SIMULATION AND INVESTIGATION OF THE BEHAVIOR OF A LARGE-SCALE DIRECT DRIVEN WIND TURBINE CONNECTED TO THE GRID

Ali EL YAAKOUBI[1], Kamal ATTARI[2], Adel ASSELMAN[3], Abdelouahed DJEBLI[4]

Under the growth increasing of the renewable energy demand, especially the wind energy one, there is a great interest to the large-scale wind energy conversion system (WECS). Hence, an expectation of the different kinds of stresses exposed to the system structures is required. In this paper, the dynamic behavior of a direct driven wind turbine system exposed to aerodynamics loads and grid fault are studied using a combination of different reliable software instruments: Modes, TurbSim, AeroDyn, FAST, which are used to model the Wind Turbine (WT); and MATLAB/SIMULINK is used to model the electrical parts of the system and the grid model. These software instruments represent a reliable platform of analysis and investigation of, the behavior of the WECS to the aerodynamics conditions, the interactions between its different parts and the uncertainties from the grid fault. The simulation results enable concluding that the system needs a damped control strategy to improve its transients response. The study will also help to identify additional control requirements and specify the control design for the WECS operation.

Keywords: Grid fault; Direct driven based wind turbine; Electromechanical interactions

1. Introduction

The renewable energy sources are considered as an alternative solution of the energy need because they are free, clean and avoid the drawbacks related to the traditional one. The main goal of a WECS is to extract an amount of the kinetic energy contained in the wind, and to convert it to electric energy. Recently this source takes a large attention in the investment and the research development

[1] Optic and Photonic Team, Faculty of Sciences, Abdelmalek Essaadi University, Tétouan, Morocco, e-mail: ali.elyaakoubi@gmail.com
[2] Optic and Photonic Team, Faculty of Sciences, Abdelmalek Essaadi University, Tétouan, Morocco
[3] Optic and Photonic Team, Faculty of Sciences, Abdelmalek Essaadi University, Tétouan, Morocco
[4] Energetics Fluid Mechanics and Materials Laboratory, Faculty of Sciences, Abdelmalek Essaadi University, Tétouan, Morocco, e-mail: abdelouhed.djebli@yahoo.fr

area around the world. In 2020 for example, the Moroccan state aims to install 2000 MW of wind energy, which represents 14% of total electricity installed capacity of the country [1]. A reliable software and hardware of development of this sources also has been taken a great part in the research area, such as FAST code, which is considered as a high-fidelity nonlinear wind turbine model used for load calculation and control implementation on WT system [2]. To achieve the underlined market, we expect that the large scales WECS will dominate the future markets. As role of the research and development in this source of energy is to reduce the cost of the energy generated. Since this cost is driven by the cost of the system itself, so improvement of the system efficiency and reduction of system cost are the two major objectives to reduce the cost of the energy produced. These objectives can be achieved by acting on the system control specially. The improvement of the system efficiency can be achieved by extract much energy from the system by following the maximum power point tracking by means of the torque controller, whereas the reduction of the system cost can attained for example by reducing the loads exposed to the system structures such as tower, blades and main shaft, by specific controller such as damper strategies [3]–[6], in order to increase its lifetime. Various works are interested to WECS performances improvement, through control strategies and parameters optimization [7]–[12], but little works are interested to system behavior investigation of the WT [14]–[16], so an accurate study and analysis is suitable to reveal its critical modes and to prove the interactions between its components. In this regard, in order to evaluate well the dynamic behavior of a WECS, especially the large-scale one, according to wind speed fluctuations, and grid faults and also to show the electromechanical interaction, a study is required through an accurate modeling and simulation of the full WECS. Hence an expectation of the stresses exposed to the system structures from the aerodynamic conditions and the grid fault is required, in order to predict their effect and so to cancel it impact [3]. According to [16] the failures related to gearbox are responsible for over 20 % of downtime of the WTs, and hence they must be replaced within 6 to 8 years. Its why the direct driven machines based on permanent magnet synchronous generator (PMSG) (i.e. machine without need to gearbox), which is chosen in this work, are very promised rather than the induction machines (the machine with gearbox).

In this paper, the dynamic behavior of a large-scale WT, based on a PMSG, in the partial load zone, i.e the zone where the wind speed is insufficient to get the rated power, is investigated using a deeper modeling and a simulation study to understand the system response for a good control configuration. Various reliable softwares are used in order to accomplish these tasks, Modes is used to find the mode shapes of towers and blades, which are then used by AeroDyn and FAST, Turbsim is used to model the wind data [17], AeroDyn does aerodynamic calculations, FAST [1] is used to perform the loads calculations on the WT based on the aerodynamics calculations. All these tools, which are developed at NREL (National Renewable Energy Laboratory) [2], are used together in order to reflect the real behavior of the WT. The electrical parts of the system, including the generator, full-scale back-to-back converters, control system and the electrical grid are modeled within MATLAB/SIMULINK. The combination of these software instruments represents a reliable platform of analysis and investigation of the full behavior of the WECS and the interactions between its mechanical and electrical parts. The impact of various operating conditions exposed to the system is assessed and presented. The rest of the paper is organized as follow. In first part, the system modeling and the tools used are presented. In the second part the simulation response to the aerodynamics loads and the grid fault are discussed, and a conclusion is given at the end.

2. Material and system modeling of the wind turbine

2.1 Turbsim

Turbsim is a stochastic, full field wind simulator. It uses statistical model to numerically simulate time series of three wind components in a dimensional grid [17]. It is used to be an input to AeroDyn program to provide it with the required wind field data. Its purpose is to provide the WT designer with the ability to drive design code simulations of advanced turbine designs with simulated inflow turbulence environments that incorporate many of the important fluid dynamic features known to affect turbine aero elastic response and loading. Readers can refers to [17] for a description of how to conduct a simulation by Turbsim. A hub height wind input file consists of time series of wind speed, direction, vertical speed, horizontal speed, horizontal shear, vertical shear, linear vertical shear, and gust speed, is used in this work [17].

2.2 AeroDyn

AeroDyn code performs the WT aerodynamic loads calculations; it calculates the aerodynamic lift, drag, and pitching moment of airfoil sections along the WT blades. AeroDyn uses information from input files on turbine geometry, as well as data from the aeroelastic simulator such as operating condition, blade-element velocity and location, and wind inflow, to calculate forces for each blade segment [18]. It uses both blade element momentum (BEM) theory and generalized dynamic wake theory for calculating the effects of turbine wake [18].

2.3 FAST

FAST is a publicly available simulator for two and three-bladed WT, it simulates the interactions of aerodynamic forces with mechanical bodies. It is an aeroelastic code capable of predicting both the extreme and fatigue loads of two- and three-bladed horizontal axis WTs. The FAST enables to control the generator torque, the pitch angle, the yaw angle of the nacelle, the high-speed shaft (HSS) brake and deploying the tip brakes. All these controllers can be implemented in Simulink, in which the FAST subroutine is interfaced with MATLAB as an S-function that can be incorporated in Simulink [1]. The model used in this paper is a 5MW WT called "NREL offshore 5-MW baseline wind turbine" tested at NREL and is considered as a benchmarking model for simulation and control purpose [2]. The parameters of this model are derived from [15], where some specifications of the wind turbine are shown in table 1.

In FAST, the blade and tower are considered flexible elements modeled by a linear modal representation. The mode shapes of the blade and tower are represented as input file required to FAST. These modes take information about the tower, the mass of the nacelle and the rotor and hence finds the mode shapes and natural frequencies of the WT.

Table 1

The specification NREL offshore 5-MW baseline wind turbine model

Parameter	Value
Power rating	5 MW
Rotor diameter	123 m
Nacelle mass	240,000 Kg
Nacelle inertia	2,6078,9000 Kg.m^2
Generator inertia	534.116 kg.m^2
Hub inertia	115.926 kg.m^2
Blade mass	17,740 kg
Hub height	90 m
Total inertia	3.09x10^7 kgm^2
Rated, cut-out wind speed	11.4 m/s, 25 m/s
Rated rotor speed	12.1 rpm

3. Electrical system modeling by Simulink

Because FAST offers an interface within MATLAB/SIMULINK, it's why the electrical parts of the system is modeled in Simulink which is considered as a reliable tool for describing the dynamics of the electrical systems.

16 degree of freedoms (DOFs) of the WT are enabled in this work, by means of the FAST code, which are: First and Second flapwise mode, First and Seconde fore-aft tower bending mode, First and Second side to side tower bending mode, First edgewise blade mode, Drive train rotational flexibility, Generator azimuth angle, and yaw angle.

3.1. Direct driven generator modeling

The direct driven machine modeling in the d-q reference frame, based on stator voltage and electromagnetic torque, is given respectively by Eq.1 and 2 [13]:

$$\begin{cases} v_d = R_s i_d + L_d \dfrac{di_d}{dt} - \omega_e L_q i_q \\ v_q = R_s i_q + L_q \dfrac{di_q}{dt} + \omega_e L_d i_d + \omega_e \Phi_p \end{cases} \tag{1}$$

$$T_e = \frac{3}{2} p \left\{ \Phi_p i_q + \left(L_d - L_q \right) i_d i_q \right\} \tag{2}$$

Where R_s is the stator resistance, p is the pair poles number, Φ_p is the flux linkage excited by permanent magnets on the rotor, v_d, v_q, i_d i_q are the d and q component of stator voltage and current respectively, and L_d, L_q are the d and q component of inductances respectively. It is assumed that $L_d = L_q$ in such manner that the electromagnetic torque of the generator is controlled by only the *q* current component, which is given by Eq.3.

$$T_e = \frac{3}{2} p \Phi_p i_q \tag{3}$$

3.2. Converter system model

A full back-to-back voltage source converter is used in this paper to connect the PMSG and the grid, through the transformer. The machine side generator is used to control the PMSG in order to perform the maximum power point tracking function from the wind [19], whereas the grid side converters is used to control the active and reactive power exchanged between the machine and the grid [15]. A dc link is used between the two converters, to enable an optimum injection of the generated energy to the grid and to allow a decoupling between the machine and the grid. The two converter are modeled by a space vector pulse width modulation (SVPWM).

3.3. Filter, Transformers and Grid models

A filter is used in order to reduce the ripples content in the converter's output to an acceptable level, and a transformer is needed to adapt the voltage of the machine with those of the grid. A scheme of the filter used in this work is given in [15]. The grid is represented by a Thevenin equivalent model, which it consists of three voltage sources connected with three impedances in series. A voltage step is applied to the voltage source in order to represent the grid fault effect.

3.4. Control system

The control system of the WECS is based on two controllers: pitch controller and torque controller. The main objective of the torque controller is to optimize the produced energy from the wind by adapting the rotational speed of the WT to the wind changes in the partial load zone of operation, where the pitch angle is kept at the optimal value $\beta = 0$[13]. The torque controller is implemented by means of field oriented control technique [15], where reference rotational speed is derived from the wind turbine characteristic. In the full load zone of operation, the pitch controller is activated to limit the speed and the power of the turbine to their rated values, where the torque is fixed at its rated value. The pitch controller, is a gain scheduling controller, structure and parameters are used in this paper is given in [2]. The nacelle yaw control and the high-speed shaft break are not considered.

4. Simulation results

The system modeled is subjected to two form of loads, in order to reflect their realistic behavior: a very turbulence wind profile generated by Turbsim and a fault from the grid represented as a dip in the voltage source at 20 second of 200 milliseconds of duration. The total wind speed profile is given by Fig.1, which takes 50 second. This wind profile is located in the partial load of operation, thus the pitch controller will be enacted and the system will be controlled in order to maximize the produced energy from the wind by means of the torque controller. A description of the system parameters are given in [15], where some relevant parameters are given in table 2.

Table 2

Parameters of the system electrical parts

Parameter	Value
Nominal grid voltage	34.5 kV
Nominal generator voltage	690 kV
Capacitance	2 mF
Poles number	18
Stator resistance	0.476 mΩ
Synchronous inductance	0.177 mH
Transformer turns ratio	1:53.0769

The simulation results represented by rotational speed, electromagnetic torque, real active power, reactive power, bus voltage and grid current are given respectively by fig.2, 3, 4, 5, 6 and 7 respectively. The reference rotational speed is designed in order to ensure a trade-off between the maximization of the produced energy from the wind and the minimization of the loads exposed to the system structures. Therefore, the reference speed is obtained, in order to follow the medium wind speed changes and not the high frequency changes, based on the WT characteristics, as shown in Fig.2.

The rotational speed of the generator follows well the set point value, whether the reference speed increase or decrease, thus demonstrating the reaction of the electromagnetic torque of the generator to the wind speed changes as can be seen from Fig.3, thus the system enables to maximize good their production. However, as can be seen from the Fig.2, the large masses of the system does not allow the WT to follow effectively the wind changes, thus can be translated by an amount of losses in the produced energy. Even though the oscillations in the drive train are related to the turbulence come from the wind speed, but in this case, the reference rotational speed is applied just as steps. Thus, these can be explained by the reaction of the electromagnetic torque on the WT at the level of the drive train, and hence the illustration of the electromechanical interactions within the WECS. Eventually these oscillations necessities others control requirements such as damped strategies. The electrical real active power is much maximized as expected, as shown in Fig.4, because it follows well the immediate changes of the wind speed. The reactive power exchanged between the generator and the grid is regulated well to zero in order to maintain a unit power factor as shown in Fig.5. The voltage of the dc link is regulated at its rated value, 1.5 kV as shown in Fig.6, and thus illustrating that the real active generated is transferred fully to the grid.

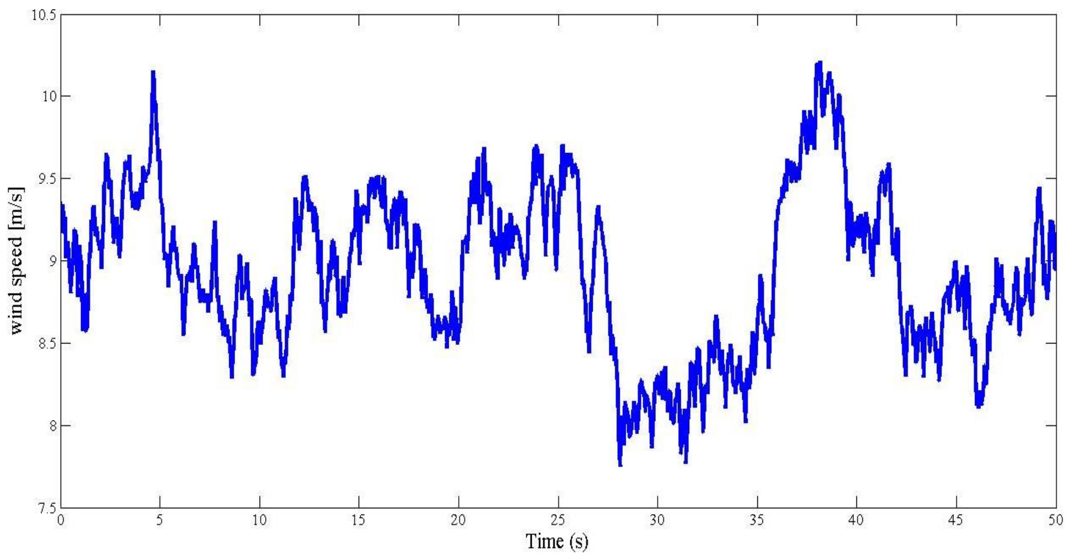

Fig.1 Total wind speed profile

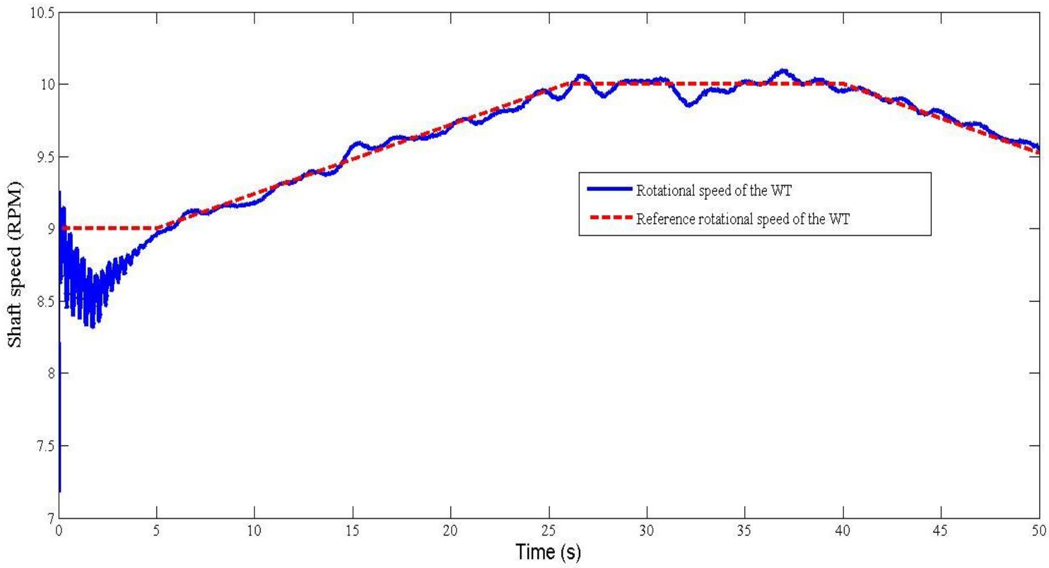

Fig.2 Rotational speed of the turbine

According to the simulation results of the figures mentioned above, oscillations are appeared on the reactive power, grid current and the dc link at the moment of the applied fault, but these oscillations are removed effectively when the fault is removed. These can illustrate the capacity of the PMSG to cancel the grid uncertainties effect and thus to contribute actively to fault ride through operation.

The load factor of the WT is the fraction of the produced and the rated power. The generated power is about 1.900 MW, as shown in Fig.4, and the rated power of the WT is 5 MW then the load factor is 38 %. From this work it is concluded that the dynamic behavior of the studied system is influenced by two factors: transients loads come from the aerodynamic conditions, and the grid faults effect. The aerodynamic conditions can attack the stability of the system and therefore to excite its system modes, whereas the grid fault conditions, as can be stated through the results, presents small effect on the system, though are negligible on the mechanical components the WT of this kind of machine.

At their turn, the current flowed to the grid follows well the wind speed trends, as can be illustrated in Fig.7, which prove the ability of the system to extract a maximum energy from the wind.

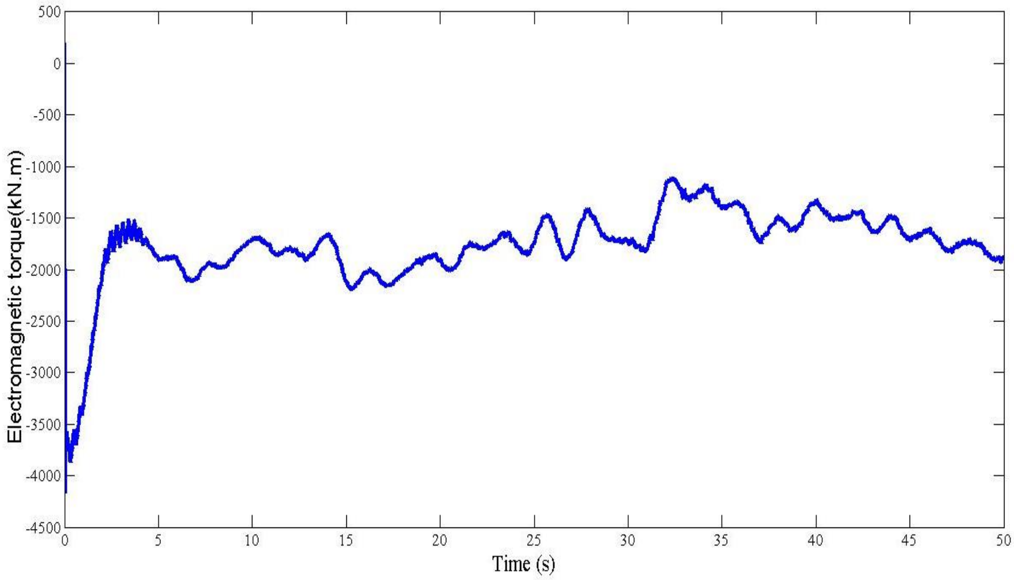

Fig.3 Electromagnetic torque applied on the wind turbine shaft

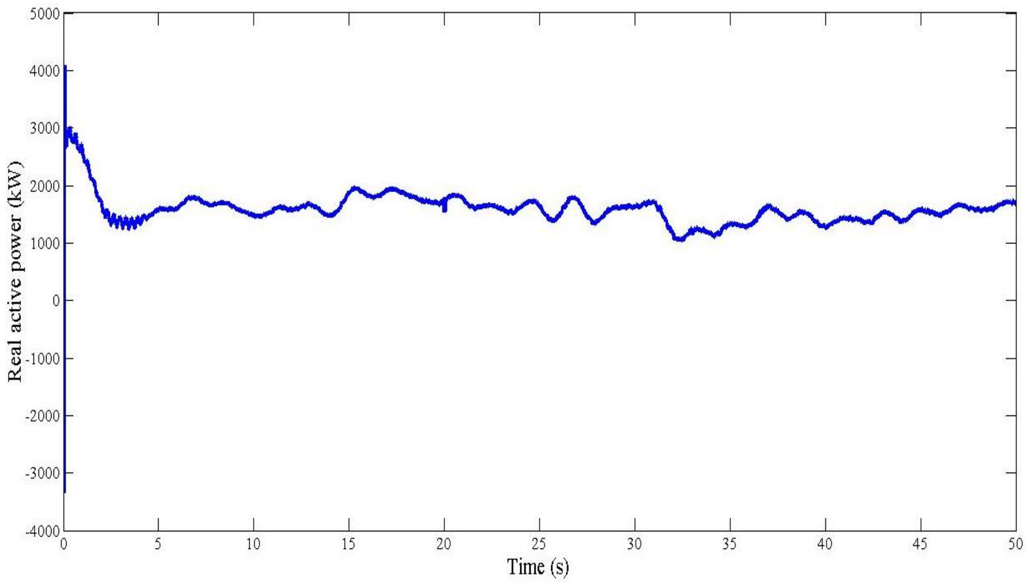

Fig.4 Electrical power generated

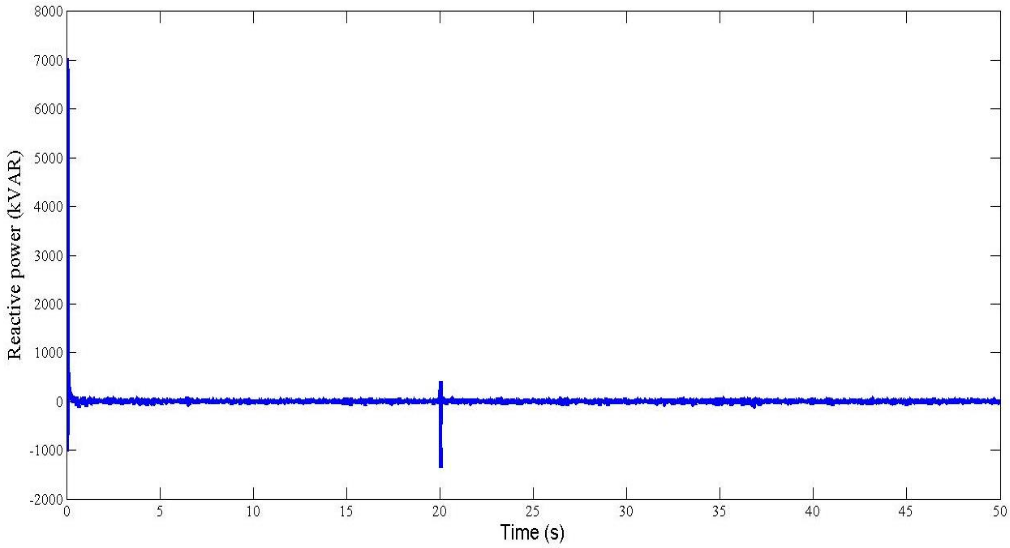

Fig.5 Reactive power exchanged between the generator and the grid

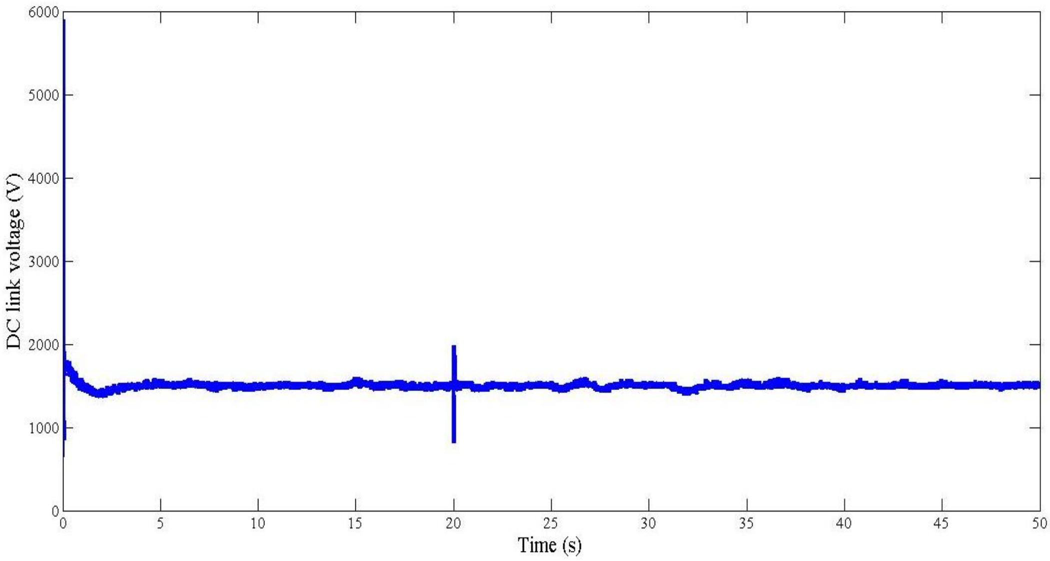

Fig.6 DC link voltage

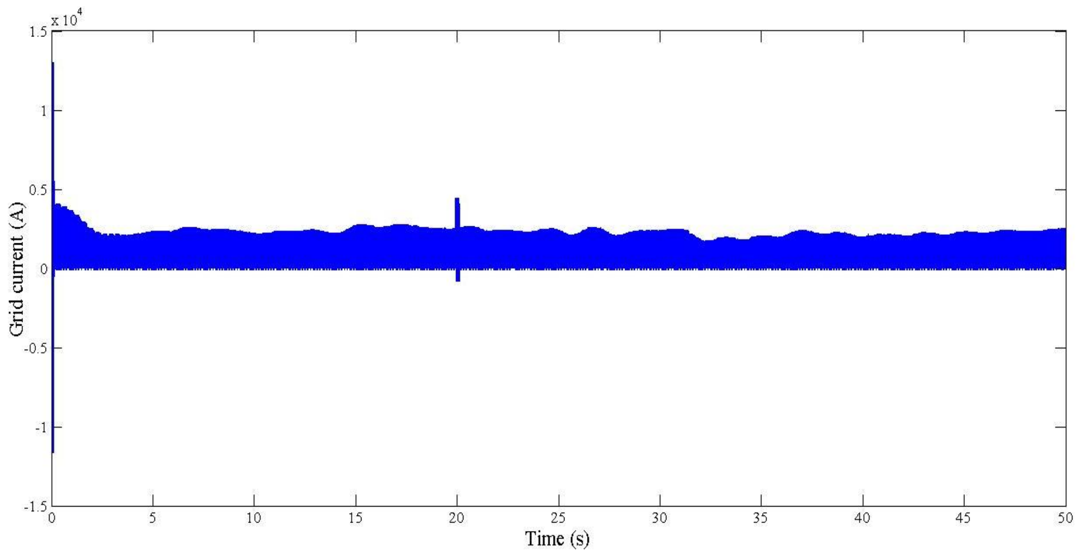

Fig.7 Current at the grid side converter output

5. Conclusion

In this work, we have simulated and investigated the dynamic behavior of a large-scale direct driven wind turbine. The simulation was conducted by reliable simulation tools Modes, AeroDyn, Turbsim, FAST and MATLAB/SIMULINK. The system is subjected to two operation conditions: a very turbulent wind profile and a dip of the voltage which represent the uncertainties from the utility grid. The simulation results enable to conclude that the dynamic behavior of the studied wind turbine is very sensitive to the aerodynamic conditions. It is proved that the electromechanical interactions affect the reliability of the drive train component, as it can affect the efficiency of the system due the amount of energy lost at the component. Therefore, it is necessary to mitigate their impact by means of additional control requirements. Moreover, it is proved that the extracted energy from the system is injected optimally to the utility grid with negligible grid fault effects on the wind turbine. Thus, illustrating the electiveness of the PMSG to operate under grid fault effects and to contribute actively to fault ride through operation.

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