

Dynamic response characteristics analysis of the doubly-fed wind power system under grid voltage drop

Y Chen^{1,3}, J Wang¹, H H Wang², L Yang¹, W Chen¹ and Y T Xu¹

¹School of Electrical Engineering, Wuhan University, Wuhan 430072, China

²Dispatching Control Center, China Southern Power Grid, Guangzhou, P. R. China

Email: chenyiwhu@whu.edu.cn

Abstract. Double-fed induction generator (DFIG) is sensitive to the disturbances of grid, so the security and stability of the grid and the DFIG itself are under threat with the rapid increase of DFIG. Therefore, it is important to study dynamic response of the DFIG when voltage drop failure is happened in power system. In this paper, firstly, mathematical models and the control strategy about mechanical and electrical response processes is respectively introduced. Then through the analysis of response process, it is concluded that the dynamic response characteristics are related to voltage drop level, operating status of DFIG and control strategy adapted to rotor side. Last, the correctness of conclusion is validated by the simulation about mechanical and electrical response processes in different voltage levels drop and different DFIG output levels under DlgSILENT/PowerFactory software platform.

Keywords: Time doubly fed induction generator; mechanical response characteristics; electrical response characteristics; voltage drop; operating status; control strategy

1. Introduction

With the reduction in resources reserves and decline in environmental quality, it is popular to develop clean and renewable energy. Wind energy is the most promising green energy in all renewable energy and in recent years wind power technology is improved [1]. Doubly fed induction generators (DFIG) are preferred for wind turbine application [2-4], accounting for 70% to 80% ratio of total installed capacity of wind power, because they offer variable speed, keep the size of the controllers small so as to reduce the costs and decouple control of active and reactive power [5-6]. However, the security and stability of the grid and the DFIG itself are under threat with the rapid increase of DFIG because of the diffidence between DFIG and conventional synchronous generators [7-10], including the diffidence of electrical dynamic response characteristics in the case of grid failure, weaker disturbance rejection with the small capacity converter and so on [11-12]. Voltage drop is the most common and serious failure in a variety of grid failure [13-14]. So it is necessary for grid stability to study on mechanical and electrical response processes of DFIG under grid voltage drop.

Nowadays, there are lots of researches on response characteristics of wind turbine during the grid failure at home and abroad. According to [15-16], the conclusion is drawn that different control strategies will lead to different response processes by the analysis of a multi-coupling model for wind turbines. From [17], it can be concluded that electrical response process of DFIG is more severe with

³ Address for correspondence: Y Chen, School of Electrical Engineering, Wuhan University, Wuhan 430072, China. Email: chenyiwhu@whu.edu.cn.



deeper voltage falling and greater slip value. In [18], the differences of dynamic response of the DFIG are discussed with different drive system model and different rotor-side controller parameters; According to [19], Electrical parameters of DFIG including its Stator flux, rotor flux, voltage and current are related to not only parameters and Control Strategy of Wind Turbines but also the Grid operation status.

On the base of previous studies, the dynamic response characteristics are related to voltage drop level, operating status of DFIG and control strategy adopted to rotor side. However, while electrical response characteristics are adequately studied, mechanical response characteristics are ignored. In this paper, firstly, mathematical models and the control strategy about both mechanical and electrical response processes is respectively introduced. Then through the analysis of response processes, it is concluded that the dynamic response characteristics are related to voltage drop level, operating status of DFIG and control strategy adopted to rotor side. Last, the correctness of conclusion is validated by the simulation about mechanical and electrical response processes in different voltage levels drop and different DFIG output levels.

2. Analysis of mechanical part

Mechanical part is mainly composed of wind turbine, shaft and pitch angle control. Wind turbine catches wind energy and turns it into rotational kinetic energy. Shaft transmits Mechanical energy from wind turbine to generator. Pitch angle control Tracks power change quickly and maintains stability. The parameters of mechanical part which should be paid attention to are rotor speed, wind turbine speed, pitch angle and mechanical power. Mechanical response processes is relatively slow.

2.1. Wind turbine

For a horizontal axis wind turbine, the amount of mechanical power P_w that a turbine produces in steady state is given by:

$$\begin{cases} P_w = \frac{1}{2} \rho \pi R^2 C_p(\beta, \lambda) V_{eq}^3 \\ C_p(\beta, \lambda) = 0.22 \left(\frac{116}{\lambda_1} - 0.4\beta - 5.0 \right) e^{\frac{-12.5}{\lambda_1}} \\ \lambda_1 = \frac{1}{\frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}} \\ \lambda = R\omega_{tur}/V_{eq} \end{cases} \quad (1)$$

Where, ρ is the air density. R is the turbine radius. V_{eq} is the equivalent wind speed and C_p is the power coefficient, which for pitch controlled wind turbines depends on both the pitch angle β and the tip speed ratio λ . ω_{tur} is the rotor turbine speed.

According to equation (1), mechanical power is related to β , V_{eq} and ω_{tur} . In steady-state operation, when V_{eq} is a constant, the fan will be running at the maximum power point, where the ω_{tur} and P_w are in the most appropriate state. However, in power system fault, the ω_{tur} will be accelerated and P_w will be decreased because of unbalance torque to maintain stability.

2.2. Shaft

In steady-state analysis, the shaft is always a one mass model ignoring torsional vibration because of electro-mechanical decoupling and the effect of inverters. However, in serious power system fault, a detailed model, mostly a two mass model is used to describe the shaft for better analysis of its

transient characteristics , as follows:

$$\begin{cases} 2H_{tur} \frac{d\omega_{tur}}{dt} = T_{tur} - K_s \theta_s - D_{tur} \omega_{tur} \\ 2H_{gen} \frac{d\omega_{gen}}{dt} = K_s \theta_s - T_E - D_{gen} \omega_{gen} \\ \frac{d\theta_s}{dt} = \omega_0 (\omega_{tur} - \omega_{gen}) \end{cases} \quad (2)$$

Where, subscripts of tur and gen respectively denote the parameters of wind turbine and generator. H is inertia time constant. ω is rotor speed. ω_0 is synchronous speed. K_s is stiffness coefficient D is damping factor. θ_s is the angular difference between the two ends of the flexible shaft. T_{tur} and T_E are mechanical torque and electromagnetic torque.

According to the model above, ω_{gen} has an oscillating increase and ω_{tur} increases slowly without oscillation under power system short-circuit fault.

2.3. Pitch control

The aims of pitch control are to track maximum power point and to limit mechanical power in high wind speed preventing the fan running too fast. The principle is that if β is bigger, and then P_w will be lower according to equation (1). Under grid voltage drop, the rotor will increase speed because electromagnetic power of fan is limited causing torque to become unbalanced. To make the fan and power system safe, it is need to increase β to reduce mechanical power of fan on the basis of principle above.

There are two common methods used for pitch control. One is that β is adjusted according to the change of active power of fan, another is that β is adjusted according to the change of rotor speed. However, in both of the two methods the reference is fixed value set in advance which makes the adjustment valid only in the high wind speed. So in this paper, the reference will be changed on the base of the wind speed. Given fast degeneration of active power which is not good for the stability of pitch angle, the second method is chose, as it shown in figure 1.

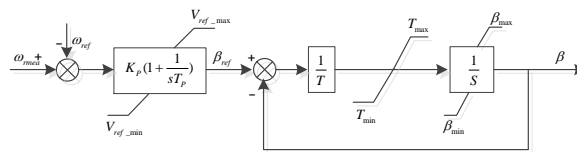


Figure 1. Pitch angle control

When measurement of rotor speed is bigger than the reference of it according to current wind speed, the output of β will be larger than 0° making the pitch angle to change.

2.4. Mechanical response process

The deeper the voltage drops, the greater mechanical power differs from electromagnetic power and the greater parameters in mechanical part change.

Once grid occurs short circuit fault, the voltage will drop and active power transmit will be limited leading to the unbalance between mechanical torque and electromagnetic torque and acceleration of the rotor speed ω_{gen} . Then according to equation (2), ω_{gen} has an oscillating increase and ω_{tur} increases slowing. The difference between ω_{tur} and the reference speed ω_{ref} will make the pitch control work to increase β according to Figure 1. The increase of β will reduce the mechanical power P_w , which will

affect operation of shaft and change θ_s 、 ω_{tur} 、 ω_{gen} . It has been cycling on each other until the fault is cleared.

3. Analysis of electrical part

Electrical part is mainly composed of generator model, rotor-side converter and its control model, and special control strategies in low voltage. Generator model is the key component to achieve electromechanical energy conversion. Rotor-side converter and its control model is the key part to realize active and reactive power decoupling. Special control strategies in low voltage are the key method to prevent secondary attack caused by the disconnection of the fan. The parameters of this part which should be paid attention to are active power, reactive power, voltage and current. Electrical response processes is relatively fast. To simplify the analysis, the grid-side power converter and the power outputted by the rotor are not considered here.

Doubly fed induction generator model, rotor-side converter and its control model are referred to [5], which are typical. In this paper, special control strategies in low voltage are mainly introduced.

3.1. Special control strategies in low voltage

Grid codes will require wind turbines to have Low Voltage Ride Through (LVRT) capability to prevent suffered secondary attack caused by the disconnect of the fan in voltage drop fault [20]. It means that DFIG can continue to run and provide reactive power for the grid to help the voltage rise. However, an abrupt voltage drop can result in overvoltage or overcurrent in the rotor windings which may destroy the rotor-side converter, so it needs special control strategies to protect it. Currently, there are two ways: additional hardware and to change inverter control strategy. In this paper, combination of LVRT converter control and crowbar resistance is used to protect DFIG and make it play the best effect in the low voltage.

3.1.1. Crowbar control.

An abrupt voltage drop can result in over-currents which may destroy the rotor-side converter. To avoid the situation happening, increasing crowbar resistance can make rotor windings short and let the current flow to bypass. However, when the crowbar plays a role, DFIG will be in asynchronous state and need lots of reactive power which is harmful to the recovery of voltage. So the appropriate time of crowbar in operation is necessary and many papers have done research on this [21]. The control strategy in this paper is that when the rotor current is up to double nominal value, make the crowbar valid and cut off it automatically after 60ms.

The control strategy is shown in figure 2. The value of current decides whether crowbar is valid.

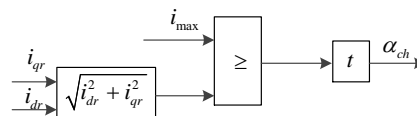


Figure 2. Crowbar control

In figure 2, i_{max} is the maximum current which can flow the rotor-side converter. t is the continue time that crowbar is valid. α_{cb} is the state of crowbar, $\alpha_{cb}=1$ means crowbar is valid, and $\alpha_{cb}=0$ means crowbar is invalid.

3.1.2. Low voltage ride through, LVRT.

The crowbar working time is short than the fault, so the rotor speed will still accelerate. According to the original control strategy, the active power will increase to decrease the rotor speed which will make the current lager and make crowbar valid again. And it needs crowbar produce reactive power to help the voltage recover. So the new strategy is needed, and low voltage ride through control strategy is designed in this paper. Once the grid has short-circuit fault, the reactive power compensation is first to be considered in the base of the degree of voltage drop. Then under the limitation of maximum

current, the active current is relatively set to provide margin for the reactive current. The aims of this strategy are supporting the grid voltage recovery as well as protecting DFIG safe.

In the voltage drop, the references of reactive and active power are provided according to the following equation:

$$\begin{cases} Q_{ref1} = U_{WT} I_{dr}, I_{dr} \leq I_N \\ I_{dr} = 1.5 I_N (0.9 - U_{WT}) \end{cases} \quad (3)$$

$$P_{ref1} = \min[P_{ref}, U_{WT} (1 - I_{dr})] \quad (4)$$

Where U_{WT} is the terminal voltage of DFIG, and $0.2 p.u. \leq U_{WT} \leq 0.9 p.u.$. I_{dr} is dynamic reactive current provided by DFIG. I_N is nominal current. P_{ref} is the active power reference in the maximum power point.

The low voltage ride through control design is shown in figure 3. The essence is to, change active and reactive power reference value input in the original closed-loop control by increasing the voltage detection aspect.

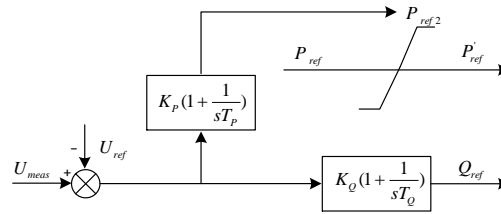


Figure 3. Low voltage ride through control

3.2. Electrical response process

Dynamic electrical characteristic of DFIG is affected by excitation control, which is related to the voltage drop level and operating status, and has a fast degeneration. When the voltage drop is shallow, excitation current is controlled to maintain the stability of active and reactive power because of the constant power control strategy. When voltage drop is heavy, special strategy -low voltage ride through control or crowbar control is valid to protect the rotor converter and help the grid recovery.

If the crowbar is valid or not, it is decided to the voltage drop level and operating status of DFIG before short fault. And DFIG will be in asynchronous machine state in which the reactive power is 0 and active power is lower. Under low voltage ride through control, DFIG mainly provides reactive power and its active power is limited which is involved in voltage drop level

The voltage drop can be divided into four levels according to the situation of converter control operation. When Voltage drop is shallow, generally $u > 0.9$, LVRT control and crowbar will be both invalid. Voltage drop is medium, $0.2 < u < 0.9$, only LVRT control will be valid. When Voltage drop is deep, $0.2 < u < 0.9$, LVRT control and crowbar will be both valid. When the voltage drop is over safety value, the DFIG will be removed.

4. Simulation results

To verify the analysis about the DFIG dynamic response characteristics in voltage drop and effectiveness of the control scheme, the following model is built in DIgSILENT/ PowerFactory. Wind farm is consisted of 30 units of 2MW DFIG and is access to single machine infinite bus system by 20/0.69kV double-winding step-up transformer. And DFIG run in rated power and low power (20%) two states. The different voltage drop levels are completed by adjusting grounding impedance in three-phases short-circuit.

4.1. Rated power state

When the wind speed is greater than the rated wind speed 11.5m/s rate, the DFIG is in rated power

state. Three-phase short circuit occurs in the 0.5s, lasted 0.625s and grid voltage drop, respectively, to 92%, 82%, and 45% of the rated voltage. The mechanical response process and electrical response process are separately shown in figure 4 and figure 5.

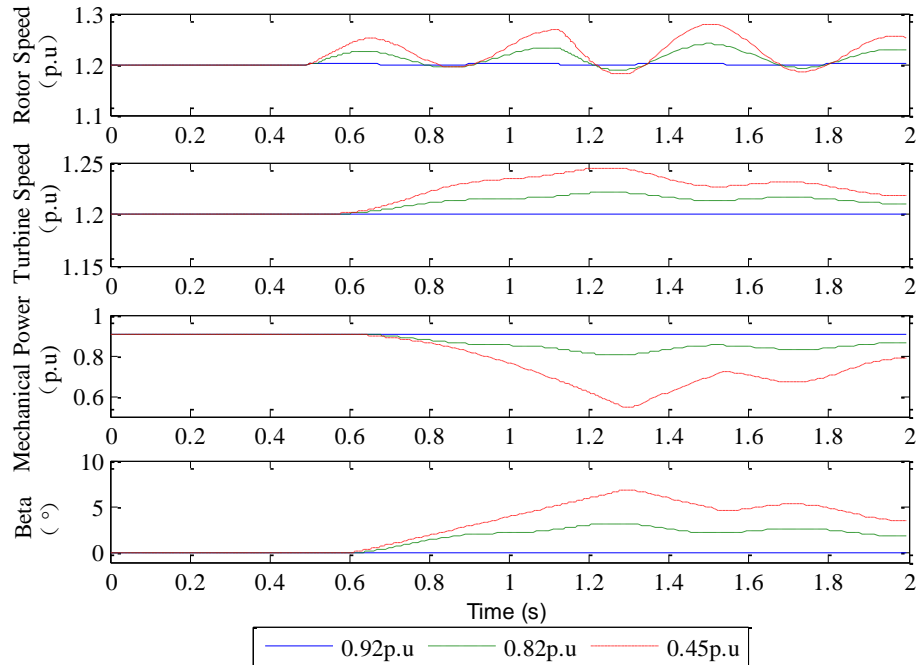


Figure 4. Mechanical response processes of DFIG, when it operated with rated power

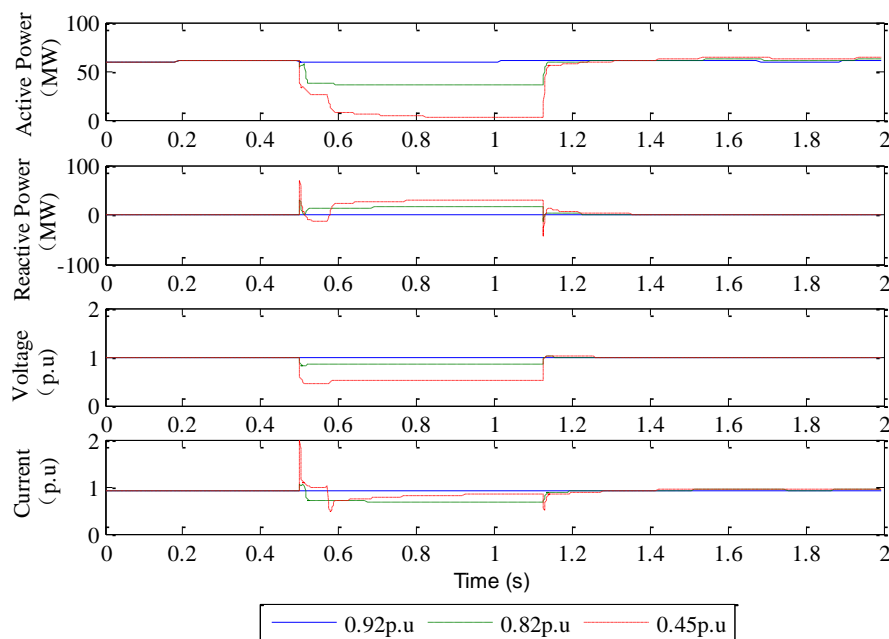


Figure 5. Electrical response processes of DFIG, when it operated with rated power

As seen from figure 4 and figure 5, when the voltage drop is shallow (0.92p.u), all amounts have been adjusted in accordance with the existing control instructions, and special control strategies are not valid.

As indicated by figure 4, mechanical responses are similar in medium and deep large voltage drop

($0.2 < u < 0.9$). Once the fault happens, ω_{gen} has an oscillating increase, ω_{tur} starts to increase after a period of time, β increases and active power decreases. Once the fault is cleared, ω_{gen} immediately begins to decrease, the remaining parameters come to recover after a while. Voltage drops deeper, the change of all parameters are larger.

As indicated by figure 5, the electrical response process will be different with different voltage drop level.

In medium voltage drop, the crowbar is invalid as the current instant surge is too small to meet 1.5p.u. Low voltage ride through control is taken resulting that the active power is limited and decreases quickly, reactive power increases fast to support voltage recovery, the voltage dips in the duration of fault and has a recovery in the process, and the current increases. In deep voltage drop, the crowbar is effective as the current instant surge is big enough to meet 1.5p.u which makes the converter invalid. The reactive power is zero, active power decreases and the current increases in that process. After 60ms, the crowbar is removed and low voltage ride through control is taken. Then reactive power is produced, and active power decreases more and the current decrease to the maximum value allowed. After clearing the fault, although mechanical parameters still oscillate, the electrical parameters recover quickly due to the excitation control.

It can be verified that different level of voltage drop will cause different mechanical and electrical response characteristics which are decided by the strategy taken in rotor side. What's more, Mechanical response is lagging, and electrical response is particularly rapid.

4.2. Low power state

When the wind speed is lower than the rated wind speed 11.5m / s rate, the DFIG is in at maximum power tracking state where its output size is determined by wind speed. In this paper, wind speed 9m/s is selected, and the DFIGs are running at 20% of rated power. Three-phase short circuit occurs in the 0.5s, lasted 0.625s and grid voltage drop, respectively, to 92%、82%、45%、and 32% of the rated voltage. The mechanical response process and electrical response process are separately shown in figure 6 and figure 7.

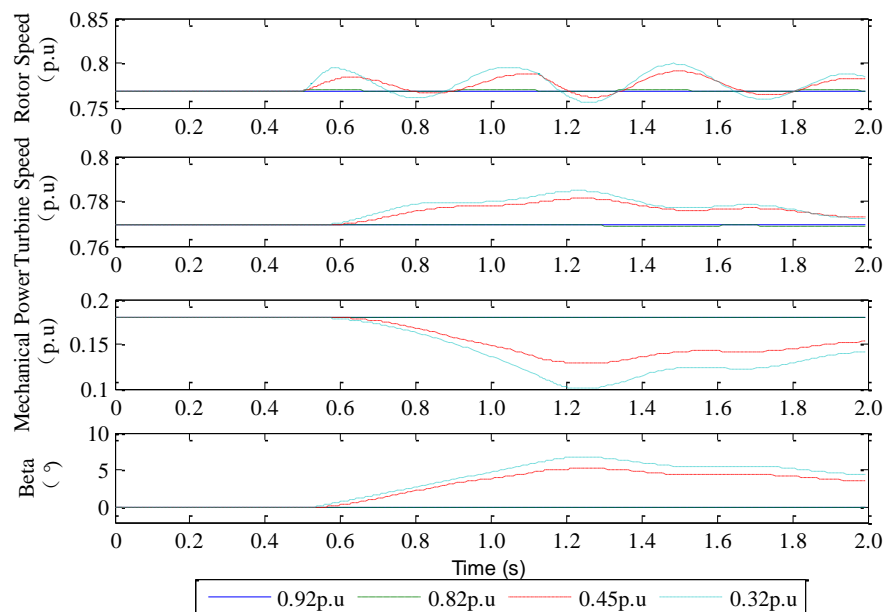


Figure 6. Mechanical response processes of DFIG, when it operated with low power

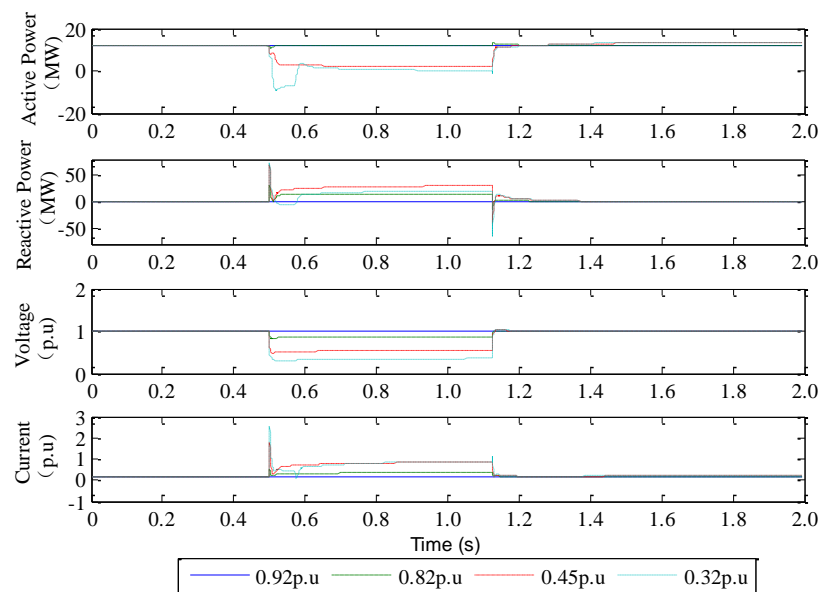


Figure 7. Electrical response processes of DFIG, when it operated with low power

As seen from figure 6 and figure 7, when the voltage drop is shallow (0.92p.u), all amounts are almost unchanged.

Compared with figure 3 and figure 6, dynamic response is different in the same voltage drop level but different speed wind. All amounts in mechanical part don't response to the medium voltage drop because the output is maintained in 20% of nominal power which isn't over the lamination and the torques are equal. The mechanical responses under deep voltage drop (0.45p.u、0.32p.u) are similar to that happen in rated power, but the degree is smaller.

Compared with figure 4 and figure 7, in medium power voltage (0.82p.u), the reactive power is only related to the voltage level and same to that provided in rated power state. There is no change in active power. In deep voltage drop, whether crowbar is valid, it is related to the current at the moment when the short circuit happens, that is to say it is related to operating status of DFIG. While the crowbar is valid in high wind speed, it is not valid in low speed when other conditions are same. When the voltage drop is deeper (0.32p.u), the crowbar is put in and its response process is similar to that in rated power state.

It can be concluded in this case that reactive power compensation is only related to the voltage drop level, while active power and crowbar are limited to the wind speed level.

5. Conclusions

In this paper, the model and control system about mechanical and electrical parts of double-fed induction generator are studied and it is conclude the mechanical and electrical response characteristic under grid fault which is verified in DIgSILENT/ PowerFactory. Conclusions are as below

- Under fault condition, mechanical response characteristic is affected by electrical characteristics. The changes of beta and mechanical power will be different because of original active power value and it after the fault. Mechanical response characteristic is hysteresis;
- Under fault condition, electrical response characteristic is decided by rotor-side control strategy including vector control for rotor voltage, low voltage ride through control and control for crowbar. What's more, using which strategy above is decided by voltage drop level、operating status of DFIG;
- After the fault is cleared, since the excitation control leads to electromechanical decoupling, Oscillation in the mechanical part does not affect the changes in the electrical part.

In conclusion, the dynamic response characteristics are related to voltage drop level, operating status of DFIG and control strategy adopted to rotor side. The conclusion is significant for transient stability of power system with large-scale wind farm large and safe operation of the wind turbine.

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