DYNAMIC SIMULATION OF DOUBLE FED INDUCTION WIND GENERATORS IN THE ROMANIAN POWER SYSTEM

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This paper describes the impact of wind power plants production to Romanian Power System's operation. The main parts of the DFIG model are the following: turbine rotor, the drive train, the generator, the rotor-side converter, the grid-side converter with the DC-link, as well as the interface and power grid models. There are also presented the results of a dynamical simulation of a DFIG model in the Romanian Power System.

Keywords: wind power plants, dynamic modeling

1. Introduction

At the beginning of 2015 the installed capacity in wind power plants (WPP) reached 2950 MW. Due to the installation of a significant number of generators sources with fluctuant operation in the Romanian Power System (RPS) such as wind power plants, special attention should be paid to the analysis of dynamic behavior of the power system under the influence of this type of power source.

2. Modeling of wind power plants

2.1. Main types of constructive solutions

In terms of velocity, there are two types of wind generators: wind generators *with fixed speed* and wind generators *with variable speed*. The ones with fixed speed use squirrel cage induction generator and the ones with variable speed can be with asynchronous or synchronous generator.

2.1.1 Fixed speed wind generator

Initially, the wind generators were operating at fixed speed, so that for theme the rotor speed of the generator is fixed and determined by the frequency of the network, by the multiplier report and by the generator type. There are designed to achieve maximum efficiency for a given wind speed. To increase power production, some wind generators were equipped with two types of coils: one for low wind speeds (typically 8-pole) and one for medium and high wind speeds (usually 4-6 poles). Obviously these fireworks were hindering the plant

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and led to increase of the overall equipment price. The asynchronous generator is equipped with condensers to produce reactive power, soft starter for proper startup and step-up transformer (0,6 / 20 kV). The soft starter is used because the starting current of asynchronous machine is very large (about 6 to 8xIn), which can lead to voltage variations in a weak network [2].

2.1.2 Variable speed double fed induction wind generator

This type of machine has the stator directly connected to the grid and the rotor connected to the grid through a bidirectional converter AC / DC / AC. Dual fed means that the stator voltage comes from the network and the rotor voltage is induced by the converter. This allows operation over a relatively wide range of variable speed [1].

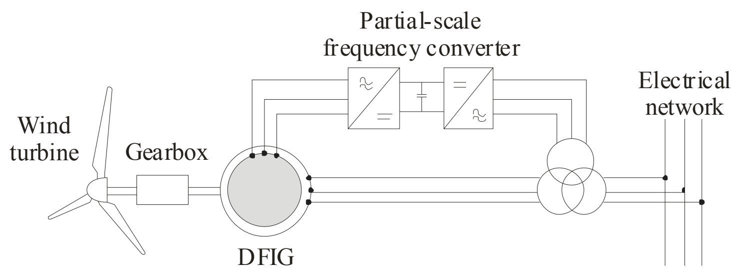

Fig. 1. The diagram of a double fed induction wind generator

2.1.3 Synchronous wind generator

A wind power plant contains a synchronous generator and a bidirectional frequency converter AC / DC / AC, through which it will connect to the network. The synchronous generator is more expensive and mechanically complex than the double fed induction generator. It is also used in applications where the entire produced power crosses the converter, which is smaller than the one at double fed asynchronous generators. Synchronous generator has the great advantage that it doesn’t need a magnetizing reactive current from the grid. The magnetic field can be created by permanent magnets or classical excitation coil – with wound rotor [3].

Synchronous generator is about 1.6 times more expensive than double fed induction generator. Main advantages of variable speed wind generators comparing to the fixed speed are the improved dynamic behavior which reduces mechanical stresses of the shaft and power fluctuations, a better quality of electricity and an increasing of electricity production.

Disadvantages compared with fixed speed wind generators consists in a more complicated electrical system using multiple components, the losses of power in the incorporating electronic components items and high cost of equipment.

2.2. Dynamic modeling of double fed induction generators (DFIG)

The general control block diagram of the DFIG wind turbine is illustrated in Fig. 2.

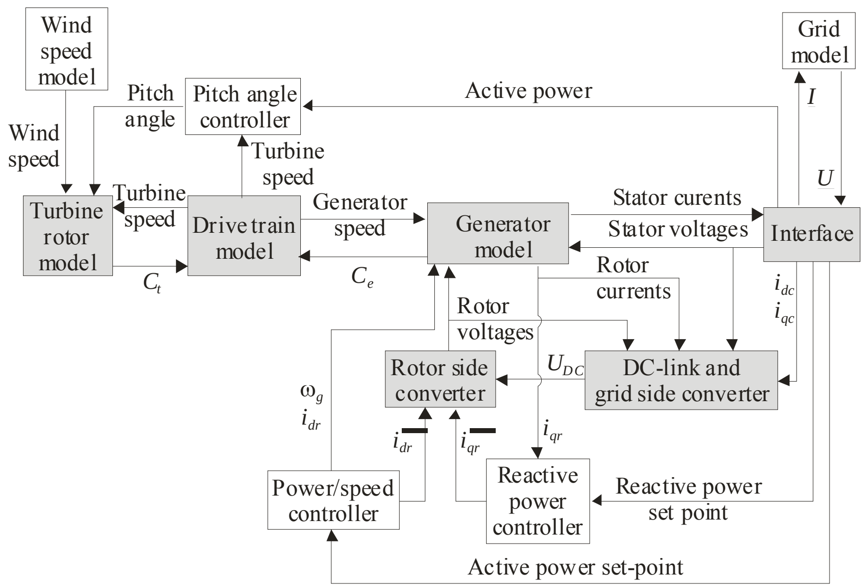

Fig. 2. Control block diagram of a DFIG wind turbine [4]

The main parts of the DFIG model are the followings: models of the **turbine rotor**, **drive train**, **generator, rotor-side converter, grid-side converter with the DC-link**, as well as the interface and power grid models. Additional models consist of different controls such as pitch angle controller, power/speed controller, reactive power controller and a wind speed model.

2.2.1. Doubly fed induction generator model.

For easier modeling of the doubly fed induction generator, the d-q reference frame is chosen. Furthermore, the generator convention is considered, which means that the currents are outputs instead of inputs, and active power and reactive have a positive sign when they are fed into the grid [1].

Using the generator convention bellow, the following set of stator and rotor equations are presented:

$$\left| \begin{aligned} u_{ds} &= -R_s i_{ds} - \omega_s \psi_{qs} + \frac{d\psi_{ds}}{dt} \\ u_{qs} &= -R_s i_{qs} + \omega_s \psi_{ds} + \frac{d\psi_{qs}}{dt} \\ u_{dr} &= -R_r i_{dr} - s\omega_s \psi_{qr} + \frac{d\psi_{dr}}{dt} \end{aligned} \right. \tag{1}$$

$$u_{qr} = -R_r i_{qr} + s\omega_s \psi_{dr} + \frac{d\psi_{qr}}{dt}$$

and the flux linkages:

$$\begin{cases} \psi_{ds} = -L_{ss} i_{ds} - L_m i_{dr} \\ \psi_{qs} = -L_{ss} i_{qs} - L_m i_{qr} \\ \psi_{dr} = -L_{rr} i_{dr} - L_m i_{ds} \\ \psi_{qr} = -L_{rr} i_{qr} - L_m i_{qr} \end{cases} \quad (2)$$

The transients in the rotor fluxes are sometimes neglected because of the complexity in modeling the converter and due to computational speed required during simulations. With the transients neglected, the following set of equations results:

$$\begin{cases} u_{ds} = -R_s i_{ds} + \omega_s (L_{ss} i_{qs} + L_m i_{qr}) \\ u_{qs} = -R_s i_{qs} - \omega_s (L_{ss} i_{ds} + L_m i_{dr}) \\ u_{dr} = -R_r i_{dr} + s\omega_s (L_{rr} i_{qr} + L_m i_{qs}) \\ u_{qr} = -R_r i_{qr} - s\omega_s (L_{rr} i_{dr} + L_m i_{ds}) \end{cases} \quad (3)$$

The electrical angular velocity of the rotor ω_r is

$$\omega_r = \frac{p}{2}\omega_m \quad (4)$$

where p is the number of poles and ω_m is the mechanical angular velocity (rad/s) [4].

The electrical torque of the generator is given by:

$$C_e = \psi_{ds} i_{qr} - \psi_{qs} i_{dr} \quad (5)$$

The total active and reactive powers exchanged by the DFIG with the electrical network are the sum of the stator and rotor powers:

$$P = P_s + P_r \quad (6)$$

$$Q = Q_s + Q_r \quad (7)$$

The stator active and reactive powers are

$$P_s = u_{ds} i_{ds} + u_{qs} i_{qs} \quad (8)$$

$$Q_s = u_{qs} i_{ds} - u_{ds} i_{qs} \quad (8')$$

and the rotor active and reactive powers are:

$$P_{\mathrm{r}} = u_{dr} i_{dr} - u_{qr} i_{qr} \tag{9}$$

$$Q_{\mathrm{r}} = u_{qr} i_{dr} - u_{dr} i_{qr} \tag{10}$$

2.2.2. Drive train of DFIG

The drive train system of a DFIG wind turbine can be modeled using a two-mass model [1]. Despite the minor influence of shaft natural damping, it is important to note that a wind turbine with a power converter, such as the one with a DFIG, is often supplied with shaft torsional active damping.

The equations representing the shaft torsional mode of oscillation can be split into two equations:

- The *mechanical equations of the induction generator:*

$$\left\| \begin{array}{l} 2H_{\mathrm{g}} \dfrac{\mathrm{d}\omega_g}{\mathrm{d}t} = \omega_{\mathrm{e}} \left(C_{\mathrm{shaft}} - C_{\mathrm{e}} \right) \\ \dfrac{\mathrm{d}\theta_{\mathrm{g}}}{\mathrm{d}t} = \omega_{\mathrm{g}} \end{array} \right. \tag{11}$$

- The *mechanical equations of the wind turbine*:
-

$$\left\| \begin{array}{l} 2H_{\mathrm{t}} \dfrac{\mathrm{d}\omega_{\mathrm{t}}}{\mathrm{d}t} = \omega_{\mathrm{e}} \left(C_{\mathrm{t}} - C_{\mathrm{shaft}} \right) \\ \dfrac{\mathrm{d}\theta_{\mathrm{t}}}{\mathrm{d}t} = \omega_{\mathrm{t}} \end{array} \right. \tag{12}$$

The incoming torque from the shaft to the induction generator, C_{shaft}, in both equations, consists of a term, C_{torsion}, representing elasticity of the shaft, and a term, C_{damping}, representing the damping torque of the shaft:

$$C_{\mathrm{shaft}} = C_{\mathrm{torsion}} + C_{\mathrm{damping}} = K_{\mathrm{s}} (\theta_{\mathrm{t}} - \theta_{\mathrm{g}}) + D_{\mathrm{tg}} \left(\omega_{\mathrm{t}} - \omega_{\mathrm{g}} \right) \tag{13}$$

The mechanical torque produced by the wind turbine C_{t} is transferred to the generator through the multiple shafts to generate the electromagnetic torque C_{e}. The equivalent shaft is characterized by the effective shaft stiffness K_{s}, expressed in p.u. torque/rad, and the damping torque D_{tg}, expressed in p.u. torque/(rad/s). In equations (12) and (13), the speed of the induction machine ω_{g} and the speed of the wind turbine ω_{t} are measured in radians per second, whereas the angular position of the machine θ_{g} and the angular position of the wind turbine/hub θ_{t} are measured in radians.

Also, the base angular speed is $\omega_e = 2\pi f$, where f is the power frequency, for example 50 Hz.

2.2.3. The power converter.

The power electronic has gained its place in power system applications because of its flexibility in operation. A back-to-back converter is used as asynchronously interconnect the rotor of the DFIG system with the electrical network, allowing power transfer in both directions [1].

The back-to-back converter consists of two VSCs and a DC link (Fig. 3). The back-to-back four-quadrant PWM-VSC, presented in Fig. 3, is widely used in wind power systems today.

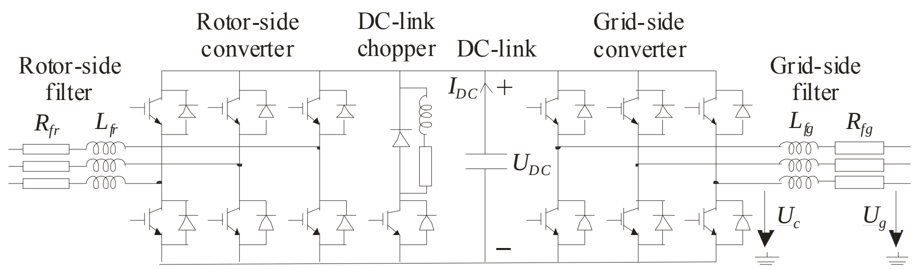

Fig. 3. Back-to-Back converter [5]

The flexibility in controlling various parameters on either side of the converter with PWM techniques has great importance. By AC-DC-AC transformation, the generator rotor frequency is decoupled from the power grid frequency. For this reason, the converter is sometimes called frequency converter. A DC link separates the two voltage source converters so that there can be controlled independently of each other [1]. On each side of the converter, R-L filters are used to remove the switching harmonics. The DC-link chopper is a protection circuit against DC-link overvoltages during grid faults. The arrangement consists of a resistor and an electronic switch, usually an IGBT. The generator rotor-side converter controls the rotor currents of the machine, and thus controls the active and reactive powers of the machine as given by (9) and (10). The rotor-side converter is designed for the maximum slip power and reactive power control capability. The grid-side converter exchanges power between the rotor-side converter and the power grid. It normally controls the DC-link voltage only. However, the converter might be employed to provide reactive power support during a grid fault, but this capability requires a larger converter rating. The power rating of the grid-side converter is mainly given by maximum slip power since it usually operates at a unity power factor.

2.2.4. The control strategy for the DFIG

As the DFIG operates either as motor or as generator, the control system has to be designed so that to allow both operating states [4]. The most employed control strategy of the DFIG is based on the *rotor current vector control* in the d-q frame. Depending on the quantity required to be controlled, the *d*-axis is aligned either to the stator flux linkage vector or to the stator voltage vector. This procedure is chosen to allow decoupled control between active and reactive power.

Fig. 4 shows the overall control system of a DFIG wind turbine, consisting of a generator control level and a wind turbine control level. This system follows mainly a rotor current vector control strategy, as shown in Fig. 4 [4].

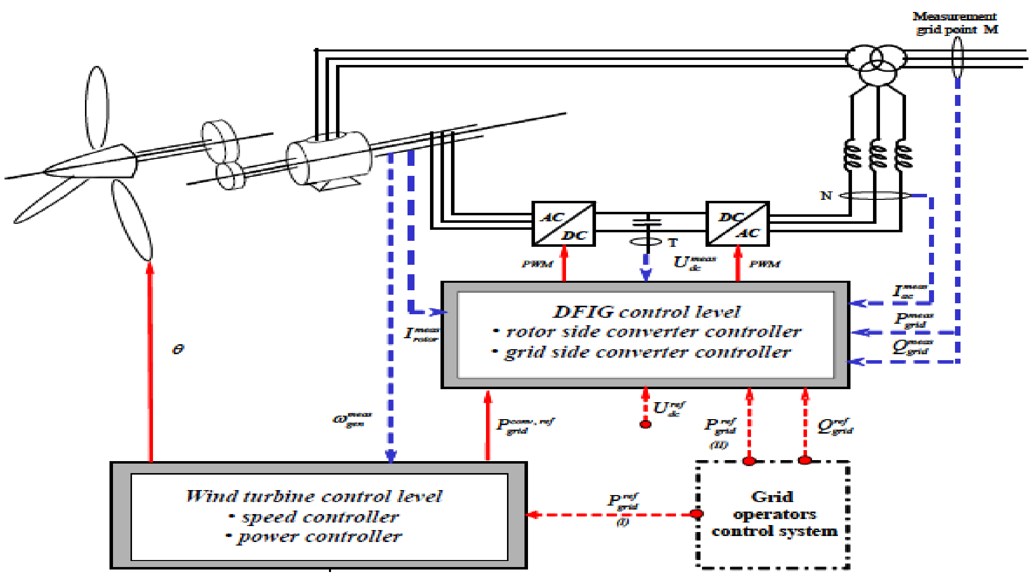

Fig. 4. Overall control system of a DFIG wind turbine [4]

The DFIG control level contains:

- **the grid –side converter control.** The general model of the grid-side converter includes the current-controlled voltage source converter, the grid-side filter, and the DC-link capacitor.

- **the rotor-side converter control.** In the vector control of the rotor – side converter, it is assumed that the d-axis is oriented along the stator flux vector position. From power grid operation point of view, the stator flux is maintained almost constant because the stator voltages are almost constant in amplitude, frequency and phase.

2.2.5. Aerodynamic model and pitch angle controller

The wind turbine converts the kinetic energy of wind into mechanical energy in the form of mechanical torque through the turbine shaft that drives the electrical generator. The mechanical torque developed by the turbine is given by

$$C_{\mathrm{t}} = \frac{P_{\mathrm{t}}}{\omega_{\mathrm{t}}} = \frac{1}{2\omega_{\mathrm{t}}} \rho V_{\mathrm{w}}^3 A C_{\mathrm{p}}(\lambda, \beta) \tag{14}$$

A way of limiting the forces acting on the turbine blades at wind speeds greater than the rated value, is by changing the pitch angle β, thus reducing the performance coefficient $C_{\mathrm{p}}(\lambda, \beta)$.

Rotation of blades around their longitudinal axis is performed by either hydraulic or electrical drives. Therefore, a pitch angle controller model (Fig. 5) has to be integrated in the wind turbine system model [4].

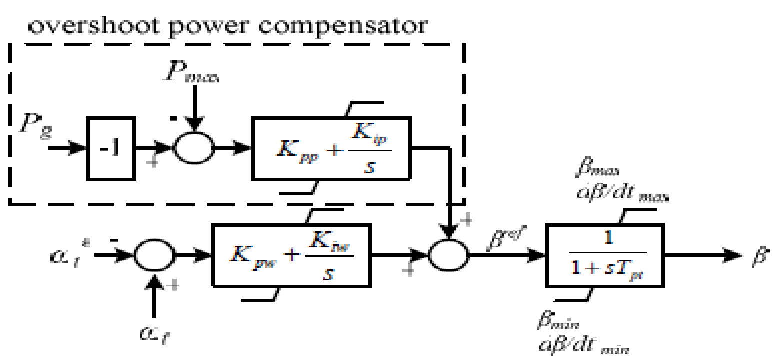

Fig. 5. Pitch angle controller model [4]

As the wind speed cannot be measured precisely, the input to the controller can be the active power and the rotor speed.

2.2.6. Control of wind power extraction of a DFIG.

The rotor-side converter is responsible for controlling the mechanical torque as well as the stator terminal voltage or the power factor. The variable speed operation of the DFIG is possible because the power converter decouples the mechanical rotor speed and the power system electrical frequency.

The rotor speed control capability facilitates also the optimization of the power extracted from the wind. Fig. 6 a shows the optimal characteristic of the mechanical power that can be developed by the turbine in terms of wind speed.

Fig. 6 b shows the electrical power developed by the generator versus rotor speed for various wind speeds.

The generator speed range is restricted to a limit between the minimum speed $\omega_{\min}$ and the maximum speed $\omega_{\max}$ .The curve of optimal power P_{opt} extracted from the wind is defined by the relationship:

$$P_{opt} = K_{opt}\omega_r^3 \tag{15}$$

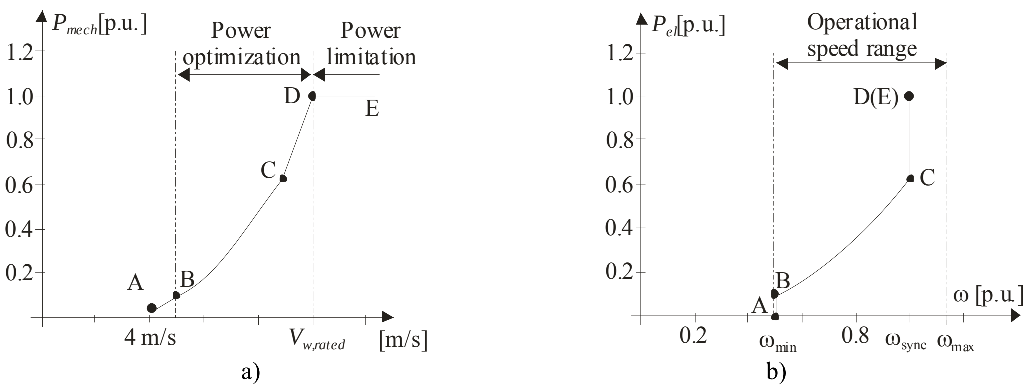

Fig. 6. Wind turbine system characteristics: (a) mechanical power versus wind speed, (b) electrical power versus rotor speed [6]

and the optimal torque is given by

$$C_{opt} = K_{opt}\omega_r^2 \tag{16}$$

where K_{opt} is a parameter obtained from the aerodynamic performance of the wind turbine.

3. Dynamic simulation of the double fed induction generator

The purpose of transient stability analysis is to describe the behavior of the wind power plants generators at short-circuits currents that occurs in the electrical network where there are connected.

Due to some external perturbations in the power system, the wind power plants can be disconnected.

In this context, the appearance of a short circuit in distribution or transmission grid of the power system can cause a voltage drops on the medium voltage busbar system below stator protection value of wind generators.

This protection system disconnects the generating units from the busbar system when the stator voltage falls below a certain limit for a period of time [7].

In accordance with Technical Order 51/2009 of Regulatory Authority in the Energy Field [8], wind power plants must remain connected to the power system during some voltage dips for a certain limit (20 % * U_n) and a certain duration (625 ms).

The transient stability was made on the interconnected Romanian Power System, that operates synchronous with continental European network, including Western Ukraine and Turkey, the OHL 400 kV Portile de Fier – Djerdab, OHL 400kV Tantareni – Kozloduy, 1 circuit, OHL 400 kV Isaccea -Dobrudja, OHL 400 kVArad - Sandorfalva, OHL 400 kV Nadab - Bekecsaba (Arad- Nadab), OHL 400 kV Rosiori - Mukacevo. For the calculation it was used a DFIG dynamic model from the Eurostag library of 100 WPP of 2 MW, connected to the 220 kV Paroșeni substation.

The wind power plant operates at a power factor between 0,98 inductive (overexcited) and 0,96 capacitive (underexcited), evacuating the power at 480 V–690 V and connected to the distribution network through 2100 kVA 0,48/0,69 kV/MT±2×2,5% (6–33 kV) transformers [9].

There were calculated transient regimes, caused by three phase short-circuit on OHL 220 kV from Paroșeni substation, isolated by the right function of the protection and switches. Paroșeni substation is located in an area with low wind energy sources.

The total protections times considered in the calculations are:

- in Paroseni, Baru Mare, Tg. Jiu substations: 0.1 s;
- on OHL 220 kV Paroșeni - Tg. Jiu, Paroșeni- Baru Mare with use of teleprotection in function/unavailable : 0.11/0.5 s.

From Fig. 7 we can mention that the critical clearing time of the three phase short-circuit on one of the OHL from Paroșeni substation is 220 ms;

Considering the single line diagram of the substation, if a fault on the 220kV Paroșeni busbar appears, all the circuit breakers connected to the busbar will be tripped by the differential busbar protection.

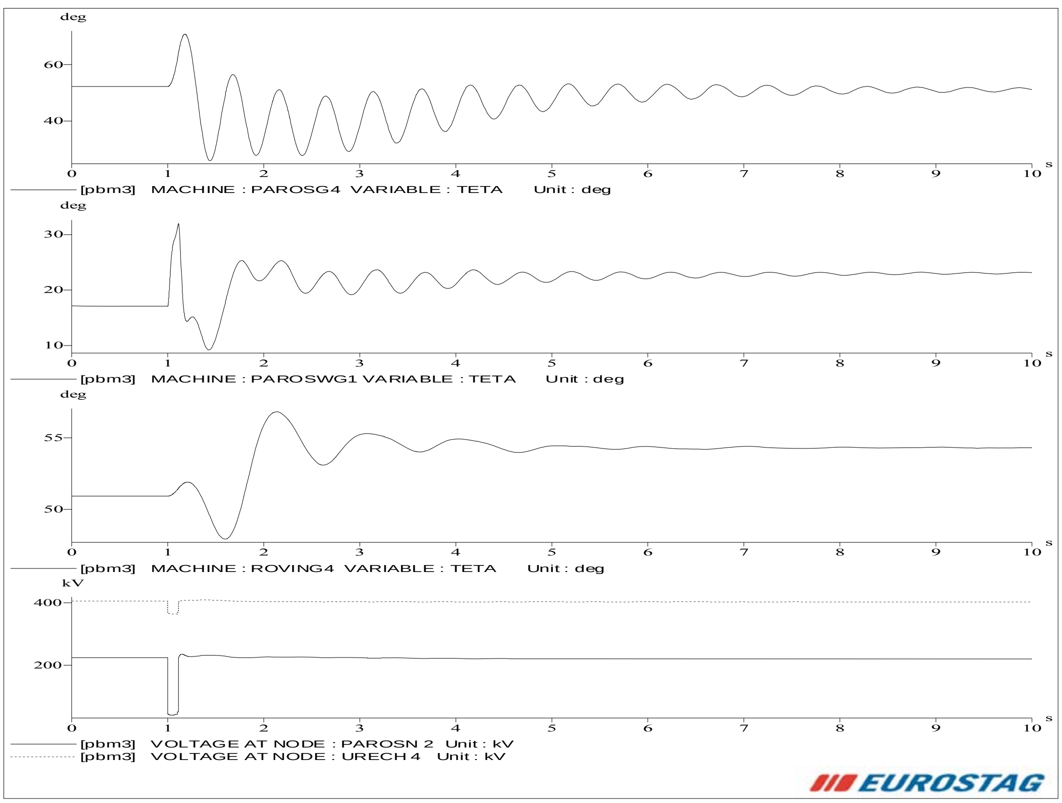

Fig. 7. Three phase shortcircuit on OHL 220 kV Paroseni-Baru Mare

4. Conclusions

This paper presented theoretical issues about wind power plants generators modeling. The main parts of the DFIG model are described: turbine rotor, the drive train, the generator, the rotor-side converter, the grid-side converter with the DC-link, as well as the interface and power grid models.

There were presented the results of a dynamical simulation of a DFIG model in the interconnected Romanian Power System.

The authors have analyzed the modeling of wind power plants generators and considered the impact of connecting 200 MW wind generation in an area with low wind energy sources. There were calculated transient regimes, caused by three phase short-circuit, isolated by the right function of the protection and switches.

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