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Influence of Crowbar and Chopper Protection on DFIG during Low Voltage Ride Through

Rita M. Monteiro Pereira [1], Adelino J. C. Pereira [1,*], Carlos Machado Ferreira [1] and Fernando P. Maciel Barbosa [2,3]

1 IPC/ Instituto Superior Engenharia de Coimbra (ISEC), Instituto Superior Engenharia de Coimbra, 3030-199 Coimbra, Portugal; rmfm@isec.pt (R.M.M.P.); cmacfer@isec.pt (C.M.F.)
2 Faculdade de Engenharia da Universidade do Porto, 4200-465 Porto, Portugal; fmb@fe.up.pt
3 The Institute for Systems and Computer Engineering, Technology and Science (INESC TEC), 4200-465 Porto, Portugal
* Correspondence: ajcp@isec.pt; Tel.: +351-239-790-300 (ext. 3221); Fax: +351-239-790-201

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Abstract: The energy sector is evolving rapidly, namely due to the increasing importance of renewable energy sources. The connection of large amounts of wind power generation poses new challenges for the dynamic voltage stability analysis of an electric power system, which has to be studied. In this paper, the traditional Doubly-Fed Induction Generator model is employed. Based on this model, a crowbar and chopper circuit is set up to protect the turbine during the short-circuit period. The EUROSTAG software package was used for the simulation studies of the system, and numerical results were obtained. Conclusions are drawn that provide a better understanding of the influence of crowbar and chopper protection on Doubly-Fed Induction Generators (DFIG), during low voltage ride through, in a system with wind power generation.

Keywords: chopper; crowbar; electric power systems; low voltage ride through; wind farms; wind generators

1. Introduction

Currently, wind power generation is developing more and more quickly around the world. Doubly-Fed Induction Generators (DFIG) are used in many wind farms [1]. Nowadays, the majority of technical difficulties concern the installation of new DFIG wind farms. This technology fulfils the grid code requirements at a lower cost than the Direct Drive Synchronous Generator (DDSG) [2]. The technology is well developed, and a set of wind power plants are already installed or will be shortly in place. They have the advantage of being based on a well-known technology—the induction generator. With the addition of power electronics, DFIG can produce reactive power during the disturbance, and consumes less reactive power than an induction generator after the disturbance. Considering this objective, two new features have been introduced: the crowbar and the chopper. The crowbar is connected on the rotor side and will be switched on in case a fault occurs [3]. This element improves the dynamic behavior of the system. One of the newest technologies is the introduction of the chopper, which is in the middle of the DC link. The chopper does not share the disadvantages of the crowbar, and therefore the behavior of the system is improved [4].

A grid code is a technical specification that defines the parameters that a facility connected to a public electric network has to meet to ensure safe, secure, and economic functioning of the electric system. An authority responsible for system integrity and network operation specifies the grid code. Concerning wind power generation, each country has its own grid codes that cover significant technical regulatory issues [5].

The content of a grid code varies, depending on the transmission company's requirements. Typically, a grid code will specify the required behavior of a connected generator, namely a wind power generator, during system disturbances. These include voltage regulation, power factor limits and reactive power supply, response to a system fault (short-circuit), response to frequency changes on the grid, and the requirement to "ride through" short interruptions of the connection [6].

Presently, the installed power in the Portuguese national system is 19,518 MW. Wind production, with an installed capacity of 5236 MW, supplied 22% of consumption last year. In Portugal, the Transmission and Distribution grid codes require that wind farms must remain connected to the grid for voltage dips resulting from three-phase, two-phase, or single-phase faults, when the voltage on the interconnection transformer (network side winding) is above the line (a gray area) shown in Figure 1.

The fault ride-through requirement for wind turbines is shown in Figure 1. It is possible to verify, for example, that for a disturbance causing a dip voltage of 0.2 p.u., with a duration equal to or less than 0.5 s, the wind farm must remain connected to the grid. For a longer dip voltage duration, there is no obligation for the park to remain connected to the grid.

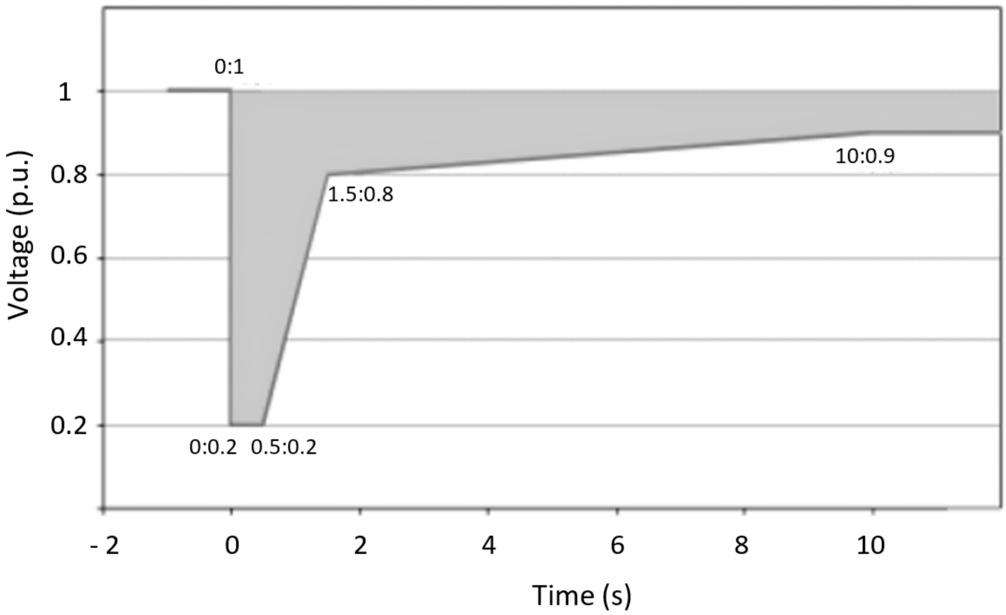

Figure 1. Fault ride-through requirement for wind turbines in the Portuguese transmission grid [7,8].

In Figure 2, the grid support during faults by reactive current injection, as stated in the Portuguese grid codes, is represented. During a voltage dip, the wind generators must supply the network with reactive current, in order to provide voltage support [7,8]. As can be seen in Figure 2, the reactive energy to be supplied by the wind farm depends on the voltage at the point of connection, and comprises two zones:

- Zone (1) corresponds to the fault and recovery mode when the voltage is below 90% of the nominal system voltage (0.9 p.u.), following the occurrence of a fault. In this case, the wind power plant should provide the grid (with a maximum delay of 50 milliseconds after detection of the voltage dip), at any time, with a quantity of reactive energy that lies within zone (1) of Figure 2.
- Zone (2) corresponds to the normal operating mode, with the voltage at the terminals of the power supply being above 90% of the nominal voltage. In this case, the wind power plant shall provide reactive power in accordance with the normal regime in force.

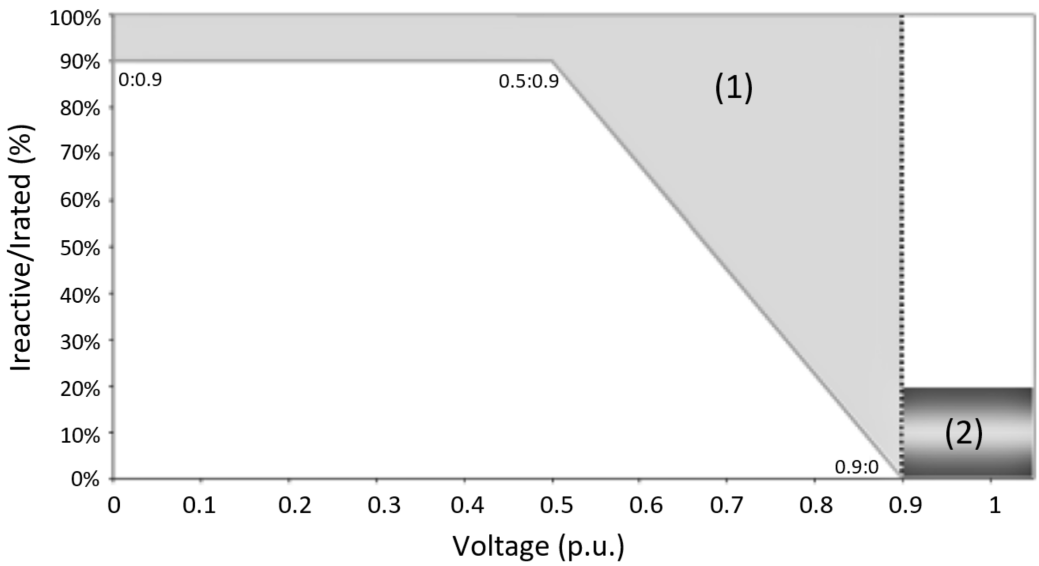

Figure 2. Grid support during faults by reactive current injection as specified in the Portuguese grid codes [7,8].

2. Model of Wind Turbine Equipped with DFIG

DFIG are electric generators where the field magnet windings and armature windings are separate. The stator of the DFIG is connected directly to the grid, while the rotor is connected through two back-to-back Voltage Source Converters (VSC) [9,10]. By feeding adjustable frequency, AC power to the field windings, the magnetic field can be made to rotate, allowing variation in motor or generator speed. This is useful, for instance, for generators used in wind turbines.

The mechanical power extracted from the wind is given by the expression [11]:

$$P_{wind} = \frac{1}{2} C_P \left(\lambda, \beta\right) P_{air} A_{rotor} V^3 \quad (1)$$

where ρ is the air density (kg/m^3); C_P is the performance coefficient; λ is the tip speed ratio; the ratio is between the blade tip speed and wind speed upstream of the rotor; β is the pitch angle of the rotor blades (degrees), and A_{rotor} is the area covered by the rotor (m^2). The performance coefficient C_P is determined by aerodynamic laws, and thus may change from one wind turbine type to another.

Variable speed induction machines, and particularly DFIG, are used more and more for wind energy conversion [12]. This allows the turbine to be operated at variable speed, therefore enhancing the conversion efficiency at low wind speed. One of the main reasons for the use of variable speed machines is the synchronizing capability of these machines. The other option is currently based on/off AC–DC–AC conversion, with the possibly of a gearless implementation. The size of the power electronic package is reduced to 30–50% when considering DFIG. This is the main reason why such an option is often selected [13].

The global scheme, including the rotor crowbar and the DC link chopper, is represented in Figure 3. The considered model of the DFIG is composed of the following different parts [11]:

- Model of the doubly-fed machine and the converters;
- Model of reactive power control;
- Aerodynamic model of the wind blades;
- Model of the wind turbine control (Pitch controller, Power controller and Main controller).

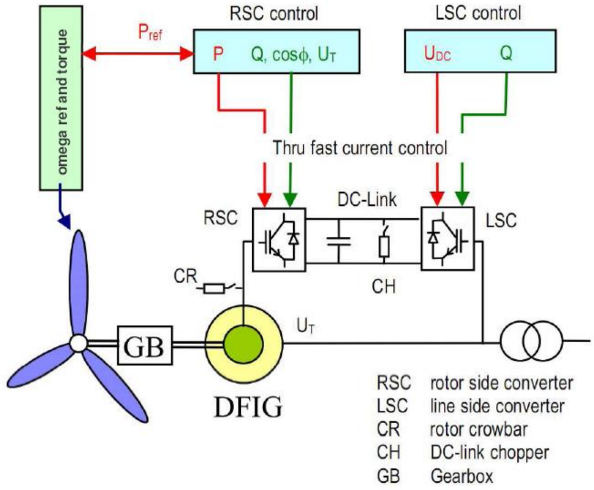

Figure 3. Model of the Doubly-Fed Induction Generator (DFIG) scheme [11].

A modern technology that enables uninterrupted connection during a fault, and production after the fault, is used by the most efficient plants nowadays. The proposed model can take into account these new technologies. The model can be used with the wind and pitch modeling macroblock of the EUROSTAG software package [11]. In this model, the DFIG (Figure 4) is an induction generator, and the rotor is connected to a voltage source (type M15) and injector (IR, II). The rotor voltage is controlled by a regulating macroblock named 'i3edfig', which is assigned to the M15 machine. The power electronics converter connected to the network, the machine, and the DC-link are modeled by macroblock 'interoI3' and assigned to the injector. The value of the active power generated by the rotor and the different protections are transmitted to the injector through parameterized interface variables. The M15 machine and the injector are then coupled. In case of voltage dips, due to short-circuit, for example, a crowbar automatic system is able to temporarily shunt the rotor to a resistance, to protect the power electronics. When the machine operates in a non-conventional mode, it is managed by the macroblock 'i3erecon'. The rotor voltage regulation is made in i3erecon, and the computed values are used in i3edfig [11]. The wind turbine is modeled by a macroblock called 'windturb', which is assigned to the M15 machine.

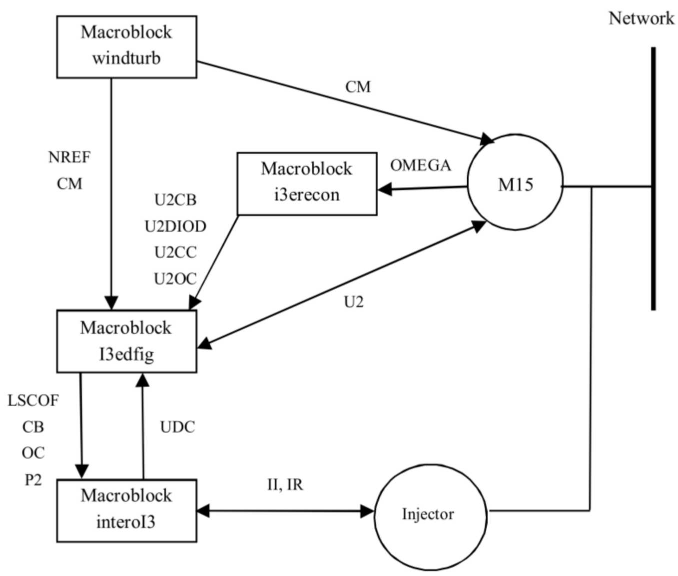

Figure 4. Scheme summarizing the modeling.

Figure 4 shows the input and output variables of the respective macroclock, where:

CB—state variable of the crowbar operating mode;
CM—rotor mechanical torque;
IR—real part of the injected current;
II—imaginary part of the injected current;
LSCOF—state variable of the converter (network side);
NREF—reference rotor speed;
OMEGA—rotor speed;
OC—state variable of the rotor in open circuit operating mode;
P2—rotor active power;
U2—rotor voltage;
UDC—voltage of the DC-bridge (in p.u.);
U2DIOD—real and imaginary component of the rotor voltage in passing diodes situation;
U2CB—real and imaginary component of the rotor voltage in a Crowbar activation situation;
U2CC—real and imaginary component of the rotor voltage in short circuit situation;
U2OC—real and imaginary component of the rotor voltage in open circuit.

The macroblocks used for the different controls are:

- i3edfig for the M15 machine;
- interoI3 for the rotor connection;
- i3erecon for the stator disconnection management;
- windturb for the wind turbine.

3. Protection Devices

The problem with this kind of generator is its behavior during a contingency. For example, during a voltage drop, the power electronics will shut down in order to protect the Insulated Gate Bipolar Transistors (IGBTs), and the equivalent system will behave as an induction generator without any command. This operating mode has to be avoided. In this study, the crowbar and chopper have been implemented in order to protect the DFIG.

3.1. Crowbar

The crowbar is a resistance, which is connected between the rotor and the rotor side converter. The four operation modes of the crowbar are presented in Figure 5 [4]:

- Mode 1: Normal mode

The machine converter feeds the rotor to generate appropriate reactive and active power. The rotor current and voltage are controlled by IGBTs, and the crowbar is disconnected.

- Mode 2: Crowbar mode

The Rotor Side Converter (RSC) is disconnected and the crowbar is connected. Then the rotor voltage is nearly zero, and the resistance connected to the rotor is equal to the crowbar and rotor resistance. The system is in this mode when U_{DC}, the voltage in the direct link, reaches 1.2 p.u. When the crowbar is on, the RSC is disconnected and the machine is no longer controlled. The current goes through the crowbar, and the rotor speed increase will be absorbed. The DFIG will stay connected for approximately 60 ms, and the DFIG will continue to operate, even if the voltage is low.

- Mode 3: No load mode or opened rotor

The RSC and the crowbar are disconnected. The rotor is opened, and so the rotor current is equal to zero. The diodes are not passing current. In this mode, the DFIG behaves like an induction generator.

- Mode 4: Diode mode

When the rotor voltage is greater than the voltage in the direct link (U_{DC}), the diodes shunt the IGBTs, which are connected in parallel. In this case, it is not possible to control the rotor current. The rotor coils are supplied through the diodes, which are in parallel with the IGBTs. A quick rise in the voltage in the direct circuit is possible, and will occur in most cases. The value of the rotor voltage is proportional to the Voltage Source Converters direct current.

Without the crowbar, the system only has two operating modes: the normal mode and the opened rotor mode. With a crowbar, the generator will not operate in the opening rotor mode for a long time. The crowbar also limits the time during which the generator is uncontrolled.

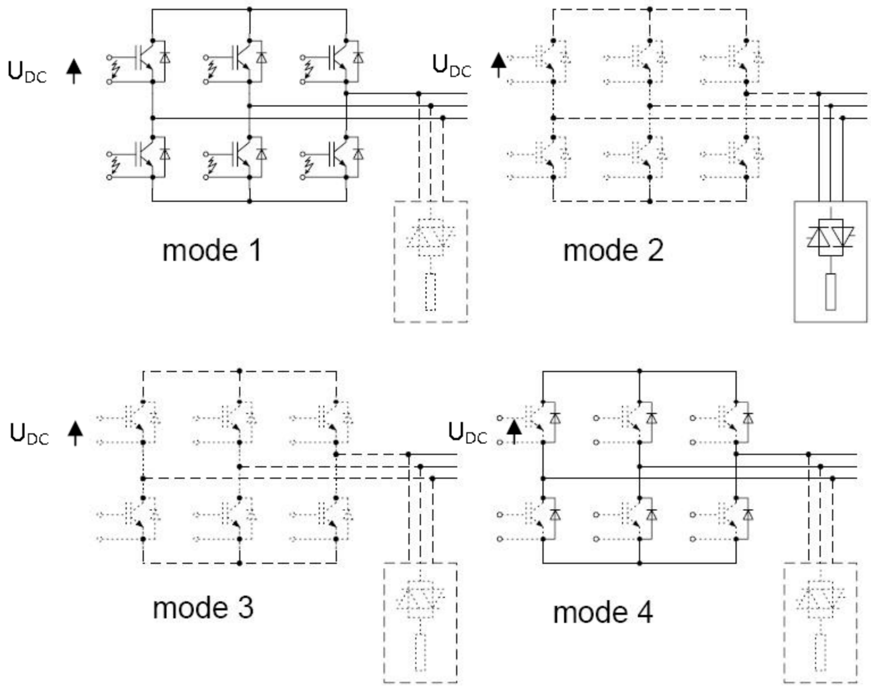

Figure 5. The four operation modes of the crowbar [4].

3.2. Chopper

The chopper is a thyristor-controlled resistance, in which the imbalance of electrical power injection into the power network by the Line Side Converter (LSC), and the electrical power injected into the DC link by the Rotor Side Converter (RSC), is dissipated. The technical solution that allowed the crowbar protection and the chopper protection to be combined was studied previously [12,14]. The chopper is the most advanced, and the most expensive, solution nowadays.

By adding a thyristor-controlled resistance in the direct current link, the entire bridge does not have to be disconnected, because it is possible to lower the voltage of the DC link. Moreover, the wind turbine can be controlled.

When the voltage in the direct link (U_{DC}) is at 1.1 p.u., the chopper will be connected, and it will be disconnected when the voltage drops below 1.08 p.u.

4. Application Example

The simulations described in this paper were carried out in the Electric Power Network, represented in the single line diagram of Figure 6, which shows the equivalent scheme of the electric system where the wind farm is inserted. The modeling of the wind farm and its interrelationship between macroblocks were explained, in more detail, in Figure 4. The network data used was presented previously [15].

The Automatic Voltage Regulators (AVR) of the generating units, and the turbine Speed Governors (SG), were taken into account. The Under Load Tap Changer (ULTC) actions of the power transformer, between busbars N3 and N4 (380/150 kV), are represented considering a time delay and a dead band. Time delays for ULTC operations are assumed to be 30 s for the first tap movement, and 5 s for subsequent tap movements. The operating point assumed in this study corresponds to a 1600 MW and 850 Mvar load level. In busbar N3, it is assumed to be a load level of 600 MW and 550 Mvar, whereas in busbar N4, the active power load is 1000 MW and the reactive power load is 300 Mvar. In busbar N4, the load was considered to have constant impedance, while in another one (busbar N3), it was assumed to have constant power. The wind farm is connected at bus N6 by a three-winding transformer 150/0.69/0.69 kV. The wind farm has 80 wind turbines, each with 2 MVA, and is represented as an aggregated equivalent model. The DFIG wind turbine is represented by an induction machine $N_{WIND}S$, with the rotor connected to an injector $N_{WIND}R$. It was simulated by a three-phase short-circuit in the busbar N6, at 50 s for 500 ms. Generator G2 is considered as an infinite busbar.

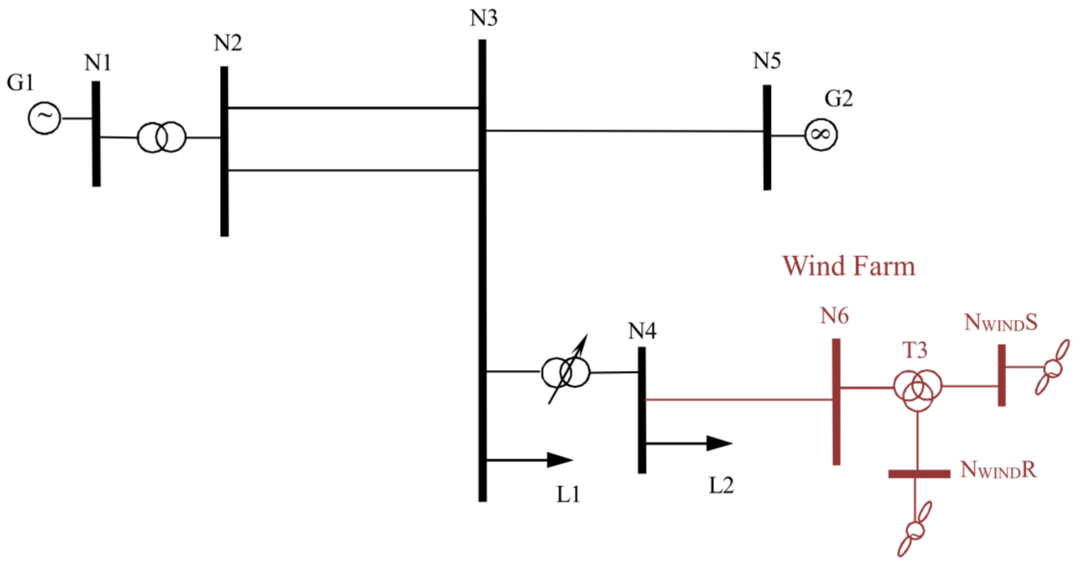

Figure 6. Single line diagram of the power network.

In this study, two scenarios were simulated and analyzed. In the first scenario (case I), the wind farm is modelled as wind turbines equipped with DFIG, a crowbar, pitch control, and without a chopper. In the second situation (case II), the wind farm is modelled as wind turbines equipped with DFIG, pitch control, a crowbar, and a chopper.

5. Results

The simulation results are presented in two parts, for a better understanding: part A is devoted to case I, part B to case II, and part C is dedicated to comparing case I with case II.

5.1. Part A—Case I

Suppose that, prior to the three-phase short-circuit occurring in busbar N6, the generator operates at constant speed, and produces 112 MW and 5 Mvar in normal mode (mode 1). After the short-circuit, the DFIG accelerates, and the rotor current will rise to a high value (Figure 7b1). The DC voltage will rise due to the increase in the rotor current (Figure 7c1), which flows through the RSC. When the DC voltage reaches 1.2 p.u., the crowbar will be connected to protect the DC link, disconnecting the RSC (mode 2). The crowbar will be switched for 60 ms (Figure 7a1). After this time, the rotor stays in opened rotor mode (mode 3), with the RSC disconnected. In this mode, the value of the current in the rotor becomes null (Figure 7b1), the thyristors are deactivated, and the crowbar is disconnected.

When the crowbar is activated, the RSC is disabled and the DFIG behaves like a squirrel cage induction generator, directly coupled to the network. The magnetization of the generator that was provided by the rotor side converter in nominal condition is lost, and the generator consumes reactive power from the stator, and thus from the grid (Figure 7d2) [4].

During the short-circuit, active power generation is low, since the value of the bus voltage at the wind farm connection (N6) is also low (Figure 7e1, e2 and f).

DFIG systems are more stable, therefore less reactive current is consumed, when compared with induction generators. The machine can also produce reactive power just after the clearance of the fault, which helps the system to restore the voltage faster.

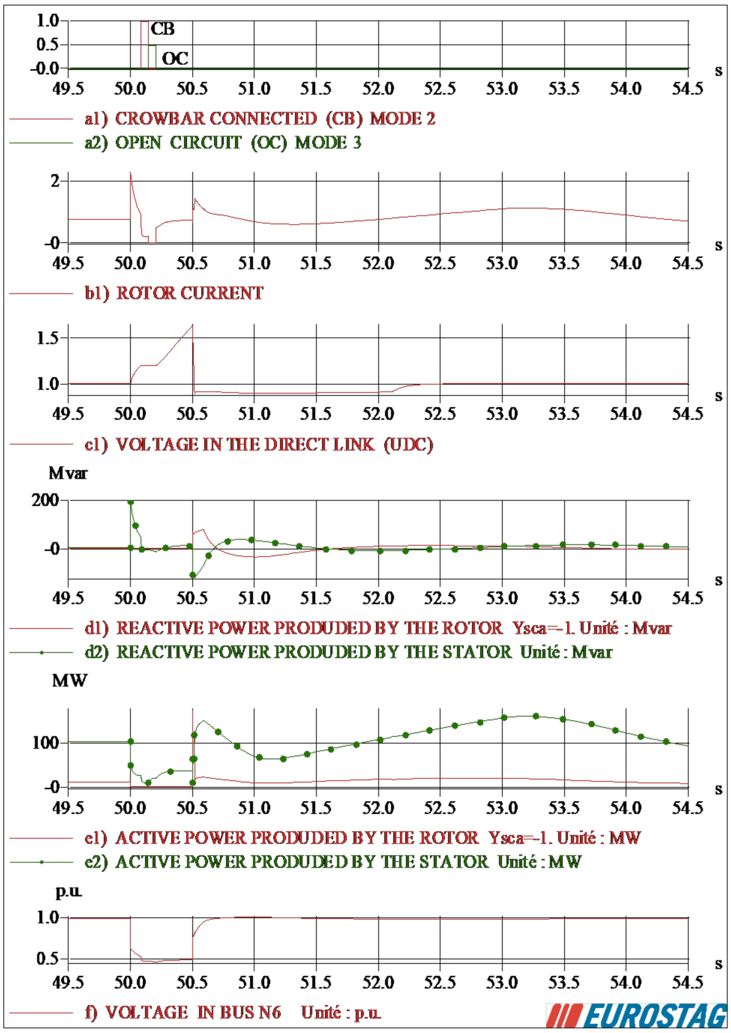

Figure 7. Dynamic analysis of the protection model crowbar without a chopper.

5.2. Part B—Case II

In this case, the DFIG is modelled with a chopper, and the short-circuit is cleared in 500 ms. Figure 8 presents the results of the dynamic study for the short-circuit.

As in case I, before the short-circuit, the DFIG operates at a constant speed. After the short-circuit, the DFIG will accelerate and the rotor current will rise to a high value. The DC voltage will rise because of the increase in the rotor current (Figure 8b1), which flows through the RSC. When the DC voltage reaches 1.1 p.u., the chopper will be connected to protect the DC link (Figure 8c1). The chopper remains connected during the short-circuit (Figure 8a1). At this time, the DC voltage remains constant at 1.1 p.u. (Figure 8c1), and the rotor current decreases to values similar to the pre-fault values (Figure 8b1). As the DC voltage does not exceed 1.1 p.u. (the crowbar will be connected at 1.2 p.u.), the crowbar is not connected in this case.

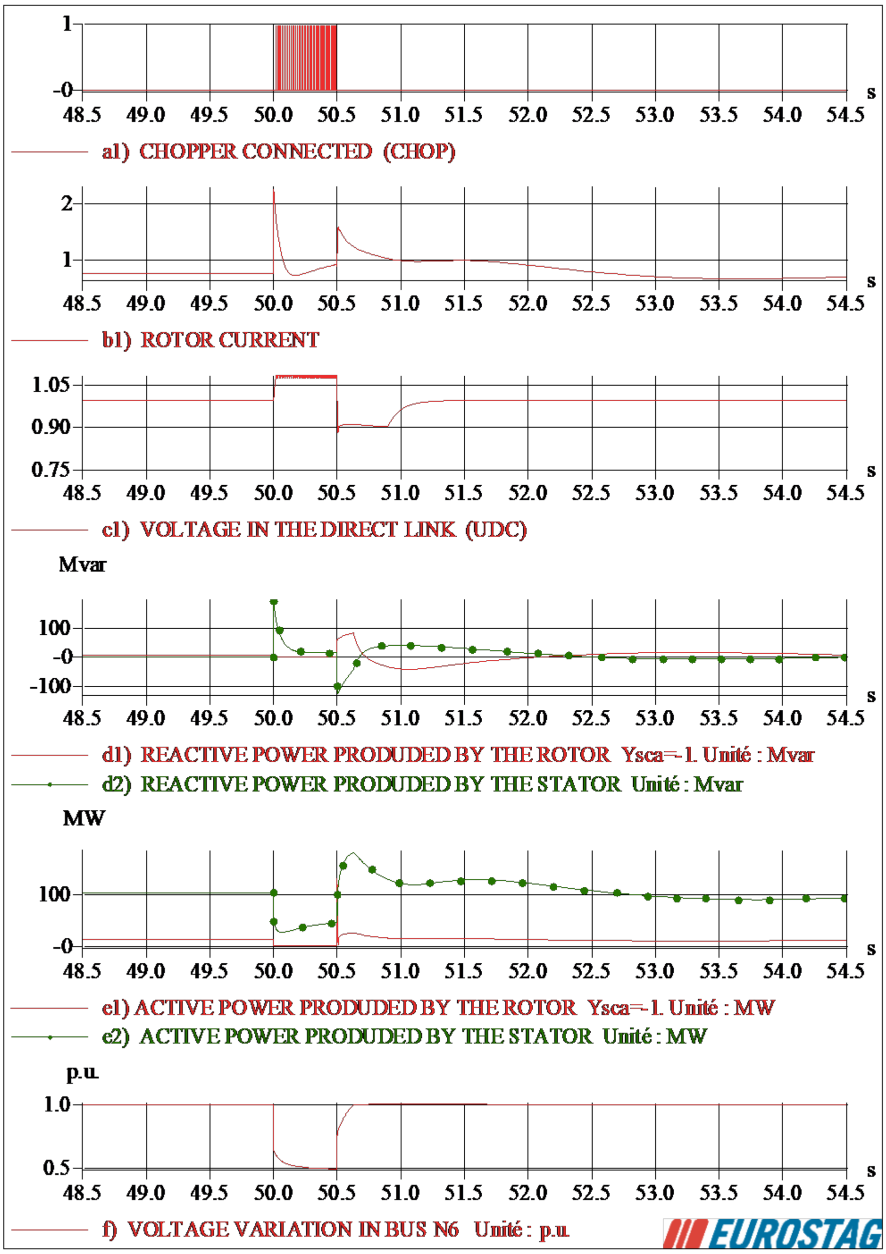

Figure 8. Dynamic analysis of the protection model crowbar with a chopper.

5.3. Part C—Comparison between Case I and Case II

In this section, the two previous cases are compared, in order to assess the importance of these models for the protection of converters, before the occurrence of a short-circuit in the busbar of the wind farm.

In case I, when the DC voltage reaches 1.2 p.u., the crowbar will be connected. From this moment, the rotor current decreases, but during the short-circuit (Figure 9) the DC voltage continues to increase. When the rotor stays in opened rotor mode, the value of the rotor current becomes null. Figure 9c2 shows that when the RSC is disabled (mode 2 and mode 3), the DFIG behaves like a squirrel cage induction generator, directly coupled to the network. The magnetization of the generator, which was provided by the rotor side converter in nominal condition, is lost, and the generator consumes reactive energy from the stator, and thus from the grid, violating the grid codes.

In case II, the chopper operates when the DC voltage reaches 1.1 p.u., and this keeps the voltage value during the short-circuit constant. The rotor current also decreases, reaching values close to the pre-fault values. It is possible to produce reactive power during the fault, thereby respecting the grid codes, if the chopper activates instead of the crowbar, as the DC link stays connected (Figure 9).

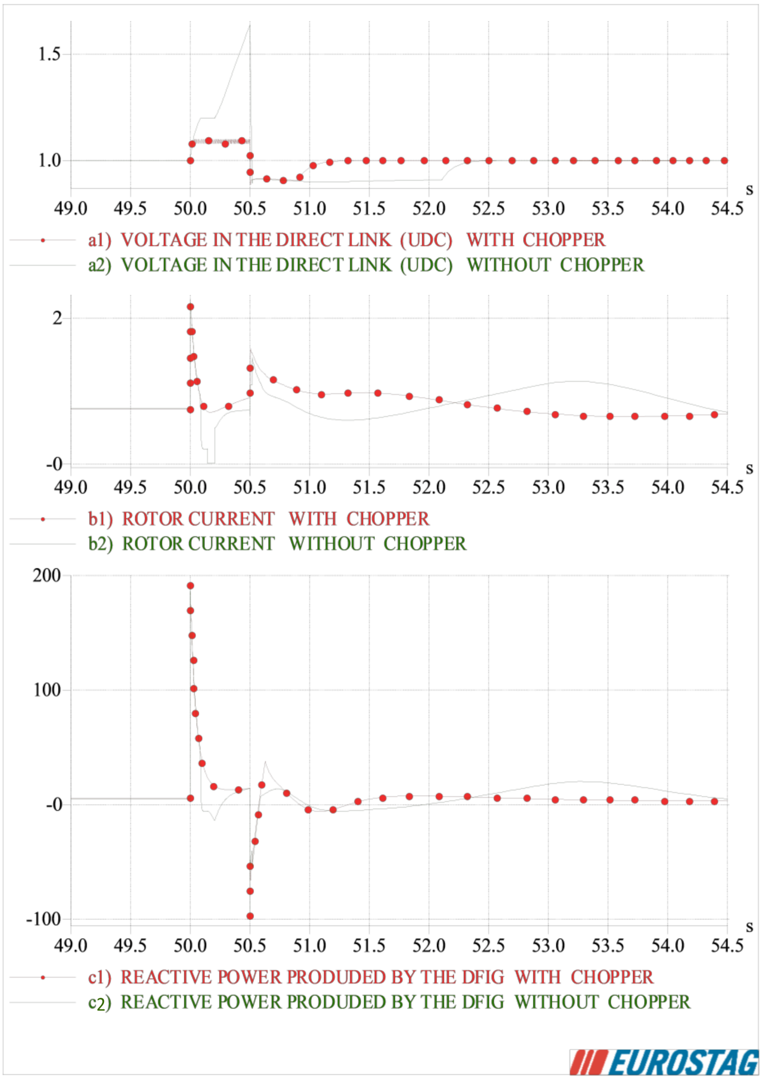

Figure 9. (**a1**,**a2**) Variation of voltage in the direct link with and without a chopper; (**b1**,**b2**) Variation of rotor current with and without a chopper; (**c1**,**c2**) Variation of reactive power produced with and without a chopper.

With the occurrence of a short-circuit at 50 s, the DFIG speed increases in both cases, however, the increased speed and the oscillation is much higher without a chopper (Figure 10).

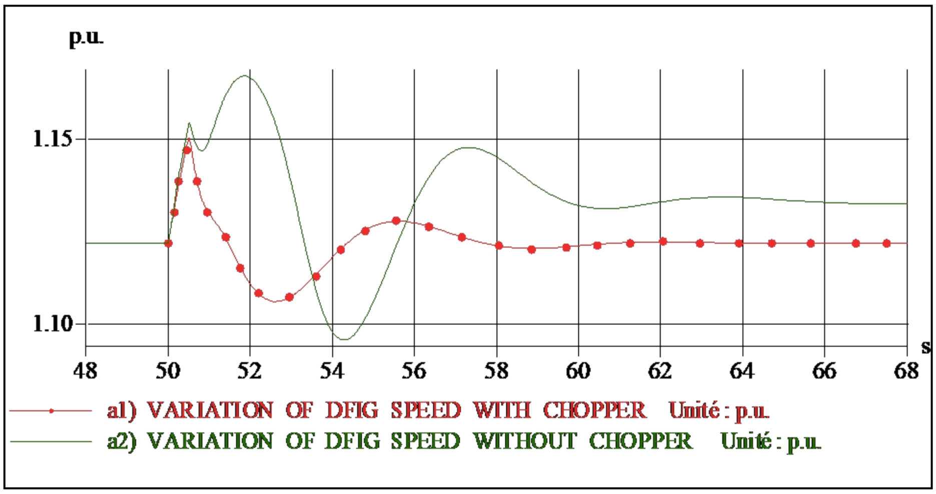

Figure 10. Variation of DFIG speed with and without a chopper.

The voltage variation at bus N6 for case I and case II, when the wind farm is connected to this bus, is depicted in Figure 11.

As can be seen in Figure 11, the voltage with and without a chopper has a profile that satisfies the curve shown in Figure 1, and allows the wind farm to remain connected to the network during the voltage dip due to the short-circuit. It was observed, in case I, that in the period in which there was consumption of reactive power, the voltage has a lower value.

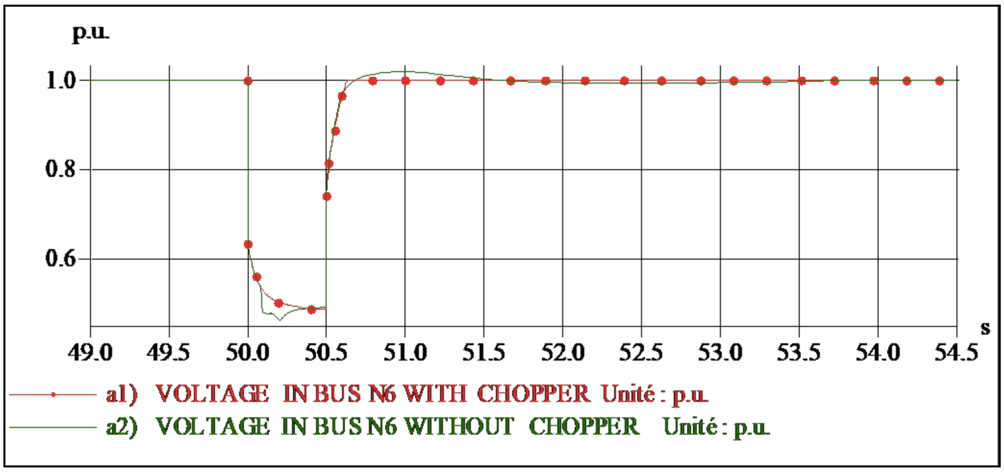

Figure 11. Variation of voltage in busbar N6 with and without a chopper.

6. Conclusions

The influence of crowbar and chopper protection on DFIG, during low voltage ride through, in an electric power system with wind power generation, considering the two doubly-fed induction generator protection devices, was studied, and the results presented in this paper. The Portuguese grid codes were considered when analyzing the impact of the voltage ride through requirements of the grid codes, and the grid support, during faults by reactive current injection.

During a disturbance, the static converter, which plays an important role for the control of the DFIG, can come out of service when the maximum rotor current is exceeded, significantly influencing the performance of the DFIG. During the temporary removal of the converters, the rotor of the machine is short-circuited and, therefore, the DFIG temporarily operates as an induction generator rotor cage (mode 2 and mode 3), consuming reactive power. Depending on the threshold value of the rotor current, the converters can be removed again several times, when being restarted due to current peaks during re-engagement, which leads to reactive power consumption by the DFIG.

The chopper is a technically advanced and very expensive solution, such that few wind farms are equipped with this type of technology. The chopper allows the DFIG to produce reactive power during the fault, maintaining constant voltage on the DC bus, thereby preventing activation of the crowbar. This system allows the behavior of the DFIG, before the occurrence of severe short-circuits in the electrical network, to be substantially improved, fulfilling the technical requirements of connecting to the grid.

Author Contributions: Rita M. Monteiro Pereira designed and performed the experiments and analyzed data, Adelino J. C. Pereira, Carlos Machado Ferreira and Fernando P. Maciel Barbosa helped perform the analysis with constructive suggestions, revised the manuscript. All authors read and approved the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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