DFIG WIND TURBINE DYNAMIC UNDER THE STRESS OF POWER SYSTEM FAULTS

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REZUMAT. Una din cerinţele impuse parcurilor eoliene este funcţionarea continuă, chiar şi atunci când apar fluctuaţii ale tensiunii în reţea, conform specificaţiilor din normative. Capabilitatea de a funcţiona la tensiune scazută este o cerinţă de bază a turbinelor eoliene pentru a fi în acord cu codurile de reţea. În cazul turbinelor eoliene ce folosesc generatoare cu inducţie cu dublă alimentare, reacţia la perturbaţiile din reţea este evidentă şi imediată. Este necesară utilizarea unui circuit de protecţie pentru protejarea convertorului de pe partea rotorului de supracurenţi pe durata defectelor din reţea.

Cuvinte cheie: generator cu inducţie cu dublă alimentare, defecte în reţea, trecere prin defect, circuit de protecţie crowbar

ABSTRACT. A technical requirement for wind energy system is continuous operation, even in power system voltage fluctuations, according to standards specifications. Low Voltage Ride Through is an important feature for wind turbine systems to fulfill grid code requirements. In case of wind turbines using Doubly-Fed Induction Generators, the reaction to grid disturbances is sensitive. A crowbar protection must be implemented to protect the rotor side converter from overcurrents during grid faults.

Keywords: doubly-fed induction generator, grid faults, fault ride through, crowbar

1. INTRODUCTION

Renewable energy generation, including solar, wind, geothermal, hydro, has undergone rapid developments in the last years. Particularly, wind turbine increased performances allowed wind energy to become an advantageous solution to classical electrical energy generation. Insertion of wind energy in power system involves stability, compatibility or power quality issues occurred during short-circuit faults or supply voltage variations.

According to recent wind farm grid code, wind generators have to contribute to the control of voltage and frequency and also to continue their operation during a disturbance in the grid under specified conditions. The Doubly-Fed Induction Generator (DFIG) has very attractive characteristic as a wind generator because the power processed by the ower converter is only a fraction of the total power rating of the DFIG, that is typically 20-30%, and therefore its size, cost and losses are insignificant compared to a full size power converter used in other variable speed wind generators. DFIG can operate at a wider range of speed depending on the wind speed or other specific operation requirements. Hence, it allows a better capture of wind energy [1]. On the other hand, DFIG have shown better behavior in terms of system stability during short-circuit faults in contrast with Induction Generator (IG), because of its capability of decoupling the control of active and reactive power output. The superior dynamic performance of the DFIG results from the Variable Frequency Converter (VFC) which typically operates with sampling and switching frequencies of above 2 kHz [2]. At lower voltages down to 0% the Insulated Gate Bipolar Transistors (IGBTs) of the DFIG are switched off and the system remains in standby mode. If the voltages are above a certain threshold value during fault, the DFIG system can be synchronized very quickly and back in operation again [3]. On the other hand, IG is used in general as fixed speed wind turbine (FSWT) generator due to their superior characteristics like rugged construction, low cost, maintenance free and operational simplicity, but requires large reactive power to recover the air gap flux when a short circuit fault occurs in the power system. IG technology has limited ability to ensure voltage control, thus require reactive power compensation.

During a grid fault, the VFC can be damaged due to large rotor currents generated, which causes to raise the DC-link voltage above nominal value. A crowbar switch has been considered for protecting DFIG during fault conditions.

The paper shows simulations concentrated on the dynamic of DFIG wind turbine under the action of power systems faults and analyses the influence of the crowbar resistance on the DFIG. Different values of the crowbar resistors result in a different behaviour.

2. DOUBLY FED INDUCTION GENERATOR CONCEPT

DFIG is the generator model of the wind turbines, that growed more and more in terms of installed capacity and number of sold units. The machine is a wound rotor induction generator with the stator fed directly to the grid and the rotor fed to the grid through a variable frequency converter (VFC). The VFC is formed by two different converters: rotor side converter (RSC) and grid side converter (GSC) and uses only 25 ÷ 30 % from the machine rated power. That allows the control of generated reactive power and speed variation in the range of ± 30 % around the synchronous speed.

According to [4] the main goals of RSC are:

o to maintain a constant frequency of the DFIG stator voltages;

o to control the magnitude of the DFIG stator voltage to a set value;

The main goals of GSC are:

o to maintain the DC-link voltage constant in terms of magnitude and direction of the rotor power;

o to trim the reactive power exchanged with the grid.

Figure 1 illustrates the concept of doubly-fed induction generator.

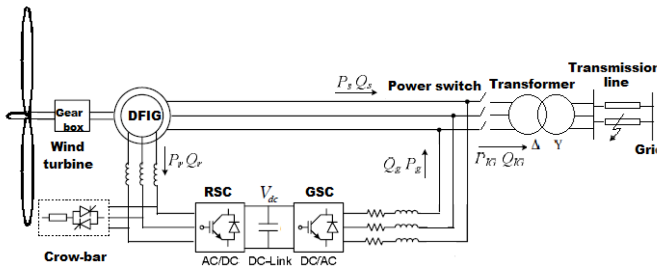

Fig. 1. Doubly-fed induction generator system.

In Figure 2, the equivalent circuit diagram of the DFIG can be seen.

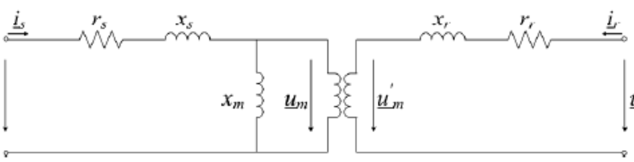

Fig.2. Equivalent circuit of the doubly-fed induction generator

According to [5] and [6], the model equations with ω_{ref} rotating reference frame will be derived as:

$$\underline{u}_s = r_s \underline{i}_s + \frac{d\underline{\psi}_s}{\omega_n dt} + j\frac{\omega_{ref}}{\omega_n}\underline{\psi}_s \quad (1)$$

$$\underline{u}_r = r_r \underline{i}_r + \frac{d\underline{\psi}_r}{\omega_n dt} + j\frac{\omega_{ref} - \omega_g}{\omega_n}\underline{\psi}_r \quad (2)$$

The flux linkage can be expressed by the following relations:

$$\underline{\psi}_s = (x_s + x_m)\underline{i}_s + x_m \underline{i}_r \quad (3)$$

$$\underline{\psi}_r = x_m \underline{i}_s + (x_m + x_r)\underline{i}_r \quad (4)$$

The mechanical equation is expressed by the following relation:

$$J\frac{d\omega_g}{dt} = t_m + t_{el} \quad (5)$$

The electrical torque is calculated from the stator flux and the stator current:

$$t_{el} = \mathrm{Im}(\underline{\psi}_s \underline{i}^*_s) \quad (6)$$

The equations (1) to (6) form the machine model of 5th order, model that expresses rotor and stator transients accurately.

2. DOUBLY FED INDUCTION GENERATOR PROTECTION BASED ON CROWBAR

Without any protection system, the concern in DFIG is the fact that large disturbances lead to large fault currents in the stator due to the direct connection to the grid, involving large fault currents in the rotor also [2],[7].

It is necessary to protect the converter against overcurrents and the rotor against overvoltages.

A simple protection method of the DFIG under grid faults is to short circuit the rotor through an external rotor impedance, so called crowbar, which is triggered if high transient currents and voltages occur in the generator or convertor.

When the crowbar is applied, the equivalent circuit of the DFIG [6] can be drawn as in Figure 3.

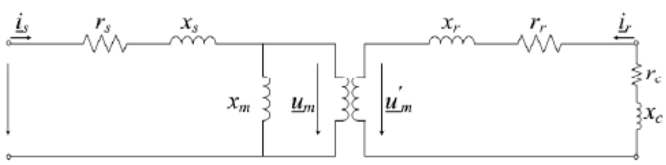

Fig.3. Equivalent circuit of the DFIG with inserted crowbar protection (r_c and x_c)

The crowbar limits the voltages and provides a safe route for the currents by bypassing the rotor. When the crowbar is triggered, the RSCs pulses are desibled and the machine behaves as a conventional Squirel Cage Induction Generator (SCIG) with an increased rotor resistance.

The value of the crowbar resistance is dependent on the generator condition. Crowbar circuits can be antiparallel thyristor crowbar, diode bridge crowbar or other unusual configurations [8].

The machine loses its magnetization; hence it absorbs a large amount of rective power from the grid. This can lead to a decrease in voltage level, which is not permitted in grid codes [9].

Before the crowbar's by-passing after a pre-defined time, the control of the DFIG by the converter is naturally lost. The equation (2) for the rotor-voltage and the equation (4) for the rotor flux linkage can be written as follows:

$$\underline{0} = (r_r + r_c)\underline{i}_r + \frac{d\underline{\psi}_r}{\omega_n dt} + j\frac{\omega_{ref} - \omega_g}{\omega_n}\underline{\psi}_r \qquad (7)$$

$$\underline{\psi}_r = x_m \underline{i}_s + (x_m + x_r + x_c)\underline{i}_r \qquad (8)$$

The RSC is restarted, and the reactive current component of the generator is ramped up in order to support the grid. Certainly, the crowbar will be triggered again if a too-high rotor current or dc-link voltage is encountered after the turn off of the crowbar. This is often the case with severe two-phase faults that have a high negative-sequence voltage component in the stator. The negative sequence component has a high rotor slip ($s \approx 2$). Hence, very high voltages are induced in the rotor windings which make impossible to control the rotor current with the available dc-link voltage. Thus, for the most severe unsymmetrical grid faults, the RSC cannot be started before the fault has been cleared.

3. CROWBAR RESISTANCE VALUE

As noted previously, the value of the crowbar resistance is dependent on the generator condition.

According to [10] the maximum stator current is given as:

$$i_{s,\max} \approx \frac{1.8u_s}{\sqrt{x_s^{'} + r_c^2}} \qquad (9)$$

It can be observed that the maximum short circuit current of the DFIG depends on the crowbar resistance value. A lower value will lead to higher currents in the rotor of the DFIG. Therefore, the maximum value of crowbar resistance is more important than the minimum value.

As all parameters are transfered to the stator side, the maximum rotor current will have approximately the same value with maximum stator current from (9). The voltage across the crowbar, and thus across the rotor and RSC is:

$$\sqrt{2}u_r \approx r_c i_{r,\max} \qquad (10)$$

From equations (9) and (10), the maximum value of the crowbar resistance can be determined as:

$$r_c < \frac{\sqrt{2}u_{r,\max} x_s^{'}}{\sqrt{3.2u_s^2 - 2u_{r,\max}^2}} \qquad (11)$$

where $u_{r,\max}$ is the maximum permissible rotor voltage.

According to [10], (11) is an approximation and it based on a number of assumptions and approximations.

4. DFIG BEHAVIOUR TO GRID FAULTS – SIMULATION EXAMPLES

The fundamental of proposed method is to improve the performance quality of DFIG and is based on two rules. First, the power electronic switches in both GSC and RSC and DC-link must be protected from over voltages; second, the grid codes based on supplying reactive power during fault and restoring active power after the clearance of fault should be satisfied.

DFIG behavior to three phase grid fault, without fault ride through (FRT) measures.

In this paper the E_ON standard is used. According to this standard, voltage before the fault occurrence is 1p.u. and the injected reactive power is 0 p.u. [11],[12].

If the system needs the reactive power, the control system should be able to supply the power during fault.

To demonstrate the effect of a grid fault, a DFIG based wind turbine has been simulated using a detailed time domain model. This example is aimed to show the effects of a three phase voltage dip without FRT measures on the converter and generator side. The fault is considered to be produced in moment t_1 = 100 ms and lasts until t_2 = 200 ms. The grid voltage dip is transmitted immediately to the generator's stator due to direct connection (Figure 4a). This leads to overcurrents' occurence in stator, which reaches over two times the rated value (Figure 4b). Due to magnetic coupling beetwen the stator and the rotor, the stator overcurrents are transmitted to the rotor. These overcurrents can exceed three times the rated value, as can be seen in Figure 4c, and can destroy the RSC. When the grid voltage drops in the fault moment, The GSC is not able to transfer the power from the RSC to the grid, the energy charging the DC-link capacitor, thus leading to high voltage.

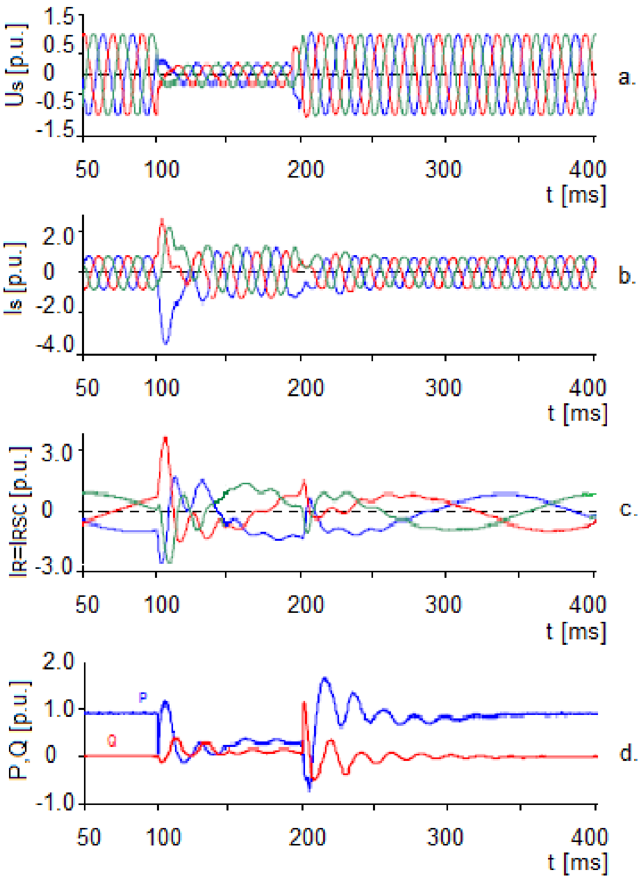

Fig.4. DFIG behavior during a three phase voltage dip without crowbar protection for FRT: a. stator voltages; b. stator currents; c. rotor and RSC currents; d. active and reactive power

DFIG behaviour to 50% three phase grid fault, with crowbar protection.

Simulations have been made using the Matlab/ Simulink platform for a 2 MW wind turbine equipped with DFIG as shown in Figure 1.

The simulation parameters are given in Table 1. The DFIG behavior, protected by the conventional crowbar is illustrated in Figure 5. It was considered a three phase 50% voltage dip of 100 ms duration at the medium voltage level 20 kV as in Figure 5a.

In the fault moment (t = 100 ms), because the stator voltages decrease to half (Figure 5b), high fault currents arrise in the stator and rotor windings (Figure 5c,d). In order to compensate for the increasing rotor currents, the RSC increase the rotor voltages reference, which involves a power infusion from the rotor through the converter. When the rotor currents exceed the maximum level, the crowbar is triggered to protect the RSC from overcurrents. It can be noticed from Figures 5d and 5e that RSC currents no longer exceed the rated value as in the first case. The overcurrents are transferred to crowbar. The crowbar has to be triggered several times during the volatage dip (Figure 5e). When the RSC is in operation, the machine magnetization is provided by the rotor, but every time the crowbar is triggered, the RSC is disabled and therefore it is not able to provide the reactive power for generator magnetization and for reactive power control during voltage dip, which is compulsory condition in nowadays grid codes.

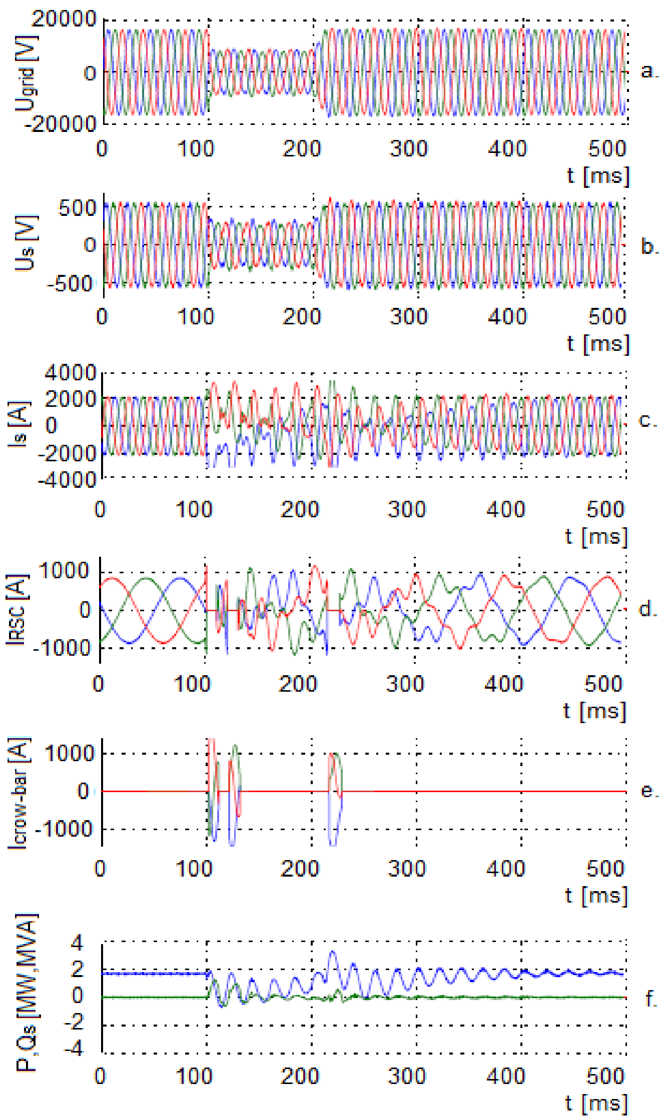

Fig.5. DFIG behavior during a 50% three phase voltage dip with crowbar protection for FRT: a. grid voltages; b. stator voltages; c. stator currents; d. RSC currents; e. crowbar currents; f. active and reactive power

Table 1

Simulation parameters

Symbol	Name	Value
U_{grid}	Grid voltage level	20 kV
U_l	Low voltage level	690 V
ω	Line angular frequency	2 π 50 Hz
P_{DFIG}	Wind turbine rated power	2 MW
N_{sr}	Stator to rotor transmission ratio	1 / 2.5
n	Rated speed	1800 rot/min

5. CONCLUSIONS

✓ This paper is focused on the behavior of DFIG during grid disturbances. Two cases were studied: three phase fault without FRT measures and three phase fault with crowbar protection. The obtained waveforms are analyzed to emphasize the concern of crowbar used as protection equipment for power converters and generator's rotor.

✓ FRT is an important feature for wind turbines to fulfill grid codes requirements.

✓ Without FRT measures, the overcurrents that occur in the rotor windings and in RSC can exceed three times the rated value, or even more in some situations. As shown in graphs, this problem can not be found when it is used the protection circuit of RSC, the overcurrents being absorbed by crowbar.

✓ The maximum short circuit current of the DFIG depends on the crowbar resistance value. A lower value will lead to higher currents in the rotor of the DFIG. Thus, the maximum value of crowbar resistance is more important than the minimum value. An equation for maximum value of crowbar resistance was proposed, based on a number of assumptions and approximations.

✓ The use of crowbar was proved to be a simple and effective method for DFIGs to fulfill the FRT requirement, imposed by the grid codes.

ACKNOWLEDGEMENT

This paper was realised with the support of POSDRU CUANTUMDOC "Doctoral Studies for European Performances in Research and Inovation" ID79407 project funded by the European Social Found and Romanian Government.

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