Modal Analysis of Three-dimensional Model of Turbogenerator Stator End Windings

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Abstract. Concerning the structural complexity of large-scale turbogenerator stator, this research aims at establishing the windings model of the large-scale turbogenerator stator ends by using ANSYS, including the ends of upper and lower conductor bars, spacer blocks between adjacent conductor bars, and inter-layer rings between the upper and lower conductor bars. Moreover, the modal analysis of the stator end windings was performed with the help of ANSYS, and the parameterized finite element analysis was further conducted on the space blocks that may affect the overall structural mode and natural frequency of the ends, and the influence trend of the space blocks on the natural frequency of the elliptical mode was obtained. It provides a reference for the design of the generator end structure and its improvement, and also provides a basis for the subsequent research on the electromagnetic vibration of the end windings and the stator windings.

1. Introduction

The vibration of the generator during its operation will adversely affect its service life. The increase of the single unit capacity of the generator makes the vibration of the generator more violent. For stator windings with complex structures, structural modal analysis and research on electromagnetic vibration are even more important [1]. In the design of the end windings structure, the natural frequency corresponding to the mode of its specific shape is required to avoid the resonance region [2]. Therefore, the research on the dynamic characteristics of the stator end windings structure is of great significance to study the optimization scheme of the end windings structure.

Modal analysis is a modern method for studying the dynamic characteristics of structures. Modal refers to the natural vibration characteristics of mechanical structures, each modal has a specific natural frequency, damping ratio, and mode shape, through modal analysis, the vibration of the mechanical structure can be determined, the vibration characteristics of the structure and its natural frequency and modal shape are obtained [3].

For the modeling of end windings, there are currently more mature methods. Chen R used the ANSYS to establish a spatial curve geometric model of the stator windings with a finer single conductor bar, and simulated the three-dimensional model of the stator windings [4]. Zhao Y established a fine finite element model of the end windings, which considered almost all the components of the end windings. Parametric finite element simulations are performed on various factors that may affect the modal of the end windings [1]. Wu D obtained the natural frequency distribution by analyzing the modal analysis of stator windings in ANSYS [5]. Senske K obtained the equivalent stiffness and elastic modulus of conductor bars and straps through experiments, and
established a three-dimensional finite element model of the end windings of a 170MVA air-cooled generator [6].

The rest of this article is organized as follows. In the next section, we will build a three-dimensional model of the stator end windings and carry out a modal analysis. In section 3, the modal analysis is done under varying the stiffness and number of space blocks, and the variation trend of natural frequency in elliptical mode is discussed. Finally, Section 4 serves as the summary.

2. Establishment of 3D model of stator end windings and modal analysis

Turbine generators are mainly composed of a stator and a rotor, the stator mainly includes three parts: a stator windings, a stator core and a stator frame. As an important component in the turbogenerator, the stator windings is embedded in the core slot and works with the rotating magnetic field to achieve the purpose of energy conversion and output of electrical energy. The structural forms of the windings include concentric windings, frog windings and basket windings. Turbogenerators use basket windings or stacked windings. Each coil is composed of two upper and lower conductor bars located in different slots, the linear part is located in the core slot, the end is in the form of an involute, the upper and lower layers are also formed with a certain taper, the nose end is passed through a head cover or butt welding, the head forms a closed coil [7].

2.1 Establishment of 3D model

The stator end windings mainly includes the ends of the upper and lower conductor bars, the spacer between adjacent conductor bars, and the inter-layer rings between the upper and lower conductor bars. The 3D solid model of the components is shown in Figure 1, and the 3D solid diagram finally created is shown in Figure 2.

Figure 1. Component of stator end winding.
(a) conductor bar. (b) connector. (c) inter-layer ring. (d) space block.
2.2 The analysis of model

According to the end windings structure and the connection characteristics between the components, the connection relationship between the components can be determined as follows:

1. Binding connection between the condutor bar and the space block.
2. Binding connection between the condutor bar and the condutor bar connector.
3. Binding connection between condutor bar and inter-layer ring.
4. Binding connection between the space block and the inter-layer ring.

Because the end of the condutor bar is connected to the condutor bar in the stator core, the condutor bar is fixed in the core slot. Due to the high stiffness of the stator, the straight end of the condutor bar is fixed and restrained. The application of the displacement boundary conditions of the finite element model is shown in Figure 3.

In the finite element model of the stator end windings, all components are discreted using hexahedral eight-node units, and the entire structure is discreted using 54840 hexahedral elements. The mesh is shown in Figure 4.

Many materials are included in the ANSYS model library, and the material properties can also be set by themselves. In order to reflect the material properties more accurately, this article adopts self-set material properties, mainly including density, elastic modulus, and Poisson's ratio, as Table 1. Using ANSYS for modal analysis, the resulting modal shapes are shown in Figure 5 and natural frequency in the Table 2.

| Member         | Young's modulus (Mpa) | Poisson's ratio | Density (kg/m³) |
|----------------|-----------------------|-----------------|-----------------|
| Conductor bar  | 38000                 | 0.3             | 8800            |
| Space block    | 23125                 | 0.364           | 1798            |
Table 2. Modal frequency distribution of stator end windings.

| Mode shape order | Horn | Shake | Ellipse | Three-lobed | Four-lobed | Five-lobed |
|------------------|------|-------|---------|-------------|------------|------------|
| Frequency (Hz)   | 41.372 | 34.879 | 32 | 38.063 | 48.395 | 55.913 |
|                  | 34.88 | 32.009 | 38.065 | 48.397 | 55.914 |

Based on the modal frequency distribution of the stator windings, the following conclusions are drawn:

1. The modal frequency distribution of the stator windings bar assembly model has repeatability and similarity, and a certain mode may correspond to several consecutive natural frequencies.

2. It can be seen from the frequency distribution table that the distribution of natural frequencies is in accordance with the natural frequency and modal test specified in the reference [2]. The frequency range of the ellipse natural frequency of the entire end should be avoided "≤95Hz, ≥110Hz ", and the data used in the model establishment refer to the data of a turbogenerator, set within a reasonable range, and refer to the results obtained from relevant literature, so the model establishment is correct and effective, the modal analysis performed is also of reference value.
3. Changes in spacers

3.1. Changes in spacer stiffness
This section studies the effect of the stiffness change of the spacer on the modal and natural frequency of the end windings. The stiffness of the spacer is considered only for the physical stiffness, that is, only the change in Young's modulus is considered. Assume that the Young's modulus of the spacer is $0.5E$, $E$, $2E$, $10E$, where $E$ is the actual Young's modulus of the spacer. The natural frequencies corresponding to the elliptical modes of the end windings obtained from ANSYS finite element analysis are shown in the Table 3. The corresponding modal diagram is shown in Figure 6. It can be seen that as the stiffness of the spacer increases, the elliptical mode of the end windings hardly changes, but the natural frequency corresponding to the elliptical mode increases slightly.

| Elliptical mode | 0.1E  | 0.5E  | E    | 2E   | 10E  |
|-----------------|-------|-------|------|------|------|
| 1               | 30.056| 31.566| 32   | 32.705| 33.329|
| 2               | 30.07 | 31.575| 32.009| 32.729| 33.363|

Table 3. Natural frequencies of elliptic modes of end windings for changing Young's modulus of spacer blocks.

![Figure 6. Elliptical mode of stator end windings.](image)

(b) Young's modulus is 0.5E.
(c) Young's modulus is 2E.
(d) Young's modulus is 10E.

3.2. Changes in spacer numbers
This section studies the effect of the number of spacers on the modal and natural frequencies of the end windings. In the original model, there are 7 space blocks between the upper and lower adjacent bars. Assume that the number of spacer blocks on the upper and lower layers is six, seven and eight.
The natural frequencies corresponding to the elliptical modes of the end windings obtained from ANSYS finite element analysis are shown in Table 4. The corresponding modal diagram is shown in Figure 7. It can be seen that as the number of spacers increases, the elliptical mode of the end windings hardly changes, but the natural frequency corresponding to the elliptical mode increases slightly.

| Elliptical mode | 6   | 7   | 8   |
|-----------------|-----|-----|-----|
| 1               | 27.859 | 32  | 33.683 |
| 2               | 27.89  | 32.009 | 33.726 |

Figure 7. Elliptical mode of stator end windings.
(a) Number of spacer blocks is 6. (b) Number of spacer blocks is 8.

4. Conclusion
By analyzing the natural frequency distribution obtained through modal analysis of the stator windings in ANSYS, the purpose of verifying the validity of the model is achieved, and the modeling method is simpler and more intuitive than other models and methods. With the help of ANSYS, a more convenient structural dynamics analysis of the 3D model was built. The finite-element model is obtained by using the actual material parameters and boundary conditions. Through analyzing this model, the natural frequency and mode shape are obtained, and the effectiveness of the model is proved; the stiffness and number of the space blocks are analyzed by changing the stiffness and number of space blocks. The influence of the overall modal of the rod was found that with the increase of the spacer stiffness and the increase of the number of spacers, the elliptical modal of the end windings hardly changes, but the natural frequency corresponding to the elliptical modal increases slightly. It has laid a solid foundation for the subsequent simulation of stator windings electromagnetic vibration.

References
[1] Zhao Y, Yan B, Zeng C, et al 2016 Dynamic response analysis of the electromagnetic force acting on the stator end of a large turbo-generator Journal of Electrical Engineering Technology 31(5) pp 199-206
[2] People's Republic of China Electric Power Industry Standard. Measurement and Evaluation of Dynamic Characteristics of Large Wind Turbine Generator Stator Windings Ends
[3] Jiao M 2013 Research on modal analysis of ANSYS finite element analysis method Enterprise Herald (11) pp 290-295
[4] Chen R 2015 Finite element analysis of stator windings bars of large turbo-generators Design and Research 1(2) pp 27-31
[5] Wu D 2018 3D Modeling and Modal Analysis of Stator Windings of Large Turbogenerator Electrical Engineering (4) pp 5-10

[6] Senske K, Kulig S, Kauhoff J and Wünsch D 1997 Vibrational behaviour of the turbogenerator stator end windings in case of electrical failures Conférence Internationale des Grands Réseaux Electriques pp1-12

[7] Chen R 2015 Research on Virtual Prototype of Stator Windings Braided Structure of Large Turbogenerator Xi’an: Xi’an Engineering University pp 45-50