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Transient Voltage Control Of Grid-Connected Wind Turbines With Dfig At External Short-Ciruit Fault

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***Abstract*—The rapid development of the wind energy system requires the use of the modern methods to complete the process of connecting the wind turbines to the public network efficiently and high quality. Most of the previous researches used a model which consider the main parts of the wind turbine during normal operation only without considering the connecting them to each other and their connections to the public network as well as the consequent important considerations such as the quality of the load and the speed of control in the characteristics of the turbines during sudden failures. Also, the control method of wind turbine energy is limited to control turbine blades without integration with rotor control of the electric generator, causing slow control of the turbines, weak response to voltage compensation, decrease in the quality of the energy generated during the external disturbances and the slow return to normal operation which may result in power cuts on loads and consumers.**

This research focuses mainly on transient analysis of variable speed wind turbines with doubly fed induction generator (DFIG) after clearance of external short-circuit fault. It also presents a new and concise modeling of the basic and influential parts of the characteristics and operation of the wind turbine together with its connection to the public network during normal operating and emergency situations due to external network failures. The new and abbreviated model will play an important and effective role in the creation of effective control method containing both the rotor control together with the pitch control for speed control of the turbine. This new model will help also to restore the turbines to normal state while maintaining the stability of the public network during external faults such as transient short circuit.

A simulation model of mw-level wind turbine is performed using program called Power System Computer Aiding Design (PSCAD). One of the most important results of the simulation of a short circuit in the public grid connected to the wind turbine is that the new strategy of speed control and wind turbine blades together with the separation of some of the protection devices in the transmission lines will play an important and effective role in rebuilding the turbine voltage and returning it to normal value without separation from service and not cutting off energy from the consumer (loads). Such good types of turbine control will maintain the stability of energy quality and the public network efficiently, while significantly reducing the loss of electricity.

Keywords— Doubly fed induction generator (DFIG), short circuit fault, transient analysis, wind turbines.

I. INTRODUCTION

Due to the conventional energy sources consumption and increasing environmental pollution, efforts have been made to generate electricity from renewable sources, such as wind energy sources.

Institutional support on wind energy sources, together with the wind energy potential and improvement of wind energy conversion technology, has led to a fast development of wind power generation in recent years [1].

The continuous increase of wind power penetration level is likely to influence the operation of the existing utilities networks, especially the power system stability. Specifications are now being revised to reflect new requirements for wind turbine integration to the network.

According to the new requirements, after the clearance of a short-circuit fault in the external network, the grid-connected wind turbine should restore its normal operation without disconnection caused by inrush current and dipped voltage [4]. The reason is when the wind power penetration level is high, the protective disconnection of a large amount of wind power may cause an increase of loss energy that may threaten the power system stability [2].

Regarding fixed speed wind turbines with conventional induction generators, the normal operation restoration after the clearance of an external system fault may be assisted with dynamic reactive compensation, adjustment of relay settings of wind turbines, and control ability of wind turbines. For variable speed wind turbines with slip control, dynamic slip control and pitch control may contribute to restore the normal operation and maintain power system stability after the clearance of an external short-circuit fault [3].

Variable speed wind turbines with DFIG, the most popular installed variable speed wind turbines worldwide, have shown better behaviors concerning system stability during short circuit faults in comparison with fixed speed wind turbines. One of the reasons may be its capability of decoupling control of output active and reactive power. It is quite interesting to study the normal operation restoration of such kind of wind turbines after the clearance of an external short-circuit fault.

This paper concentrates on transient analysis of variable speed wind turbines with DFIG after the clearance of an external short-circuit fault. A simulation model of a MW-level wind turbine with DFIG developed in PSCAD/EMTDC is presented, and the control and protection models of the wind turbine are described. Based on the wind turbine model, the stability of wind turbine after a short-circuit fault has been investigated. The simulation results show how the control models effectively manage to restore the wind turbine's normal operation after the clearance of an external short circuit fault [6].

II. WIND TURBINE MODEL

The wind turbine considered here is a doubly fed induction generator using a back-to-back PWM voltage source converter in the rotor circuit. Variable speed operation of the wind turbine can be realized by appropriate adjustment of the rotor speed and pitch angle [5].

A complete wind turbine model includes the wind speed model, the aerodynamic model of the wind turbine rotor, the mechanical model of the transmission system and models of the electrical components, namely the induction generator, PWM voltage source converters, transformer, and control and supervisory systems. (Figure 1) illustrates the main components of a grid connected wind turbine.

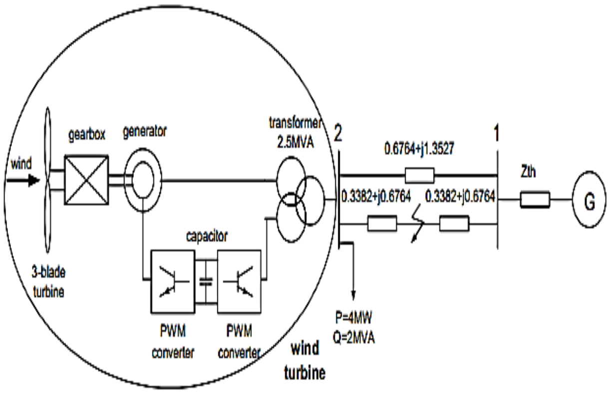


Fig.1. Block diagram of a grid connected wind turbine with a doubly fed induction generator.

The simulation model of the wind turbine is developed in the dedicated power system analysis tool “PSCAD/EMTDC”. The grid model and the electrical components of the wind turbine are built with standard electrical component models from PSCAD/EMTDC library. The models of the wind speed and the aerodynamic, mechanical and control components of the wind turbine are built with custom components developed in PSCAD/EMTDC.

Wind simulation plays an important task in wind turbine modeling, particularly for dynamic interaction analysis between wind farms and the power system to which they are connected [4].

The structure of the wind model is built into two steps:

The first step of the wind model is the park scale wind model which simulates the wind speed in hub height at each wind turbine, considering the park scale coherence.

The second step of the wind model is the rotor wind model which includes the influence of rotational sampling and the integration along the wind turbine blades as the blades rotates. The rotor wind model provides an equivalent wind speed for each wind turbine, which is conveniently used as input to a simplified aerodynamic model of the wind turbine [7].

A simplified aerodynamic model is normally used when the electrical behavior of the wind turbine is the main interest of the study. The relation between the wind speed and aerodynamic torque may be described by the following equation:

$$T_W = \frac{1}{2} \rho \pi R^2 v_{eq}^2 C_P(\theta, \lambda)/\lambda \qquad (1)$$

Where T_W is the aerodynamic torque extracted from the wind [Nm], ρ is the air density [kg/m^3], R is the wind turbine rotor radius [m], v_{eq} is the equivalent wind speed [m/s], θ is the pitch angle of rotor [deg], $\lambda = W_{WTR} R / v_{eq}$ is the tip speed ratio, W_{WTR} is the wind turbine rotor speed [rad/s], C_P is the power coefficient.

As for the mechanical model, emphasis is put on the parts of the dynamic structure of the wind turbine that contribute to the interaction with the grid. Therefore, only the drive train is considered, while the other parts of the wind turbine structure, e.g. tower and flap bending modes, are neglected [10].

When modeling the drive train, the dynamics of the mechanical parts may be neglected, as their responses are considerably slow in comparison to the fast-electrical ones, especially for machines with great inertia. The rotational system may therefore be modeled by a single equation of motion:

$$J_{WG} \frac{d\, w_{WTR}}{dt} = T_W - T'_G - D\, w_{WTR} \qquad (2)$$

Where J_{WG} is the wind turbine mechanical inertia plus generator mechanical inertia [kg·m^2], w_{WTR} is the wind turbine rotor speed [rad/s], T_W is the wind turbine input aerodynamic torque [Nm], T'_G is the generator electromagnetic torque referred to the low speed side [Nm], D is friction coefficient [Nm/rad].

The PSCAD software library provides a custom model for the coiled rotary induction generator. In this paper, a custom model for a rotary induction generator is applied with a detailed description of the fixed and rotational axis currents (or flow) with the rotor speed. For the PWM voltage source converter used in the wind turbine model, an ideal model based on the principle of energy conservation is used [9].

III. CONTROL AND PROTECTION MODELS

For a variable speed wind turbine with a doubly fed induction machine, it is possible to control the load torque at the generator directly, so that the speed of the turbine rotor can be varied within certain limits.

An advantage of variable speed wind turbine is that the rotor speed can be adjusted in proportion to the wind speed in low to moderate wind speeds so that the optimal tip speed ratio is maintained. At this tip speed ratio the aerodynamic efficiency CP is a maximum, which means that the energy conversion is maximized.

In general, variable speed wind turbines may have two different control goals, depending on the wind speed. In low to moderate wind speeds, the control goal is maintaining a constant optimum tip speed ratio for maximum aerodynamic efficiency. In high wind speeds, the control goal is the protection wind turbines from over speed damage and maintenance of the rated output power [8].

Two control models are implemented in the wind turbine model: speed control and pitch control. The speed control can be realized by adjusting the generator power or torque. The pitch control is a common control method to regulate the aerodynamic power from the turbine.

A. Speed Control

Vector-control techniques have been developed well for doubly fed induction generators using back-to-back PWM converters. Two vector-control models are designed respectively for the rotor-side and grid-side PWM converters. The vector-control model for the rotor-side PWM converter is illustrated in (Figure 2).

The induction generator is controlled in a synchronously rotating dq-axis frame, with the d-axis oriented along the stator-flux vector position, which ensures decoupling control of stator-side active and reactive power flow into the grid. It provides the generator with wide speed-range operation, which enables the optimal speed tracking for maximum energy capture from the wind [11].

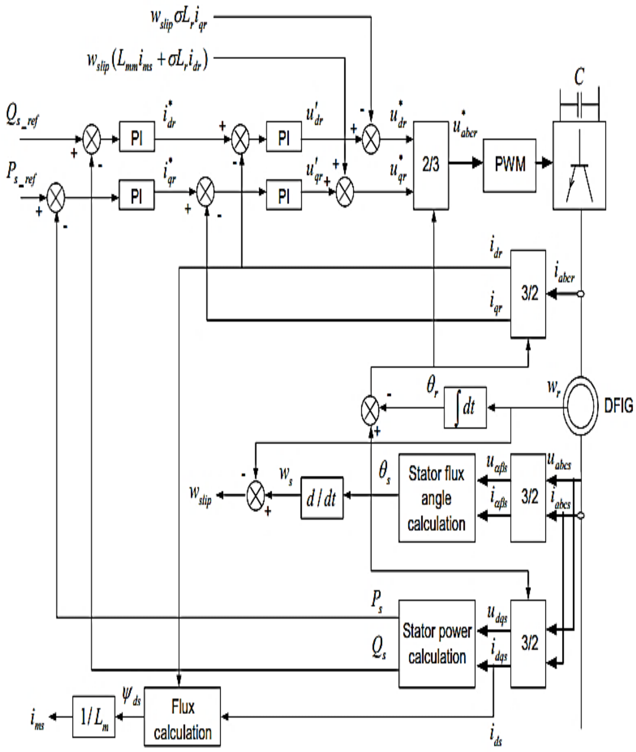


Fig. 2. Vector-control model for rotor-side PWM voltage source converter.

The induction generator is controlled in a synchronously rotating dq-axis frame, with the d-axis oriented along the stator-flux vector position, which ensures decoupling control of stator-side active and reactive power flow into the grid. It provides the generator with wide speed-range operation, which enables the optimal speed tracking for maximum energy capture from the wind [14].

The stator-side active and reactive power P_s , Q_s flow into the grid can be expressed as in equations (3) and (4), where u_s is the magnitude of the stator phase voltage [V], i_{dr} , i_{qr} are the rotor currents in d- and q-axis respectively [A], L_s , L_m are the stator and mutual inductances [H], w_s is the electrical angular velocity of the stator flux [rad/s].

$$P_s = \frac{3}{2} \frac{L_m}{L_s} u_s\, i_{qr} \qquad (3)$$

$$\boldsymbol{Q_s = \frac{3}{2} u_s \left(\frac{L_m}{L_s}\, i_{dr} - \frac{u_s}{w_s\, L_s}\right)} \qquad (4)$$

Assuming the stator voltage is constant, the stator-side active power and reactive power can be controlled via $\boldsymbol{i_{qr}}$ and $\boldsymbol{i_{dr}}$, which are regulated using the q- and d-axis rotor voltage $\boldsymbol{u_{qr}}$, $\boldsymbol{u_{dr}}$ respectively as shown in (Figure 2).

Additionally, the electromagnetic torque is proportional to the q-axis rotor current:

$$\boldsymbol{T_G = \frac{3}{2} p \frac{L_m}{L_s} \frac{u_s}{w_s} i_{qr}} \qquad (5)$$

Where $\boldsymbol{p}$ is the number of pole pairs.

(Figure 3) shows the vector-control model for the grid-side PWM converter. The objective of the vector-control model for the grid-side PWM converter is to keep the DC-link voltage constant while controlling reactive power flow into the grid.

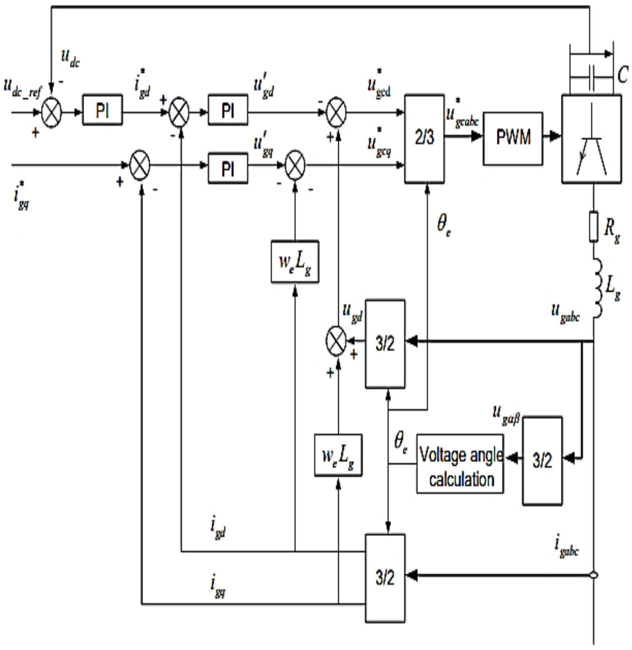


Fig. 3. Vector-control model for grid-side PWM voltage source converter.

The reference frame used here is oriented along the stator (or the grid) voltage vector position, enabling decoupling control of the DC-link voltage and the reactive power flow between the grid and the grid-side converter. The DC-link voltage u_{dc} can be expressed as following:

$$\boldsymbol{C \frac{d\, u_{dc}}{dt} = \frac{3}{4}\, m\, i_{gd} - i_{dcr}} \qquad (6)$$

Where i_{gd} is the d-axis current flowing between the grid and the grid-side converter [A], i_{dcr} is the rotor-side DC current [A], C is the DC-link capacitance [F], m is the PWM modulation depth of the grid-side converter [12].

The reactive power flow into the grid Q_g is as follows

$$\boldsymbol{Q_s = \frac{3}{2}\, u_g\, i_{gd}} \qquad (7)$$

Where $\boldsymbol{u_g}$ is the magnitude of the grid phase voltage [V], $\boldsymbol{i_{gd}}$ is the q-axis current flowing between the grid and the grid side converter [A].

It is seen from equations (6) and (7) that the DC-link voltage and the reactive power flow into the grid can be controlled via $\boldsymbol{i_{gd}}$ and $\boldsymbol{i_{gq}}$, which are regulated using the d- and q-axis grid-side converter voltage $\boldsymbol{u_{gcd}}$, $\boldsymbol{u_{gcq}}$ respectively. Normally the $\boldsymbol{i_{gd}}$ reference value is set to zero to ensure zero reactive power flow between the grid and the grid-side converter [13].

B. Pitch Control

The aerodynamic model of the wind turbine has shown that the aerodynamic efficiency is strongly influenced by variation of the blade pitch with respect to the direction of the wind or to the plane of rotation. Small changes in pitch angle can have a dramatic effect on the power output.

In low to moderate wind speeds, the turbine should simply try to produce as much power as possible, so there is generally no need to vary the pitch angle. The pitch angle should only be at its optimum value to produce maximum power. In high wind speeds, pitch control provides a very effective means of regulating the aerodynamic power and loads produced by the rotor so that design limits are not exceeded. The relationship between pitch angle and wind speed is shown in (Figure 4).

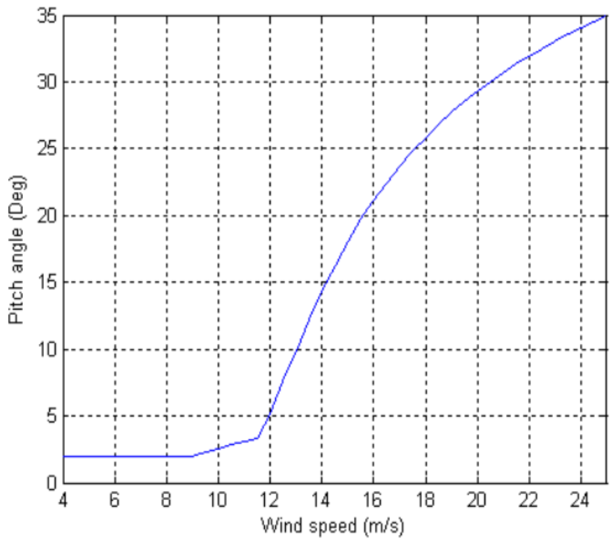


Fig. 4. The relationship between pitch angle and wind speed.

C. Protection model

Suitable protection should be provided in wind power generation systems to minimize the effects of possible abnormal operating conditions. The rotor current limit and DC-link voltage limit are included in the DFIG model, which are set depending on the wind turbine capacity and converter rating. In this model 1.5 times nominal value is implemented for both rotor current limit and DC-link voltage limit. The excess of either limit will activate the protection, which short circuits the generator rotor and deactivates the rotor-side converter, while the induction generator and the grid-side converter are kept in connection with the grid [9].

IV. CASE STUDY AND SIMULATION RESULTS

The simulation study has been conducted on the system shown in (Figure 1), which represents a typical situation, where a load at bus 2 is supplied by a wind farm with DFIG represented by a single machine and by the external power system represented by a constant voltage source connected in series with its Thevenin's equivalent impedance. The external power system connected to bus 2 through two parallel lines, and bus 2 is the point of common coupling.

The wind turbine drives a 2 MW doubly fed induction generator connected with a back-to-back PWM voltage source converter in the rotor circuit. Table I provides the parameters of the generator in detail. During rated state operation the wind turbine generates 2 MW real power, which provides ½ of the load at Bus 2, while the output reactive power of the wind turbine is normally controlled as zero to keep the unity power factor.

TABLE I. Generator parameters.

Parameter	Value
Rated power (P_{rated})	2 MW
Rated voltage (U_{rated})	0.69 kV
Base angular frequency (w_{rated})	314.16 rad/s
Stator/ rotor turns ratio (n)	0.4333
Angular moment of inertia (J_{WG})	1.9914 p. u.
Mechanical damping (D)	0.02 p. u.
Stator resistance (r_S)	0.0175 p. u.
Rotor resistance (r_r)	0.019 p. u.
Stator leakage inductance (L_{lS})	0.2571 p. u.
Rotor leakage inductance (L_{lr})	0.295 p. u.
Mutual inductance (L_m)	6.921 p. u.

The transient stability of wind power generation system after an external short-circuit depends on many factors, such as fault condition and network parameters. When the post-fault situation is not serious enough to trigger the rotor protection devices, the control models of the DFIG operates as normal and try to restore the wind turbine's normal operation after the fault is cleared.

The transient process will be analyzed in detail and demonstrated by the simulation results as follows. If the post-fault situation is serious enough, the protection devices in the rotor circuit will be triggered which yields a result that the generator rotor is short-circuited and the rotor side converter is deactivated. In this situation, how to re-establish the voltage at the wind turbine terminal and restore the wind turbine's normal operation is another study.

The wind turbine is considered in this case, the park scale wind model is not included and only the rotor wind speed is applied. The fault event is a single-phase to ground short-circuit fault at the midpoint of one of the two parallel lines, as shown in (Figure 1), which begins at 2 sec and after 150 msec the line is tripped. The simulation results for the transient process in an external short-circuit fault situation are shown in (Figurer 5).

During the post-fault transient process, the DC-link voltage remains below 1.5 times nominal value, which will not trigger the protection devices in the rotor circuit. It is seen from the simulation results that the control models operate as normal and are capable of forcing the rotor speed down and reestablishing the voltage at the wind turbine terminal after the clearance of the short-circuit fault.

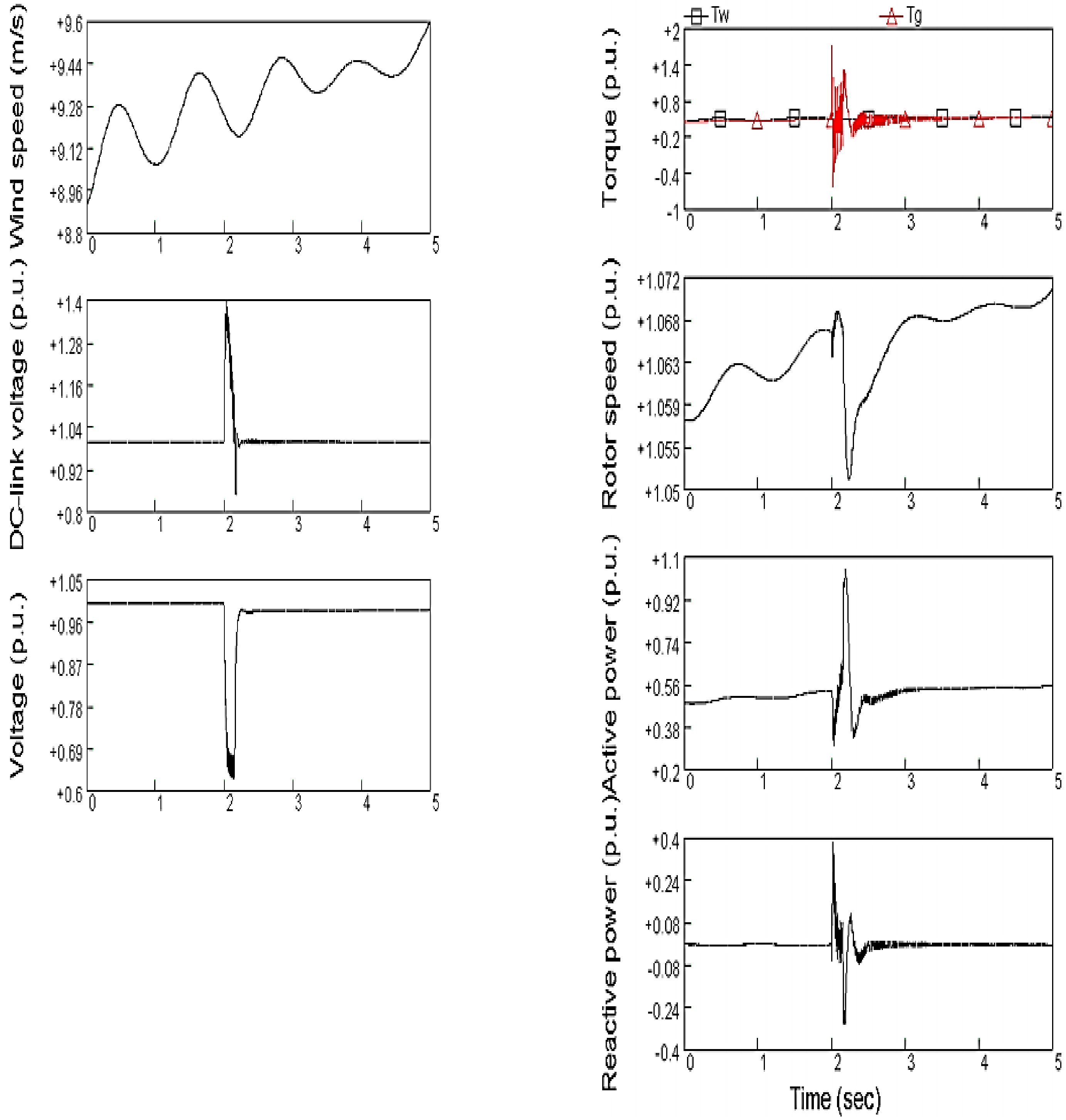


Fig. 5. Wind speed, DC-link voltage, voltage, torques (aerodynamic torque and electromagnetic torque), generator rotor speed, active power and reactive power in the simulated case.

Immediately after the fault occurs, the stator voltage and flux drop, which results in the significant reduction in the electromagnetic torque and power. Assuming the mechanical torque is kept constant, any reduction in the electromagnetic torque causes the rotor to accelerate.

After the fault is cleared at 2.15 sec, as a result of control, the electromagnetic torque and power increase, which forces the generator rotor speed down. After a short time of oscillation, the voltage at the wind turbine terminal is rebuilt and the wind turbine retrieves its normal operation. During the transient process the control models try to control the wind turbine output reactive power as zero.

The transient process is divided into two stages as follows, and in each stage the performances of the control models are analyzed in detail. The corresponding simulation results are shown in (Figure 6) where the timing axis is zoomed.

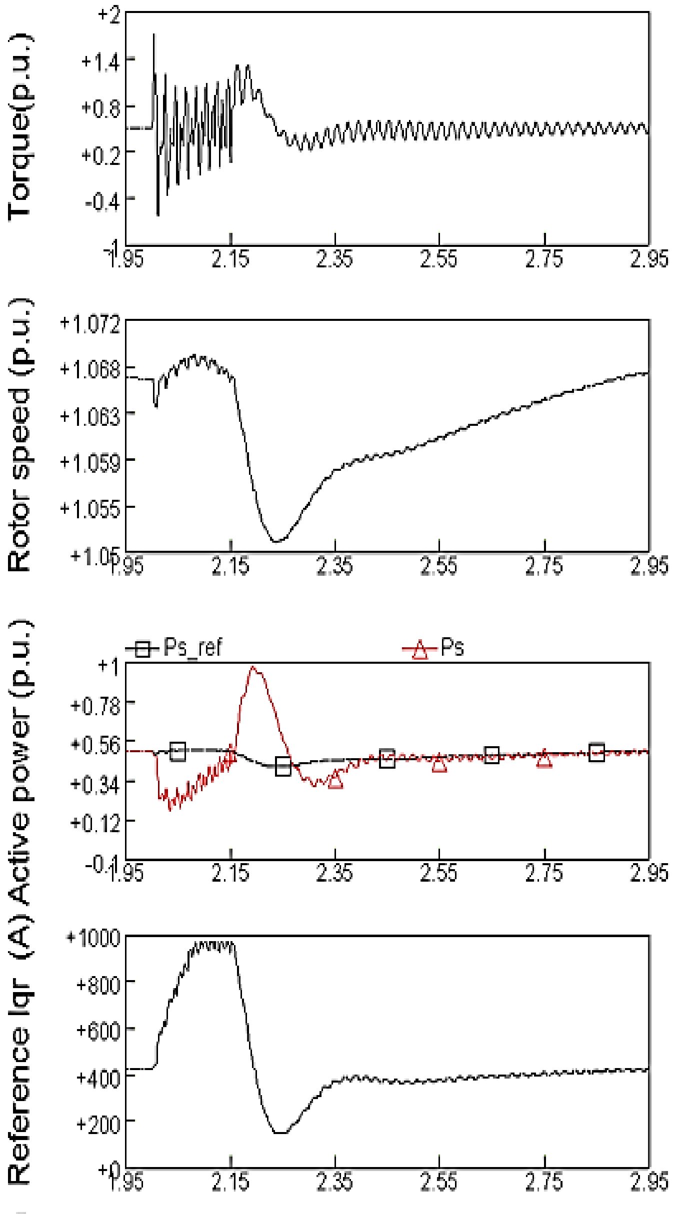
A. During the Fault

Immediately after the fault occurs at 2 sec, the voltage at the wind turbine drops. It is seen from equation (5) that the electromagnetic torque is proportional to the stator voltage. Thus the electromagnetic torque decreases as shown in (Figure 6). Since the aerodynamic torque is kept constant at this moment, any reduction in the electromagnetic torque causes the generator rotor to increase.

It is known from equations (3) and (4) that, as the stator voltage dips, the stator-side active power $\boldsymbol{P_s}$ decreases while the stator-side reactive power $\boldsymbol{Q_s}$ increases, which are identified in (Figure 6).

The drop of $\boldsymbol{P_s}$ causes the active power difference $\boldsymbol{\Delta P} = \boldsymbol{P_{s\_ref}} - \boldsymbol{P_s}$ to increase, which is amplified by the PI controller as shown in (Figure 2). Therefore the reference value of the q-axis rotor current $\boldsymbol{i^*_{qr}}$ increases as well. Similarly, the rise of $\boldsymbol{Q_s}$ makes the reactive power difference $\boldsymbol{\Delta Q} = \boldsymbol{Q_{s\_ref}} - \boldsymbol{Q_s}$ to decrease, which is amplified by the PI controller either. This leads to the reduction of the reference value of the q-axis rotor current $\boldsymbol{i^*_{dr}}$. The variations of $\boldsymbol{i^*_{qr}}$ and $\boldsymbol{i^*_{dr}}$ are reflected in the changes of the injected q- and d-axis rotor voltage $\boldsymbol{u_{qr}}$, $\boldsymbol{u_{dr}}$, which manage to control $\boldsymbol{P_s}$ and $\boldsymbol{Q_s}$ to approach their reference values, as shown in (Figure 6).

As the fault occurs the DC-link voltage increases. However, the control model for the grid-side converter then tries to control the DC-link voltage back to its reference value as shown in (Figure 6).



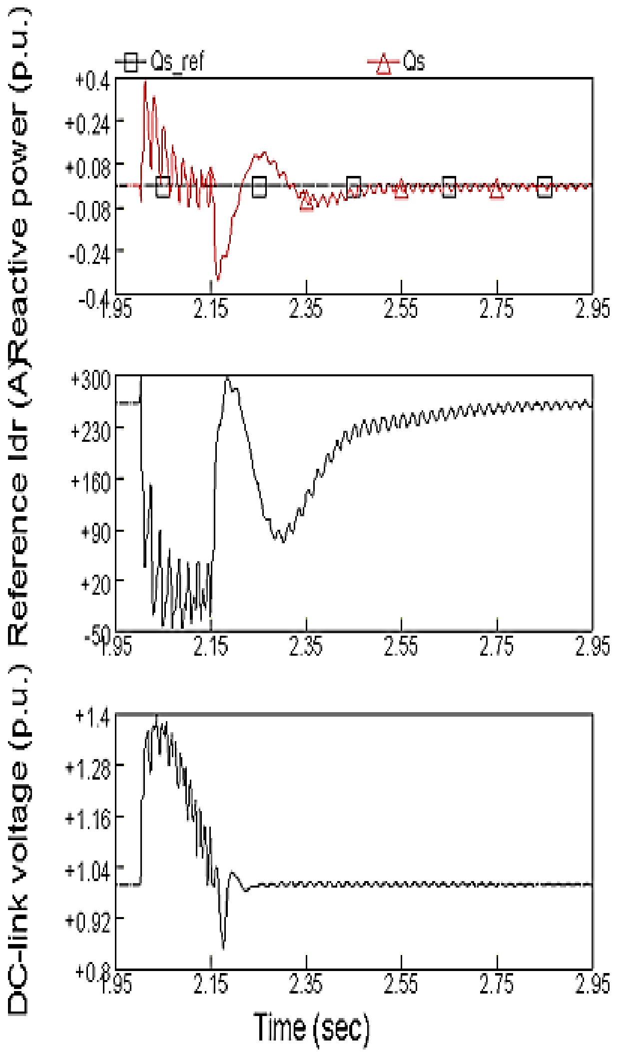


Fig. 6. Electromagnetic torque, generator rotor speed, stator-side active power (reference value and real value), reference value of the q-axis rotor current, stator-side reactive power (reference value and real value), reference value of the d-axis rotor current, DC-link voltage in the simulated case.

B. AFTER THE CLEARANCE OF THE FAULT

Once the short-circuit fault is cleared at 2.15 sec, the voltage at the wind turbine terminal starts to rise. The electromagnetic torque which is proportional to the voltage increases instantly which results in the generator rotor speed dips.

As a result of the voltage increase, the stator-side active power $\boldsymbol{P_s}$ increases while the stator side reactive power $\boldsymbol{Q_s}$ decreases. Similar as the analysis mentioned above, it is learned that as the voltage rises $\boldsymbol{i^*_{qr}}$ decreases while $\boldsymbol{i^*_{dr}}$ increases. The variations of $\boldsymbol{i^*_{qr}}$ and $\boldsymbol{i^*_{dr}}$ are reflected in the changes of the injected q- and d-axis rotor voltage $\boldsymbol{u_{qr}}$, $\boldsymbol{u_{dr}}$ which manage to control $\boldsymbol{P_s}$ and $\boldsymbol{Q_s}$ to approach their reference values. It is seen from (Figure 6) that the wind turbine restores its normal operation after a short-time oscillation.

V. CONCLUSION

A simulation model of a MW-level wind turbine with DFIG developed in PSCAD is presented. The control and protection models of the wind turbine are described in detail. Based on the wind turbine model, the transient stability of the wind turbine after a short-circuit fault has been investigated.

When the post-fault situation is not serious enough to trigger the protection devices in the rotor circuit, the control models of the DFIG operates as normal and are capable of forcing the rotor speed down and re-establishing the voltage at the wind turbine terminal after the short-circuit fault is cleared. The simulation results demonstrate how the control models effectively manage to restore the wind turbine’s normal operation after the clearance of an external short-circuit fault.

A new control strategy is proposed to contribute to re-establish the voltage at the wind turbine terminal without any wind turbine disconnection after a short-circuit fault. This control strategy takes advantage of the benefits of pitch controlled variable speed wind turbine. To carry out the control strategy, the emergency pitch regulation model which is mentioned above will be applied.

After an occurrence of a short-circuit fault in the external networks, the following control steps are performed:

1. The excess of either the rotor current limit or the DC-link voltage limit will activate the protection to short-circuit the generator rotor and deactivate the rotor-side converter, while the induction generator and the grid-side converter are kept in connection with the grid.

2. Regulating the pitch angle reduces the aerodynamic power, which helps to force the generator rotor speed down and re-establish the voltage at the wind turbine terminal.

3. After the clearance of the short-circuit fault and the voltage recovery of the wind turbine, the rotor-side converter is put back into work and the DFIG restores it normal operation.

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