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The influence of turbine generator rotor damping structure and material on first swing stability

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ABSTRACT

In this paper, we study the influence of rotor damping structure and material on First Swing Stability (FSS) of turbine generator connected to power system after three-phase short circuit. Considering the complex rotor damping structure of turbine generator, we make crucial improvements in finite element discrete strategy reflecting skin effect of eddy current and establish field-circuit-network coupled time-step finite element model. We test this model by the experiment of 7.5 kW model machine. Based on this model, we take a 300 MW turbine generator as an example to study the influence of damping bar, rotor iron core and conductive slot wedge on FSS. We investigate the importance of the rotor damping structure to FSS and find its impact is not negligible. By comparing the FSS limits affected by three components of rotor damping structure respectively, we conclude that the effect of rotor slot wedge and iron core is not linear superposition but Coupling relationship. Since we have several rotor slot wedge materials to choose from and the conductivity of these materials is different, we establish the relationship between FSS limit and conductivity of rotor slot wedge. The result shows that the FSS limit gradually increases as the conductivity of rotor slot wedge changes from σ_{al} (conductivity of aluminum alloy) to $0.05\sigma_{al}$.

1. Introduction

The First Swing Stability (FSS) is the ability of power system to maintain synchronism in the first oscillation period after three-phase short circuit. The FSS is an important factor to estimate the maximum transmission power of turbine generator and guarantee the safety and stable operation of power system [1–4]. A first swing stable system is considered stable if the system has adequate damping [5]. System damping generally includes electrical damping of rotor body and damping effect caused by power electronic equipment. The influence factors, such as automatic voltage regulation (AVR), transformer, system impedance, FACTS and SVC were investigated in the other people research [1,4–8]. Up to now, few people explore the influence of rotor body damping structure on FSS.

A typical turbine generator rotor damping structure consists of damping bars which are made from copper and distributed on both sides of pole face, rotor iron core made from magnetic alloy steel, slot wedge made from aluminum or stainless steel [9–11]. The three components are represented by (1), (2) and (3) in Fig. 1. The eddy current induced in three components of rotor damping structure is different during transient process since the spatial distribution and material of damping bar, rotor iron core, slot wedge is different. Therefore, the damping effect of three components of rotor damping structure on FSS is also different.

In addition, the damping effect of rotor body is also related to the skin effect of eddy current. The strength of skin effect reflects in the depth of magnetic penetration. In the transient process of the turbine generator, the relationship between the depth of magnetic penetration in rotor conductors and angular frequency of magnetic field (ω), permeability (μ), conductivity (σ) is $d \approx \sqrt{2/(\omega\mu\sigma)}$ [12]. Thus, the skin effect of eddy current is not only depending on material but also the angular frequency of magnetic field. While the process of first swing stability includes electromagnetic transient during three-phase short circuit (stage I in Fig. 2) and electromechanical transient after fault clearance (stage II in Fig. 2). The angular frequency which is approximately equal to synchronous angular frequency during electromagnetic transient process has a great difference with the angular frequency during electromechanical transient process. Therefore, the damping effect of rotor body in the process of first swing stability is very complicated.

Traditionally, when people study the FSS of synchronous generator, they base on generator model which considers the damping effect of rotor body as several equivalent fictitious windings [13,14].

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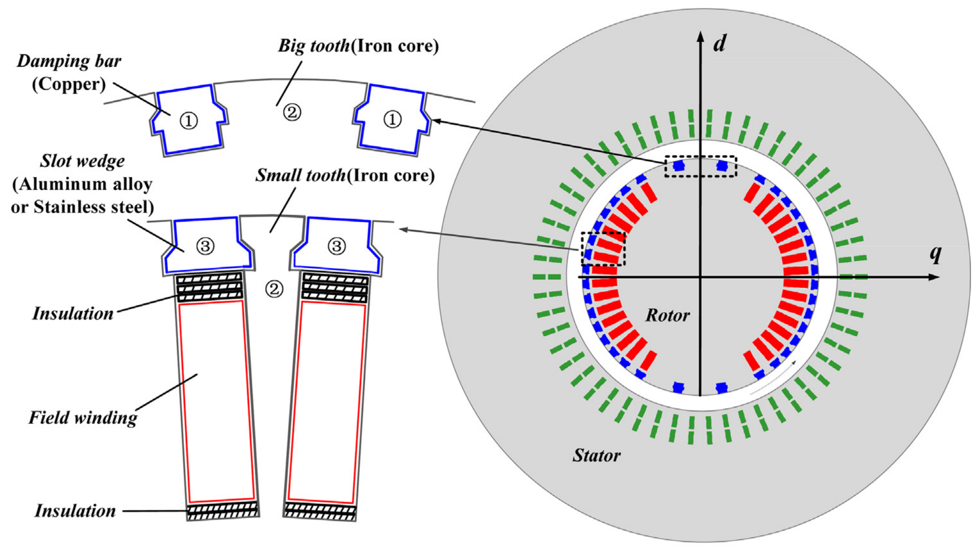

Fig. 1. Typical cross section of turbine generator.

However, the accurate parameters of damping bar, iron core and slot wedge are hard to calculate separately because of the complex rotor damping structure [15–17]. Some people have used reduced order generator models or the models which neglect damping effect of rotor body in their research of first swing stability [1,5,7]. As they introduce some assumptions and approximations in their simulation calculations, the precision of their simulation calculations is not satisfactory.

At present, time-step finite element model (T-S FEM) is very popular simulation tool to study the dynamic behaviors of synchronous generator [18–20]. The T-S FEM takes account of the damping effect of three components of rotor damping structure and the nonlinear factors include skin effect of eddy current, magnetic saturation and cross-magnetizing on the dynamic process [21–23]. Other people's research shows that the T-S FEM simulation results are consistent with experiments very well [24–26]. While the calculation results of steady stated stability limit and critical clearing time of Park equations have a large discrepancy with T-S FEM simulation results [27,28]. Therefore, T-S FEM which is used to study the impact of three components of rotor damping structure on FSS is more reliable and can guarantee the precision of simulation results.

In this paper, we make crucial improvements in finite element discrete strategy reflecting skin effect of eddy current and establish field-circuit-network coupled time-step finite element model and study the influence of rotor damping structure on FSS. Firstly, we take a 300 MW turbine generator as an example to investigate the influence of rotor damping structure on FSS limit. Then we compare the FSS limits affected by three components of rotor damping structure respectively; according to the comparison we find that the effect of rotor slot wedges on FSS is most important among three components of rotor damping structure and establish

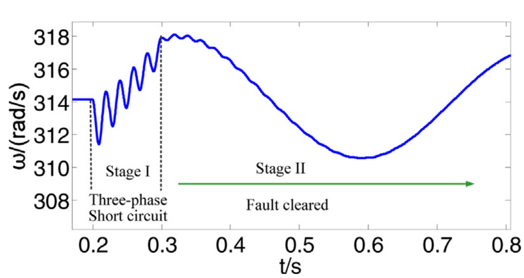

Fig. 2. Angular velocity during and following three-phase short circuit.

the relationship between FSS limit and conductivity of rotor slot wedge. The above results provide theoretical basis for turbine generator modeling and equivalent of rotor damping in power system simulation.

2. Field-circuit-network coupled time-step finite element model to analyze rotor damping effect of generator

2.1. System simulation model of turbine generator connected to power grid

We study the first swing stability of turbine generator by a schematic representation of power system shown in Fig. 3. It consists of a turbine generator connected to an infinite bus through a step-up transformer and a transmission system made up of two parallel lines. The representation of turbine generator is based on 2-D Finite Element Model. We establish the field-circuit-network coupled time step finite element model by the combination of magnetic field equations, electrical circuit equations and network equations. To reveal relationship between FSS and damping effect of rotor body, the impact of automatic voltage regulator and turbine fast valving action are neglected in this paper.

2.2. Field-circuit coupled time step finite element model

2.2.1. Field-circuit coupled equations

Since our research work concentrates on the damping effect of damping bar, rotor iron core, slot wedge, the end-leakage inductance is assumed to constant during the transient, we use a two-dimensional (2-D) model in the simulation calculation.

According to Maxwell's equations, the electromagnetic equation of turbine generator is:

$$\begin{cases} \Omega : \dfrac{\partial}{\partial x}\left(\dfrac{1}{\mu}\dfrac{\partial A}{\partial x}\right) + \dfrac{\partial}{\partial y}\left(\dfrac{1}{\mu}\dfrac{\partial A}{\partial y}\right) = -(J_{\text{source}} + J_e) \\ \Gamma : A = 0 \end{cases} \tag{1}$$

where A is the magnetic vector potential, μ is the permeability, J_{source} is the source current density and J_e is the current density in rotor conductors.

Source current density (J_{source}) includes current density of stator winding (J_{st}) and current density of field winding (J_f), which