount of reactive power stated in Fig. 2 rotor-side converter must be fast reconnected (less than 150 ms). This is only possible if the transient currents of the rotor are low enough. The grid-side converter acting as STATCOM could recover the voltage of the grid sufficiently to avoid high transients. Therefore, this fast intervention of the two converters requires a fast synchronization in both grid-side with a faulted grid and rotor-side with rotor voltages. In this paper symmetrical faults are considered which implies faster synchronization. However, unsymmetrical faults or distorted grids could make this task harder and more time consuming than allowed. Time of synchronization is limited by the requirements to less than 150 ms in the case of rotor-side converter and few milliseconds to grid-side if the effect of acting as STATCOM has to be felt when rotor-side converter reconnects.

Second exception is not considered although the reactive power consumption is bigger when the fault is cleared rather than when it starts. This is because two reasons. Firstly, the reactive power allowed to absorb rises from 0.6 to 1.5 pu because it is known that when voltage recovers the machine is re-magnetized and transients similar to starting can be found and, secondly, if previous requirements have been met the voltage recovery is enough to produce a reduced second transient. Moreover, it can be seen in Fig. 9 that after the clearance (500 ms) the reactive power goes up, as in the beginning of faults.

When requirements are not fulfilled it is necessary to use supplementary devices such as Static Var Compensators (SVC) or Static Synchronous Compensators (STATCOM) [15], [16] or wind generators employing full-size converters.

However, simulations carried out in this work cannot determine with precision if the requirements are satisfied because they are not based in real situations. The main objective of the work was to check whether it was possible to fulfill the requirements with a DFIG because it looked very difficult with this kind of machines. In future woks more realistic simulations, with more realistic network, models, synchronization performance, etc. should be carried out.

VII. Conclusion

As the wind power penetration grows up, more difficult requirements are applied. The latest one announced in Spain sets the amount of reactive current that a wind turbine must generate during a voltage dip.

These requirements may be difficult to accomplish for the majority of variable speed turbines equipped with DFIG since the rated power of their converters is around 30% of the rated power of the machine and their stator is connected directly to the grid. At present, most of these wind generators employ a crowbar as a protection system. Proper selection of both resistance value and time of actuation can be useful to meet the generation of reactive power required. Grid-side converter acting as a STATCOM is also necessary to achieve a fast reconnection of the rotor-side converter.

When it is not possible to cope with the requirements additional reactive power compensation or other type of wind turbine configuration should be considered. This would produce an increase in wind farm cost.

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