Voltage Recovery Control Of Grid-Connected Wind Turbines At An External Short-Circuit Fault

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***Abstract*—The documented investigation in this paper examines main power quality issues of grid-connected wind turbines and the interaction between wind turbines and the grid. The main goal is to investigate the most popular type of grid-connected wind turbines with doubly fed induction generators (DFIG) during continuous operation, as well as the voltage recovery of grid-connected wind turbines after the clearance of a short circuit fault in the grid.**

Most models introduced above have some complexity and details. They spotted only on the normal operation of single wind turbines, without consideration of grid interaction faults. In these models either slip control alone or pitch control alone have been used leading to some voltage recovery or stability problems.

This paper firstly introduces the configuration of main portions of grid-connected wind turbines which plays a very important role in the operation of wind power plants. Secondly, it proposes a new compact modeling of grid-connected wind turbines, which is free of any complex or details. This new model includes a combined control technique in which the dynamic slip control and pitch control are used together in such a way that the dip voltage after the clearance of faults is successfully rebuild and the grid-connected wind turbines maintain their stability efficiently.

A simulation model of MW-level wind turbine is developed in the simulation tool program called power system computer aiding design (PSCAD). The simulation results show how the combination of dynamic slip control and pitch control could help the voltage to be rebuild and the power system stability be maintained efficiently.

Keywords— wind turbines; wound rotor; doubly feed induction generator; dynamic slip; pitch.

I. INTRODUCTION

In recent years wind power generation has received considerable attention worldwide. Institutional support on renewable energy sources together with the wind energy potential have led to a fast development of wind power generation.

At the end of 2002, the total installed capacity of wind power generation in the whole world is summed to 31,128 MW, in which Germany had the biggest installed capacity, 12,001 MW, followed by Spain, USA and Denmark [1]. The installed capacity of wind power generation grew very fast in the past years so that a dramatic increase in the level of wind power generation penetrating existing utilities network could be expected in the future [3].

The continuous increase of the number of integrated wind turbines is likely to influence the operation of the existing networks and the design and planning of the future distribution networks. One of the major concerns related to the high penetration of integrated wind turbines into the existing utilities networks is the impact on power system stability. The system operators being responsible for maintaining power system stability and reliable power supply, have formulated specifications for wind turbine integration to the network.

According to the specifications, at a short circuit fault in the external network, the voltage shall be reestablished after clearing the fault without wind turbine disconnection caused by inrush current and dipped voltage. The reason is when the wind power penetration level is high, the protective disconnection of a large amount of wind power will be an unacceptable consequence that may threaten the power system stability.

During the short-circuit fault, the short circuit current arises, the voltage at the wind turbine terminal drops. Due to the voltage dip, the output electrical power and the electromagnetic torque are significantly reduced. Assuming the mechanical torque is kept constant, any reduction in the electromagnetic torque causes the rotor to accelerate. This in turn leads to an increase in the kinetic energy of the rotating mass.

After the clearance of the fault, reactive power is supplied by the power system to recover the air-gap flux. This causes high inrush current to be drawn by the wind turbine from the power system, which in turn causes a voltage drop at the wind turbine terminal. The resulting electromagnetic torque acts on the rotor in a direction opposite to that of mechanical torque applied by wind turbine. If the energy stored in the newly established rotating magnetic field becomes higher than that stored in the rotating mass, rotor speed is forced to slow down and the wind turbine retains its normal operating condition eventually. On the contrary, the rotor speed could continue to increase until appropriate protection devices trip it. When this happens, the voltage at the wind turbine terminal drops [2].

The voltage recovery after the clearance of a fault can be assisted with dynamic reactive compensation, adjustment of relay settings of wind turbines, and control ability of wind turbines [3]. Adjusting the protective relay settings may be necessary for the wind turbines to stay grid-connected during a longer time at post-fault operational situations. This makes it possible to rebuild the voltage with other means. However, the arrangement of adjusting the relay settings alone is not enough to solve the whole problem of re-establishing the voltage.

By this paper which concentrate on the voltage recovery assisted with controls of wind turbines. A model of a MW-level wind turbine with dynamic slip control and pitch control in the simulation tool of PSCAD is presented. Based on the wind turbine model, the stability of wind turbine after a short circuit fault has been investigated. After the clearance of the fault, the energy in the newly established rotating magnetic field may be strengthened by adjusting the generator slip, and the kinetic energy in the rotating mass may be reduced by regulating the pitch angle, which help to slow the rotor speed down and re-establish the voltage at the wind turbine terminal.

The simulation results show how the combination of dynamic slip control and pitch control could help to rebuild the voltage and maintain power system stability efficiently.

II. MODLLING OF WIND TURBINE

The overall molding of wind turbine can be divided into the following main portions:

A. Wind Model

Wind simulation plays an important role in wind turbine modeling, particularly for power quality analysis of wind farm and its interaction with the grid to which it is connected. The wind models describe the fluctuations in the wind speed, which cause the fluctuations in the power production of the wind turbines [4].

A wind model has been developed to support studies of the dynamic interaction between large wind farms and the grid to which they are connected, and to support improvement of the electric design of wind turbines as well as grid connection. The wind model is based on a power spectral description of the turbulence, which includes the coherence (in park scale) between wind speeds at different wind turbines in a wind farm, together with the effect of rotational sampling of the wind turbine blades in the rotors of the individual wind turbines [6].

Both the spatial variations of the turbulence and the shadows behind the wind turbine towers are included in the model for rotational sampling. The model is verified using measured wind speeds and power fluctuations from wind turbines.

The park scale coherence is included, because it ensures realistic fluctuations in the sum of the power from all wind turbines, which is important for estimating the maximum power and power standard deviation of the wind farm [5].

The effect of the rotational sampling is included because it is a very important source to the fast power fluctuations during continuous operation of the wind turbine. The fast fluctuations are particularly important to assess the influence of the wind turbines on the voltage recovery levels in the power system [7].

The structure of the wind model is shown in (Figure 1). It is built in two steps.

The first step of the wind model is the park scale wind model, which simulates the wind speeds V_{hub} in hub height at each wind turbine, taking into account 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 they are rotating. The rotor wind model provides an equivalent wind speed V_{eq} that is conveniently used as input to a simplified aerodynamic model of the wind turbine [9].

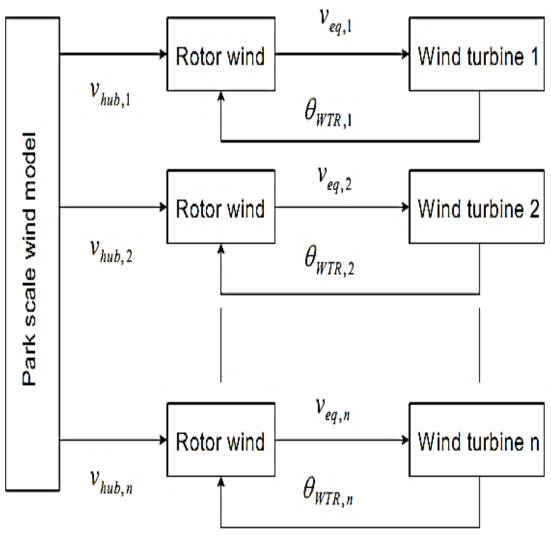

Fig.1. Structure of the wind model.

B. AERODYNAMIC MODEL

Wind turbine power production depends on the interaction between the wind and the turbine rotor. The blades of a wind turbine rotor extract some of the energy flow from air in motion, convert it into rotational energy, and then deliver it via a mechanical drive unit to the generator. The wind turbine rotor that extracts the energy from the wind, and converts it into mechanical power is a complex aerodynamic system. For state of the art modeling of the rotor, blade element theory must be used. Modeling the rotor using blade element theory has a number of drawbacks:

A. Instead of only one wind speed signal, an array of wind speed signals has to be applied.
B. Detailed information about the rotor geometry should be available.
C. Computations become complicated and lengthy.

To solve these problems, a simplified way of modeling the aerodynamic behavior of the wind turbine rotor is normally used when the electrical behavior of the wind turbine is the main interest of the study [8]. The relation between the wind speed and aerodynamic power may be described by the following equation:

$$P_W = \frac{1}{2} \rho \pi R^2 v_{eq}^3 C_P(\theta, \lambda) \qquad (1)$$

The corresponding aerodynamic torque can be expressed as:

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

Where; P_W is the aerodynamic power extracted from the wind [W], T_W is the aerodynamic torque extracted from the wind [Nm], ρ is the air density [kg/m3], 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], and C_P is the power coefficient.

Numerical approximations have been developed to calculate C_P for given values of θ and λ. Here, the following approximation is used:

$$C_P(\theta, \lambda) = 0.22\left(\frac{116}{\lambda_i} - 0.4\,\theta - 5.0\right) e^{\frac{-12.5}{\lambda_i}} \qquad (3)$$

With

$$\lambda_i = \frac{1}{\frac{1}{\lambda+0.08\theta} - \frac{0.035}{\theta^3+1}} \qquad (4)$$

C. MECHANICAL MODEL

In the mechanical model, emphasis is put only on the parts of the dynamic structure of the wind turbine that contribute to the interaction with the grid, i.e. which influences significantly on the output power of the wind turbine. Therefore, only the drive train is considered because this part of the wind turbine has the most significant impact on the output power, while the other parts of the wind turbine structure, e.g. tower and flap bending modes, are neglected [6].

Neglecting the dynamics of the mechanical parts, the drive train may be modeled with a single lumped mass. Since there exists a gearbox, the quantities on the high-speed side have been referred to the low speed side. The lumped model of the mechanical drive train thus can be expressed as:

$$J_{WG} \frac{dw_{WTR}}{dt} = T_W - T'_G - D\, w_{WTR} \qquad (5)$$

Where; J_{WG} is the wind turbine mechanical inertia plus generator mechanical inertia [kg·m2], 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], and D is friction coefficient [Nm/rad].

The voltage recovery level is usually quantified by the short-term voltage recovery severity, which is normally measured over a ten-minute period. Since the measurement lasts so long a time, the dynamics of the mechanical parts may be neglected. Therefore, the lumped mechanical model can be used for voltage recovery study of grid-connected wind turbines.

The modeling of the wind turbine mechanical drive train has impact on the transient analysis of the wind turbine in an external short-circuit fault situation. The effect of the way the mechanical drive train of the wind power generation system is modeled in terms whether using the lumped model or a shaft model has been investigated [10].

The wind power generation system using the shaft model is liable to lose stability after an external short-circuit fault, in comparison with the one using the lumped model. Due to the shaft model, the transient response of the wind power generation system is subjected to relatively high oscillations while that of the wind power generation system using the lumped model almost contains no oscillation.

The aim of the voltage recovery study of the grid-connected wind turbines is not focused on in which post-fault situation the wind turbines will lose stability, but on proposing effective measures or control strategies for wind turbine voltage recovery in unstable situations. Thus, the voltage recovery study may be carried out on a wind turbine using the lumped mechanical model, and the proposed measures or control strategies may be extended to wind turbines using more detailed mechanical drive train models [14].

D. Electrical Components Model

PSCAD provides dedicated models for the electrical components of the wind turbine, namely generator, capacitor banks for reactive power compensation and transformer, etc. The generator in this study is a wound rotor induction machine. Besides the electromagnetic description, the generator model in PSCAD also contains the mechanical inertia of the generator rotor. Wound rotor induction generators usually permit intervention via the slip rings [12].

Wind turbines are subject to random periodic output fluctuations due to wind speed fluctuations, tower-shadowing effects, natural resonance of components, etc. Regulating the slip value can significantly relieve the drive train stress and reduce output power fluctuations. In this wound rotor induction generator model, an external resistor is connected to the rotor and may be adjusted to change the generator slip.

E. Control System model

The wind turbine may be controlled through two ways: dynamic slip control and pitch control. It is possible for the wind turbine to adjust the electromagnetic torque and the aerodynamic torque by dynamic slip control and pitch control. As mentioned above, controlling the slip value of the generator can smooth the output power fluctuation of the wind turbine. For a continuous adjustment of slip, a rapid change of rotor circuit resistance between short-circuited rotor winding and full resistance of the external resistor in the rotor circuit can be implemented by a switching device as shown in (Figure 2) to produce output-smoothed or efficient operating areas [13]. Thus, in the partial-load area, low slip values can be set and altered slightly to achieve a high level of efficiency.

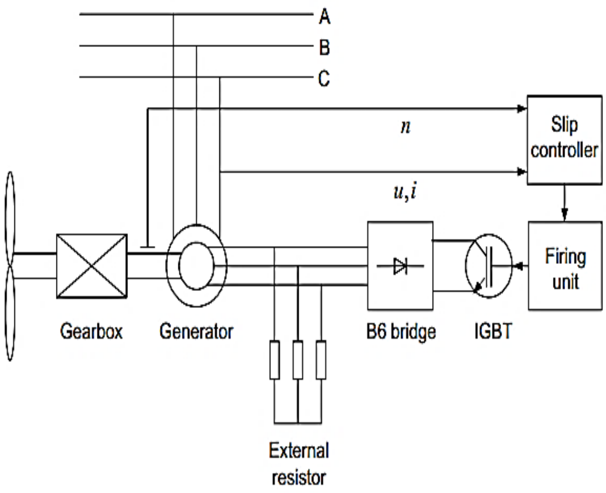

Fig. 2. Dynamic slip control of wind turbine by three-phase external resistor with direct current pulsing.

The average resistance in series with the rotor circuit is expressed as:

$$r_a = D_s\, r \qquad (6)$$

Where; r_a is the average resistance in series with the rotor circuit [Ω], r is the full resistance of the external resistor [Ω], $D_s = T_{off}/T_t$ is the switching duty ratio of the semiconductor switch, where T_{off} is the switch off time [s] and T_t is the switching period [s].

In practice, below rated torque the generator acts just like a conventional induction machine. Once the rated torque is reached, the resistors in series with the rotor circuit are adjusted by switching the semiconductor switch on and off at several kHz, and the average resistance is changed by varying the switching duty ratio. As the average resistance increases, the generator torque-slip curve changes so that the torque is kept at the rated value.

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 the plane of rotation [11]. Regulating the rotor blades provides an effective means to regulate or limit the turbine power in high wind speed, or other abnormal conditions. When the wind speed is above the rated value, the output power of the wind turbine can be kept to the rated power by the pitch control. To put the blades into the necessary position, various control systems are employed. A simple pitch mechanism driven by an AC servomotor which subjects to external pitching moments (disturbances to the system). The basic control mechanism is shown in (Figure 3).

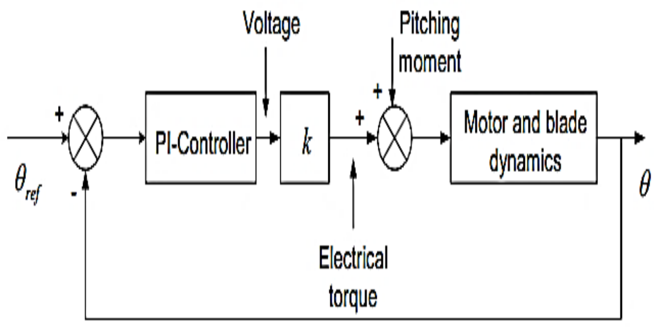

Fig. 3. Closed-loop pitch control mechanism.

III. CASE STUDY AND SIMULATION RESULTS

The simulation study has been conducted on the system shown in (Figure 4), where a load at bus 2 is supplied by a wind farm with wound rotor induction generators represented by a single machine at bus 3, 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 connects to the bus 2 through two parallel lines, and the bus 2 is the point of common coupling.

(Table 1) provides the parameters of the generator in detail. During rated state operation the wind turbine generates 2 MW real power, which provides 1/3 of the load at Bus 2 in the system. At the same time, the wound rotor induction generator absorbs 1.34 MVAR reactive power from the grid. The capacitors at the wind turbine terminal supply most of the reactive power required by the generator and only a small portion is supplied by the external power system.

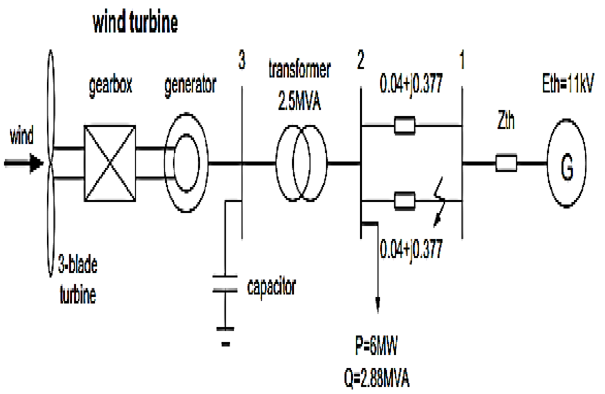

Fig. 4. Block diagram of a wind turbine connected to a grid

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 park scale wind model is not included and only the rotor wind speed is applied. The wind speed and the output power of the wind turbine in normal operation are shown in (Figure 5).

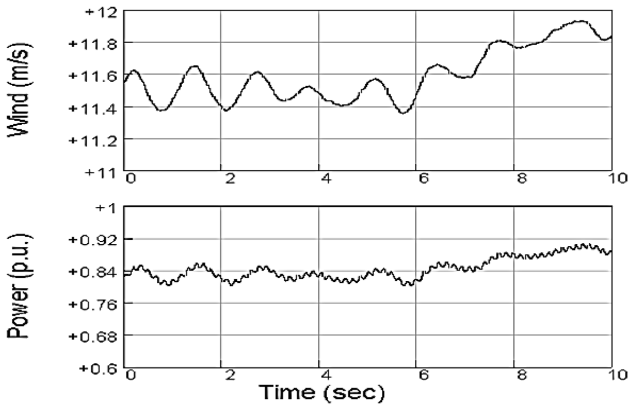

Fig. 5. Wind and output power of the wind turbine in the case of normal operation.

The fault event is a three-phase to ground short-circuit fault on one of the two parallel lines. It begins at 2 s and after 150 ms the line is tripped. As explained earlier, the voltage at the wind turbine drops during the fault period, which leads to the reduction in the electromagnetic torque. This reduction causes the rotor to accelerate, which in turn leads to an increase in the kinetic energy of the rotating mass. After the clearance of the fault, the electromagnetic torque recovers.

If the energy stored in the newly established rotating magnetic field is lower than that stored in the rotating mass, the rotor speed will continue to increase and the induction generator could draw high inrush current from the external power system until appropriate protection devices trip it. In this condition, voltage at the wind turbine terminal (Bus 3) dips and the output power of wind turbine drops, as shown in (Figure 6) then the system loses stability and the wind turbine has to be disconnected [14].

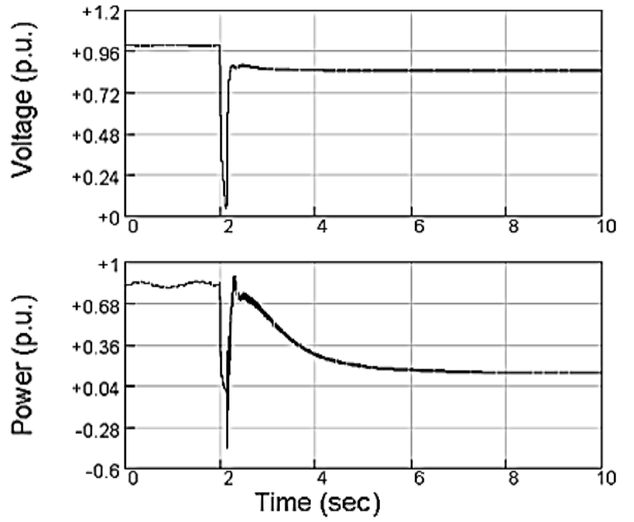

Fig. 6. Voltage and output power of the wind turbine in the case of unstable situation.

A. PITCH CONTROL

From the aerodynamic model of the wind turbine, it can be seen that it is possible to control the aerodynamic torque of the wind turbine by regulating the blade pitch angle. After the clearance of the fault, the aerodynamic torque may be reduced by increasing the pitch angle to reduce the energy stored in the rotating mass. When the kinetic energy decreases, it is easier to slow the rotor speed down and re-establish the voltage at the wind turbine terminal [7].

It is assumed that a control signal to order the reduction of aerodynamic torque is given when the RMS voltage at the wind turbine terminal has been below 0.90 p.u. for at least 250 ms, which includes the delays introduced by signal transmission and pitch angle calculation. The pitch rate is limited by ± 5° / sec.

(Figure 7) shows the case of re-establishing the voltage by regulating the blade pitch angle after the clearance of a short circuit fault, where T_w is the aerodynamic torque (Nm) and T_g is the electromagnetic torque (Nm). During the short-circuit fault, i.e. 2 – 2.15 s, the short circuit current arises, the voltage at the wind turbine terminal drops. Due to the voltage dip, the output electrical power and the electromagnetic torque are significantly reduced. Since the aerodynamic torque is almost kept invariable, any reduction in the electromagnetic torque causes the rotor to accelerate.

After the clearance of the fault, i.e. 2.15 s, reactive power is supplied by the power system to recover the air-gap flux. This causes high inrush current to be drawn by the wind turbine from the power system, which in turn causes a voltage drop at the wind turbine terminal. Since 2.25 s the pitch angle is regulated to reduce the aerodynamic torque as well as the energy stored in the rotating mass, which helps to slow the rotor speed down and re-establish the voltage at the wind turbine terminal. After the voltage has been recovered, i.e. approximately 5.25 s, the pitch angle is adjusted back to the initial value to produce more power. It can be seen from the figure that pitch control is an effective measure for voltage recovery.

B. DYNAMIC SLIP CONTROL

Another way to stabilize the system is to strengthen the electromagnetic torque as well as the energy stored in the newly established rotating magnetic field after the clearance of the fault. It can be realized by controlling the external resistor added to the rotor to change the generator's torque slip curve. It is quick and convenient to switch the semiconductor switch on and off to change the switching duty ratio, which means the average resistance in series with the rotor changes. As the generator's torque-slip curve has been changed, the electromagnetic torque changes too.

(Figure 8) shows the contribution of dynamic slip control to voltage recovery. The transient analysis is similar with that in case of pitch control. At 2.25 s, the switching duty ratio is regulated to strengthen the electromagnetic torque as well as the energy stored in the newly established rotating magnetic field, which helps to slow the rotor speed down and reestablish the voltage at the wind turbine terminal. Since the switching duty ratio may be changed without any rate limit, the generator rotor speed is quickly slowed down and the voltage is recovered much faster than that in case of pitch control. After the voltage has been recovered, i.e. approximately 4.5 s, the switch duty ratio is adjusted back to the normal value to gain higher efficiency.

There is another advantage of dynamic slip control for voltage recovery. The aim of pitch control is to reduce the aerodynamic torque driven by the wind turbine, which means a reduction of input power to the wind turbine system. However, dynamic slip control may re-establish the voltage without reducing the input power [13].

C. COMBINED CONTROLS

The pitch angle and the generator slip can be regulated at the same time to help to rebuild the voltage after a short circuit fault, as shown in (Figure 9). The transient analysis is similar with that in the above two cases. Since 2.25 s, the pitch angle and switching duty ratio are regulated to reduce the aerodynamic torque, and at the same time, to strengthen the electromagnetic torque.

After the voltage has been recovered, i.e. approximately 3.75 s, the pitch angle and switch duty ratio are adjusted back to the initial values. It can be seen that the voltage recovery with combined control is much quicker than that in the former two cases, the pitch control only and dynamic slip control only. Additionally, the adjusting magnitudes of both the pitch control and dynamic slip control are less than the former two cases, which means the combined control is a better way to recover the voltage.

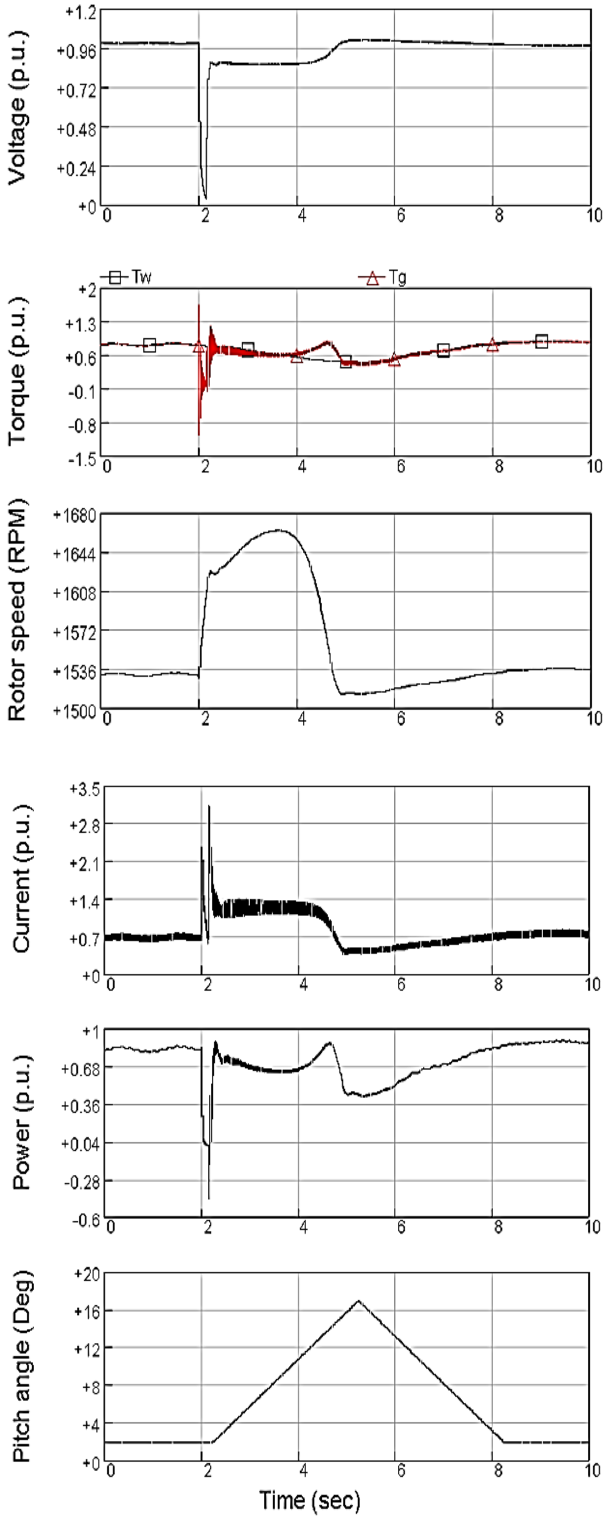

Fig. 7. Voltage, torque, generator rotor speed, current, output power and pitch angle in the case of pitch control.

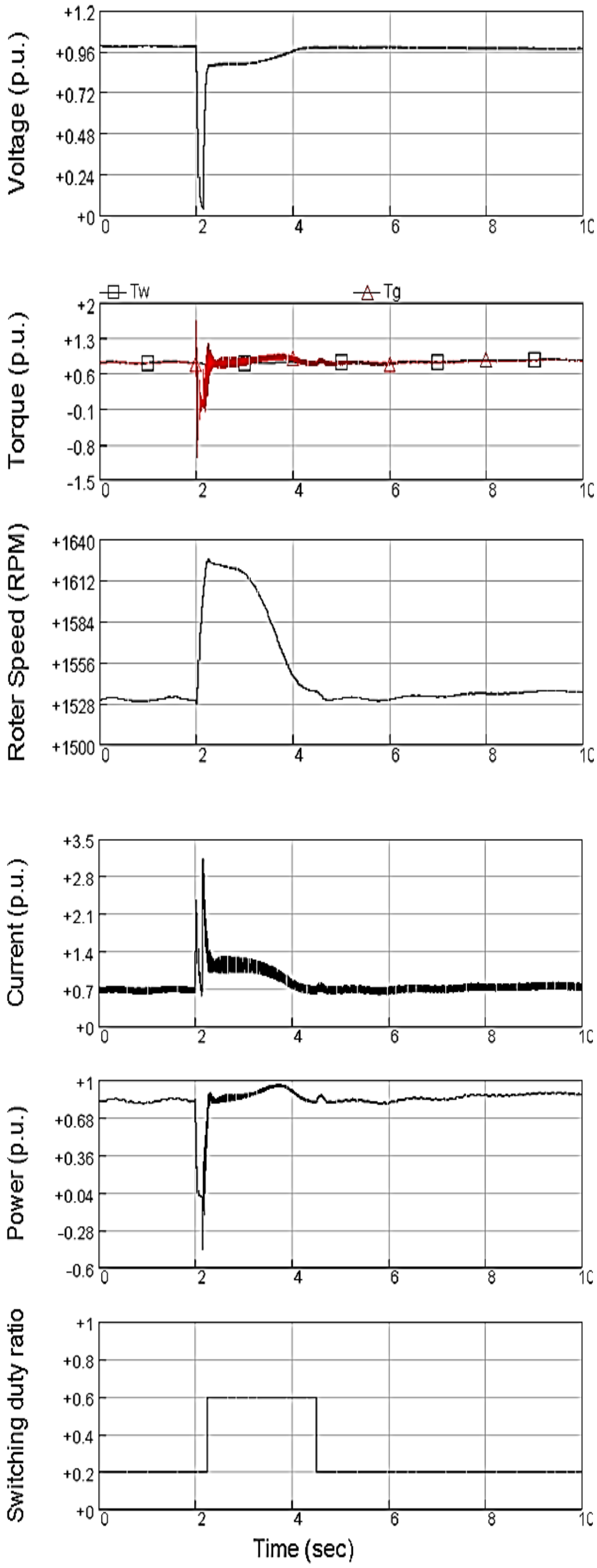

Fig. 8. Voltage, torque, generator rotor speed, current, output power and switching duty ratio in the case of dynamic slip control.

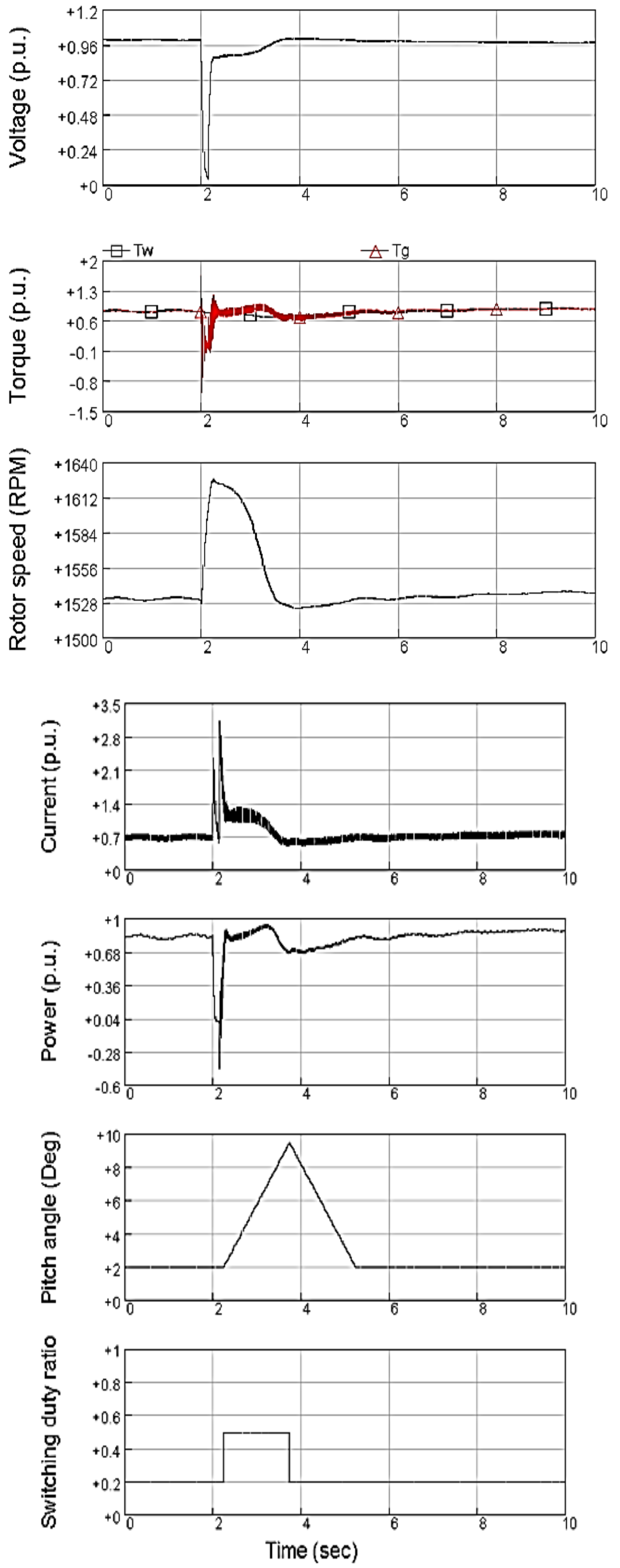

Fig. 9. Voltage, torque, generator rotor speed, current, output power, pitch angle and switching duty ratio in the case of combined control.

IV. CONCLUSION

This paper studied the methods of re-establishing the voltage after the clearance of a short-circuit fault by controlling the electromagnetic torque and aerodynamic torque of the wind turbine. The simulation results show that the application of both dynamic slip control and pitch control together are the most effective tool to perform the voltage recovery as well as for maintaining the stability of the power system.

For a wind turbine equipped with a doubly fed induction generator, where the rotor circuit is connected to the AC system through power electronic converters, it is possible to control the output active power and reactive power simultaneously for improving the system stability. The control and system performance of such a wind energy conversion system during short-circuit faults is almost similar to wound rotor generator.

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