

Transient Stability Analysis of Grid-connected Wind Turbines with Time Domain Simulation

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Abstract

With an ever-increasing penetration of wind power into power system, the influence to overall system behavior and stability becomes obviously. Therefore, it is so necessary to require wind turbines have good grid adaptability. This paper investigates the effect of directly grid-connected front-end speed controlled wind turbines (FSCWT) on transient stability of power system. For this purpose, a voltage based synchronous generator model is used and the drive train model with WinDriver is built. By using a fast excitation control of FSCWT exciter, the FSCWT wind turbines can successfully ride through grid fault and have no problem of angular stability when connected to grid. Simulation studies are carried out to demonstrate and compare the transient performance of the IEEE 5-machine 14-bus system with FSCWT replace by double fed induction generators (DFIG) during a three phase fault. Results show that a better transient stability performance is achieved with an intergration of FSCWT in comparsion with DFIG, which can even bring some benefits on power system transient performance and stability.

Keywords: critical fault clearing time (CCT), low voltage ride through (LVRT), transient stability, front-end speed controlled wind turbine (FSCWT), power system

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1. Introduction

At present, the main types of wind turbines in power systems are DFIG and permanent magnet synchronous generator (PMSG) with direct drive, the generators require to consume reactive power from grid during a severe grid fault [1,2], as a result, a voltage stability reduction of power system is made. Compared with the wind turbines equipped with inverters, The FSCWT has an automatic gearbox WinDriver with variable ratio as hydrodynamic mechatronical system for speed control of wind turbines combien with an electrically excited synchronous generator at middle voltage level ($\geq 10\text{KV}$), which has a good grid adaptability and transient fault ride-through (FRT) capability with broad prospects for development and application. Thus, it has great significance on a reliable and stable operation of power systems with studing on transient stability of FSCWT.

Wind power generation changes the load flow, transmission line load, the swing modes and the inertia of the connected power system [3], which inevitably result in grid transient stability performance. It believes that appropriate increasing of the wind capacity can effectively improve the stability of the connected system in both CCT and $\delta - t$ behavior [4]. In paper [5], the stability of conncted power system and the wind generator itself is analyzed under different CCT for currently used constant speed wind turbine (CSWT), DFIG and PMSG wind turbine, the effect of generator parameters on system transient stability performance is discussed additionally. By analyzing the transient stability of DFIG wind turbine under constant power factor and constant voltage control, respectively, reference [6] shows that, reactive power control can effectively maintain the generator vlotage above the bus voltage limit. And reference [7] shows that drive train model with diffierent order can affect the trasient stability.

However, no matter DFIG or PMSG wind turbines, the transient stability performance is improved all by back-end inverter control, which would result in a pool transient stability once the inverter failures. This paper investigated the effect of FSCWT integration on power system transient stability, base on the IEEE 5-machine 14-bus system in which FSCWTs are added.

Simulation studies are carried out in MATLAB/SIMLINK and PSAT to demonstrate the transient stability performance in compare with equivalent capacity DFIG wind turbines during a 3-phase grid fault.

2. Modeling and Control of FSCSG

The FSCWT uses an electrically excited synchronous generator (EESG), which structure can be seen in figure 1. The wind power is captured by wind rotor and is delivered as mechanical input of WinDriver with constant spindle speed via spindle and a two stage gearbox, the synchronous generator coupled directly to the grid produces grid-friendly electricity and omission of the frequency converter and step-up transformers minimizes the wind turbine's complexity in compare with traditional DFIG and PSMG wind turbines, which can works like conventional power plants in the event of severe voltage drops and can meet the requirement of LVRT by excitation control.

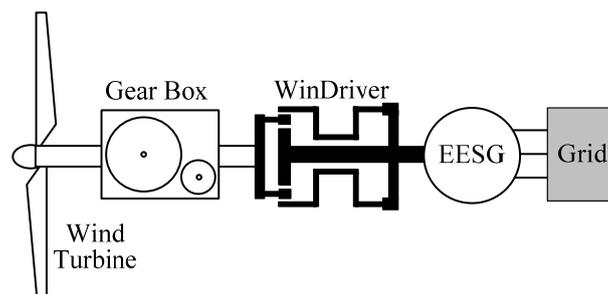


Figure 1. Structure of FSCWT

2.1. Drive Train Model Including WinDriver

Figure 2 shows the simplified structure of FSCWT drive train derived from figure 1. Where, n_r is the wind rotor speed, n_t , n_q and n_j represent the sun gear speed, the ring gear speed and the planetary gear speed of the hydrodynamic torque converter WinDriver, n_r , n_B and n_D represent the speed of the turbine wheel, pump wheel and the guide vanes, respectively.

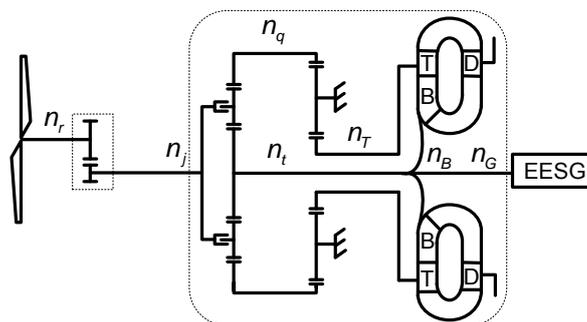


Figure 2. Simplified structure of drive train

Figure 2 shows the speed relationship between wind rotor and planetary gear: $n_j = n_r \alpha_1$, where α_1 is the gear ratio of gearbox while the sun gear speed. The ring gear speed and the planetary gear speed satisfy the relation: $n_t + \alpha_2 n_q = (1 + \alpha_2) n_j$, in which α_2 is the structure

parameter of differential gear trains. The relationship among the sun gear, pump wheel and the generator rotor speed satisfy with: $n_t = n_B = n_G$, the turbine wheel and the ring gear speed also satisfy $n_q = -n_t \alpha_3$, as α_3 is the structure parameter of fixed gear trains. Therefore, the transitive relation from wind rotor to generator rotor can define as [8-9]:

$$n_t = n_G = n_B = (1 + \alpha_2)n_R \alpha_1 + n_T \alpha_2 / \alpha_3 \quad (1)$$

Thus the torque equation can be derived like:

$$\begin{cases} M_j = \alpha_1 M_R \\ M_q = -M_T / \alpha_3 \\ M_t = M_q + M_j = M_B + M_G \end{cases} \quad (2)$$

where M_T , M_B and M_G stand for turbine torque, the pump wheel torque and the generator input torque, respectively. M_t , M_q and M_j separately stand for the torque of sun gear, ring gear and the planetary gear, which satisfy:

$$M_t : M_q : M_j = 1 : \alpha_2 : (1 + \alpha_2) \quad (3)$$

The generator input power can be derived from equation (1), (2) and equation (3):

$$P_G = M_G \omega_G = M_R \omega_R \beta_1 - M_B \omega_B + M_B \omega_B \beta_2 \beta_3 \quad (4)$$

where β_1 , β_3 stand for the transmission efficiency from wind rotor to the planetary carrier and the transmission efficiency from center wheel to ring gear, separately while β_2 is the efficiency of hydrodynamic torque converter.

2.2. Model of Electrically Excitation Synchronous Generator

The synchronous generator discussed in this paper is an EESG used brushless exciter, Figure 3 and Figure 4 show the structure of excitation system and the d-q equivalent circuit of EESG without damper winding.

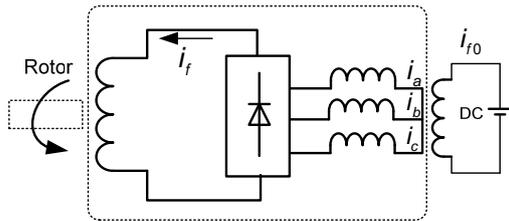


Figure 3. Simplified structure of brushless exciter

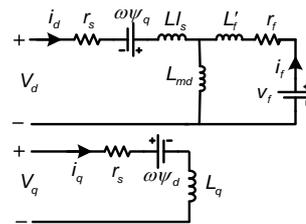


Figure 4. Equivalent Circuit of EESG without damper winding

The brushless exciter can be described as:

$$\begin{cases} V_d = R_a i_d + \frac{d\Psi_d}{dt} + p\omega\Psi_q \\ V_q = R_a i_q + \frac{d\Psi_q}{dt} + p\omega\Psi_d \\ V_f = R_f i_f + \frac{d\Psi_f}{dt} \end{cases} \quad (5)$$

the flux Ψ_d , Ψ_q and Ψ_f in equation (5) are

$$\begin{cases} \Psi_d = L_d i_d + L_{md} i_f \\ \Psi_q = L_q i_q + L_{md} i_f \\ \Psi_f = (L_{md} i_f + L_f') i_f - L_{md} i_d \end{cases}$$

where V_d and V_q stand for d-axis and q-axis excitation voltage, R_a , R_f represent rotor resistance and field winding resistance, Ψ_d , Ψ_q and Ψ_f are the total flux of d-axis, q-axis and field winding, respectively. L_{md} is excitation inductance of d-axis, L_f' is the field winding reactance. i_f is excitation current and ω is the mechanical rotor angular speed.

For EESG, the SG model based on voltage model is used, the voltage equations are shown as [10]:

$$\begin{cases} v_q = -r_s i_q - x_d' i_d + E_q' \\ v_d = -r_s i_d - x_q' i_q + E_d' \end{cases} \quad (6)$$

$$\begin{cases} T_{d0}' \frac{dE_q'}{dt} + E_q' = E_f - (x_q - x_q') i_d \\ T_{q0}' \frac{dE_d'}{dt} + E_d' = E_g - (x_q - x_q') i_q \end{cases} \quad (7)$$

and the rotor electromagnetic torque equation can be written as:

$$T_{em} = -[E_q' i_q + E_d' i_d + (x_q' - x_q) i_d i_q] \quad (8)$$

where, v_d and v_q are the voltage of d-axis and q-axis while i_d and i_q represent the current of d-axis and q-axis accordingly. x_d' , x_q' are transient impedance of d-axis and q-axis, x_q is the q-axis impedance, E_d' , E_q' stand for transient electromotive force in both d-axis and q-axis, T_{d0}' and T_{q0}' are the d-axis and q-axis open-circuit time constant, E_f , E_g are field winding voltage of d-axis and q-axis, T_{em} is electromagnetic torque, r_s is stator resistance.

The following analysis of SG all uses a three phase fault as study case, when a three phase fault occurred, the stator current i_d and i_q can be describe as:

$$\begin{cases} i_d = \left[\left(\frac{1}{X_d''} - \frac{1}{X_d'} \right) e^{-\frac{t}{T_d'}} + \left(\frac{1}{X_d'} - \frac{1}{X_d} \right) e^{-\frac{t}{T_d}} \right] U \cos \delta + \frac{E}{X_d} - \frac{U}{X_d''} e^{-\frac{t}{T_a}} \cos(t + \delta) \\ i_q = \left(\frac{1}{X_q''} - \frac{1}{X_q'} \right) e^{-\frac{t}{T_q'}} U \sin \delta + \frac{U}{X_q} e^{-\frac{t}{T_a}} \sin(t + \delta) \end{cases} \quad (9)$$

where δ is the power angle, U is the RMS of phase voltage, T_a is the aperiodic stator current decay time constant. The three phase voltage of stator winding is :

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos \theta & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ \sin \theta & \sin(\theta - 2\pi/3) & \sin(\theta + 2\pi/3) \end{bmatrix} v_s \quad (10)$$

where v_s can be written as:

$$V_s = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} V_f \\ -V_f/2 - jV_f\sqrt{3}/2 \\ -V_f/2 + jV_f\sqrt{3}/2 \end{bmatrix}$$

where V_f is field voltage, θ can be defined as:

$$\theta(t) = \int_0^t \omega(t)dt + \theta_0$$

where ω is magnetic speed of SG, θ_0 is the angle between winding axis of phase A and d-axis of rotor winding.

3. Study Case of System Transient Stability

The transient stability performance is directly affected with integration of wind farms, in this paper, an IEEE 5-machine 14-bus system is used for transient stability analyzing case, which can be seen in Figure 5.

In the study case, all generators are considered with automatic voltage regulator (AVR) and a power system stabilizer (PSS) is applied to No.1 SG (connected to Bus_1) and connected to grid with adjustable transformers. The rated power of FSCWT is 2 MW while the DFIG wind turbine is 1.5 MW. All wind turbines connected in Bus_8 and integrated to grid with a step-up transformer. The total active power of proposed system is 785MW and the reactive power ranges from -3036 Mvar to 3284 Mvar, system active load is 747.5 MW and reactive load is 223.4 Mvar, detailed parameters can be seen from [11].

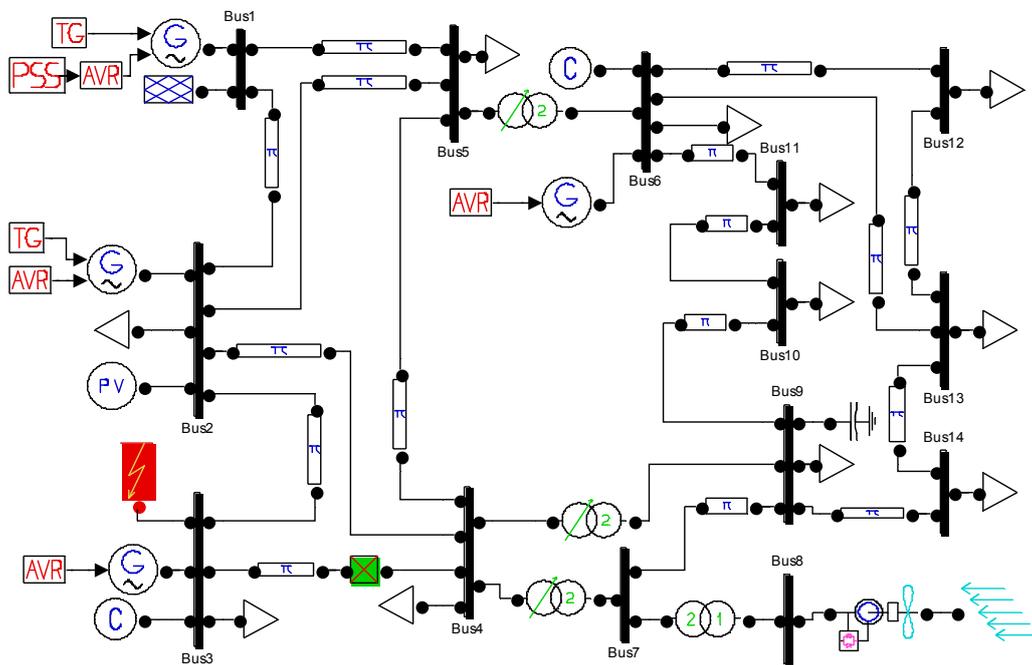


Figure 5. IEEE 5-machine 14-bus system

4. Simulation Analysis

The simulation test is carried out by MATLAB/SIMULINK and PSAT with the defined system in Figure 5, comparative analysis of LVRT and CCT is made under different wind power proportion in the connected system.

4.1. Low Voltage Ride Through Capability

For the power system with wind turbines integrated, once a severe fault occurs, the electromagnetic power of DFIG reduced rapidly, which lead to the rotor speed increases, the operation point of DFIG will move from the optimum point of speed-torque characteristic curve to the speed increase direction. And the mechanical torque will decrease during severe fault, accordingly. At the same time, the rotor current will have a sharp rise, to ensure the generator with a stable operation, the rotor have to short with crowbar to consume the excess energy and SVGs or STATCOMs will be put in for reactive power compensation, otherwise the DFIG will off operation in grid [12,13]. The different is the FSCWT will operation under a over-excitation status to generate sufficient reactive power to maintain bus voltage balance with grid connected, which brings benefits to the connected grid in transient stability performance.

A three phase fault is applied to the study case proposed above, which is occurred at 3.0 s with 320 ms lasted, the stator voltage of DFIG is 575 V, other parameters are: $R_s = 0.00706$, $L_{ls} = 0.171$, $R_r = 0.005$, $L_{lr} = 0.156$, $L_m = 2.9$ and $H = 5.04$. All parameters of FSCWT is shown in Table 1.

Table 1. Parameters of FSCSG

| Labels | Values |
|---|----------|
| Field resistance R_f (pu) | 0.0037 |
| d-axis synchronous reactance x_d (pu) | 1.52 |
| q-axis synchronous reactance x_q (pu) | 0.996 |
| d-axis transient reactance $x'd$ (pu) | 0.152 |
| d-axis subtransient reactance $x''d$ (pu) | 0.116 |
| q-axis subtransient reactance $x''q$ (pu) | 0.192 |
| d-axis open circuit transient time constant $T'd$ (s) | 0.208 |
| d-axis open circuit subtransient time constant $T''d$ (s) | 0.022 |
| q-axis open circuit subtransient time constant $T''q$ (s) | 0.011 |
| Rotor Inertia H (kgm ²) | 109.0223 |

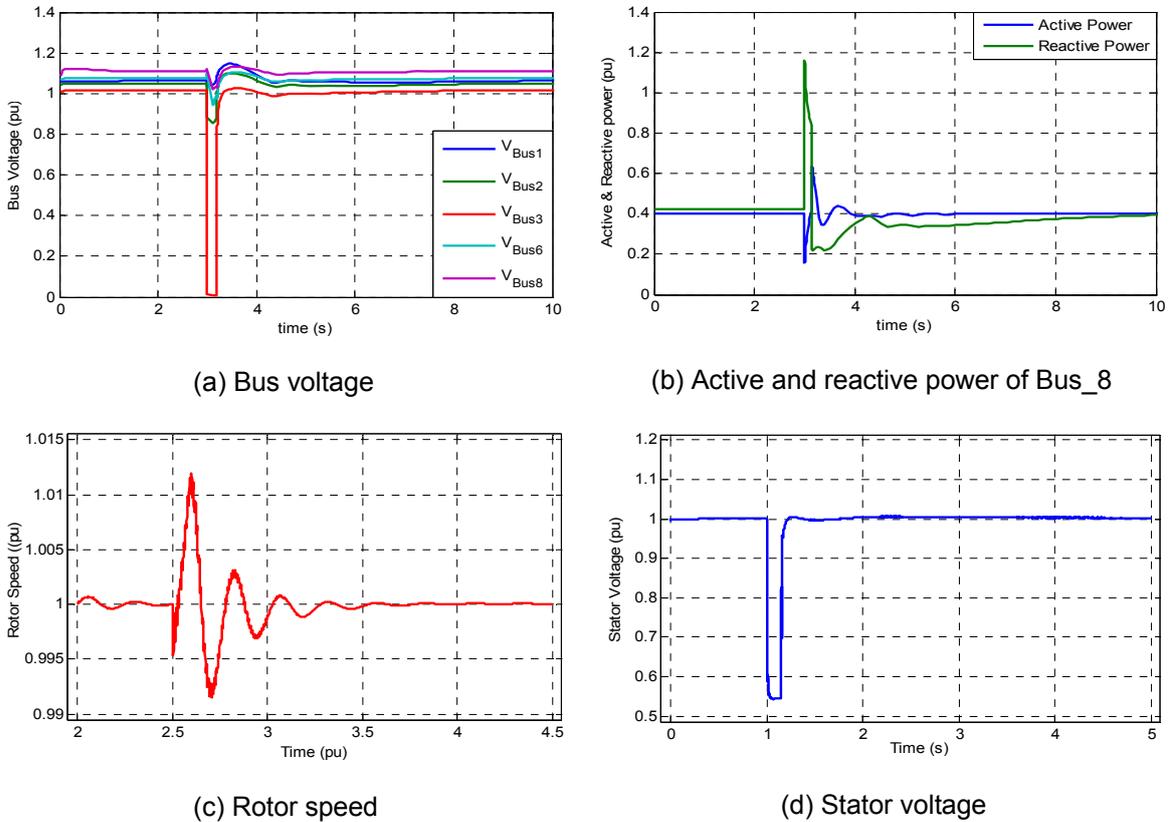


Figure 6. Transient response of the study case

What we can see from Figure 6(a) is that, when a three phase fault occurred in Bus_3, the bus voltage dropped rapidly, Bus_1, Bus_2, Bus_3 and Bus_8 also dropped the same as Bus_3. During the fault, The FSCWT can achieve LVRT by over excitation to produce adequate reactive power to maintain bus voltage, which is shown in Figure 6(b). Figure 6(c) is the transient response of generator rotor speed and Figure 6(d) is the stator voltage of SG.

4.2. Critical Fault Clearing Time of System

To every SG in power system, the active power injected into the grid P_0 under normal conditions is balance with the mechanical power P_1 , which is known as the rotor motion equation [14], once a severe fault occurs, the electromagnetic power P_0 decreases rapidly while the mechanical input power P_1 can not change rapidly, which result in power inbalance: $P_1 > P_0$,

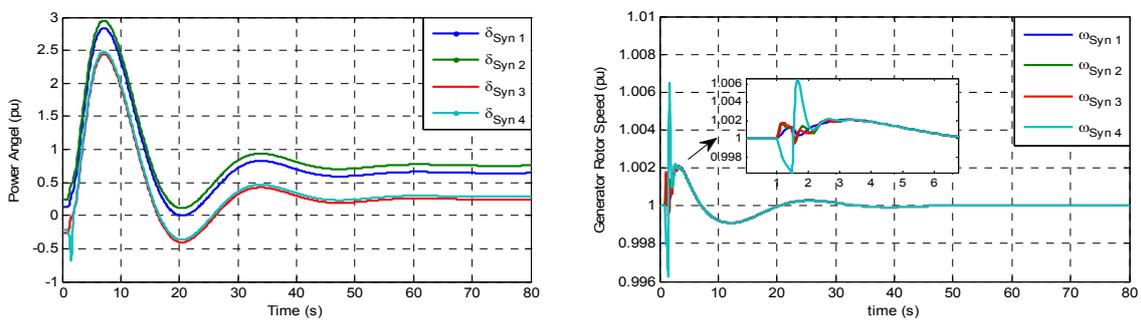


Figure 7. Power angle and rotor speed at 518 ms

excess torque will cause a rotor speed ω and power angle δ increasing steadily. If the fault can not be removed timely, the SG will lose synchronization eventually. Figure 8 and Figure 9 show the rotor speed and power angle changes with different CCT.

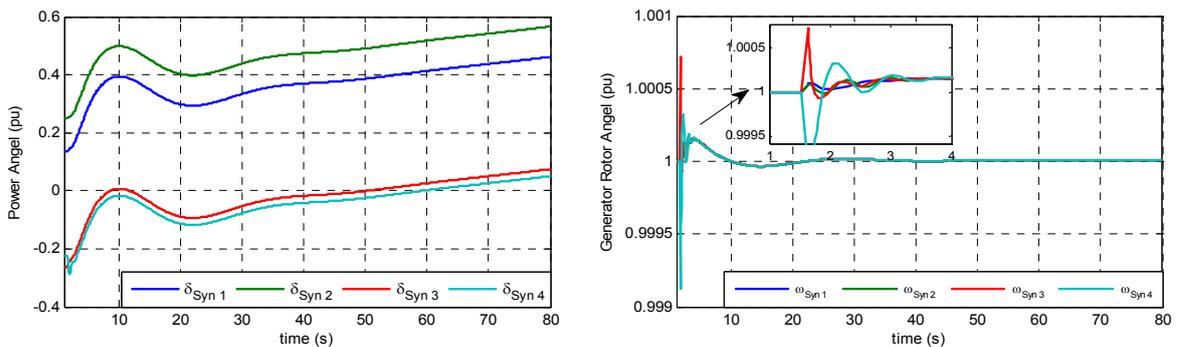


Figure 8. Power angle and rotor speed at 519 ms

Figure 8 shows the rotor speed and power angle with CCT 518 ms and CCT 519 ms in Figure 9, as is shown, the power angle remains stable at 518 ms but goes instability at 519 ms. To illustrate the stability more clear, a contrast of the stability between DFIG and FSCWT is made as is shown in Table 2.

Table 2. Contrast of the stability between DFIG and FSCWT

| Wind power Capacity | Percentage of wind power | Faut clear time (ms) | Stable status (Y/N) | |
|---------------------|--------------------------|----------------------|---------------------|-------|
| | | | DFIG | FSCWT |
| 40MW | 5.10% | 510 | N | Y |
| | | 480 | Y | Y |
| 60MW | 7.10% | 430 | N | Y |
| | | 350 | Y | Y |
| 120MW | 13.26% | 220 | Y | Y |
| | | 168 | N | Y |
| 250MW | 24.15% | 100 | Y | Y |

As it can be seen that, with the same capacity wind power integration and different fault clear time, FSCWT can keep stable longer than DFIG. Therefore, the application and integration of FSCWT can benefit the connecte grid and improves the system transient stability in a large extent.

5. Conclusion

To the grid-connected wind turbines, the effect of power system stability, especially transient stability is crucial to the stable operation of connected grid. By an analysis of FSCWT transient performance when integrated into IEEE 5-machine 14-bus system with a three phase short simulation and compared with DFIG, the FSCWT shows a good LVRT capability and transient stability, large numbers integration of FSCWT can contribute to enhance system transient performance.

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