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The influence of damping resistance on first swing stability of turbine generator considering stator transient

Xu Guorui, Zhan Yang*, Zhao Haisen, Liu Xiaofang

School of Electrical and Electronic Engineering, North China Electric Power University, Beijing 102206, China

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ABSTRACT

Generally, the ignored stator transient of turbine generator result in the unidirectional electromagnetic torque caused by damping resistance is neglected. While, the unidirectional electromagnetic torque has a braking effect which can reduce the rotor acceleration following the disturbance and improve the stability of power system. With a 300 MW turbine generator as an example, the large disturbance characteristic and First Swing Stability (FSS) limit are calculated by Time-Step Finite Element Model (T-S FEM) and three practical models of turbine generator in this paper. The unidirectional electromagnetic torque caused by stator transient is investigated and its important role in FSS is analyzed. Since there are several material options for damping windings, the influence of damping resistance on the large disturbance characteristic and FSS limit are calculated and compared under different damping resistance. The result shows that the FSS limits calculated by the practical model with stator transient are increased than that without stator transient; the FSS limits of turbine generator with damping windings made from stainless steel are larger than that made from aluminum and beryllium bronze by the four kinds of generator models. The result provides theoretic basis of generator modeling for precise simulation of power systems.

1. Introduction

Due to the increasing capacity of turbine generators and the development of long distance power transmission, First Swing Stability (FSS) which is the ability of power system to maintain synchronism in the first oscillation period after a disturbance has become a leading factor that restricts the transmission capacity [1,2]. On the other hand, more precise transient modeling of power systems is needed as AC-DC power transmission and fast switching power electronic devices are widely applied to power systems [3,4]. However, the traditional model of synchronous generators, the most important element in a power system, is not sufficiently accurate for simulation analysis of modern power system as it neglects the stator transient process [5,6]. The ignored stator transient result in the unidirectional torque caused by damping resistance is neglected. While, the unidirectional torque has a braking effect which can improve the stability of power system; meanwhile, the damping windings have several materials to choose from. Therefore, it is essential to study influence of damping resistance on first swing stability of turbine generator considering stator transient.

The traditional study of synchronous generator FSS is based on the practical model of synchronous generators which neglects the stator transient [7]. The practical model is considered to be three identical lump windings called d, q, and 0, symmetrically placed in the stator, and four unequal lump windings called f, D, g and Q in the rotor [7,8]. Windings d, q, 0 are obtained by Park transformation. While windings f and D represent the field winding and the damping winding in direct axis, windings g and Q represent the damping winding in quadrature axis [9,10].

There are two types of voltage terms in the stator voltage equations, that are speed-voltage terms ($\omega\psi$) and transformer voltage terms ($p\psi$) [5,11]. The speed-voltage terms represent the stator winding voltages that are created by the flux wave rotating in synchronism with the rotor. The transformer voltage terms, which represent the stator transients and prevent ψ_d and ψ_q from changing instantaneously, are usually neglected in stator voltage equations [12]. With these terms neglected, the stator quantities contain only fundamental frequency components and the stator voltage equations appear as algebraic equations.

With several assumptions three popular practical models of synchronous generators are used in power system simulation, and they are all based on Park equations and can be defined as Assumed A, Assumed B and Assumed B-1 [7]. The difference between the physical essence of Assumed A and Assumed B is whether to take into account the mutual leakage flux linkage between field winding and damping winding or the self-leakage flux linkage of damping winding. Assumed B-1 is derived

* Corresponding author.
E-mail address: yang.zhan@ncepu.edu.cn (Y. Zhan).

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from Assumed B by simplifying several parameters about damping winding.

In order to analyze the precision of FSS limit calculated by the practical models with and without stator transient, the simulation results are checked by Time-Stepping Finite Element Model (T-S FEM) [13]. T-S FEM can take into account the nonlinear factors including skin effect, magnetic saturation and cross-magnetizing in the dynamic process [14–16]. The previous research shows that the T-S FEM simulation results agree with experimental results very well [17,18]. T-S FEM can be used to verify the simulation results of the practical models though it is not suitable for large-scale simulations due to the large time consumption.

Although many references have studied the stator transient and back swing of the rotor, they have not analyzed the difference of the results calculated by different generator model and have not studied the influence of damping resistance on FSS. This paper take a 300 MW turbine generator as an example to compare the influences of stator transient on the large disturbance characteristic and FSS by time-step finite element model and three practical models. Since the ignored stator transient result in the unidirectional torque caused by damping resistance is neglected and there are several material options for rotor damping windings, the influence of damping resistance on FSS are also studied. The result provides theoretic basis of generator modeling for precise simulation of power systems.

2. Simulation models of synchronous generator

2.1. The practical models of synchronous generator

It has become common practice to discuss synchronous machine behavior in terms of a set of parameters and state variables other than the Park variables. The parameters are the steady-state, transient and sub-transient inductances, and the associated time constants. The state variables are transient and sub-transient electromotive forces. The models represented by the above parameters and state variables are called practical models which are based on Park equations and can be defined as Assumed A, Assumed B and Assumed B-1, respectively [8,10], according to different assumptions of rotor parameters. The rotor equations of three practical models are listed in Appendix A. The differences of three models are listed in the following Table 1.

$\Psi_{fD\sigma}$ is the mutual leakage reactance between field winding and damping winding in d-axis; $\Psi_{gQ\sigma}$ is the mutual leakage reactance between g winding and damping winding in q-axis; $\Psi_{D\sigma}$ is the self-leakage reactance of damping winding; $\Psi_{Q\sigma}$ is the self-leakage reactance of damping winding in q-axis; x_d', x_d'' are the direct axis transient, sub-transient reactance; x_q', x_q'' are the quadrature axis transient, sub-transient reactance; i_D, i_Q are currents of damping winding.

There are two types of voltage terms in the stator voltage equations of Park equations. One is the speed voltage terms ($\omega\psi$) which represent a flux wave rotating in synchronism with the rotor and creating voltages in stator winding, the other is the transformer voltage terms ($p\psi$) which represent the stator transient and prevent ψ_d and ψ_q from changing instantaneously.

Table 1
The relationship between three practical models.

	Assumed A	Assumed B	Assumed B-1
Considering	$\Psi_{fD\sigma}$, $\Psi_{gQ\sigma}$	$\Psi_{D\sigma}$, $\Psi_{Q\sigma}$	Based on Assumed B, it is also assumed that $(x_q''-x_l)/(x_q'-x_l)=1$, $(x_d''-x_l)/(x_d'-x_l)=1$ in sub-transient equation, and $i_D=0$, $i_Q=0$ in transient equation
Neglecting	$\Psi_{D\sigma}$, $\Psi_{Q\sigma}$	$\Psi_{fD\sigma}$, $\Psi_{gQ\sigma}$	

$$\begin{cases} u_d = p\psi_d - \omega\psi_q - r_a i_d \\ u_q = p\psi_q + \omega\psi_d - r_a i_q \\ u_0 = p\psi_0 - r_a i_0 \end{cases} \quad (1)$$

where ψ_d, ψ_q and ψ_0 are stator flux linkages in d, q ad 0 axis, respectively; u_d, u_q and u_0 are stator voltages in d, q and 0 axis, respectively; i_d, i_q and i_0 are stator currents in d, q and 0 axis, respectively; r_a is stator resistance.

Traditionally, in order to reduce the order of the overall system model and computational cost, the transformer voltage terms are often neglected in power system simulation analysis [5]. With these terms neglected, the stator voltage equations appear as algebraic Eq. (2).

$$\begin{cases} u_d = -\omega\psi_q - r_a i_d \\ u_q = \omega\psi_d - r_a i_q \\ u_0 = -r_a i_0 \end{cases} \quad (2)$$

According to Ref. [19], the relationship between magnetic linkage and sub-transient electromotive force is obtained as follows:

$$\begin{cases} \psi_d = e_q'' - x_d'' i_d \\ \psi_q = -e_d'' - x_q'' i_q \end{cases} \quad (3)$$

With (3) substituted in (1), the stator voltages with stator transient can be expressed in terms of sub-transient electromotive forces as follows:

$$\begin{cases} u_d = pe_q'' - x_d'' p i_d + \omega(e_d'' + x_q'' i_q) - r_a i_d \\ u_q = -pe_d'' - x_q'' p i_q + \omega(e_q'' - x_d'' i_d) - r_a i_q \\ u_0 = x_0 p i_0 - r_a i_0 \end{cases} \quad (4)$$

where e_d'' and e_q'' are the direct axis and quadrature axis sub-transient electromotive forces; x_d'' and x_q'' are the direct axis and quadrature axis sub-transient reactance.

With (3) substituted in (2), the stator voltages without stator transient can be expressed in terms of sub-transient electromotive forces as follows:

$$\begin{cases} u_d = \omega(e_d'' + x_q'' i_q) - r_a i_d \\ u_q = \omega(e_q'' - x_d'' i_d) - r_a i_q \\ u_0 = -r_a i_0 \end{cases} \quad (5)$$

2.2. Field-circuit coupled time-stepping finite element model

2.2.1. Field-circuit coupled equations

In order to accurate analysis the influence of stator transient and rotor damping resistance on FSS, we build the Field-Circuit Coupled Time-Stepping Finite Element Model (T-S FEM) as shown in (6) by combine Maxwell's equations, the electrical circuit equations. In this paper, two- dimensional (2-D) T-S FEM is used and the following approximations are applied:

(a) The end-leakage inductance is assumed to remain constant during the transient;
(b) The magnetic hysteresis effects are neglected.

$$\begin{bmatrix} \boldsymbol{D}_s + \boldsymbol{D}_d + \boldsymbol{D}_r & \boldsymbol{0} & \boldsymbol{0} \\ -l_{ef}\boldsymbol{C}_s^T & -\boldsymbol{L}_s & \boldsymbol{0} \\ -l_{ef}\boldsymbol{C}_f^T & \boldsymbol{0} & l_f \end{bmatrix} \frac{d}{dt} \begin{bmatrix} \boldsymbol{A} \\ \boldsymbol{I}_s \\ i_f \end{bmatrix} = \begin{bmatrix} -\boldsymbol{K} & \boldsymbol{C}_s & \boldsymbol{C}_f \\ \boldsymbol{0} & \boldsymbol{R}_s & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & -r_f \end{bmatrix} \begin{bmatrix} \boldsymbol{A} \\ \boldsymbol{I}_s \\ i_f \end{bmatrix} + \begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{U}_l \\ u_f \end{bmatrix} \quad (6)$$

where $\boldsymbol{A}$ is magnetic vector potential; k is the ratio of transformer; $\boldsymbol{K}$ is the stiffness matrix; $\boldsymbol{C}_s$ and $\boldsymbol{C}_f$ are incidence matrices of the stator current and field current; $\boldsymbol{D}_s$, $\boldsymbol{D}_r$ and $\boldsymbol{D}_d$ are the incidence matrices reflecting the eddy currents of damping windings; I_s and i_f are the stator