Investigation of DFIG Based Wind Turbine Influence on the Utility Grid

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***Abstract*–This paper deals with the interaction analysis of a doubly fed induction generator (DFIG) based wind turbine (WT) with the electric power system during different disturbances in the grid.**
In the first part of the paper the modeling process of the WT with DFIG using Matlab-Simulink will be introduced and the control system will be presented. In the second part of the paper a case study including different disturbances will be carried out and evaluated. The resulting dynamic characteristic of DFIG will be presented and the main features commented upon.

Keywords- ***doubly fed induction generator, wind turbine, back-to back converter, power system***

I. Introduction

In the last decade the renewable energy sources, especially wind generation, have gained significant interest throughout the world due to the phasing out of conventional electrical power generation. This is caused by the global goals for the reduction of greenhouse gas emissions, which to a high extent result from the use of traditional fossil fuel operated power plants. According to the European Union Concept in the year 2010 the total installed power of renewable generation units should amount to 75GW and in 2020 it should reach the level of 150GW. Comparing these EU plans to the current situation it can be noticed that at the end of 2009 the total installed power from only wind generation in Europe already exceeded the value of 74 GW [1] and a further 40 GW of wind generation is planned on the sea till 2020 according to forecasts of European Wind Energy Association [2]. Furthermore, according to the last EU initiative, the so called 20-20-20 program, the overall generation from renewable in Europe has to amount to 20% of the total power generation while the energy demand and the emission of green house gasses have to be reduced by20% till 2020 [3].

Thus wind energy will play a significant role in the future power supply and, therefore, will have an even stronger influence on the behavior of the interconnected European power system ENTOS-E [4]. This concerns different issues such as maintaining the required electrical energy quality, providing appropriate dynamic behavior during disturbances, optimal integration into the power system operation as well as control and protection. Thus, analysis and investigation of wind turbine influence on the power system operation plays a crucial role in order to guarantee a stable and secure operation.

In this paper the aspects of dynamic behavior of DIFG based wind turbines during parallel operation with the grid will be investigated. For this purpose an appropriate model of the WT with DIFG will be introduced. In the second part of the paper some case studies will be introduced concerning some typical disturbances and the interaction of the WT will be analyzed.

II. Wind Turbine Model

The overall model of the wind turbine consists of different components such as aerodynamic rotor (also called directly wind turbine), electric generator, and the control and protection system. The common structure of a wind turbine model with main input-output signals as well as with the main model parameters is summarized in Fig.1.

Function approximation is a way of obtaining relatively accurate representation of the aerodynamics rotor. It is done by using a few parameters for input data to the rotor model as discussed in [5]. Generally, modeling a wind turbine consists of two steps. The first step is the conversion of the kinetic energy of moving air into mechanical energy, which is then used for driving the electric generator. The relation between wind speed and the aerodynamic mechanical power extracted from the wind can be described as

$$P_m = \frac{\rho}{2} \cdot A_{wt} \cdot C_p \cdot (\lambda, \beta) \cdot v_w^3 \qquad (1)$$

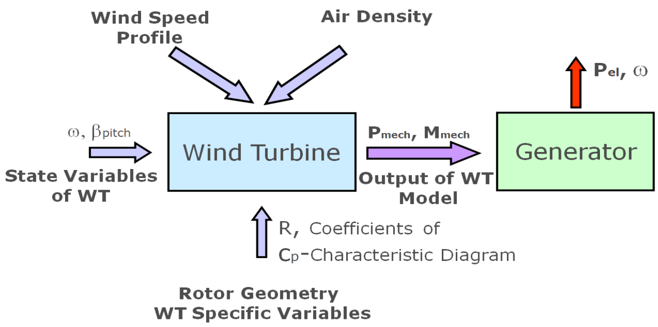

Figure. 1. General structure of the wind turbine model

where:

P_m :mechanical power of the wind turbine[W]

ρ :air density [kg/m^3]

C_p :power coefficient as a function of tips speed- λ and pitch angle- β

λ :tip speed ratio

β :blade pitch angle [°]

v_w :wind speed [m/s]

A_{wt} :is the area swept by the WT rotor [m^2] that is equal:

$$A_{wt} = \pi \cdot R^2 \tag{2}$$

with:

R: rotor radius[m]

The tip speed ratio is defined as:

$$\lambda = \frac{\omega_r \cdot R}{v_w} \tag{3}$$

where: ω_r is the angular speed of the wind turbine rotor and is related to the generator angular speed by Eq. (4)

$$\omega_r = t_G \cdot \omega_m \tag{4}$$

with:

t_G :transmission ratio of the gear box

ω_m :mechanical rotor speed of the generator [rad/s]

The second step is the conversion of mechanical energy, using a generator, into electricity that is transmitted to the electrical grid. This will be described in the next section.

III. DFIG MODEL

The main advantage of using a doubly fed induction generator (DFIG) in wind turbines is that they provide direct connection to the grid without additional converters in the main (stator) circuit while, at the same time, providing significant flexibility of operation. DFIG is a wounded-rotor slip-ring induction machine, in which the stator winding is directly connected to the grid and the rotor winding is fed from the grid using a back-to-back voltage source converter that includes a rotor side converter (RSC) and a grid side converter (GSC). A detailed structure of the considered wind turbine model with indicated necessary measurements for the control system is shown in Fig.2

Vector control techniques have been developed for DFIG using back-to-back PWM converters which allow the generator to operate above and below the synchronous speed in order to optimize the operational point to get the maximal energy yield. In order to represent the behavior of the DFIG in the most realistic way, both stator and rotor signals, such as currents, voltages and flux linkages, refer to their corresponding natural reference frames. This means that the parameters connected to the stator side of the machine refer to a stationary reference frame, while the rotor side currents and voltages refer to a reference frame rotating at rotor electrical speed ω_r .

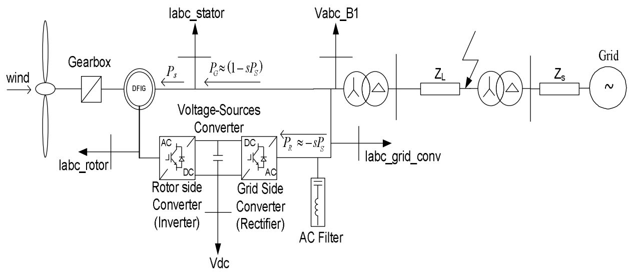

Figure 2. Detailed structure of the considered WT model

The three-phase stator electrical signal *X*, that can represent voltage, current or flux linkage, can be transformed to the corresponding reference frame; direct, quadrature and zero sequence components as follows:

$$\begin{bmatrix} X_d \\ X_q \\ X_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos(\gamma_k) & \cos(\gamma_k - \frac{2\Pi}{3}) & \cos(\gamma_k + \frac{2\Pi}{3}) \\ \sin(\gamma_k) & \sin(\gamma_k - \frac{2\Pi}{3}) & \sin(\gamma_k + \frac{2\Pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} \tag{5}$$

where: γ_k is the position of the synchronously rotating reference frame).

Three-phase rotor electrical signal X_r can be transformed to the corresponding reference frame; direct, quadrature and zero sequence components as follows:

$$\begin{bmatrix} X_d \\ X_q \\ X_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos(\gamma_k - \gamma) & \cos(\gamma_k - \gamma - \frac{2\Pi}{3}) & \cos(\gamma_k - \gamma + \frac{2\Pi}{3}) \\ \sin(\gamma_k - \gamma) & \sin(\gamma_k - \gamma - \frac{2\Pi}{3}) & \sin(\gamma_k - \gamma + \frac{2\Pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} X_{ra} \\ X_{rb} \\ X_{rc} \end{bmatrix} \tag{6}$$

where γ is electrical rotor angular position

The Clarke's inverse transformation allows for obtaining the three phase value from direct, quadrature, and zero components as follows;

$$\begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & 1 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & 1 \end{bmatrix}\begin{bmatrix} X_d \\ X_q \\ X_0 \end{bmatrix} \tag{7}$$

if γ_k and γ start from "0" value

IV. CONTROL SYSTEM OF GRID SIDE CONVERTER

The grid side converter is responsible for controlling the voltage level at the DC capacitor and reactive power exchange with the grid.

The control system for the grid side converter is presented in Fig 3. The necessary measurements for the control system are AC voltages and currents at the grid side as well as the value of the DC voltage while the AC signals are transformed into the dq-system.

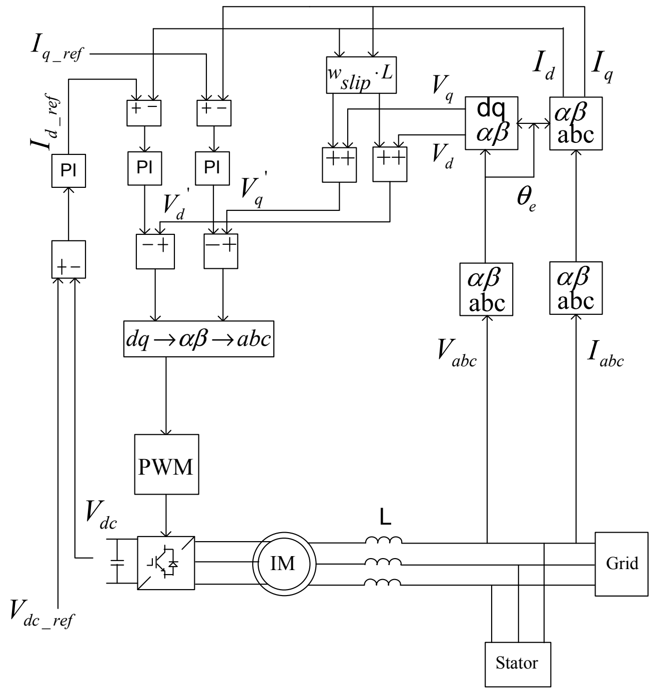

Figure 3. Structure of control system for grid side converter

The controller has a two-level structure with outer and inner control loops. The outer loop consists of PI controller for the DC voltage. Output of the DC voltage controller is I_{d_ref} which is an input signal for the PI current controller that corresponds to the inner control loop. The inner control loop consists of a current controller, which controls the magnitude and phase of the AC voltage synthesized by the grid side converter at the grid interconnection point. The scheme of the grid side converter is shown in Fig. 3.

V. CONTROL SYSTEM OF ROTOR SIDE CONVERTER

The rotor-side converter is used to control the active power of the DFIG and the voltage level (respectively reactive power) measured at the stator terminals. The control of the DFIG output active power is highly significant for wind turbines since it is used to adapt the angular speed of the turbine rotor in order to maximize the power extracted for the current wind situation. Using the reactive power control makes it possible for the reactive power demand of the machine, which is typical for standard induction machines, to be minimized to zero, and even capacitive operation could be possible. The scheme of the rotor side converter control system is shown in Fig. 4. Similar to the case of a grid-side converter it also has a two-level structure with outer and inner control loops.

Control of the rotor side converter is presented in Fig. 4.

VI. STUDIES

A. Model specification

A 2 MW wind turbine is connected to a 25 kV distribution power system that exports power to a 120 kV grid through a 30 km line. Table 1 shows the electrical parameters of simulated machine.

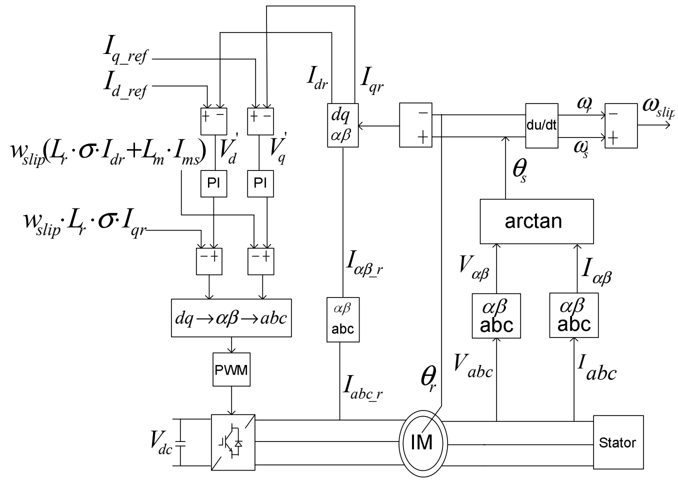

Figure 4. Structure of control system for rotor side converter

TABLE I. ELECTRICAL PARAMETERS OF THE MACHINE

DFIG Parameters	Value
R_s – Stator Resistance [pu]	0.00706
X_{ls} – Stator Inductance [pu]	0.171
X_m – Magnetizing Inductance [pu]	2.9
R_r – Rotor Resistance [pu]	0.005
X_{lr} – Rotor Inductance [pu]	0.156

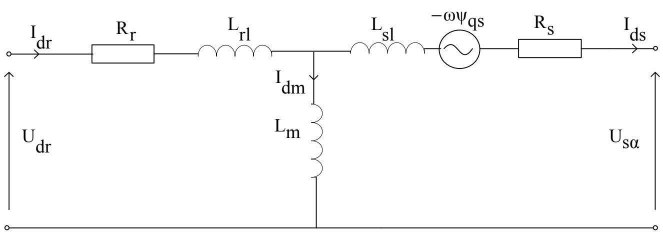

Figure 5. Structure of generator model

Dynamic parameters of the model are defined as follows;

$$L_m = \frac{X_m}{2\Pi f_s} \tag{8}$$

$$L_{ls} = \frac{X_{ls}}{2\Pi f_s} + L_m \tag{9}$$

$$L_{lr} = \frac{X_{lr}}{2\Pi f_s} + L_m \tag{10}$$

where:

X_m : magnetizing reactance

X_{ls} :stator transient reactance

X_{lr} :rotor transient reactance

L_m :magnetizing inductance

B. *Initialization of the DFIG model*

A correct initialization of the models plays an important role especially in the case of complex systems, since transients at the beginning of simulation can lead to numerical instabilities. Otherwise, due to the long time constants of the electromechanical part of the wind turbine model it is necessary to wait for tens of seconds before reaching steady state. Therefore, model developed in this work was set-up with all states initialized so that the simulation can start in steady-state.

In order to find the initial conditions for the DFIG, block POWERGUI was used that provided the following parameters:

- measurements of steady-state voltages and currents in the model
- active and reactive power of the machine
- mechanical power obtained from the wind turbine
- slip of the machine

These parameters were saved for each chosen operating point and then automatically loaded during the simulation start.

C. *Steady-state operation*

In the first step the model was analyzed in the steady state operation in order to check the correctness of the initialization process. As shown in Fig. 6 – Fig. 9 it was possible to start the model in the steady state without any additional and unnatural transients. The controllers kept the voltage in the DC circuit of the machine at the reference value and the small oscillation present in the signals are evoked by the detailed representation of the voltage source converter using valve-representation.

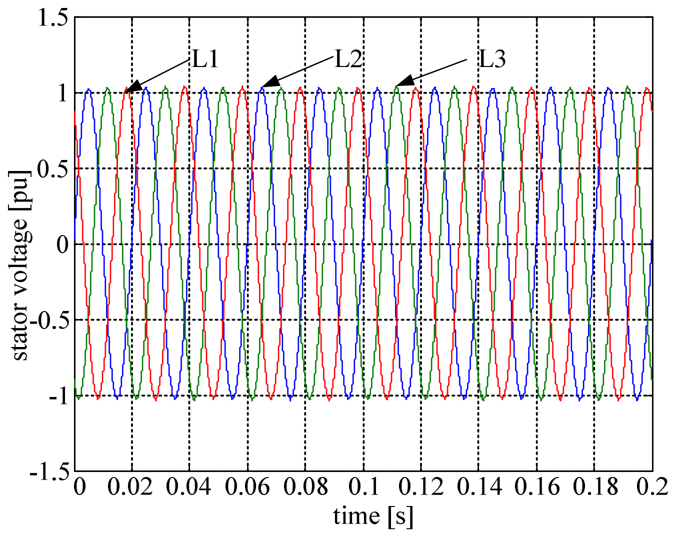

Figure 6. Stator voltage

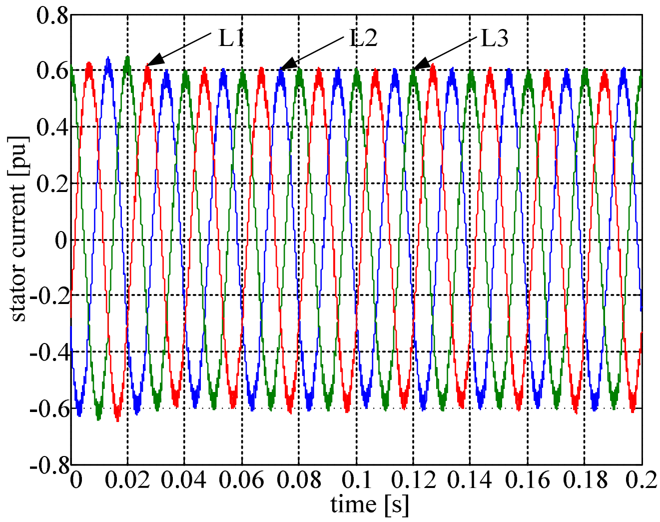

Figure 7. Stator current

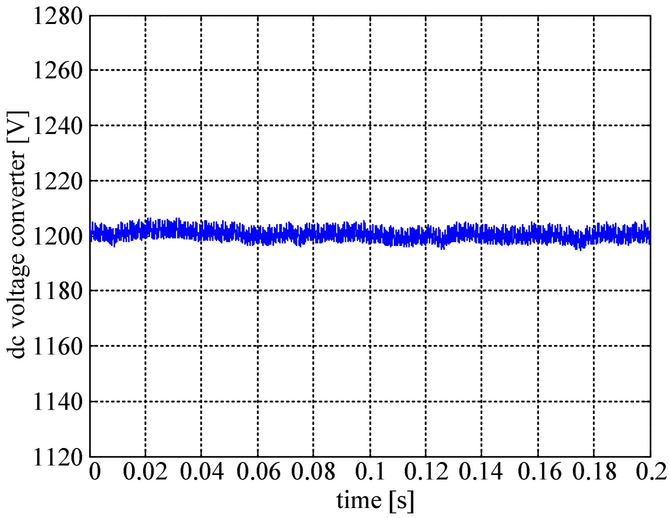

Figure 8. DC voltage converter

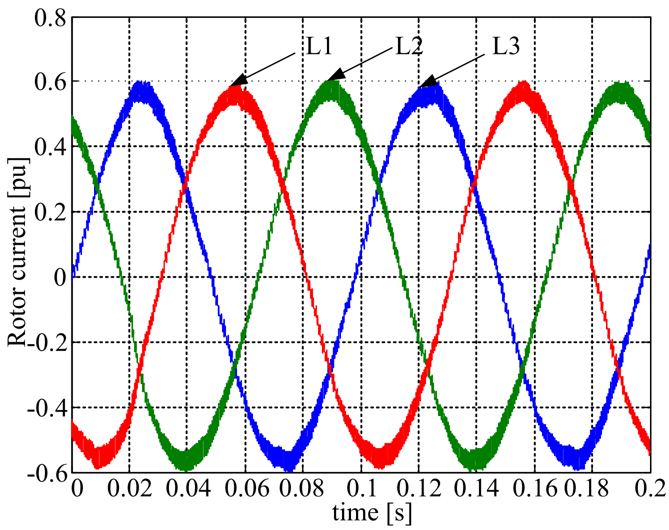

Figure 9. Rotor current

DC link nominal voltage is equal to 1200V. Regulators are used in the model to keep DC voltage at an approximately constant value.

Frequency of the rotor current depends on the slip of the machine. Small oscillations in signals arose in the presence of the voltage source converter.

D. Symetrical fault and two-phase fault circuit in the grid

In order to analyze the dynamic behavior of the developed wind turbine model a symmetrical three-phase fault at the 20kV busbar was simulated. This fault caused the voltage to drop at the terminals of the wind turbine to a value of 0.1 pu. Figures 8, 9, 10 and 11 show the effect of this disturbance on wind turbine behavior. The duration of the fault was set to 100 ms, from time 0.5s to 0.6s.

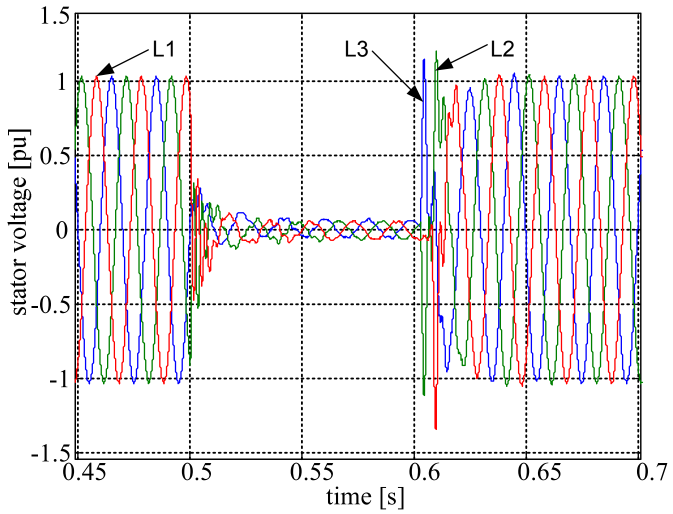

Figure 8. Stator voltage

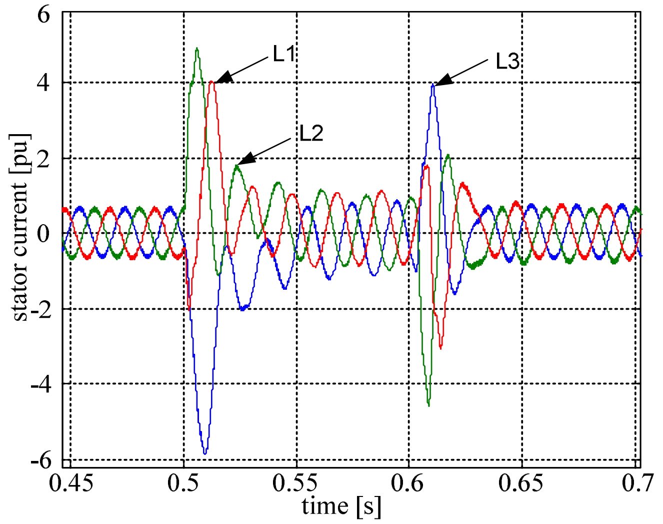

Figure 9. Stator current

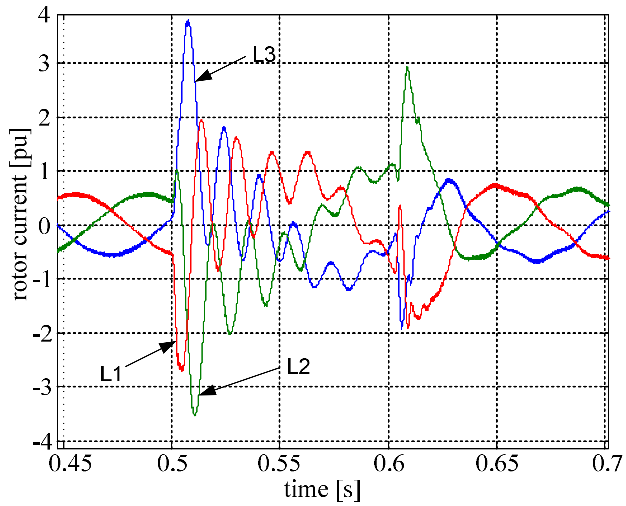

Figure 10. Rotor current

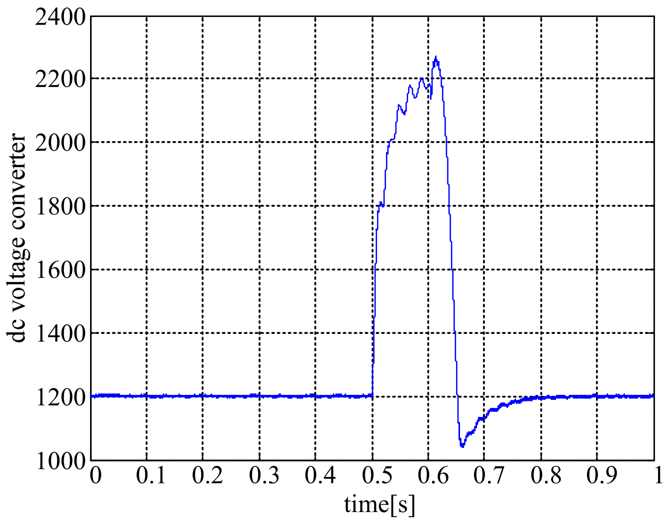

Figure 11. DC voltage converter

This figures showed that without any protection system, the main concern in DFIG is usually the fact that large disturbances lead to large fault currents in the stator due to its direct connection to the grid. Because of the magnetic coupling between the stator and the rotor, the stator disturbance is further transmitted to the rotor. Rapid increases of DC converter voltage can destroy elements of the converter, so in case of limiting inrush current, it is necessary to apply a device called “crowbar”. This device is an additional resistance that is connected to the rotor circuit of the machine if the current exceeds the allowable value, and in this way the frequency converter will be by-passed for the fault current.

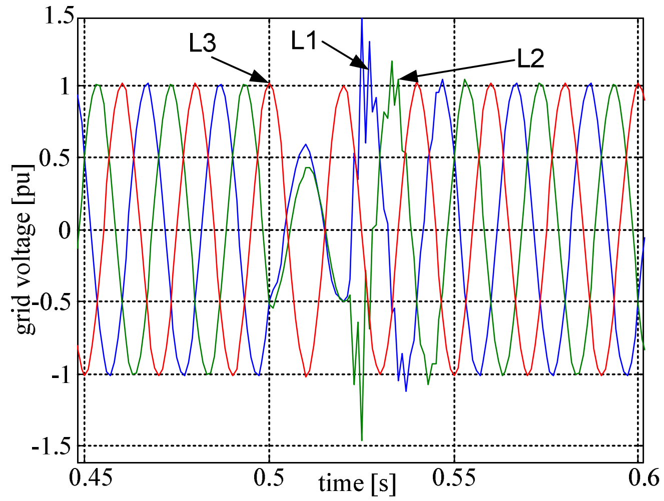

Figure 12. Grid voltage

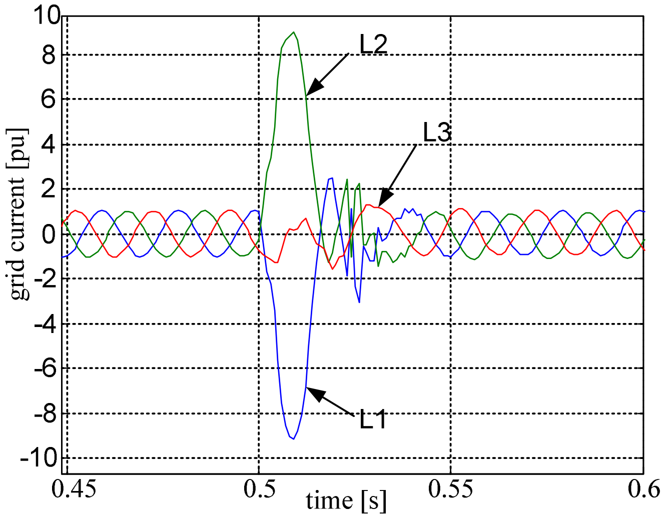

Figure 13. Grid current

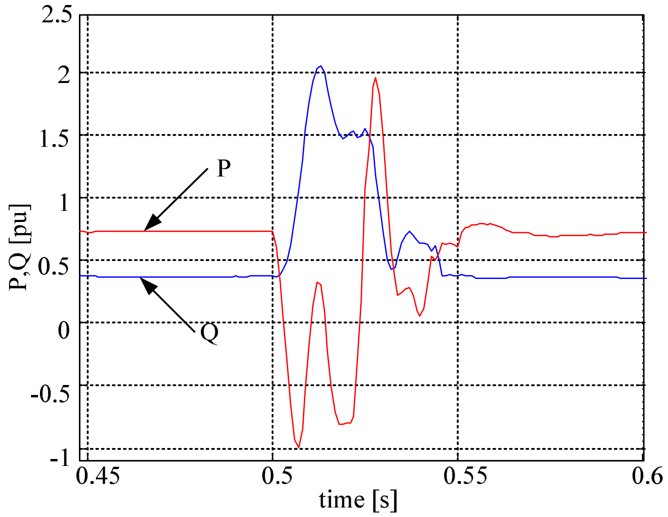

Figure 14. Active and reactive power in the grid

Figures 12, 13, and 14 present signals measure in the grid during a two phase fault at the middle voltage terminal. The fault last from 0.5 to 0.52s. The generator introduces active and reactive power to the grid. The current of the grid is eight times higher than the nominal value. After the fault, signals reach steady state very fast.

E. Change of voltage level at DFIG terminals

In order to investigate the influence of small voltage changes on the reaction of the control system a voltage drop to 0.8 pu was applied to the external grid as shown in Fig.2 The duration of this state was set to 70 ms. This step-wise change of the voltage that can be interpreted as remote disturbance in the power system influenced the machine voltages and currents as presented in Fig. 15 – Fig. 18.

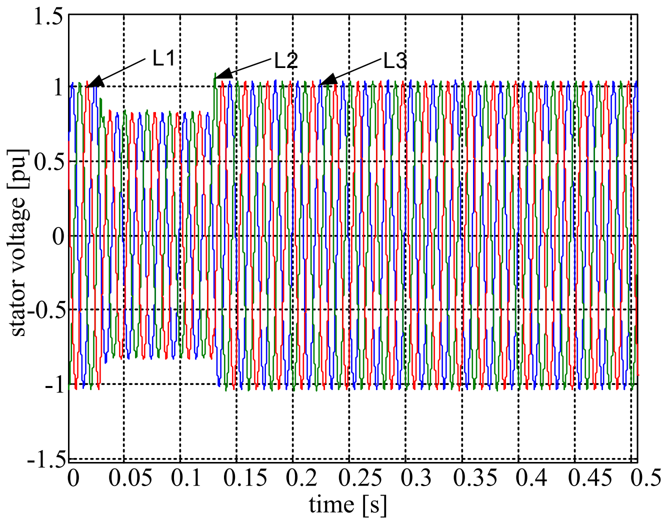

Figure 15. Stator voltage

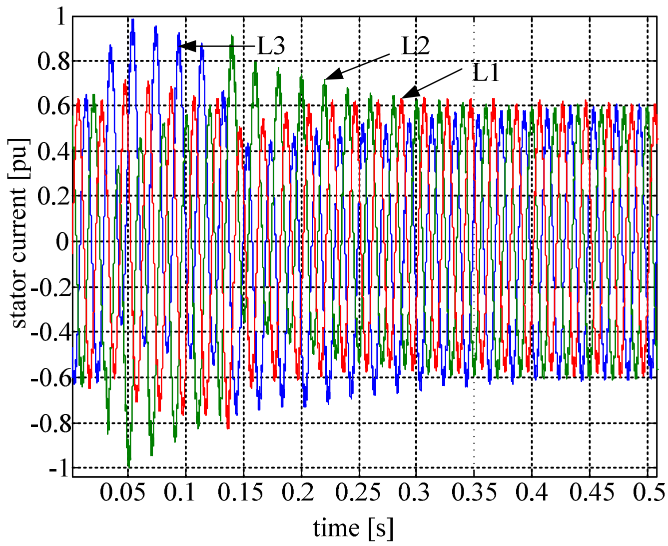

Figure 16. Stator current

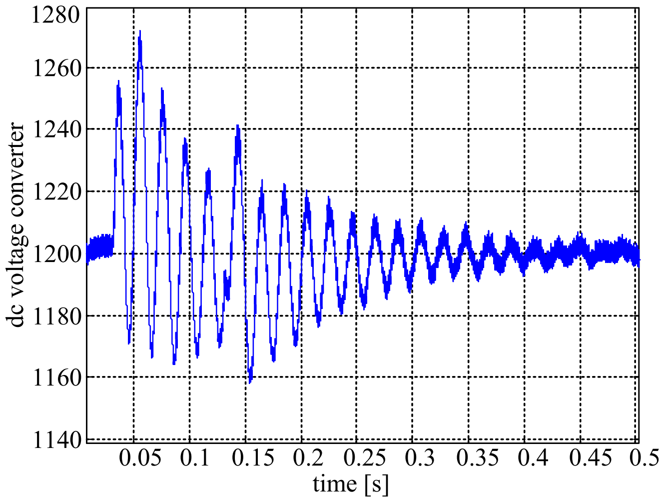

Figure. 17. DC voltage converter

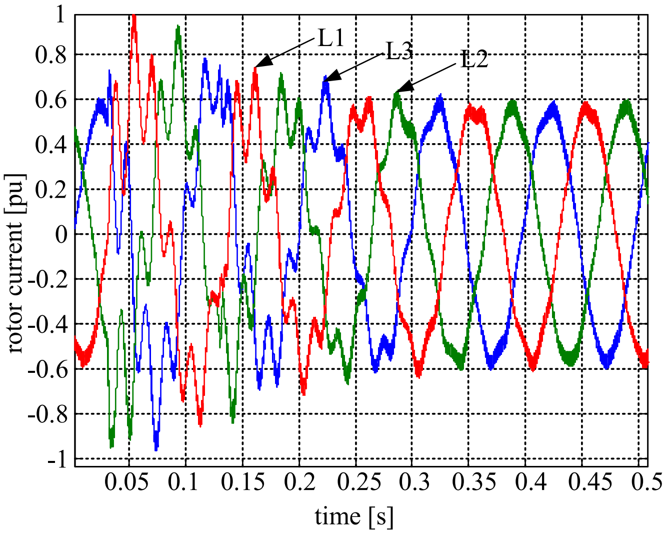

Figure 18. Rotor current

The simulation results show that in general the control system operates correctly but the control time to reach the new steady state point is relatively long, which can indicate not optimal settings of the control system.

VII. CONCLUSION

This paper presented a detailed model for a wind generator based on a DFIM, with special attention paid to the grid side and rotor side converter description. The overall control system was made in Matlab-Simulink. To test the correctness of this model, simulations for the steady state, three phase fault, two-phase fault and change of supply voltage were conducted.

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