Transient Stability Analysis of Distributed Generation Connected with Distribution Network

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***Abstract*—The transient stability problem of Distributed Generations (DGs) has become one of the constraints for the inter-connection between a large number of DGs and the distribution network. In this paper, DGs connected to the distribution network are divided into DGs based on synchronous generator interface, induction generator interface and inverter interface according to the different DG interface types, and the mathematical models of DG are established based on different interface types. Then through the simulation on the typical one machine infinite bus systems, the paper analyses the transient process and the corresponding fault critical clearing time of DGs under the terminal fault conditions. Finally on the basis of the transient stability analysis of DGs, it puts forward corresponding measures for DGs based on different interface types to improve transient stability.**

***Index Terms*—distributed generation, transient stability, synchronous generator, induction generator, inverter, fault critical clearing time**

I. Introduction

The rapid development of distributed power generation technology makes DGs play a more and more important role in the power system [1]. They can be divided into DG with synchronous generator interface, induction generator interface and inverter interface according to the different interface types. DGs connected with the grid makes distribution network change from single power supplying and few loop to multi power supplying and multi loop, which will certainly affect transient stability of distribution network.

Current standards on the interconnection between DGs and the grid request to remove DGs after the occurrence of the fault without considering the transient process. Aiming at the problem above, the paper studies the dynamic characteristic of DGs and analyses the ability to withstand faults after the occurrence of the fault [2], which provides the bases for the treatment measures of DGs after faults occur and provides the guidance for the protection of the distributed network with DGs. The research on the transient stability of DGs is not much currently. In [3], the influence of distributed power is analyzed on the transient stability of distribution network. In [4], the transient stability of DGs based on induction generator interface is studied and several measures are proposed to enhance the transient stability of induction generator. In [5], the transient stability of micro-grids with a variety of DGs is studied under different control strategies. In [6], the transient process of AC distributed power in micro-grids is analyzed through the simulation, but transient stability analysis of inverter based distributed power does not involve.

This paper studies the transient stability of DGs based on different interface types, and establishes the mathematical model. Then through the simulation on the typical one machine infinite network, it analyses the transient process and the corresponding fault critical clearing time of DGs under the terminal fault conditions, and discusses the related physical phenomenon. Finally, the corresponding measures are put forward to improve transient stability.

II. DG Models Based on the Different Interface Types

There are many kinds of DGs， according to the different interfaces, they can be divided into DGs with synchronous generator interface, induction generator interface and inverter interface. The interface types of common distributed generation are as shown in Table I.

TABLE I. The Interface Types of Common Distributed Power

Distributed generation	Interface type
Wind power generation	Inverter/ Induction generator
Small hydropower	synchronous generator
Photovoltaic cells	Inverter
Micro-turbine	synchronous generator
Electric vehicle	Inverter
Battery	Inverter
Fuel cell	Inverter
Biomass energy	synchronous generator/ Inverter

A. Synchronous Generator Model

Synchronous generator is common power generation equipment in the traditional power system. The speed of rotor is as same as stator magnetic field. By changing the excitation magnetic field, the terminal voltage and reactive power of synchronous generator can be controlled. In the dq coordinate system, stator winding

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voltage equations and flux equations of synchronous generator can be respectively expressed as:

$$\begin{cases} u_d = -r_a i_d - \omega\psi_q + p\psi_d \\ u_q = -r_a i_q + \omega\psi_d + p\psi_q \\ u_f = r_f i_f + p\psi_f \end{cases} \tag{1}$$

$$\begin{cases} \psi_d = -X_d i_d + X_m i_f \\ \psi_q = -X_q i_q \\ \psi_f = -X_m i_d + X_f i_f \end{cases} \tag{2}$$

where u_d , u_q are the d and q axis quantity of synchronous generator stator voltage; i_d , i_q are the d and q axis quantity of stator current respectively; ψ_d , ψ_q are the d and q axis quantity of stator flux linkage; r_a , r_f are the resistance of stator winding and excitation winding; u_f , i_f , ψ_f are the voltage, current and flux linkage of excitation winding; X_d , X_q are the d and q axis quantity of reactance; X_m is the cross resistance of stator and rotor; X_f is the reactance of excitation winding.

This paper adopts the three order model of synchronous generator, and assumes that:

(1) Ignore the transient stator winding that in the stator voltage equation assume:

$$p\psi_d = p\psi_q = 0 \tag{3}$$

(2) In the stator equation, set $\omega \approx 1$;

(3) Ignore D and Q winding, whose role can be replaced by adding the damping term in the rotor motion equations.

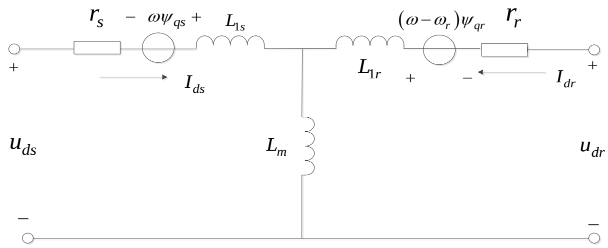
Then the three order model of synchronous generator can be derived [7]:

$$\begin{cases} T'_{d0} pE'_q = E_f - E'_q - (X_d - X'_d) i_d \\ 2H\dfrac{d\omega}{dt} + D(\omega - 1) = T_m - [E'_q i_q - (X'_d - X_q) i_d i_q] \\ \dfrac{d\delta}{dt} = \omega - 1 \end{cases} \tag{4}$$

where E'_q is q axis transient internal voltage; E_f is the stator electromotive force; i_d , i_q are the d and q axis quantity of stator current; X_d , X_q are the d and q axis quantity of stator resistance; X'_d is the d axis transient reactance; T'_{d0} is the d axis open circuit time constant; D is the damping coefficient.

B. Induction Generator Model

As the interface type of DGs, induction generator has wide uses. Without excitation system, induction generator cannot control the terminal voltage. When working, induction generator sends active power to power grid, and absorbs reactive power from the grid at the same time. In this paper, induction generator adopts the four order state equation to describe the electrical motor, the equivalent structure diagram is shown in Fig. 1.



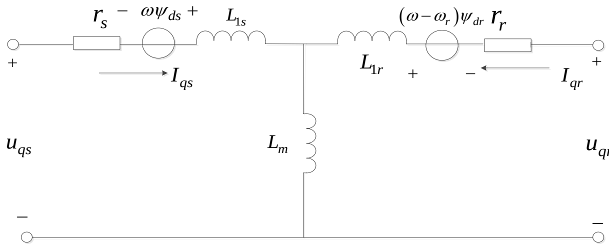


Figure 1. The equivalent circuit of the asynchronous generator: (a) D axis equivalent circuit and (b) Q axis equivalent circuit.

In Fig. 1, r_s , L_{1s} are the resistance and leakage inductance of stator winding; r_r , L_{1r} are the resistance and leakage inductance of rotor winding; L_m is the excitation inductance; ψ_{ds} , ψ_{qs} are the d axis and q axis flux quantity of rotor winding; ω is the rotating angular speed of stator magnetic field; ω_r is the angular rotor speed.

In the dq coordinate system, stator winding voltage equations and rotor winding equations of induction generator can be respectively expressed as:

$$\begin{cases} u_{ds} = r_s i_{ds} - \omega\psi_{qs} + p\psi_{ds} \\ u_{qs} = r_s i_{qs} + \omega\psi_{ds} + p\psi_{qs} \\ u_{dr} = r_r i_{dr} - (\omega - \omega_r)\psi_{qr} + p\psi_{dr} \\ u_{qr} = r_r i_{qr} + (\omega - \omega_r)\psi_{dr} + p\psi_{qr} \end{cases} \tag{5}$$

$$\begin{cases} \psi_{dr} = (L_{1r} + L_m) i_{dr} - L_m i_{ds} \\ \psi_{qr} = (L_{1r} + L_m) i_{qr} - L_m i_{qs} \\ \psi_{ds} = (L_{1s} + L_m) i_{ds} - L_m i_{dr} \\ \psi_{qs} = (L_{1s} + L_m) i_{qs} + L_m i_{qr} \end{cases} \tag{6}$$

where u_{ds} , u_{qs} are the d and q axis quantity of induction generator stator voltage; u_{dr} , u_{qr} are the d and q axis quantity of asynchronous generator rotor voltage.

The rotor motion equations of asynchronous generator can be expressed as:

$$\frac{d\omega_m}{dt} = \frac{1}{2H}(T_e - F\omega_m - T_m) \tag{7}$$

where T_m is the mechanical torque; T_e is the electromagnetic torque; ω_m is the mechanical angular speed of rotor; H is the unit inertia time constant; F is the constant damping coefficient.

C. Inverter Model

Inverter interface based DG is connected with power grid through the inverter without direct coupling relation.

The basic structure of the voltage source inverter interface based DG is shown in Fig. 2.

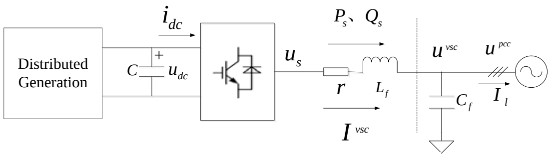


Figure 2. Basic structure of VSI.

According to the different types of DGs and the purpose of interconnection between DGs and distribution system, the inverter interface based DG adopts different control strategies. Typical control strategies include constant power control strategy (PQ control), droop control strategy and constant voltage and frequency control (V/f control) [8], [9].

When DGs connected with the distribution network, the frequency of system and terminal voltage of DGs are supported by the distribution network and DGs generally adopts the PQ control strategy. PQ control is to make that the output active power and reactive power of DGs are same with the value given to reference. The essence of constant power control is to control he active power and reactive power decoupled respectively. The principle diagram is shown in Fig. 3.

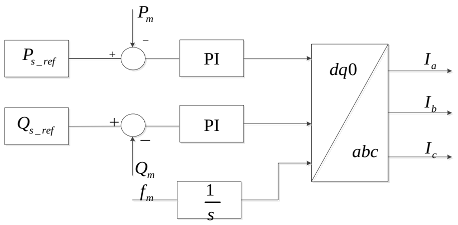


Figure 3. The principle diagram of PQ control.

However, the distributed power adopting PQ control does not participate in voltage regulation and frequency regulation of the power grid, and it is unable to withstand the load fluctuation and the disturbance of frequency of the grid.

III. The Transient Stability Analysis of DGs

The accession of DGs changes the single way receiving and consuming energy from distribution network, and leads to research on the transient stability problem of the distribution network. The transient stability of DG based on different interface types is different. The paper analyses the transient stability of DGs based on different interface types when the terminal fault occurs on the typical one machine infinite bus system below. The fault mentioned in this paper refers to three-phase fault. The one machine infinite bus system used by the paper is shown in Fig. 4:

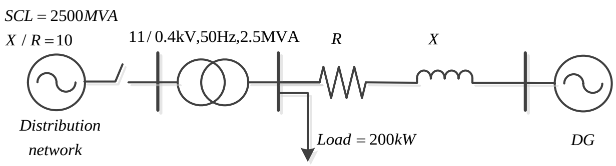


Figure 4. The typical one machine-infinite bus system.

where the line parameters:

$$r + jx = 0.242 + j0.365(\Omega / km),\ L = 50m$$

A. The Transient Stability Analysis of Synchronous Generator Interface Based DG

Synchronous generator is a common interface type of DG [10]. The transient stability of synchronous generator interface based DG is analyzed below. Assume the mechanical power input unchanged before and after the fault and the fault occurs at 2.0s. The simulation results are obtained with different fault duration as shown in Fig. 5.

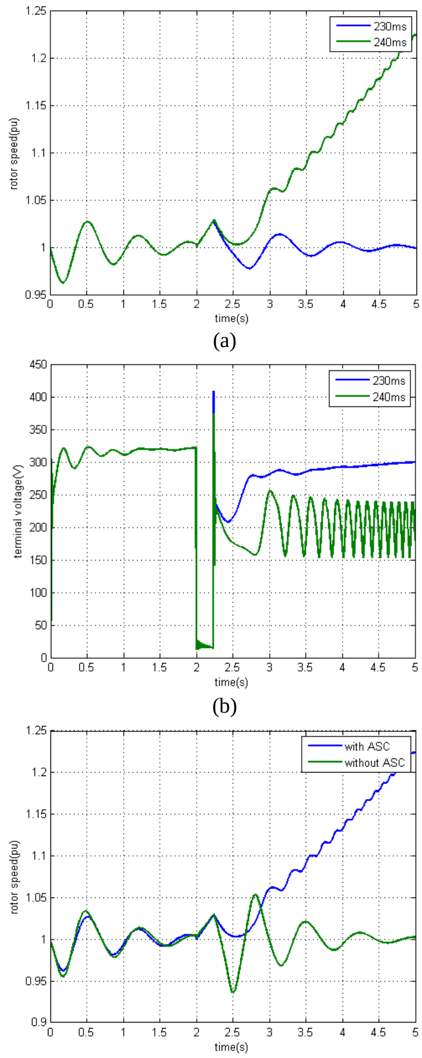


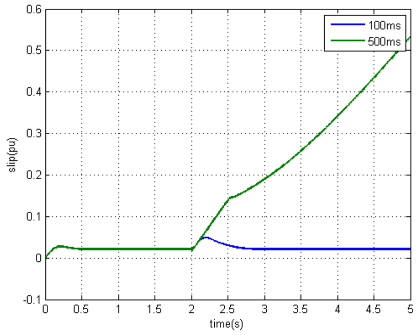
Figure 5. The dynamic response of the synchronous generator before and after fault: (a) the change of speed; (b) the change of terminal voltage; (c) the effect of ASC system on transient stability.

The transient stability of synchronous generator is analyzed through the power angle characteristic curve. Whether the system is stable that is judged by the change of power angle, namely the change of speed integral. As shown in Fig. 5, when the terminal faults of synchronous generator occur, the terminal voltage will decrease instantaneously and the speed fluctuates. From the dynamic simulation, fault critical clearing time is obtained and the critical clearing time is 230ms. If the fault is removed before the critical clearing time, the speed of synchronous generator will tend to a stable value after fluctuating for a short time. If the fault removed too late, the speed will increase rapidly and the synchronous generator will lose stability finally. Therefore removing faults in time can ensure the stability of the synchronous effectively.

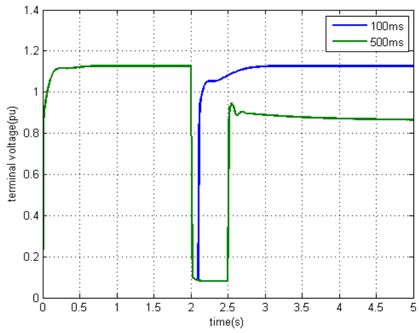
The simulation above is carried out under the premise of constant mechanical power. Improving the Automatic Speed Control (ASC) device and changing mechanical power by adjusting speed can improve the transient stability effectively. As shown in Fig. 5(c), when the machine without ASC device loses the stability, the machine with ASC device is still able to maintain transient stability.

B. The Transient Stability Analysis of Induction Generator Interface Based DG

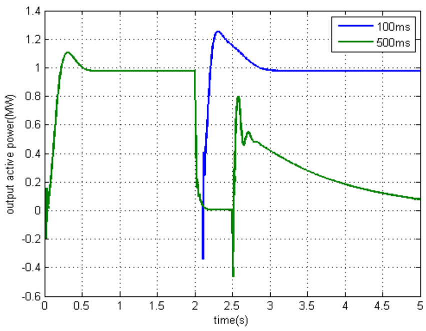
As the interface type of DGs, induction generator has wide uses [11]. The transient stability of induction generator interface based DG is analyzed below. Assume the fault occurs at 2.0s. The dynamic responses of induction generator with the fault continuing 100ms and 500ms are obtained by the simulation respectively. The simulation results are shown in Fig. 6.



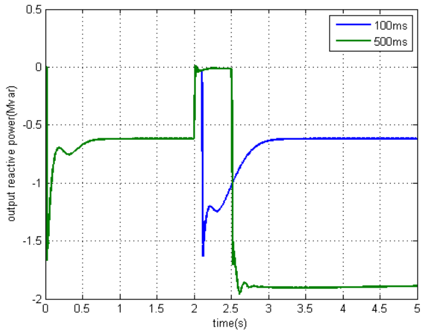
(a)



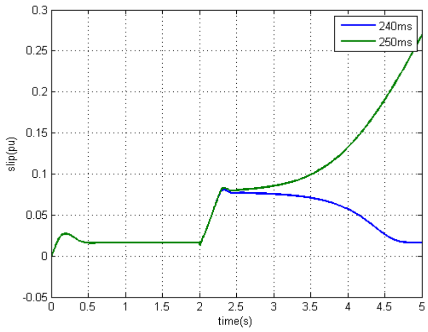
(b)



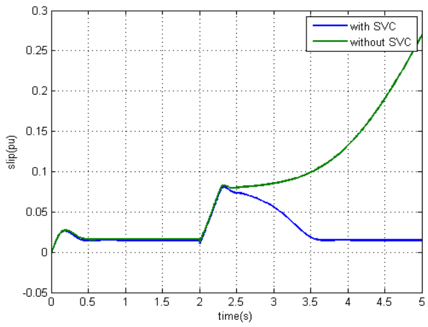
(c)



(d)



(e)



(f)

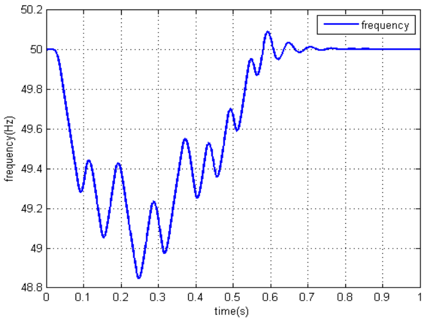
Figure 6. The dynamic response of asynchronous generator before and after the fault: (a) the change of slip; (b) the change of terminal voltage; (c) the change of active power; (d) the change of reactive power;(e) critical clearing time of faults in induction generator; (f) effect of reactive power compensation on transient stability.

Induction generator uses electromagnetic torque slip curve to analyze the transient stability [12]. Whether the system is stable that is judged by the change of slip or rotor speed. As shown in Fig. 6(a), induction generator is able to maintain transient stability when the fault continues 100ms and will lose transient stability when the fault continues 500ms. And through the further simulation, the fault critical clearing time is obtained and the critical clearing time is 240ms as shown in Fig. 6(e). Therefore, in order to ensure the transient stability of induction generator, the fault must be removed timely. As shown in Fig. 6(b) and Fig. 6(c), the terminal voltage and the output active power will decrease rapidly when the fault occurs. After the fault disappears, voltage will rise again in a very short period of time and reach a constant value. The recovery of the output active power requires a transient process because the induction generator absorbs active power from the grid firstly and delivers active power to the grid when the voltage recovers. As shown in Fig. 6(b) and Fig. 6(d), when the induction generator loses stability, the slip will increase rapidly, but the terminal voltage can reach a constant value which is because the induction generator absorbs a large amount of reactive power from the grid to ensure the stability of voltage.

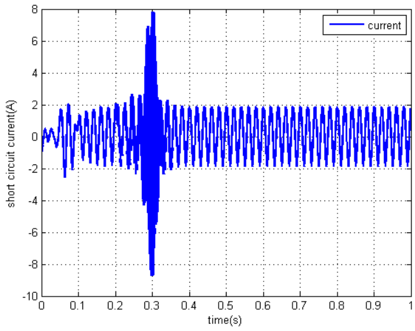
For the induction generator, measures like reducing the slip increase rate and increasing the recovery rate of the terminal voltage can be taken to maintain the stability. In addition, SVC device added in the terminal of the induction generator can improve the transient stability effectively. As shown in Fig. 6(f), the induction generator with SVC device can maintain transient stability when the induction generator without SVC device loses stability under the same condition.

C. The Transient Stability Analysis of Inverter Interface Based DG

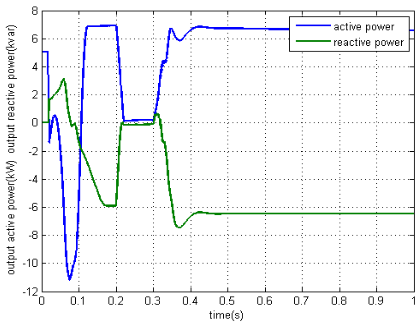
The transient stability of the inverter interface based DG based on PQ control strategy is analyzed below. Set the output active power is 5kW and the output reactive power is -3kvar. Assume the fault occurs at 0.2s and be removed after 100ms. The dynamic response of inverter interface based DG before and after the fault is shown in Fig. 7.



(a)



(b)



(c)

Figure 7. The dynamic response of inverter interface based distributed generation before and after the fault: (a) the change of frequency; (b) the change of current; (c) the change of output.

As shown in Fig. 7(a), when a fault occurs, the frequency of system will fluctuate largely which is because the inverter interface based DG based on the PQ control strategy cannot maintain the frequency itself. Supported by the system, the frequency will return to power frequency (50Hz) after the fault removed. As shown in Fig. 7(b), when the fault occurs, a large short circuit current will be produced. The ability of power electronic devices to withstand short circuit current is limited, so the appropriate overcurrent protection should be set. As shown in Fig. 7(c), due to the existence of inductance components, the output of DG has also experienced a transient process before and after fault occurs. When the terminal fault occurs, the output of DG will reduce to 0 gradually.

Under the precise of constant load, the transient stability of the inverter interface based DG is good. Attention that the protection of the inverter interface based DG should be set reasonably to avoid the instantaneous fault current damaging the power electronic components.

IV. CONCLUSIONS

Aiming at the trend of DGs connected to the distribution network, the research of relay protection for distribution network with DG should be taken to detect and remove of faults in distribution network timely which can ensure the stable operation of the system.

For synchronous generator interface based DG, the transient stability can be improved by improving the performance of ASC system which is used adjusting the mechanical power of prime mover by adjusting the speed. For induction generator interface based DG, SVC devices can be paralleled to improve the transient stability. For inverter interface based DG, we can make reasonable grid connection control strategy according to the characters of the inverter to improve transient stability.

Through the analysis on transient stability of DGs based on different interfaces and the research on the improvement measures, the current standards on the interconnection between DGs and the grid can be improved to improve the generation efficiency of DGs. And then DGs in distribution network can be used as efficiently as possible to meet the local load demand and then transmit energy to the grid.

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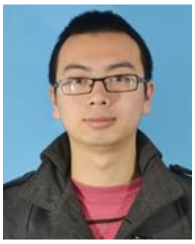

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