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WIND GENERATION MODELING FOR SLOW DYNAMICS ANALYSIS

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***Abstract**:* Efforts have been made in the application of renewable energy sources, allocated in a distributed manner. Among renewable sources, wind energy has lately become very promising. Simulation tools for mid and long term phenomena are useful to study systems with wind farms. The paper presents models of fixed and variable-speed wind devices, which are implemented in a slow dynamics simulator (fast simulator). Studies are realized in a test system, showing the superiority of variable-speed device. Moreover, the results confirm that slow dynamics analyses are important in systems with wind generators.

***Keywords**:* Wind Power, Distributed Generation, Slow Dynamics, Fast Simulator, Voltage Stability

1. INTRODUCTION

In the past, power systems were developed with local generation supplying local demand. This way, the transmission and distribution networks were practically inexistent and the system operation was quite simple. Nowadays, the power systems work in an integrated way, which make them very complex, but more efficient and reliable. Economical reasons and environmental concerns have often constrained construction of new transmission lines and large generation power plants. Therefore, there has been a considerable revival of interest in connecting generation to the distribution systems that has come to be known as dispersed generation [1].

A lot of efforts have been made in the application of renewable energy sources, which in general, cause low environmental impact when compared to conventional generation plants. Moreover, the strategic allocation of small generation blocks can reduce transmission cost, as energy sources can be installed close to load centers.

Even though distributed generation can bring a lot of benefits to the system, with its significant penetration, some technical impact can be observed like changes in the voltage profile, power quality, protection philosophy, dynamic system behavior and forms of operation [2].

Among the distributed energy resources that use renewable sources, wind energy has lately become very promising [3]. Nowadays, the amount of installed capacity in wind plants is just a small fraction of the total generating capacity. However, there is a tendency of increasing the number of wind farms around the world, many motivated by the necessity to decrease the greenhouse effect. In Brazil, it may be seen as a complement energy resource to its hydro generation, since peak wind conditions coincide with the dry season. So, the development of computational models of wind plants is fundamental to study the impact of high penetration of wind energy in power systems.

This paper presents two wind generators models: a fixed and a variable-speed machine. The fixed-speed machine is a directly connected induction generator consisting of a common squirrel cage induction machine. The variable-speed machine is a doubly-fed induction generator consisting of a wound rotor induction machine with field quantities controlled by a back-to-back converter.

Simulation tools for mid and long term phenomena are useful to study systems with distributed generation, especially with wind farms. The fast simulation method is based on dynamic model simplifications, eliminating the fast transient effects [4]. In this way, the fast simulator becomes very useful for problems associated with voltage control, which can be worsened due to wind generators presence (random wind behavior).

In Section 2, some aspects of the distributed generation and wind power will be discussed. Section 3 describes the models used in this work. Finally, sections 4 and 5 will show the simulation results and the work conclusions.

2. DISTRIBUITED GENERATION

2.1 General Concepts

Distributed or dispersed generation can be understood as any kind of energy source installed to supply local loads, without the need of a transmission network. Generally, distributed generation plants have small capacity (up to

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30 MW) and can be of any nature, including hydro, thermal, wind, photovoltaic, biomass, etc.

From the technical point of view, distributed generation, especially with high penetration level, can cause some impact in the system. This impact depends on the technology employed and can occur due to generators location (usually, in the distribution grid).

In conventional power systems, the power flows from the high voltage level substation to the low voltage level substation. The protection systems and operation instructions relies on this premise. With high penetration of distributed generation, the power flow (active and reactive) may be reversed in some parts of the network. In this case, the distribution system will export power to the transmission grid. So, the way as the system is controlled, operated and protected has to be reviewed.

2.1 Wind Generation

The exploitation of the wind energy is a rapidly growing area worldwide. Although the fundamental working principle of a wind turbine is straightforward, a wind turbine is a complex system in which knowledge of various fields is combined [5].

The presence of wind turbines in electrical systems produces different performance when compared with conventional power plants. Moreover, there are different kinds of wind turbines and their impact in the system may be different too. Depending on the wind generator type, various control philosophies, forms of operation and connection to the grid is found. Hence, it is important to know and model each kind of turbine with the adequate detail level to the intended study.

Usually, the wind turbines are classified in fixed or variable-speed devices. The fixed-speed turbines employ asynchronous generators directly connected to the electrical grid. On the other hand, variable-speed wind turbines employ synchronous or asynchronous machines connected to the grid throw power electronic converters.

3. WIND GENERATION MODELING

This section will present models for a fixed and a variable-speed wind system. The fixed-speed system is composed by an induction machine directly connected to the electrical grid and does not have any voltage or speed control. The variable-speed system consists of a doubly-fed induction machine and it is equipped with reactive power and speed control.

3.1 Mechanical Model

The mechanical model is treated here in the same manner for the two types of turbines described. The mechanical power extracted by the wind turbine is given by [2]:

$$P_m = \frac{1}{2} \cdot \rho \cdot A \cdot v^3 \cdot C_P(\lambda,\beta), \tag{1}$$

where:

- P_m is the mechanical power [W];
- ρ is the air density [kg/m^3];
- A is the rotor area [m^2];
- v is the wind speed [m/s];
- C_P is the aerodynamic power coefficient;
- β is the pitch angle [degrees];
- λ is the tip speed ratio, defined as:

$$\lambda = \frac{\omega_{blades} \cdot R}{v}, \tag{2}$$

where:

- R is the rotor radius [m];
- ω_{blades} is mechanical speed of the blades [rad/s], computed as:

$$\omega_{blades} = \frac{\omega_m}{GBR} \cdot \frac{2}{p}, \tag{3}$$

where:

- GBR is the gear box ratio ($1 : GBR$);
- p is the generator number of poles;
- ω_m is the generator rotor speed [rad/s].

The power coefficient is a function of the tip speed ratio and the pitch angle. In variable-speed turbines, the optimal tip speed ratio can be obtained changing the generator speed according to wind variations. This way, the maximum turbine efficiency can be achieved, which is not possible in fixed-speed devices. Some turbines are equipped with pitch angle control to limit the power extracted from the wind in the nominal value. In the models used in this work no pitch angle control was considered. The gear box is necessary to adequate the blades speed (slow) to the generator speed (high).

The mechanical torque is given by the relationship between the mechanical power and the blades speed:

$$T_m = \frac{1}{2} \cdot \pi \cdot \rho \cdot R^3 \cdot v^2 \cdot \frac{C_P(\lambda,\beta)}{\lambda}, \tag{4}$$

Neglecting dynamics of mechanical parts of the turbine, the motion equation is given by:

$$\frac{d\omega_m}{dt} = \frac{1}{2H}\left(T_m - T_e\right), \tag{5}$$

where:

- ω_m is the generator rotor speed [pu];
- H is the total inertia constant [s];
- T_e is the generator electrical torque [pu].

Equation (5) represents the traditional single mass model and gives the balance between the wind turbine and the electrical generator torques. Some works have shown the importance to include the model of the coupling shafts that connect the turbine with the generator through the gearbox in stability studies [6] [7]. As the focus of this work is in slow dynamics analysis, the single mass model will be used.

3.2 Directly Connected Induction Generator Model

Induction generators (squirrel cage) directly connected to the electrical grid are widely used in wind power plants. They operate within a narrow range of speed slightly higher than the synchronous speed, so they are called as fixed speed wind turbines. The main advantages of directly connected induction generators (DCIG) is that they are mechanically rugged, inexpensive and easy to operate when compared to variable speed devices [3].

Considering generation convention and neglecting the stator transients, the well-known equations for induction machines are [8]:

$$\begin{cases} \frac{dE'_q}{dt} = -\frac{1}{T'_o} \cdot \left[E'_q + (X_s - X') \cdot I_{ds} \right] - (\omega_s - \omega_m) \cdot \omega_b \cdot E'_d \\ \frac{dE'_d}{dt} = -\frac{1}{T'_o} \cdot \left[E'_d - (X_s - X') \cdot I_{qs} \right] + (\omega_s - \omega_m) \cdot \omega_b \cdot E'_q \end{cases}, \quad (6)$$

where:

- E'_d, E'_q are the internal voltage components;
- T'_o is the transient time constant of open circuit;
- X_s is the stator reactance;
- X' is the transient machine reactance;
- I_{ds}, I_{qs} are the stator current components;
- S is the machine slip;
- ω_b is the nominal system frequency;
- ω_s is the synchronous speed.

The electromagnetic torque is computed as:

$$T_e = \varphi_{qr} \cdot I_{dr} - \varphi_{dr} \cdot I_{qr}, \quad (7)$$

where:

- φ_{dr}, φ_{qr} are the rotor flux linkage components;
- I_{dr}, I_{qr} are the rotor current components.

All quantities in equations (6) and (7) are in [pu] in the machine basis, except for T'_o (s), ω_b (rad/s) and the time t (s). Details about this model can be found in [8].

3.3 Doubly-Fed Induction Generator Model

Doubly-fed induction generator (DFIG) is classified as an adjustable speed machine. A lot of advantages of this kind of generator can be mentioned when it is compared to fixed-speed machines like the DCIG, such as the reduction of mechanical stress, the improvement of power quality and the increase in the system efficiency.

In doubly-fed induction generators, the rotor is composed by a three phase winding that is connected to the grid throw a back-to-back converter (Fig. 1). The four-quadrant ac-ac converter is based on insulated gate bipolar transistors (IGBT) and operates in a high switching frequency using the PWM control technique.

The machine model is similar to the squirrel cage induction machine, except for the rotor winding voltage. In the squirrel cage machine, the rotor voltage is zero, since the squirrel cage is short-circuited. In the doubly-fed machine, the rotor voltage is determined by the rotor side converter. The equation (6) is modified and becomes:

$$\begin{cases} \frac{dE'_q}{dt} = -\frac{1}{T'_o} \cdot \left[E'_q + (X_s - X') \cdot I_{ds} \right] - \\ -(\omega_s - \omega_m) \cdot \omega_b \cdot E'_d + \omega_b \cdot \frac{X_m}{X_r} \cdot V_{dr} \\ \frac{dE'_d}{dt} = -\frac{1}{T'_o} \cdot \left[E'_d - (X_s - X') \cdot I_{qs} \right] + \\ +(\omega_s - \omega_m) \cdot \omega_b \cdot E'_q - \omega_b \cdot \frac{X_m}{X_r} \cdot V_{qr} \end{cases}, \quad (8)$$

where:

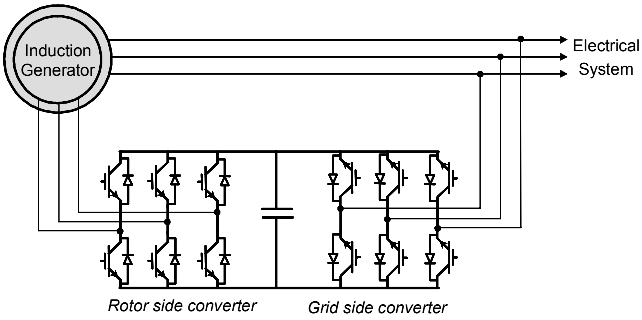

Figure 1 – Doubly-fed induction generator

- V_{dr}, V_{qr} are the rotor voltage components;
- X_r is the rotor reactance;
- X_m is the machine mutual reactance.

Equation (8) is different from equation (6) because it has additional terms which are functions of the rotor voltage components.

DFIG Controls

The DFIG modeled in this paper is similar to the one presented in reference [9]. It is equipped with two controls loops: the speed and the reactive power controls. These controls are made using the stator flux linkage as reference (filed oriented control) for the d-axis [10].

If the stator flux linkage is set as reference and taking into account that the stator resistance influence is small, the electromagnetic torque can be expressed as:

$$T_e = -\frac{L_m \cdot V^f_{qs}}{L_s + L_m} \cdot I^f_{qr}, \quad (9)$$

where:

- f indicates the new reference frame;
- L_m is the mutual machine inductance;
- L_s is the stator leakage inductance;
- V_{qs} is the stator voltage q-component.

Equation (9) indicates that the torque control is accomplished by the q-component of rotor current. The desired q-component of rotor current is obtained through a speed controller as shown in Fig. 2.

The actual generator speed is compared to a reference value. The error passes through a PI (Proportional-Integral) controller yielding the desired q-component of rotor current. The speed reference value is computed in order to obtain the optimal tip speed ratio as the wind speed varies, according to equations (2) and (3). The optimal tip speed ratio gives the maximum turbine efficiency (maximum aerodynamic power coefficient).

In the DFIG model, it was assumed that no reactive power

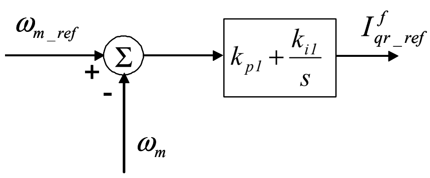

Figure 2 – Speed/torque control

is delivered throw the grid side converter, that is, the grid side converter operates at unity power factor. In addition, the dc capacitor bank voltages is maintained constant, i.e. the active power in the rotor side converter is equal to the active power in the grid side converter [11].

With field-oriented control using the stator flux linkage as reference, the reactive power generated by the DFIG is:

$$Q = -V_{qs}^{f} \cdot \left[\frac{V_{qs}^{f} + \omega_s \cdot L_m \cdot I_{dr}^{f}}{\left(L_s + L_m\right) \cdot \omega_s} \right], \tag{10}$$

Equation (10) shows that reactive power can be controlled through d-component of rotor current. The desired d-component of rotor current is obtained through the reactive power controller as shown in Fig. 3.

The actual reactive power is compared to a reference value. The error passes through a PI controller yielding the desired d-component of rotor current. In the control system implemented in this work, the reference reactive power is set according to some specification. However, it could be generated by an additional loop to control terminal voltage or the power factor of the wind farm.

The electronic converters are modeled as instantaneous current sources. In this way, the components of rotor current produced by the speed and the reactive power controllers are considered equal to the currents injected by the converters. In [11], it is shown that this approximation can be done with a good level of accuracy for transient stability studies.

In the DCIG, the rotor current components can not be controlled, since the current is induced in the rotor. In the DFIG, this type of control is possible.

4. SIMULATION RESULTS

The simulations were performed using a program, named *FastSim*$^{++}$ that uses advanced concepts of Object-Oriented Modeling (MOO) in C^{++} [4]. The computational platform integrates a power flow, a fast simulator and a full-time domain simulator using the same data base.

The simulated system is shown in Fig. 4. It is composed by an equivalent transmission system supplying a distribution network that contains a load and a feeder dedicated to a wind farm connection. The transmission system is represented by an infinite bus in series with its equivalent short-circuit impedance. The wind farm contains 10 unites of 1 MW and is modeled as DCIG or as DFIG. Furthermore, it is shown a capacitor bank (5 Mvar) connected to bus #4 that is presented only in the case of DCIG simulations, so the reactive power required by the generator is supplied by the capacitor bank. This compensation could also be done using other reactive power compensation equipment like SVCs.

Two types of studies were performed. In the first case, the daily system operation was analyzed. This way, the load and the wind behavior were represented considering 24 hours of operation. In the second case, a wind speed ramp with few seconds of duration was considered. So, it was possible to observe the system voltage profile as the wind increases.

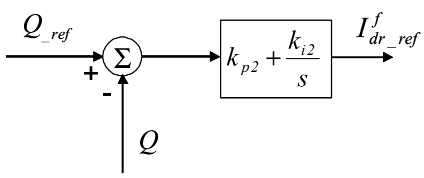

Figure 3 – Reactive power control

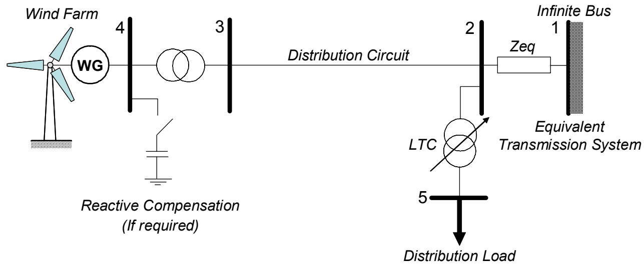

Figure 4 – Studied system

4.1 Daily Operation

To study one day of system operation, the load, which is connected to the grid throw an automatic on load tap changer, is represented by its daily curve shown in Fig. 5. This figure shows that the load peak occurs between 17 and 18h, when stays close to 15 MW. The load power factor is maintained constant and its value is 0.92 (inductive). It is important to say that the load is modeled as a voltage dependent load (ZIP model) and its characteristics are described in Tab. 1. The values presents in the daily curve refers to values at nominal voltage (1.0 pu).

Table 1 – Load Model

Participation	Active Load	Reactive Load
Z [%]	40	100
I [%]	0	0
P [%]	60	0

The wind speed behavior along the day can be seen in Fig. 6. The wind speed is quite constant between 0 and 12:10h and stays close to 12 m/s, which is the nominal value. At 12:10h, the wind speed starts to decrease, reaching a new value at 15h, around 11.5 m/s.

Fig. 7 shows the load voltage profile (bus #5), considering both DCIG and DFIG models. The voltage behavior is similar in both cases, i.e. it follows the load variations. Furthermore, it is possible to see the wind oscillations influence in the voltage profile, which is more pronounced in the case of squirrel cage machine (see detail in Fig. 7).

The reactive power control of the DFIG is set to maintain a constant generation of 1 Mvar. On the other hand, the DCIG demand reactive power all the time. Fig. 8 presents these results. The reactive power demand by the squirrel cage machine varies according to the voltage variation,

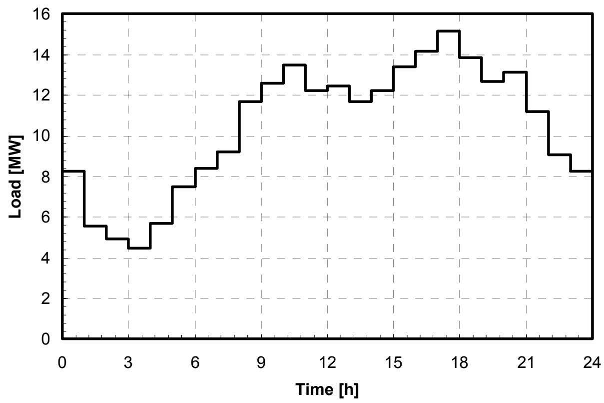

Figure 5 – Daily system load curve

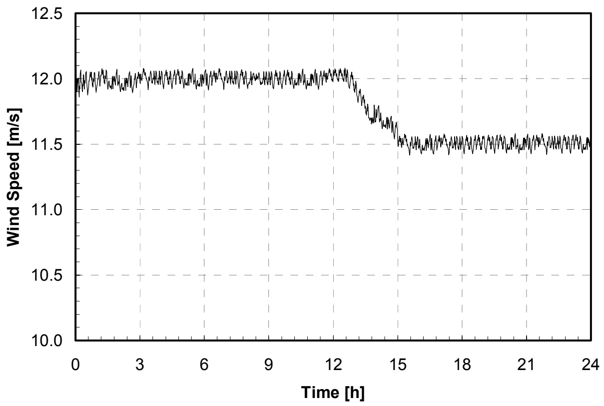

Figure 6 – Simulated wind speed

but its value stays always between 5.6 and 6.5 Mvar.

Fig. 9 presents DCIG and DFIG slip. As expected, the DCIG operates with practically constant slip (fixed-speed device). On the other hand, the speed control loop of DFIG acts according to the wind variation to maintain the turbine in the optimal point of operation (maximum efficiency).

Another interesting result refers to the active power provided by the DFIG via rotor which is shown in Fig. 10. At the beginning of the simulation, the machine is operating above the synchronous speed. This way, the rotor supplies active power. When the wind speed decreases, the machine operates below synchronous speed, so the rotor demand active power. It means that a portion of the active power produced via stator feeds the rotor throw the electronic converter.

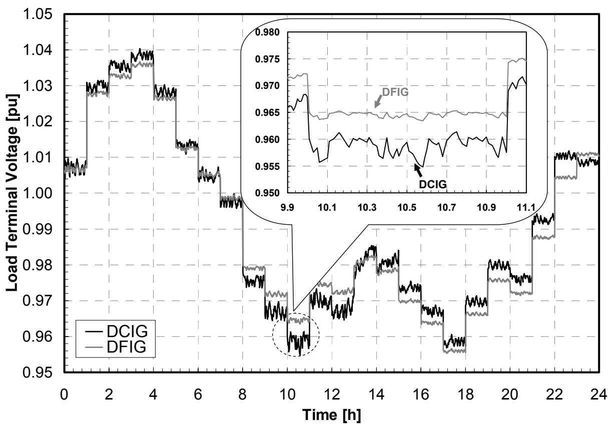

Figure 7 – Load voltage profile

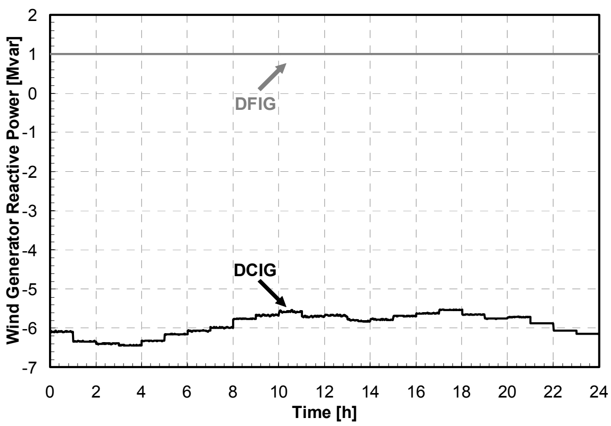

Figure 8 – Wind generator reactive power

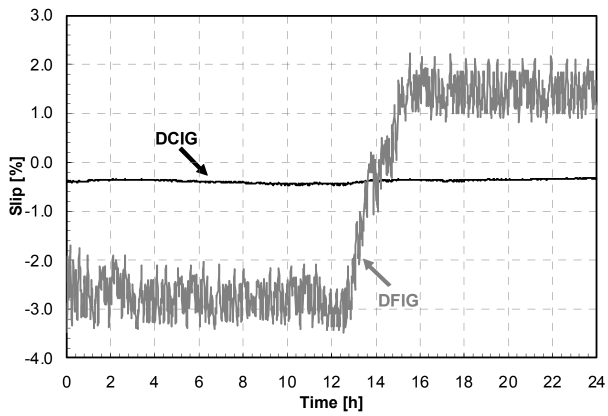

Figure 9 – Machine slip

4.2 Gust of Wind Simulation

To analyze the system behavior in presence of a gust of wind, the load was maintained constant and the wind speed was varied according to a ramp starting in 8 m/s and reaching 13.6 m/s in 60 s. At this point the wind speed remains constant in 13.6 m/s.

Fig. 11 and Fig. 12 show system voltages when DCIG and DFIG are used, respectively. For the system with the squirrel cage machine, the simulation program does not achieve numerical convergence for simulation time above 46 s. In the load terminal voltage (bus #5) profile it is possible to see the OLTC action in 45 s, trying to raise the voltage (Fig. 11). In contrast, the system with the doubly-fed machine supports the gust of wind. In Fig. 12, it is possible to see the OLTC action conducting the system voltages to a higher profile.

The main difference between the two systems consists in the support of reactive power. Fig. 13 presents the reactive power measured in the wind farm output on the high-side voltage of the farm transformer. In this figure, only the first 46 s of simulation are shown for the DCIG and for DFIG.

Although the reactive power in the system with doubly-fed machine also decreases, in the system with direct connected machine the drop is more accentuated. So, it is easy to conclude that the non-convergence in the case of system with DCIG occurs because of the need of reactive power, characterizing a voltage collapse situation.

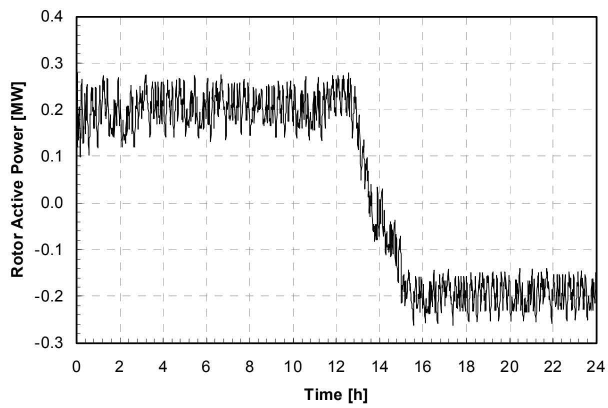

Figure 10 – Active power on the grid side converter

5. CONCLUSIONS

The paper has presented the modeling of a fixed and a variable speed wind systems: the directed connected induction generator (DCIG) and the doubly-fed induction generator (DFIG). The wind generator models were implemented in a fast simulator, which is suitable for analysis of mid and long-term dynamics.

Simulations were performed to evaluate the impact of the wind turbines in the system. Daily operation was study, considering load and wind variations. Besides, a gust of wind was simulated in order to compare the DCIG and DFIG performances.

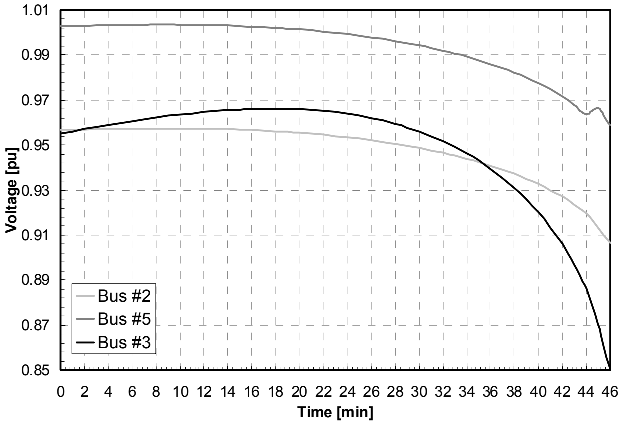

Figure 11 – System voltages (DCIG)

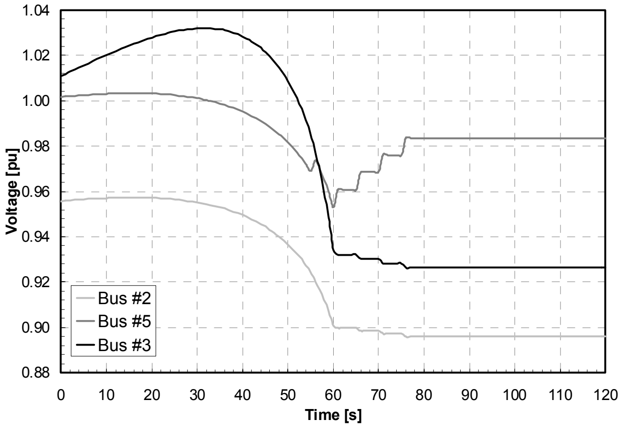

Figure 12 – System voltages (DFIG)

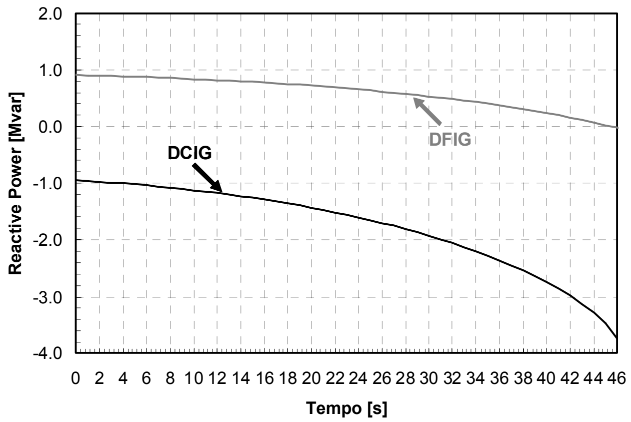

Figure 13 – Reactive power

The simulation results have shown the superiority of DFIG in presence of wind speed variations, obtaining a better power quality level. In addition, DFIG provides a greater voltage stability margin, since it can provide reactive power support to the system.

The analyses have confirmed the importance of slow dynamic studies in systems containing wind power generators.

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