Comparison and Evaluation of Induction Generator Models in Wind Turbine Systems for Transient Stability of Power System

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Abstract**-- In order to analyze the transient stability of grid-connected squirrel cage induction generators (SCIG) in wind power generating systems, various mathematical models, including the detailed and reduced generator models as well as the one-mass and two-mass shaft system models, are studied in this paper. Based on the different wind turbine system models, the dynamic behaviors are simulated and compared by using Matlab/Simulink, under the condition that the generator stator terminal is subjected to a three-phase short-circuit fault. In addition, the critical clearing time (CCT) is calculated and compared by using a direct method with critical clearing slip of induction generators and a method of trial and error by simulation, for different system models at the various operation conditions. The models and methods suitable to analyze the transient stability of the wind turbine systems based on SCIG are discussed in detail. Several comparative results have shown that the valid transient stability model of SCIG in wind turbine systems has to incorporate the two-mass shaft system model, the direct method of CCT estimation based on critical clearing slip is incompatible to determine the transient stability limit, owing to the large multi-oscillation of the generator rotor speed during the fault period.**

Index Terms**—Wind turbines; induction generation; critical clearing time; transient stability; models**

I. Introduction

Grid-connected squirrel cage induction generators (SCIG) are an important alternative for large-scale wind farm because of its rotor structure, simplicity of construction and maintenance-free operation. As the penetration of wind power in electrical power systems increases, wind turbines may begin to influence overall power system operation [1][2]. So it is very necessary and important to study the transient stability of the wind farms with SCIG [1-4]. It is well known that a severe voltage sag due to a fault in the connecting network may cause a significant speed increase of the turbine and generator rotor. After voltage recovery, the rotor speed of the SCIG may be so high that it does not return to a stable value. A definition is given which refers to the ability of an induction machine to remain the connection to the electric power system and running at a mechanical speed close to the speed corresponding to actual system frequency after being subjected to a large disturbance. The definition of the transient stability is different from rotor angle stability of conventional synchronous generator and voltage stability of power system [5]. With the large-scale wind power integration into the transmission electric power network, how to assess effectively the transient stability limit of SCIG based on wind turbine system is increasingly attraction in power system security and reliability.

As general, the critical clearing time (CCT) is determined as a criterion for transient stability of power system. Methods of transient stability estimation may be divided into numerical analysis techniques (e.g. time domain simulation) and direct methods [6][7]. In the former case, transient stability analysis is performed by utilities exclusively by means of the numerical integration of nonlinear differential equations describing the on-fault and post-fault system, which is extremely inefficient for on-line estimation of stability limit of large power systems and its nonlinear nature [7]. In the latter case, the possible range of system transient stability is estimated by using a limited value (threshold). So trial and error processing is unnecessary in the direct methods, it is efficient to achieve faster computational stability limit, to obtain qualitative information on system stability behavior, and to identify the critical generators that are severely affected by the disturbance. Due to these promising features, it has become an effective online transient stability estimation method in conventional power systems.

In order to study the dynamic stability and its impact to the grid, there are a few literatures to present some models and methods of transient stability analysis of induction generator [3][4][8-14]. However, the conventional step-by-step time-domain simulation method is common choice for the transient stability analysis of SCIG. Based on the first-order generator model, the simple method of CCT calculation is presented in [9], but it is dependent on the characteristics of steady state torque-slip. Considering the speed contribution of the shaft stiffness of the wind turbine drive train, a direct method by calculating the generator speed with the on-fault trajectory and

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compared with critical clearing speed of SCIG is presented in [14], but this method is also based on the steady state torque-slip characteristics. So it is worthy of evaluating and determining the transient stability limit of SCIG in wind turbine systems.

In order to compare and analyze the validity of the assessment of the transient stability limit of wind turbine system based on SCIG, some different system models including the detailed and reduced generator transient models, the one-mass and two-mass shaft models are presented in this paper. When the generator stator terminal is subjected to a three-phase short-circuit fault, the dynamical behavior for different system models are simulated and compared by using Matlab/Simulink. The CCT is calculated and compared for different wind turbine system models in the various initial operation conditions, by using the direct method based on critical clearing slip of induction generators and the conventional step-by-step time-domain simulation method. The model suitable to transient stability analysis of wind turbine systems based on SCIG is obtained; the direct method of determining the transient stability limit is evaluated by various comparative results.

II. Stability Limit Of SCIG In Wind Turbine Systems

In order to theoretically analyze the transient stability limit of grid-connected SCIG, a three-phase short-circuit fault at the generator stator terminal is considered as a large electrical disturbance, the steady state torque-slip characteristic is used. The first-order motion equation can be described as

$$2H\frac{ds}{dt} = T_e - T_m \qquad (1)$$

Where H is the sum of constant inertia of the rotating mass in per unit; s is the slip of SCIG; T_e is the electromagnetic torque of SCIG; T_m is the input mechanical torque from the wind turbine.

At the steady-state condition, the electromagnetic torque, T_e, is equal to the mechanical torque, T_m, and the machine is operating at the slip s_0, as shown in Fig.1. Immediately after

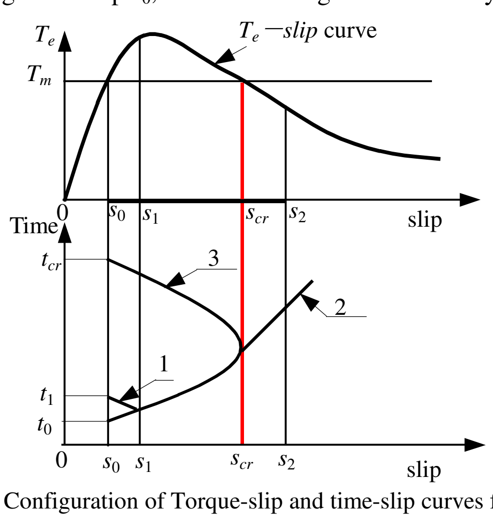


Fig.1 Configuration of Torque-slip and time-slip curves for three-phase short-circuit fault

the fault occurs, T_e would be zero (if the electrical transients are ignored), while the slip remains at s_0. Thus, there is a net accelerating torque and the slip gradually increases according to the above equation. If the fault is cleared at a slip s_1, then T_e is assumed to increase instantaneously (assuming the post-fault voltage is the same as the pre-fault). However, the slip remains the same, at this operating point, the electrical torque is higher than the mechanical torque, the rotor decelerates (curve-1 of the slip-time curve in Fig.1.) and returns back to the original slip s_0.Instead of clearing the fault at slip s_1, if the fault is cleared at a slip s_2, then even the T_e increases from zero, it will be less than T_m and the machine continues to accelerate, so the SCIG will become instable for its over speed, which is shown as curve-2 of slip-time curve in Fig.1. Similar dynamic behaviour can be expected, if the fault is cleared at any point beyond the slip s_{cr} in Fig. 1. Therefore, the slip s_{cr} can be called as the critical clearing slip for this operating point; and its corresponding speed is critical clearing speed [9][14]. This implies that the fault is cleared before the slip reaches s_{cr}, the generator will not be over-speed and not be disconnected grid. It is noticeable that the obtained conclusion is completely dependent on the steady state torque-slip curve of induction generator. Incorporating the generator electrical transients and the low shaft stiffness features of the wind turbines mechanical system, it may be incapable of determining the transient stability limit of wind turbine systems.

Unlike the steam and the hydro units, apart from the difference in the source of conventional energy, the induction generator in wind turbine system is featured by having high turbine inertia by comparison with generator rotor and low stiffness of the shaft between the turbine and generator. During the power system fault condition, T_e collapses and the stored potential in the wind turbine shaft is released and transformed into kinetic energy of the generator. By using the law of conservation of mechanical energy, the speed change of the generator rotor after a fault inception can be expressed [14]

$$\Delta\omega_G = \frac{T_M}{\sqrt{H_G K_s}} \qquad (2)$$

Where H_G is per unit inertia constant of SCIG; K_s is the wind turbine shaft stiffness.

It is simple that the effects of the low shaft stiffness to transient stability limit of wind turbine systems is the speed change of the generator rotor in equation (2), the implementation of this direct method of the CCT estimation is described in [14]. But this method is also dependent on the critical clearing slip of SCIG based on the steady state torque-slip curve, so its validity needs to be discussed in detail.

III. Different Models Of Wind Turbine Systems

A. Different Induction Generator Models

According to a standard per-unit notation [3], in the synchronously rotating frame, the induction generator can be represented by the detailed differential equations of the flux linkages.

$$v_{sd} = -R_s i_{sd} - \omega_s \psi_{sq} + \frac{1}{\omega_B} p \psi_{sd} \tag{3}$$

$$v_{sq} = -R_s i_{sq} + \omega_s \psi_{sd} + \frac{1}{\omega_B} p \psi_{sq} \tag{4}$$

$$v_{rd} = -R_r i_{rd} - s\omega_s \psi_{rq} + \frac{1}{\omega_B} p \psi_{rd} \tag{5}$$

$$v_{rq} = -R_r i_{rq} + s\omega_s \psi_{rd} + \frac{1}{\omega_B} p \psi_{rq} \tag{6}$$

Where ω_s is the synchronous speed (in per-unit, $\omega_s = 1$); ω_B is the system base frequency which is equal to the synchronous frequency, $\omega_B = 2\pi f$; p is the d/dt operator.

The electromagnetic torque, T_e, can be expressed as

$$T_e = L_m (i_{sd} i_{rq} - i_{sq} i_{rd}) \tag{7}$$

The constitutive flux linkage-current relationships are

$$\psi_{sd} = -L_{ss} i_{sd} - L_m i_{rd} \tag{8}$$

$$\psi_{sq} = -L_{ss} i_{sq} - L_m i_{rq} \tag{9}$$

$$\psi_{rd} = -L_m i_{sd} - L_{rr} i_{rd} \tag{10}$$

$$\psi_{rq} = -L_m i_{sq} - L_{rr} i_{rq} \tag{11}$$

Considering generators are usually represented as a voltage source behind transient impedance in power system stability studies, the detailed transient model of SCIG can be established as (where the d and q components of rotor voltage are zero, respectively).

$$\begin{aligned}\frac{X'}{\omega_s \omega_B} p i_{sd} &= -(R_s + \frac{X - X'}{T_0}) i_{sd} + X' i_{sq} \\ &+ (1-s) E_d - \frac{1}{T_0} E_q - v_{sd}\end{aligned} \tag{12}$$

$$\begin{aligned}\frac{X'}{\omega_s \omega_B} p i_{sq} &= -(R_s + \frac{X - X'}{T_0}) i_{sq} - X' i_{sd} \\ &+ (1-s) E_q + \frac{1}{T_0} E_d - v_{sq}\end{aligned} \tag{13}$$

$$\frac{1}{\omega_s \omega_B} p E_d = -\frac{1}{T_0} (E_d - (X - X') i_{sq}) + s E_q \tag{14}$$

$$\frac{1}{\omega_s \omega_B} p E_q = -\frac{1}{T_0} (E_q + (X - X') i_{sd}) - s E_d \tag{15}$$

$$T_e = E_d i_{sd} + E_q i_{sq} \tag{16}$$

Where

$$X = \omega_s L_{ss} = \omega_s (L_{s\sigma} + L_m) \,;\, X' = \omega_s (L_{ss} - \frac{L_m^{\;2}}{L_{rr}}) \,;$$

$$T_0 = \frac{L_{rr}}{\omega_s R_r} \,;\, E_d = -\frac{\omega_s L_m}{L_{rr}} \psi_{rq} \,;\, E_q = \frac{\omega_s L_m}{L_{rr}} \psi_{rd}$$

If the stator transients are very fast, when compared with the rotor ones, it is possible to neglect them. Upon neglecting the stator flux linkage transients, the reduced transient models of SCIG are obtained by taking equations (3) and (4) as algebraic equations

$$v_{sd} = -R_s i_{sd} + X' i_{sq} + E_d \tag{17}$$

$$v_{sq} = -R_s i_{sq} - X' i_{sd} + E_q \tag{18}$$

$$\frac{1}{\omega_s \omega_B} p E_d = -\frac{1}{T_0} (E_d - (X - X') i_{sq}) + s E_q \tag{19}$$

$$\frac{1}{\omega_s \omega_B} p E_q = -\frac{1}{T_0} (E_q + (X - X') i_{sd}) - s E_d \tag{20}$$

$$T_e = E_d i_{sd} + E_q i_{sq} \tag{21}$$

B. Different mechanical drive train system models

Considering the features of low stiffness of the shaft between the turbine and generator, the two-mass drive train models can be expressed as

$$2H_M \frac{d\omega_M}{dt} = T_m - K_s \theta_s \tag{22}$$

$$2H_G \frac{d\omega_G}{dt} = K_s \theta_s - T_e \tag{23}$$

$$\frac{d\theta_s}{dt} = \omega_B (\omega_M - \omega_G) \tag{24}$$

Where H_M, H_G are the inertia constant of the wind turbine rotor and the generator rotor, respectively. ω_M, ω_G are the wind turbine and generator speed, respectively. K_s is the shaft stiffness; θ_s is the shaft tensional twist angle.

If the wind turbine, gearbox, shafts and generator are lumped together into an equivalent mass, the drive train model of wind turbines is described as the one-mass model, which is presented in equation (1), here, the lumped inertia constant is the sum of the turbine rotor and the generator rotor.

IV. Transient Behavior Analysis And Comparison For Different System Models

In order to analyze the transient behaviour of different system models, and testify the validity of the direct method of CCT calculation based on the critical clearing slip, the transient stability of SCIG in wind turbine systems is compared and analyzed for the different generator models and the wind turbine drive train models at the various initial system operation conditions.

The four different system models are adopted and described in TABLE I.

TABLE I
Description Of Different System Models

Symbol	Electrical equation	Mechanical model
DD	Detailed transient model (12)-(16)	Two-mass model (22)-(24)
RD	Reduced transient model (17)-(21)	Two-mass model (22)-(24)
RS	Reduced transient model (17)-(21)	One-mass model (1)
SS	Steady state model	One-mass model (1)

The system considered is a single SCIG equivalent wind farm connected to an infinite bus through a double circuit transmission line as shown in Fig.2. The main data of SCIG and system parameters are described in TABLE II.

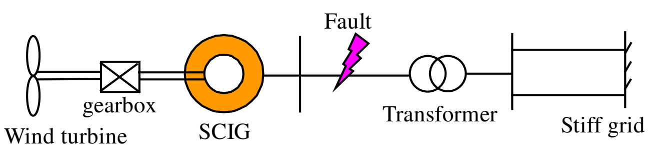


Fig.2 Configuration of SCIG in wind turbine systems

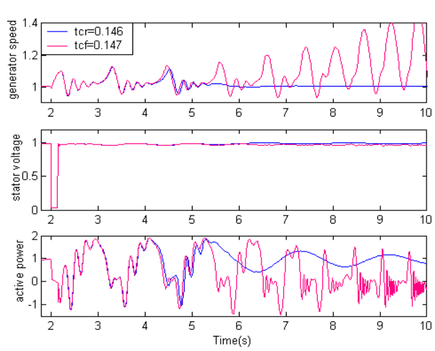
TABLE II
SCIG Data And System Paraments

Main parameters	Value
Rated power P_N (MW)	3
Rated voltage U_N (V)	575
Rated frequency f_N (Hz)	60
Stator resistance R_s (p.u.)	0.004843
Rotor resistance R_r (p.u.)	0.004347
Stator leakage inductance $X_{s\sigma}$ (p.u.)	0.1248
Rotor leakage inductance $X_{r\sigma}$ (p.u.)	0.1791
Mutual inductance X_m (p.u.)	6.77
Generator rotor inertia constant H_G (s) in per unit	0.5
Wind turbine rotor inertia constant $H\omega$ (s) in per unit	4.54
Shaft stiffness K_s (p.u./el.rad)	0.3
Transformation reactance X_{tr} (p.u.)	0.025
A single transmission line reactance X_l (p.u.)	0.0013

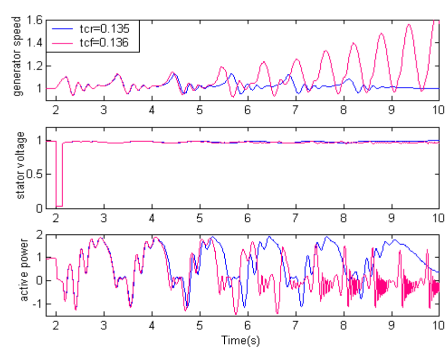
A. *Transient behavior simulation*

In the following simulation, assuming the initial input mechanical torque *Tm* is normal torque. The three-phase short-circuit fault at the stator terminal of SCIG occurs at the time t=2s, the generator rotor speed, stator voltage and active power are simulated for the case of the critical stable and an unstable case, respectively. The transient behaviors of different system models are shown in Fig. 3. Where *tcf* and *tcr* are fault-clearing time. The *tcr* is critical clearing time, obtained by the trial and error method.

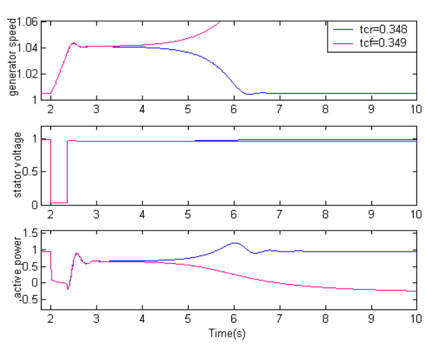
As it can be seen that the generator rotor speed and active power present large oscillations during the on-fault and post-fault for the case of the two-mass shaft system model, so that the stability region is reduced in comparison with the one-mass



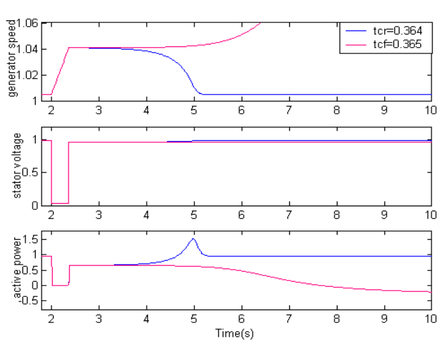
a) DD system model



b) RD system model



c) RS system model



d) SS system model

Fig.3 Transient behavior of wind turbines system for different system model shaft model. The transient behaviors are similar between the DD model and RD model, even though the obtained CCT of RD model is smaller than the case of DD model. In addition, the behaviors are also similar between RS model and SS model, however, the SS model is so simple that the active power seldom occur oscillation at the moment of clearing fault, and the CCT is too optimistic. Comparison with SS model, the active power and speed occur some oscillation in RS model, owing to considering with the rotor electrical transients.

B. *CCT estimation*

Based on the direct method of CCT estimation with the critical clearing slip of generator torque-slip curve in steady state condition, CCT is calculated and compared for different system models on the condition of various initial input mechanical torques. Detailed results are shown in TABLE III. Where CS denotes the direct method based on the critical clearing slip; TE denotes the trial and error method by simulation.

TABLE III

THE CALCULATION RESULTS OF CCT FOR DIFFERENT SYSTEM MODELS

Initial input mechanical torque T_m (p.u.)	CCT (s)							
	DD model		RD model		RS model		SS model	
	CS	TE	CS	TE	CS	TE	CR	TE
1	0.058, 0.311, 0.571, 0.970, 1.054	0.115	0.056, 0.296, 0.568, 0.965, 1.043	0.103	0.398	0.348	0.363	0.362
0.9	0.072, 0.321, 0.578, 0.985, 1.072	0.435	0.061, 0.302, 0.574, 0.983, 1.061	0.409	0.521	0.468	0.475	0.473
0.8	0.101, 0.351, 0.602, 1.021, 1.101	0.614	0.091, 0.331, 0.592, 1.012, 1.093	0.612	0.682	0.627	0.634	0.631
0.7	0.149, 0.464, 0.641, 1.594, 1.601	0.831	0.141, 0.454, 0.632, 1.581, 1.595	0.822	0.911	0.842	0.854	0.850
0.6	0.721, 1.126, 1.692	1.181	0.695, 1.104, 1.632	1.176	1.284	1.186	1.195	1.192
0.5	1.331, 1.684, 2.272	1.750	1.271, 1.654, 2.252	1.743	1.838	1.754	1.769	1.764

From the results in TABLE III, some scenario are obtained as (1) At the same condition of input mechanical torque, the CCT calculation with the two- mass shaft model is smaller than that of the one-mass shaft model by using TE method. Furthermore, with the input mechanical torque increase, the difference of CCT calculation is more and more obvious, especially at the normal operation condition, the CCT is almost 0.11s with the two-mass shaft model, however, it is about 0.36s with the one-mass shaft model.

(2) It is noticeable that several different time values are obtained in DD model and RD model by using CS method at the same initial input mechanical torque, and all of them aren't close to CCT value obtained by TE method. That is to say, the CS method is invalid to calculate the CCT in DD model and RD model. In order to explain the multi-values of the two-mass shaft model, the response of generator speed of RD model and RS model during the fault period are shown in Fig. 4, where the initial input mechanical torque is normal value.

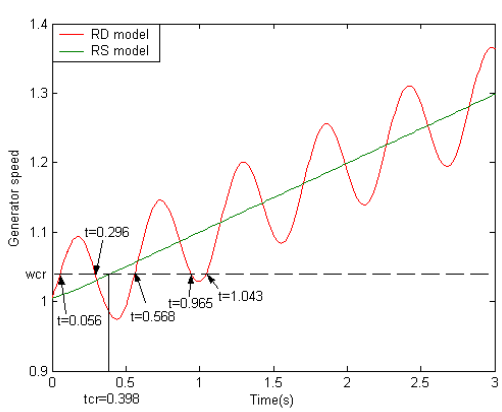


Fig.4 generator rotor speed curves of RD model and RS model during the fault period

As it can be seen from Fig.4, the electromechanical interaction is seen as tensional oscillation in the shaft systems equipped with gearboxes, the generator rotor speed curve of RD model appears large multi-swings during the fault period, so that there are some different time values corresponding to the same critical clearing speed *wcr*. In addition, the generator rotor speed response of RD model is almost a line, therefore there is an only cross point between the curves of speed change and the critical clearing speed.

(3) There are also a few discrepancies of CCT calculation in RS model by using the two methods; even though only considering with the rotor electrical transients, the CCT calculation is almost compatible to the SS model by using the two methods.

C. *Discussion*

(1) From the comparative results of the transient behaviors simulation and CCT estimation, it can be seen that the models of transient stability analysis of fixed-speed wind turbine systems should be represented with the two-mass shaft model of wind turbine drive train systems. As far as the induction generator transient models are concerned, the reduced model neglecting the stator electrical transients can be used to analyze the transient stability, even though the calculated CCT of RD is smaller than in the case of DD model.

(2) The method of CCT calculation based on the steady-state critical clearing slip of SCIG is incapable of determining the transient stability limit of the wind turbine systems, because the generator rotor speed may present multi-swings during the fault period. So the suitable methods of transient stability analysis of wind turbine systems need to be studied.

V. CONCLUSIONS

In order to investigate the models and methods for the transient stability analysis of wind turbines system with SCIG, some methods of determining the stability limit based on the critical clearing slip of SCIG are presented. Several system models including the different generator models and drive train models of wind turbines are established in this paper. Based on the four different system transient models, the transient behaviors are simulated and compared when the stator terminal of SCIG is subjected to the three-phase short-circuit fault. The CCT is calculated and compared by using the CS and TE method. The models and methods of transient stability analysis of wind turbine systems based on SCIG are discussion in detail. The obtained results have shown that the wind turbines system model incorporating the two-mass shaft model is suitable to the transient stability analysis; the direct method of calculation CCT based on the critical clearing slip is incapable of determining the transient stability limit, due to the multi-oscillation of generator rotor speed during the fault period.

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