Transient Stability Study of Distributed Induction Generators Using an Improved Critical Speed and Critical Clearing Time

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ABSTRACT

Stability is an important constraint in power system operation and the transient stability constrained optimal power flow (OPF) has always received considerable attention in recent years. In this paper, the defects of the existing models and algorithms around this topic are firstly analyzed, on the basis of which, a multi-objective optimization method is proposed. This paper proposes an improved steady state equivalent circuit method to determine transient stability of a distribution system or a micro-grid with multiple IGs. Interaction between IGs and distribution network during a fault is investigated. The relationship between network parameters and speeds of IGs is derived using the steady-state equivalent circuits of IGs. The critical speed and critical fault clearing time (CCT) for maintaining system stability are determined using the proposed technique. Case study results demonstrate the proposed multi-IG distribution system has many advantages, compared with traditional using dynamic simulation.

Keywords--- Critical clearing time, critical speed, distribution network, induction

I. INTRODUCTION

MORE distributed generators (DGs) will be embedded in distribution networks with increasing penetration of renewable power. DGs include synchronous generators, induction generators and other power sources with the electronic interface [1],[3]. On the other hand, induction motors (IMs) form large part of load in industrial distribution networks. Therefore, transient stability problem appears in distribution network operation due to the connection of various DGs [4] and IMs [5].

Unlike doubly-fed induction generator for a large wind turbine connected to high voltage transmission network through electronic interface, most squirrel-cage conventional IGs are usually used in small and medium scale hydro’s and wind farms with direct connection to sub-transmission and distribution networks as DGs due to ability to produce power at varying rotor speeds. The prime mover can be a steam turbine and gas turbine with constant mechanical torque or wind turbine with variable mechanical torque.

The squirrel-cage induction generator has received an augmented attention in distribution networks due to lower cost, smaller size, and less maintenance [6]. When a short-circuit fault occurs, the electro-magnetic torque of an induction machine decreases significantly and rotor speed accelerates due to drop of the terminal voltage. At the same time, high reactive power consumption may cause voltage collapse of the network.

An IG must be either broken emergently or disengaged if its speed exceeds the critical speed [7]. The presence of large scale IGs in a weak network would incur serious concerns about system security and stability. The IG based on the relatively mature induction motor (IM) has a significant impact on voltage stability in distribution network. In the past, the considerable attention has been paid to the reduced order modeling and stability analysis of IM [5], [8],[10].

The difference is that the IG tends to excessively accelerate instead of the stalling of IM. Therefore, IG is a factor contributing to short-term voltage instability [11]. It is important to understand the dynamic performances of IGs under normal and fault conditions and their impacts on stability of distribution networks. Following these remarks, the aim of this paper is to study the transient stability of a multi-IG distribution network. The stability of an IG denoted as speed stability was studied [12], [13]. The transient stability of a single IG has been intensively investigated using the dynamic simulation software [14]– [1], physical experiment [9] and real-time simulation tool [2]. In order to identify the instability mode, the eigenvector analysis has also been used [11].

The critical speed and critical clearing time (CCT) of a single IG in a distribution system were investigated [6], [7].

The critical speed is used as the transient stability limitation. Although the CCT of a distribution network with multiple IGs can be determined by using simulation techniques through the trying-error method, very long computation time is required. On other hand, the physical dynamic process of IGs cannot be
theoretically explained and the parameters which affect system instability are not explicit. An analytical method for analyzing large-disturbance stability of a single IG was proposed [2].

The authors [2] stated “Although the method can be applied to a multi-induction generator system by using aggregation techniques when such generators are installed electrically close to each other, the application to multi-induction generator systems, where the generators are installed electrically away from each other, is very difficult, if not impossible”. Currently there is no simulation software which can be directly used to determine CCT of a distribution network with multiple IGs. This paper proposes an analytical method to calculate the critical speed and the CCT of a multi-IG distribution network based on the transient stability characteristics.

The proposed technique is a significant improvement of the one in [14] and can significantly reduce computation burden. The transient stability interactions among IGs are investigated using the proposed technique. The proposed technique is verified using the dynamic simulation software MATLAB where IGs are presented by the fifth-order differential model. The errors between the analytical and the simulation results are analyzed.

II. TRANSIENT STABILITY OF AN INDUCTION GENERATOR

Transient stability model of an IG have been studied. The speed stability model and parameters are introduced in this section. All parameters in this paper are in per unit. The steady-state equivalent circuit of an IG connected to an infinite system bus is shown in Fig. 1.

$$\begin{align*}
    V_c &= \frac{jX_m V_s}{R_s + j(X_s + X_m)} \\
    R_s + jX_s &= \frac{jX_m(R_s + jX_s)}{R_s + j(X_s + X_m)}
\end{align*}$$

+ is the stator side impedance which includes the network impedance between the IG and the infinite bus, and are the rotor resistance and leakage reactance, respectively. is the magnetizing reactance is the rotor slip which is positive for motor operation.

For a synchronous generator, the CCT is defined as the maximum allowed time duration to clear the fault such that the system maintains transiently stable [15]. The CCT for a distribution network with multiple IGs is similarly defined as the maximum allowed fault clearing time for all IGs to retain their stability. This means that a distribution network is unstable when the speed of any of IGs reaches to it’s just before the CCT.

Fig.3 shows the torque-speed curves of an IG after a fault. For a given, the stable and unstable equilibrium points under are shown in the figure. The corresponding rotor speeds at the two points are the steady-state speed and the critical speed, respectively. When a fault occurs, the time duration for an IG to accelerate from to is defined as the CCT [7], [6]. An IG can either return to the stable point if the fault is cleared before the CCT or loss the control of its speed if the fault is not cleared before the CCT. In later case, the IG must be disconnected from the grid. It is assumed in this paper that the fault is self-cleared, which means all equipments and IGs remain connected to network after the fault cleared [1], [2]. It should be noted that is assumed to be constant during the fault period because the electrical transient die out faster than the mechanical motion dynamic [2], [4]. This assumption may also be effective for wind turbines with slow change of wind speed.

III. CCT DETERMINATION OF MULTI-IG NETWORK

A. Network Equivalent Circuit and Stable Equilibrium Point

Fig.1 shows a distribution network with nodes and IGs. The node 1 is the source node. The source is represented by a Norton equivalent. Current is used as the reference of the network and is a real number. Nodes from 2 to are IG nodes. Each IG is represented by the equivalent circuit. The IG connected to node as shown in Fig. 7 is used for illustration. New internal nodes of IGs are numbered from 2 to (m+1). The nodal voltage equations in matrix form are network with nodes are formed by inserting an internal node for each IG.

B. Rotor Speed of IGs

During Fault It should be noted that the CCT depends on location and type of fault, as well as on the fault clearing action. In practice, the single line to ground fault is the most common one among different faults in power system. However, the three phase faults represent
the worst condition in term of the stability of IGs according to the simulation results [8]. The CCTs of three phase fault need to be determined for the relay setting in distribution networks embedded with IGs [8]. Therefore the three phase faults are used in the paper to illustrate the proposed methods. Since the electric transient process is usually much faster than the response of a mechanical prime mover, the mechanical torque can be assumed to be constant during the fault. This assumption is valid for fossil source driven prime movers. It is also suitable for renewable source driven prime movers due to slow change of wind speed. The electro-magnetic torques of IGs will change with the terminal voltage during the fault.

V. SYSTEM STUDIES

The proposed method is applied to two 50-Hz distribution networks. The time step is 1ms. The CCTs and critical speeds for different fault locations are calculated. The results obtained from the proposed method are verified by the simulation results using the PSCAD/EMTDC in which the model of IGs is described by the stator and rotor voltage equations in d-q axes reference frame rotating at synchronous speed as well as the rotor motion equation.

A. Two-IG System

In order to verify the results, the speed and terminal voltage responses for different fault clearance time have been simulated using the PSCAD/EMTDC and the selective results near the analytical results are presented in Fig.6 and 7.

![Fig.4. Two-IG distribution system.](image)

B. Effect of Electrical Distance between IGs

A 2 MW IG system is analyzed to illustrate the impact of the distance between two IGs on system CCT. When the distance between Bus 2 and Bus 3 changes from 0 to 20 km, the CCTs for the two faults at Buses 1 and 2 are shown in Fig. 4. For the two faults, the system stability is determined by IG1. The CCT increases with the increase of distance. Therefore, the fault needs to be cleared in short time to protect system instability when the fault occurs near the system bus.

The critical speed curves of the two IGs are presented in Fig. 5. When the fault occurs at upstream Bus 1, the critical speeds of the two IGs are about the same for different. When the fault is at downstream Bus 2, the speeds of two IGs have large differences because of the difference terminal voltage.

C. Effect of the Short-Circuit Capacity of Substation

The short circuit capacity only affects the system impedance used in the fault calculation. The CCT curves under varying short-circuit capacity of substation for the faults at Buses 1 and 2 in Fig 4. The system CCTs decrease evidently with reducing of short circuit capacity. It means that IGs will affect the system stability significantly when the capacity of IGs is large or the short circuit capacity of system is small. When the short-circuit capacity is larger than 600 MVA, the CCT has a small increase.

\[
T_z = \frac{R_e}{s} I_e^2 = \frac{R_e}{s} \left( \frac{V_i^2}{(R_e + R_e/s)^2 + (X_e + X_e)^2} \right)
\]

\[
\frac{d\omega_c}{dt} = \frac{1}{2H} (T_e - T_m)
\]

The results of the proposed method are the same with those of the simulation. The size of IGs will also have different impacts on distribution network. The effect of IG size can also be analyzed using similar analysis for distance effect. From (2) and (3), large size means small and, which means short equivalent distance from IG terminal to infinite bus. From the simulation results of the Four IG system, the farthest IG (like a small IG with large and) in downstream of the fault will loss its stability first. On the other hand, the disconnection of a large IG will have large impact on a distribution network and more loads have to be interrupted.

![Fig.5. Proposed Model](image)
Specifically, the stair step is increased by one at each parameter value when a branch active power meets a maximum is two reasons behind the error of CCT between the analytical and simulation results. The first one is the impedance model is used for an IG in the analytical method instead of the fifth-order differential model used in the simulation. The second is that the terminal voltages of the downstream IGs are assumed to be 0 immediately when the fault occurred in the feeder. In fact, the terminal voltage of an IG will reduce according to an exponential function. This assumption will give shorter CCT. Therefore, the CCTs calculated by the proposed method is conservative compared with those using the dynamic simulation.

VI. CONCLUSION

This paper studies the qualitative assessment of voltage stability based on branch active powers in the situation that the power system is stressed by gradual load/general increase. The main results are summarized as follows.

This paper proposes an improved analytical method to calculate critical speed and CCT of multi-IG systems. The problem is formulated based on the transient stability characteristics and the parameters of distribution network and solved using iteration technique. Explicit stability criteria can be obtained using the proposed technique. Transient stability interactions among IGs are investigated using the proposed technique. The proposed technique is verified using dynamic simulation. The comparisons show that the analytical results are very close to the simulation results. The impact of fault locations and the electrical distance between IGs on system transient stability are studied. The proposed analytical technique is effective to determine the CCT and the critical speeds of multi IGs, which are very useful for transient stability analysis and protection of distribution network. In the simulation method, the CCT and the critical speeds of multi IGs is determined using a searching method from different fault durations. Furthermore, we have discussed the applications of the studies for voltage stability assessment such as the qualitative evaluation and classification of the state of power system operation conditions in terms of voltage stability. These applications are cost-effective and provide useful knowledge on voltage stability before we calculate the voltage collapse as only branch active powers are used, which can be obtained by simple computation or from measurement.

REFERENCES
