Study on Electromagnetic Force and Vibration of Turbogenerator End Windings under Impact Load(Ⅱ): Analysis of Vibration of End Windings under Impact Load

Huang Xueliang* Hu Minqiang

(Department of Electrical Engineering, Southeast University, Nanjing 210096, China)

Abstract: On the basis of the study of transient eddy current field in the end region of turbogenerator and electromagnetic force of end-region winding, this paper analyzes the electromagnetic vibration of the turbogenerator roundly. A 320 MW turbogenerator is taken as an example to specify the electromagnetic force of end-region winding and therefore the vibration in the case that the generator is affected by impact load. Some conclusions are drawn on the basis of the specification. Vibration of windings under imaginary faults is simulated, so that the vibration law of the end winding of turbogenerator can be studied further. On the basis of this, the countermeasure against winding vibration can be advanced.

Key words: turbogenerator, impact load, electromagnetic vibration, fault simulation

When the generator operates under impact load, concomitant vibration may either cause instantaneous mechanical damage to end winding of the stator, or aggravate mechanical fatigue of the winding, which make up reasons of operation breakdown[1]. In order to attain the vibration amplitude and distribution of turbogenerator end-region winding under impact load, it's necessary to specify the vibration condition of turbogenerator end-region winding in such operation condition.

1 Mathematical Model of Winding Vibration in the End Region

Compared with the cross-section, the length of stator winding in the end region of turbogenerator is much larger in size. Therefore, the end winding can be regarded as elastic structure system that is composed of slim beam segments. The cross vibration of slim beam is shown in Fig.1.

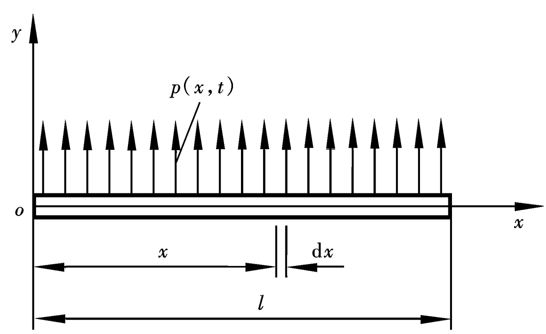

Fig. 1 Sketch of vibration in the cross direction of the beam

Fig.2 shows a separate tiny beam with the length of dx and the force it bears. Where Q, M are shear force and flexural torque on the cross-section, $\rho A \mathrm{d}x \dfrac{\partial^2 y}{\partial t^2}$ is the inertia force born by the tiny beam segment dx. From the force balanced equation

$$\frac{\partial Q}{\partial x} = p - \rho A \frac{\partial^2 y}{\partial t^2} \tag{1}$$

where p is the external force; ρ is the density of the beam; A is the area of the cross-section.

From the torque balanced equation

$$Q = \frac{\partial M}{\partial x} + m \tag{2}$$

where m is the external torque.

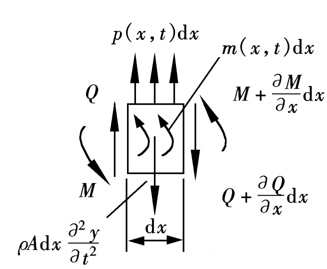

Fig. 2 Force diagram of the tiny beam segment

Substitute Eq.(2) into Eq.(1), we obtain

$$\frac{\partial^2 M}{\partial x^2} + \frac{\partial m}{\partial x} = p - \rho A \frac{\partial^2 y}{\partial t^2} \tag{3}$$

Received 2001-11-06.

* Born in 1969, male, associate professor.

Substitute the relationship between flexural torque and flexivity $M = EJ\frac{\partial^2 y}{\partial x^2}$ into Eq.(3), we obtain

$$\frac{\partial^2}{\partial x^2}\left(EJ\frac{\partial^2 y}{\partial x^2}\right) + \rho A\frac{\partial^2 y}{\partial t^2} = p(x,t) - \frac{\partial}{\partial x}m(x,t) \tag{4}$$

where E is the Young's modulus of the material and J is the moment of inertia.

The above equation is the transverse vibration equation of slim beam. For beam of uniform cross section, the bend strength EJ is constant, and Eq.(4) becomes

$$EJ\frac{\partial^4 y}{\partial x^4} + \rho A\frac{\partial^2 y}{\partial t^2} = p(x,t) - \frac{\partial}{\partial x}m(x,t) \tag{5}$$

2 Analysis of the Vibration in the End Region of Stator Winding

2.1 Assumption

Before the vibration analysis of stator winding in the end region of turbogenerator, we suppose

1) Stator winding is composed of linear elastic and continuous material.

2) The distortion extent of stator winding during vibration is much smaller than the size of the stator. Besides, the change of external force during vibration can be neglected.

3) The material accords with generalized Hooke's law, i.e., the relationship between its distortion and external force is linear.

With these assumptions, the stator winding in the end region can be regarded as linear system. Therefore, synthetical effect of various loads accords with the principle of superposition[2].

2.2 Specification of the moment of inertia of stator winding

When analyzing vibration of stator winding in generator, the moment of inertia J of the cross-section of stator winding to central axis must be attained. Fig.3 shows the sectional view of stator winding of generator.

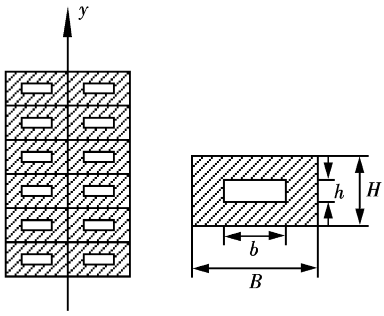

Fig.3 Sectional view of stator winding

The moment of inertia of arbitrary cross section to arbitrary pair of orthogonal axes equals to the sum of the moment of inertia of the cross section to the pair of centroidal axes that are parallel to this axes pair and the product of the cross section area and the square of the distance from the centroid of the area to the axes pair[3]. Therefore, the moment of inertia is attained by shifting the neutral axis $B/2$.

$$J = n\left[\frac{1}{12}(HB^3 - hb^3) + \frac{B^2}{4}(BH - bh)\right] \tag{6}$$

where n is conductor number of stator winding.

2.3 Analysis of transverse compulsory vibration of stator winding

The winding segment that bears continuous distributed force is supposed to be a beam with lumped mass m_i located at position i, which bears the acting force p_i. Therefore, when the beam vibrates, the relationship between flexivity y_i at position i and acting force and inertia force can be expressed as follows:

$$\left.\begin{aligned} y_1 &= k_{11}(p_1 - m_1\ddot{y}_1) + k_{12}(p_2 - m_2\ddot{y}_2) + k_{13}(p_3 - m_3\ddot{y}_3) \\ y_2 &= k_{21}(p_1 - m_1\ddot{y}_1) + k_{22}(p_2 - m_2\ddot{y}_2) + k_{23}(p_3 - m_3\ddot{y}_3) \\ y_3 &= k_{11}(p_1 - m_1\ddot{y}_1) + k_{32}(p_2 - m_2\ddot{y}_2) + k_{33}(p_3 - m_3\ddot{y}_3) \end{aligned}\right\} \tag{7}$$

The above equation can be expressed in matrix form

$$\boldsymbol{Y} = \boldsymbol{K}(\boldsymbol{P} - \boldsymbol{M}\ddot{\boldsymbol{Y}}) \tag{8}$$

where

$$\boldsymbol{K} = \begin{bmatrix} k_{11} & k_{12} & k_{13} \\ k_{21} & k_{22} & k_{23} \\ k_{31} & k_{32} & k_{33} \end{bmatrix}, \quad \boldsymbol{Y} = \begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix}, \quad \boldsymbol{M} = \begin{bmatrix} m_1 & & \\ & m_2 & \\ & & m_3 \end{bmatrix}, \quad \boldsymbol{P} = \begin{bmatrix} p_1 \\ p_2 \\ p_3 \end{bmatrix}$$

In the above equation, k_{ij} means the displacement of system from i when it bears unit force at position j.

The displacement of stator winding in the end region in the process of vibration is very small, which is usually micron order, while electromagnetic force of winding ranges from several hundred to one thousand N. As a result, the inertia force caused by accelerated speed is so small that it can be neglected[4,5] compared with electromagnetic force born by the winding. Therefore, the displacement equation according to different positions of the beam can be simplified as

$$\boldsymbol{Y} = \boldsymbol{KP}$$

3 Calculation Examples

As specified in the previous paper, the No.2 generator of HuaNeng Plant (Nanjing) is again taken as example to analyze the electromagnetic vibration of turbogenerator under impact load. The sketch end structure can be referred in Fig. 1 of the previous paper.

On the basis of calculation of electromagnetic distribution in the end region and electromagnetic force density of stator winding, vibration of stator winding of turbogenerator in the end region is specified. Fig.4 lists the curves of displacement-time of No.27 segment of stator winding under impact load respectively. From the figure below, it can be learned that the vibration displacements of the winding segment reach its maximum values after 24.32 s, because of violent fluctuation of current.

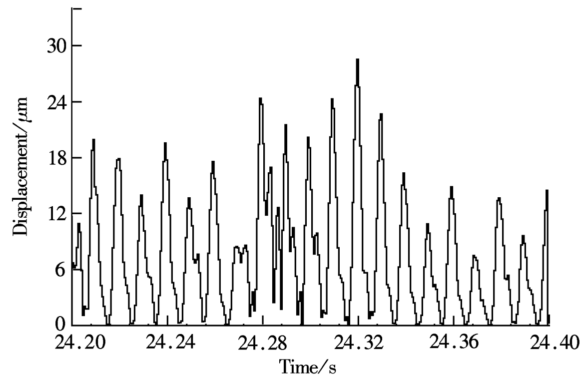

Fig.4 Vibration displacement of segment No.27 in the upper layer under impact load

Fig.5 shows the overall vibrations in the end region of stator winding at the moment t = 24.282 5 s and t = 24.32 s respectively. From both figures, it can be learned that vibration amplitude in the upper layer is much larger than that of the lower layer. Besides, no matter upper layer or lower layer, vibration amplitude near the nose is much larger than that of the linear part. This accords with the fact in operation[6].

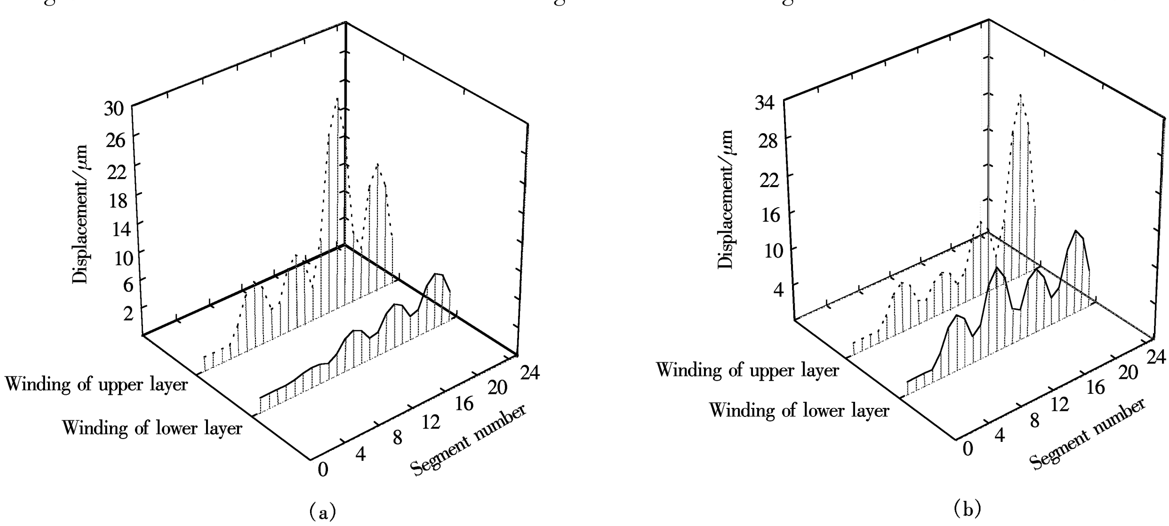

Fig.5 Vibration of winding in the end region. (a) At the moment t = 24.282 5 s under impact load; (b) At the moment t = 24.32 s under impact load

From the result, it can be concluded that the vibration displacement of stator winding under normal load is smaller than that under impact load. For example, the maximum vibration displacement of segment No.27 is 18.982 μm under the load of 80 percent of rated load, and 28.526 μm under the impact load. The former is 66.5 percent of the later in value. This reflects the extent to which vibration of the end winding aggravates.

4 Discussion

4.1 Suppose a loose bandage

If the winding vibrates violently in a long term, the settled structure of end winding becomes loose, and vibration of the winding is aggravated. Fig.6 shows the vibration of end winding at the moment t = 24.32 s in the case that a bandage near the nose of winding in the upper layer becomes loose. Fig.7 shows the curve that vibration displacement of segment No.30 of the upper layer changes with time. Obviously, when a bandage is loose, vibration displacement of the upper layer is much larger than that in normal condition. For example, the vibration amplitude of segment No.30 where the most violent vibration occurs is 267.8 μm at the moment t = 24.32 s, while vibration displacement of segment No.27 where the most violent vibration occurs in normal condition is 28.526 μm. The later makes up 10.6 percent of the former. Therefore, the settled structure of stator winding in end region of turbogenerator is very important. Loosed or broken-off structures will lead to violent vibration of stator winding.

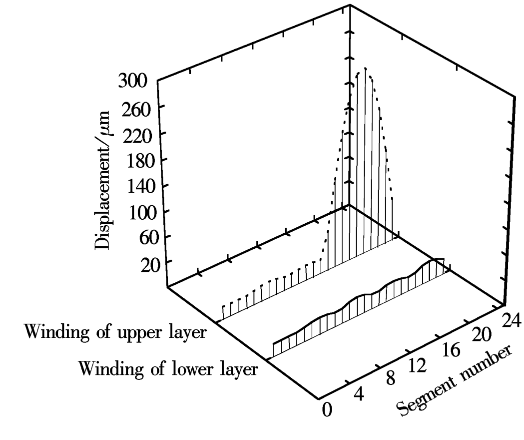

Fig.6 Vibration of end winding at the moment t = 24.32 s in the case of loose bandage

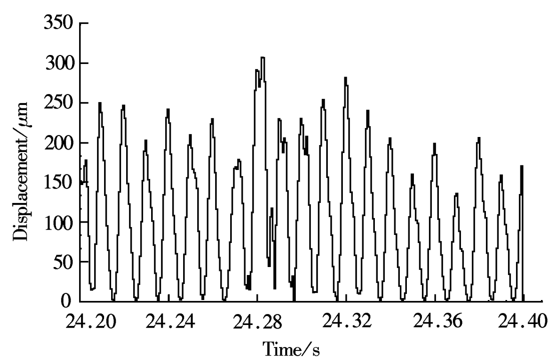

Fig.7 Displacement-time curve of vibration of segment No.30 in the upper layer

4.2 Change bandage position

In order to decrease vibration near nose of the winding, a new bandage is appended and the originally adequately distributed bandages are changed. I.e., the distance between two adjacent bandages that are near to the nose is decreased, while the distance between two adjacent bandages that are far away to the nose is increased.

Fig.8 shows the vibration of upper and lower layers of stator winding at the moment t = 1 ms in the case of three-phase short circuit after bandages are resettled as specified above.

The calculation result shows that vibration amplitude of segment No.27 is 37.8 percent of that before resettling. Therefore, the maximum vibration amplitude is decreased greatly by resettling bandage positions. Undoubtedly, in some positions, resettling the bandages has amplified the originally small vibration amplitude. However, the maximum vibration amplitude is decreased through resettling bandages. And as a whole, the vibration distribution is more uniform. From the analysis above, it can be learned that appropriate distribution of the bandage positions and increased bandage numbers can improve vibration of the winding.

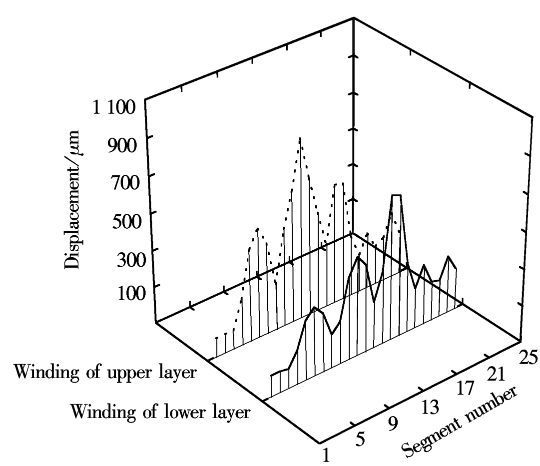

Fig.8 Vibration of stator winding at the moment of t = 1 ms after bandages are resettled

5 Conclusions

In this paper, vibration of end winding of turbogenerator under impact load is calculated. The result shows that impact load aggravates vibration of end winding. Some laws of the winding vibration are attained:

1) The vibration amplitude of end winding in different segment is a function of electromagnetic force density and position of this segment.

2) The vibration amplitude of the upper layer end winding is larger than that of the lower layer at the same time. This is mainly because of different magnetic flux density.

3) The vibration amplitude of winding near nose is larger than that of winding in the linear part.

4) According to vibration distribution law of winding, the settled structure of end winding can be resettled appropriately so that the maximum amplitude of winding vibration can be decreased, and as a result, the vibration distribution is more uniform.

References

[1] Sheng Changda. Some problems of analyzing faults in end region of generator[J]. *Large Electric Motor Technology*, 1993(2): 20-26. (in Chinese)

[2] Zhang Shiji. *Foundation of vibration*[M]. Beijing: Beijing Aerospace and Aviation University Press, 1990. (in Chinese)

[3] Ni Zhenhua. *Vibration mechanics*[M]. Xi'an: Xi'an Jiaotong University Press, 1989. (in Chinese)

[4] Khan G K M. Calculation of force and stress on generator end-windings part I: force[J]. *IEEE Trans on EC*, 1989, **4**(4): 661-670.

[5] Salon S J, Scott D J, Kusic G L. Electromagnetic force on the end windings of large turbine generators II — transient conditions[J]. *IEEE Trans on PAS*, 1983, **102**(1): 14-19.

[6] Zhou Keding. *Numerical theory and application of engineering electromagnetic field*[M]. Beijing: High Education Press, 1994. (in Chinese)

冲击负荷下汽轮发电机端部绕组电动力及其振动问题的研究(Ⅱ):端部绕组振动分析

黄学良　　胡敏强

(东南大学电气工程系,南京 210096)

摘　要　在研究汽轮发电机端部瞬态涡流场、端部绕组电动力的基础上,本文对汽轮发电机端部绕组的振动进行了全面分析.文中以1台32MW汽轮发电机作为实例,对发电机在冲击负荷下端部绕组所受到的电动力以及由此引起的强迫振动情况作了实例分析,得出了一些有益的结论.文中还对端部绕组在假想故障下的振动情况作了模拟分析,以便进一步了解发电机端部绕组的振动规律,为提出改善绕组振动的对策提供了理论依据.

关键词　汽轮发电机,冲击负荷,电磁振动,故障模拟

中图分类号　TM311