Dynamic response of large turbogenerator stator end winding under fault conditions

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Abstract. The electromagnetic fields of a 600MW turbogenerator stator end region under three-phase short circuit and two-phase short circuit are calculated by numerical simulation base on a three-dimensional electromagnetic model. The variation of electromagnetic force density can also be obtained in the same time. Then the dynamic responses consist of deformation and stress distributions of end winding under three-phase short circuit are numerically analyzed by the fine finite element model which is set up in ABAQUS software. The presented numerical models and method can in turn be used to study the dynamic responses and safety of the end structure under various operation conditions.

1. Introduction

With the single unit capacity of large turbogenerator increasing, the electromagnetic forces acted on the stator end winding bars, which vary with the square of current rise up significantly. The stresses and vibrations which caused by electromagnetic forces on the end winding bars can severely damage winding insulations, end bracings and support rings [1, 2]. If the turbogenerator meets with fault conditions such as short circuit, the consequences which induced by electromagnetic forces are even more serious. Therefore, it is necessary to investigate the dynamic responses of stator end winding under fault conditions in the design and the performance assessment of large turbogenerator.

Due to the complex structures of large turbogenerator stator end winding, the computation of electromagnetic field of end region have been gained comprehensive attention in the past several decades. In the beginning stage, the analytical methods which are based on Biot-Savart’s law are used to analysis the electromagnetic fields. Recently, the numerical approaches have been employed to compute the electromagnetic field and forces on the end winding [3-5].

In this paper, the electromagnetic force densities on the end winding bars under fault conditions such as three-phase and two-phase short circuit are determined based on the 3-D electromagnetic model of the stator end region of a 600MW two-pole turbogenerator. Then the dynamic responses of end winding under the electromagnetic forces during three-phase short circuit from full load are obtained.
2. Electromagnetic forces under fault conditions

2.1. Mathematical model for electromagnetic forces calculation
The parameters of a 600MW turbogenerator introduced in this paper is list in table 1. And the computation electromagnetic models which by means of JMAG software are shown in figure 1. The assumptions are as follows: (1) the displacement currents are neglected; (2) the current densities in the end winding bars are uniformly distributed and the higher order harmonics are omitted; (3) the stator core is isotropic and the B-H curve is a single-valued function; (4) the influence of the end winding deformation on the magnetic field is ignored.

By adopting \( A, \varphi-A \) method, we can express the mathematical model of the end region as follows [6, 7]:

\[
\begin{align*}
\nabla \times \left( \frac{1}{\mu} \nabla \times A \right) + \sigma \frac{\partial A}{\partial t} + \sigma \nabla \varphi &= J_s, \\
\n\nabla \cdot (-\sigma \frac{\partial A}{\partial t} - \sigma \nabla \varphi) &= 0 
\end{align*}
\]

where \( A \) denotes the magnetic vector potential, \( \varphi \) is the electric scalar potential, \( \sigma \) is the electrical conductivity, \( J_s \) is the source current density.

| Parameters               | Value       |
|--------------------------|-------------|
| Rated output             | 600MW       |
| Power factor             | 0.9 (lagging) |
| Revolution speed         | 3000r/min   |
| Frequency                | 50Hz        |
| Number of phases         | 3           |
| Number of stator slots   | 42          |
| Number of leads          | 6           |
| Current                  | 18524.6A    |

Table 1. Parameters of the 600MW turbogenerator.

2.2. Source currents
The parameters of excitation source during fault conditions can be determined by two-dimensional electromagnetic analysis. The currents in armature and field winding in the first 0.1s after three-phase short circuit from full load and after two-phase short circuit from no-load are shown in figure 2 and figure 3 respectively. It can be seen that the largest currents in armature winding under fault conditions are more than 10 times with those rated currents, and the largest field currents in the field winding are
nearly 8 times to the rated ones in the first period. Because of the damping winding, they all gradually decay with time.

Figure 2. Currents after three-phase short circuit from full load. (a) Armature currents. (b) Field currents.

Figure 3. Currents after two-phase short circuit from no-load. (a) Armature currents. (b) Field currents.

2.3. Electromagnetic forces densities
The electromagnetic forces, exerted on end winding bars, are typical case of Lorentz forces. The forces can be expressed as \( \mathbf{dF} = i \mathbf{dl} \times \mathbf{B} \), where \( i \) is the current of windings and \( \mathbf{B} \) is the magnetic flux density. In the finite element analysis, the Lorentz force density \( \mathbf{f} \) at a point in a current-conductor is \( \mathbf{f} = \mathbf{J} \times \mathbf{B} \), where \( \mathbf{J} \) is the current density.

The boundary conditions of the electromagnetic model are shown in figure 1 (b). The magnetic field direction is reversed every 180°. Surface \( S_1 \) and the surface located at 180° apart from \( S_2 \) satisfy the rotation and anti-periodic boundary conditions. Rotational conditions are specified on the rotor shaft and the rotor winding. In addition, symmetry boundary conditions are specified on the surfaces at the top, bottom and circumference face of the air region.

Based on the 3-D numerical model of turbogenerator end region which is shown in figure 1, the electromagnetic forces on the stator end windings are obtained. Given the limited space available, much of the results will not introduce in details. The time histories of radial electromagnetic force densities of some typical points on a pair of bars, as shown in figure 4, are shown in figure 5. It can be seen from the results that the magnitude of electromagnetic force densities increase dramatically when the fault conditions occur and they all decay with time because of the damping winding. On the other hand, the electromagnetic force densities decrease with the distance from the stator core at a moment.
It is noted that, the electromagnetic forces densities in some points under two-phase short circuit even larger than three-phase short circuit.

Figure 4. Typical points on a pair of end winding bars.

Figure 5. Time histories of radial electromagnetic force density at some points of end winding bars under fault conditions. (a) Three-phase short circuit. (b) Two-phase short circuit.

3. Dynamic responses under three-phase short circuit
A new structural analysis model which differs from the electromagnetic model is set up by means of the ABAQUS software. Then the dynamic responses of the stator end winding under electromagnetic forces during fault conditions are obtained by means of the above structural model incorporator with the electromagnetic force densities. Because the change rules of currents under two-phase short circuit are consistent with the ones under three-phase short circuit, the discussion of dynamic responses are focus on the three-phase short circuit.

The deformations of the stator end winding at typical moments in the first period are shown in figure 6. The time histories of displacements at point 8, as shown in figure 4, of the stator end winding
under three-phase short circuit are shown in figure 7. Compared with the results under rated load which come from the on-line monitoring data[8], it is evident that the largest displacement at the nose portion under three-phase short circuit is over one hundred times more than that under rated load. It also can be obtained from the numerical results that the maximum Mises stress of the end winding even above 800MPa during three-phase short circuit, which is far exceed the ultimate strength of materials in the end region.

It can be seen from the comparison results between three-phase short circuit and rated load that the end winding is so dangerous that the fault conditions should be avoided. The presented numerical models and method can in turn be used to study the dynamic responses and safety of the end structure under various operation conditions.

![Figure 6](image6.png)

**Figure 6.** Deformations of stator end winding at typical moments under three-phase short circuit (a) t=0.0102s. (b) t=0.0118s. (c) t=0.0137s. (d) t=0.0156s. (The magnification factor is 20).

![Figure 7](image7.png)

**Figure 7.** Time histories of displacements at point 8 of an end winding bar under three-phase short circuit.
4. Conclusions
In this paper, a 3D FE electromagnetic model of a 600MW stator end region is set up. Then the electromagnetic force densities under three-phase short circuit and two-phase short circuit are calculated. And the dynamic responses during three-phase circuit are numerical simulated by means of a structural model which is set up in ABAQUS software. It is concluded as follows.

(1) Compared with the rated electromagnetic force densities, the magnitude of fault conditions ones can exceed one hundred times, and the magnitude of the electromagnetic force density decreases with the distance from the stator core at a moment. The electromagnetic forces densities in some points under two-phase short circuit even larger than that under three-phase short circuit.

(2) Both of the displacements and stresses of the stator end winding under three-phase short circuit are at least dozens of times those in the case of rated load.

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