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Eddy current density asymmetric distribution of damper bars in bulb tubular turbine generator

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Abstract: The major reasons that cause the damage of damper bars in the leeward side are found in this paper. It provides a route for the structure optimization design of a hydro generator. Firstly, capacity of a 24 MW bulb tubular turbine generator is taken as an example in this paper. The transient electromagnetic field model is established, and the correctness of the model is verified by the comparison of experimental results and simulation data. Secondly, when the generator is operated at rated condition, the eddy current density distributions of damper bars are studied. And the asymmetric phenomenon of the eddy current density on damper bars is discovered. The change laws of the eddy currents in damper bars are determined through further analysis. Thirdly, through the study of eddy current distributions under different conditions, it is confirmed that the stator slots and armature reaction are the main factors to affect the asymmetric distribution of the eddy current in damper bars. Finally, the studies of the magnetic density distribution and theoretical analysis revealed the asymmetric distribution mechanism of eddy current density.

Key words: damper bars, bulb tubular turbine generator, electromagnetic field, eddy current

1. Introduction

A bulb tubular turbine generator has the advantages of large flow, a low head, high efficiency, low investment and so on. These advantages make the bulb tubular turbine generator widely used in developing low head water resources [1]. However, influenced by the external factors such as the voltage jump and short circuit fault, the oscillation phenomenon might occur during the operation of the generator. Therefore, a damper winding is generally adopted in synchronous a hydro generator. The damper winding could effectively restrain rotor vibration [2-5]. The damper winding is an important part of a hydro generator. It can not only weaken the harmonic magnetic field, but also improve the reliability of generator safety. Nevertheless, there are several problems arising in the damper bars during the generator operation [6, 7], such as heating, fusing, deformation, insulation damage and so on. There are some hydropower stations where some serious damages occurred to generator damper bars, and the commonality among the faults is that the damaged damper bars are all in the leeward side of poles. The detail circumstances of the generators are shown in Table 1.

Table 1. Situations of hydropower stations

Hydropower station	**Capacity**	**Manufacturer**	**Fault type**
Feilaixia Hydropower	39 MW	ELIN of Austria and Voestalpine	Damper bar crack
Gaotan Hydropower	19 MW	SULER and ACEC	Damper bar crack
Lingjintan Hydropower	34 MW	Hitachi Limited	Damper bar crack
Bailongtan Hydropower	32 MW	Fuji Electric	Damper bar crack
Centrale hydroelectrique D'imboulou	30 MW	Harbin Electric Machinery Company	Damper bar crack

The problems that occurred in the far right damper bar of the pole indicates that the damper bars which lies in the leeward side produce more heat or bear greater force than other damper bars. Influenced by the cogging, the harmonic magnetic fields will be generated in the air gap of the generator. Harmonic magnetic fields rotating at non-synchronous speed, and magnetic fields will cut the damper bars and produce an eddy current. When the generator is operated at an unstable state, the damper bars could weaken the negative sequence magnetic field and harmonic magnetic fields. At the same time, the damper bars will induce a large eddy current. Although the damper bars will produce more eddy currents when the generator is operated in the situations mentioned above, it could not explain the phenomenon of the damper bar that lies in the leeward side of the poles prone to failure. The eddy current loss will make the temperature of the damper bars go up, and that would threaten the stable operation of the generator. Therefore, the research on the asymmetric distribution of the eddy current density on damper bars is important for promoting the improvement of the generator performance.

Some experts and scholars have made relevant researches on the eddy current losses of a synchronous generator, such as eddy current losses in damper bars [8-10], eddy current loss in the end region of a turbo generator, eddy current losses in the clamping plate and so on [11-13]. However, there are less studies on the asymmetric distribution of the eddy current in damper bars. Therefore, capacity of a 24 MW bulb tubular turbine generator is taken as an example for the study of eddy current asymmetric distribution. The changes of eddy currents in the damper bars were analyzed when the rotor is located at different positions. The key factors that affect the asymmetric distribution of the eddy current density on damper bars are found out. Through the further researches on the distribution of the eddy current in damper bars, the influence of the asymmetric mechanism of the eddy current distribution is revealed. Based on the researches, some useful conclusions are drawn.

2. Generator model establishment and correctness verification

2.1. Model establishment

Chai J.X. hydropower station consists of four bulb tubular turbine generator sets, and the unit's capacity is 24 MW. In this paper, one generator is selected to study the asymmetric distribution of the eddy current density on damper bars. A fractional slot stator winding is adopted in the generator, and the number of slots per pole per phase is 7/4. The analysis shows that the generator is composed of 22 unit motors. In order to facilitate the research, the model of a unit motor is built in this paper. Some parameters of the generator are given in Table 2. According to the parameters of the generator, a two-dimensional (2D) transient field model is established according to the real size. The mesh division of the generator model is shown in Fig. 1.

Table 2. Parameters of the generator

Parameters	**value**	**Parameters**	**value**
Rated power /MW	24	Stator inner diameter /mm	7370
Rated voltage /kV	10.5	Length of stator core /mm	1350
Rated current /A	1388.9	Number of stator slots	462
Rated speed r/min	68.18	Conductors per slot	2
Stator outer diameter /mm	7820	Number of poles	88

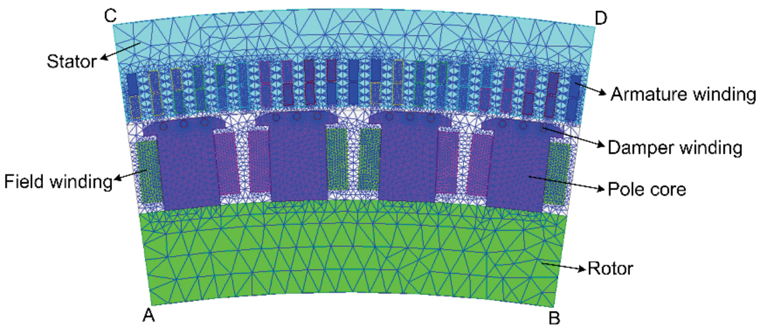

Fig. 1. Mesh generation of the generator

The boundaries of the 2D time varying electromagnetic field should meet the following conditions.

$$\begin{cases} \frac{\partial}{\partial x}(v\frac{\partial \boldsymbol{A}_z}{\partial x}) + \frac{\partial}{\partial y}(v\frac{\partial \boldsymbol{A}_z}{\partial y}) = -\boldsymbol{J}_z\sigma\frac{\mathrm{d}\boldsymbol{A}_z}{\mathrm{d}t} \\ \boldsymbol{A}\big|_{AB} = \boldsymbol{A}\big|_{CD} = 0 \\ \boldsymbol{A}\big|_{AC} = \boldsymbol{A}\big|_{BD} \end{cases}, \tag{1}$$

where: ν is the material reluctivity; $\boldsymbol{J}_Z$ is the Z-axis component of current density; A_Z is the Z-axis component of magnetic vector potential $\boldsymbol{A}$; $\sigma(\mathrm{d}A_z/\mathrm{d}t)$ is the eddy current density.

2.2. Operation characteristics of the generator

When the generator is operated at different conditions, a series of data about the generator such as an output current, induced electromotive force, an eddy current, losses and torque can be gained by finite element software. According to the data of the excitation current and induced electromotive force, the operation characteristic curves of the generator are drawn. No load and rated load characteristic curves of the generator are drawn in Fig. 2. The horizontal axis represents the rotor excitation current. The vertical axis is the induced electromotive force of the armature winding.

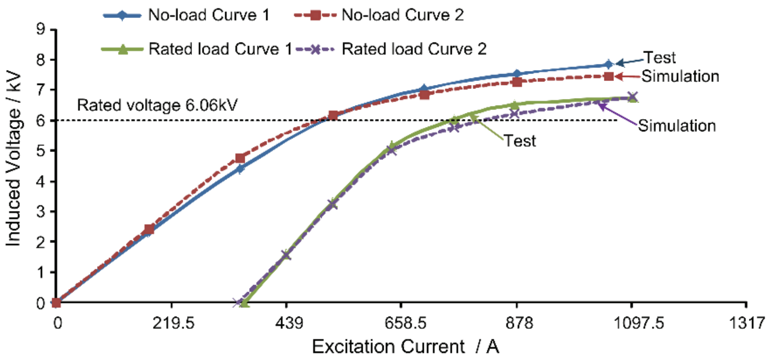

Fig. 2. Operation characteristic curves of the generator

Through the comparative studies of the experimental results and simulation data of the characteristic curves, it can be known that the errors between them are less than 7%, which meets the requirement of engineering research. The correctness of the model is verified by the above analysis.

3. Study on the asymmetric distribution of eddy current density on damper winding

The eddy current density of a damper winding directly reflects its eddy current loss, and the eddy current loss indirectly explains the heat production of the damper winding. Therefore, the researches on the eddy current density of damper winding can clearly explain the thermal condition of damper bars. In this paper, the finite element method is carried out to solve the eddy current of a damper winding. The eddy current of each division elements can be calculated by the following formula.

$$\boldsymbol{I}_e = \iint\limits_{\Delta_e} -\sigma_b \frac{\partial \boldsymbol{A}_z}{\partial t} \mathrm{d}x\mathrm{d}y \,, \tag{2}$$

where: σ_b is the conductivity of damper bars; Δ_e is a division element; $\boldsymbol{I}_e$ is the eddy current of each division elements; $\boldsymbol{A}_z$ is the *Z*-axis component of magnetic vector potential $\boldsymbol{A}$.

According to the number of the division elements of damper bars, the eddy currents can be calculated by formula (2).

3.1. Distribution and variation of eddy current of damper bars

The density distribution of eddy currents in the three damper bars at a certain time is studied, as shown in Fig. 3. Here, the generator is operated at rated condition. The maximum and minimum values of the eddy current density are marked in the figure, and the minus sign just represents the flow direction of the eddy current.

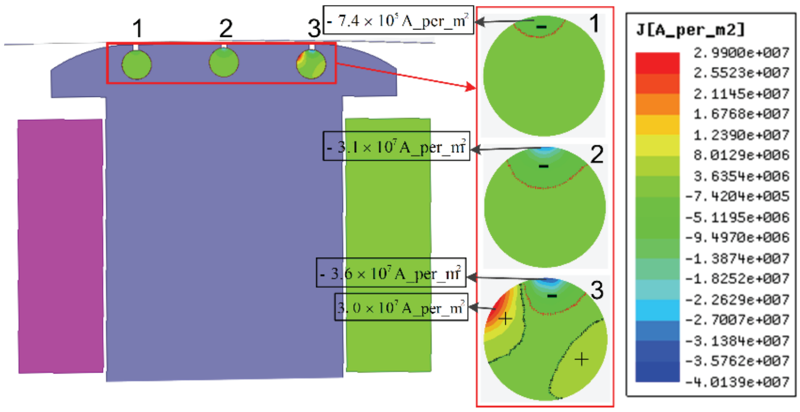

Fig. 3. Eddy current distribution of damper bars

From Fig. 3, it can be seen that the eddy current distributions of the three damper bars are different at this moment. The amount of the eddy currents generated by the damper bar 1 and 2 is lower, while, there is more eddy current on damper bar 3. It is also found that the positive and negative currents are present on damper bar 3 at the same time, and the distribution acreage of the eddy current in damper bar 3 is the largest among the three damper bars. So, in other words, the first damper bar that lies in the leeward side of the pole will generate more eddy current loss than other damper bars. The bigger the eddy current loss, the higher the probability that a damper bar fault will occur. This phenomenon is consistent with the damage situation, which has happened on the damper bars in several hydropower stations.

Taking a set of damper bars as an example, the variations of the eddy currents with time are studied. The curves of the eddy currents are shown in Fig. 4. Here, the generator is operated at rated condition.

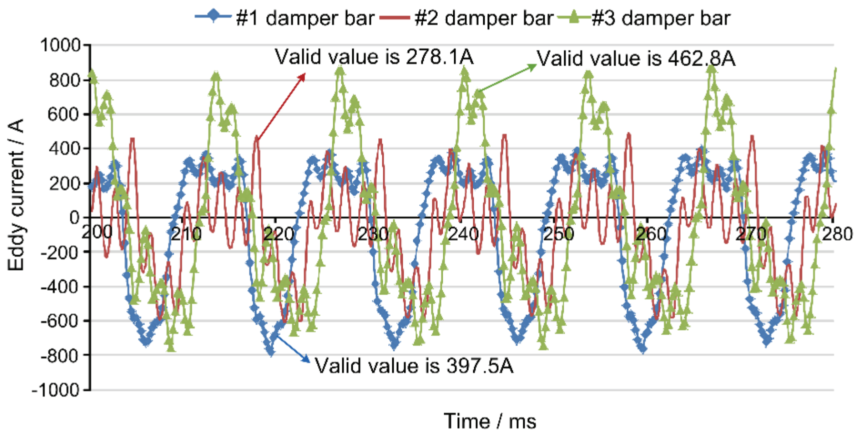

Fig. 4. Variation curves of eddy current on damper bars

From Fig. 4, it can be known that the eddy currents that were generated by damper bars 1 and 3 are significantly larger than that of damper bar 2. The valid values of the eddy currents in the three damper bars are, from left to right, 397.5 A, 278.1 A and 462.8 A. It can be known that damper bar 3 will generate more eddy current loss than the other damper bars. Therefore, damper bar 3 is more vulnerable to failure than the other damper bars. In addition, it can be concluded that the eddy current in damper bar 3 is not always the biggest, but the valid value of it is the biggest among the three damper bars on the whole.

Besides, it can also be seen that the eddy currents have an obvious characteristic of periodic changes. Affected by harmonic magnetic fields, the eddy currents in damper bars display complex periodic variation. Overall, the change period of the eddy current is 40 ms. Further analysis shows that the fluctuation period of the eddy currents of damper bars is completed in a cycle of 40/3 ms. Because the generator adopts a fractional slot winding, and the slot per pole per phase is 7/4, so there are fraction-harmonics in the generator. The analysis shows that the 2nd harmonic is taken as the fundamental wave, and the content of the 5/2nds harmonic is larger in the armature winding. The 5/2nds harmonic changes five cycles when the fundamental wave is passing through two cycles. That is to say, the period of the 5/2nds harmonic lasts 8 ms. And the rotating magnetic potential of the 5/2nds harmonic is rotating at a speed of 2/5 Ns (Ns is the synchronous speed). Therefore, the speed of the 5/2nds harmonic magnetic field relative to the rotor is 3/5 Ns. Eventually, it can be known that the period of the 5/2nds harmonic magnetic field cutting the damper bars is 40/3 ms.

Based on the asymmetric distribution of eddy current density on the three damper bars, the following section gives an in-depth study.

3.2. The mechanism of eddy current asymmetric distribution

A. The effect of cogging on eddy current distribution

It is found that the position of the rotor will affect the distribution of eddy current density on the damper bars. When the rotor is located at different positions, the eddy current density distributions of the damper bars are given in Fig. 5.

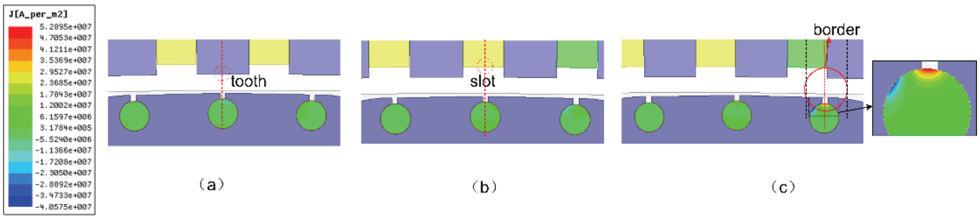

Fig. 5. Eddy current distribution of damper bars when the rotor at different positions is: facing the stator tooth (a); facing the stator slot (b); between the tooth and slot (c).

As the distance between the damper bars of a pole is one tooth pitch, therefore, the three damper bars are at the same position relative to the stator at any moment. That means the three damper bars will correspond to the stator teeth, slots or other location at the same time. From Fig. 5, it can be seen that the eddy currents in the three damper bars are low when the damper bars are aiming straight at the stator teeth or slots, and the difference in the eddy currents between the damper bars is not huge. While, when the damper bars is located at the border of stator tooth and slot, the eddy current of the far right damper bar is obviously increased.

The magnetic field distribution in the generator will be affected by the stator teeth and slots, and the change of the magnetic field will cause greater impact on the far right damper bar than that of the other damper bars. Therefore, the cogging is one of the reasons to affect the asymmetric distribution of an eddy current density on damper bars. Through the variations of the eddy currents in the three damper bars, it can be known that the eddy current of the far right damper bar is not always the biggest when the damper bar is located at the border of stator teeth and slots. Therefore, there are still other factors that will affect the asymmetric distribution of the eddy current in damper bars.

B. The effect of the armature reaction on eddy current distribution

Another reason for the asymmetric distribution of eddy current in the damper bars is the armature reaction, which could result in the distortion of the magnetic field. The magnetic fields on both side of the pole shoe are affected by the armature reaction, one side is enhanced and the other side is weakened. Because the main magnetic field of the synchronous generator is ahead of the resultant magnetic field, and the rotor is rotating in a counter clockwise direction, so the distribution of the magnetic field is tilted to the right side. The magnetic density on the right side of the pole is strong, and it will make the far right damper bar produce large magnetic potential difference. The influences of the armature reaction on eddy current distribution were studied in the following section. To avoid the influence of the stator teeth and slots, the generator has been equipped with the magnetic slot wedges. The generator structure is shown in Fig. 6(a). When the generator is operated at no load and rated load condition respectively, the distributions of magnetic density on the pole are studied, as shown in Figs. 6(b) and (c).

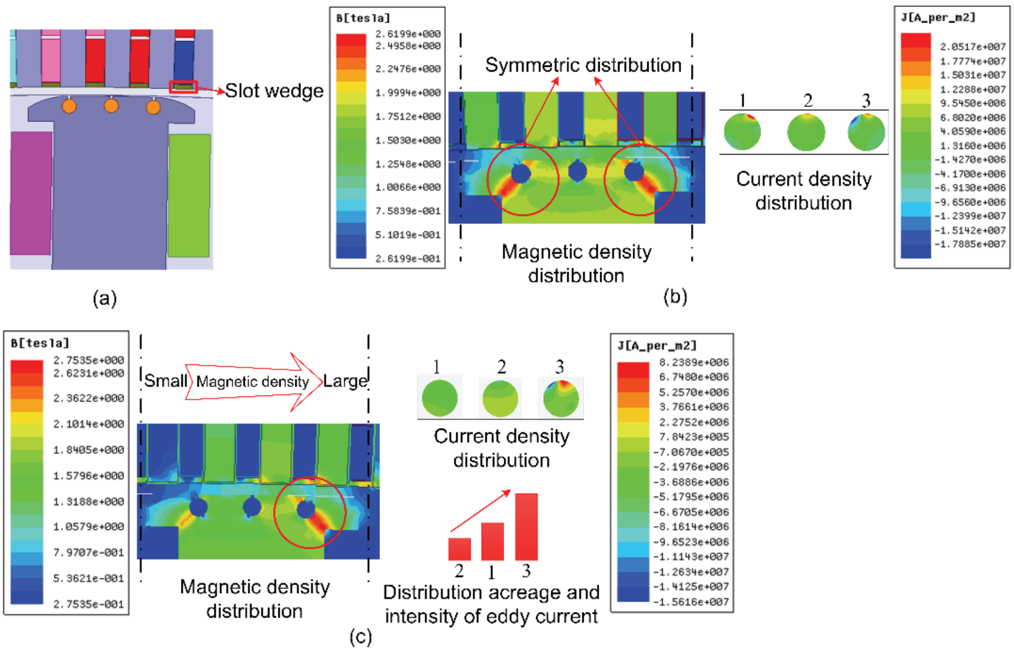

Fig. 6. Generator structure (a); magnetic and eddy current density distribution when the generator operated at no load condition (b); magnetic and eddy current density distribution when the generator operated at rated load condition (c)

Fig. 6(b) shows that the magnetic density is symmetrical when the generator is operated at no-load condition, and the maximum value of the magnetic density appears at both sides of the pole shoes. From Fig. 6(c), it can be seen that the magnetic field is tilted to the right side of the pole when the generator is operated at rated condition. At this time, the maximum value of magnetic density appears at the right side of the pole shoe. In addition, compared with the no load condition, the magnetic intensities of damper bars 1 and 2 are reduced. While, the distribution acreage and intensity of the eddy current in damper bar 3 are obviously increased.

From the above analysis, it can be known that the armature reaction causes the magnetic field offset to a certain degree, which results in the uneven distribution of the magnetic flux density, and eventually leads to the far right damper bar generation more eddy currents. The stronger the magnetic field at the damper bar is, the more eddy current it generates. The following section gives a detailed analysis on the above.

C. Theoretical researches

Similarly to the electric field, the magnetic potential difference exists in a magnetic field. When the large difference of magnetic potential exists around the damper bars, the rotation of the generator's rotor will cause great influence on the magnetic field around the damper bars. Eventually the damper bars will generate more eddy current losses. Influenced by the skin effect, the eddy currents are mainly distributed on the surface of the damper bars. The distribution of the eddy current density is given in the following equation.

$$\dot{\boldsymbol{J}} = \frac{\partial \boldsymbol{H}}{\partial x} = -\boldsymbol{H}_0 \frac{1+j}{\Delta} e^{-(1+j)\frac{x}{\Delta}} = -\boldsymbol{J}_0 e^{\frac{x}{\Delta}} e^{-(\frac{x}{\Delta}-45°)} . \tag{3}$$

Further derivation:

$$x = -\ln(-\frac{\Delta \dot{\boldsymbol{J}}}{\sqrt{2\boldsymbol{H}_0}} , \tag{4}$$

where: $\boldsymbol{J}_0$ is the current density at the conductor surface; $\boldsymbol{H}_0$ is the magnetic intensity at the conductor surface; Δ is the skin depth of the magnetic field; x is the skin depth of the current density. Among them:

$$\boldsymbol{J}_0 = \frac{\sqrt{2\boldsymbol{H}_0}}{\Delta} , \tag{5}$$

$$\Delta = \sqrt{\frac{2}{\omega\mu\sigma}} , \tag{6}$$

where: ω is the angular frequency; μ is the conductivity; σ is the magnetic conductivity. The conductivity and magnetic conductivity are fixed values when the material is determined.

Eq. (3) shows that the eddy current density is proportional to the surface magnetic intensity of the conductor. From Eq. (4), it can be seen that the skin depth of the eddy current is in positive correlation with the skin depth of the magnetic field.

The above analysis shows that the penetration depth of eddy current in the conductor is related to the magnetic intensity around it. The stronger the magnetic intensity, the deeper penetration depth of the eddy current becomes. However, the cogging and armature reaction will affect the magnetic field distribution, which will have a certain impact on the surrounding environment of the damper bars. According to the above study of the eddy current density distribution in the damper bars, it can be concluded that the magnetic intensity of the far right damper bar is stronger than that of the other damper bars. Therefore, the damper bar that lies in the leeward side of the poles prone to failure is explained.

3.3. The methods to prevent the asymmetric distribution of eddy current

Through the above analysis, it can be known that the cogging effect and the armature reaction are the main factors to affect the asymmetric distribution of an eddy current in damper bars. The cogging effect can be weakened when the generator is installed with magnetic slot wedges. The installation of magnetic slot wedges can not only reduce the reluctance, improve the heat conduct ability, but also can improve the magnetic field intensity. As for the armature reaction, it can be controlled by adjusting the power-angle of the generator. In real life, the generator is required to produce a certain amount of reactive capacity to meet the needs of some equipment. Therefore, the influence of the armature reaction on the asymmetric distribution of an eddy current in damper bars is difficult to solve.

4. Conclusions

In response to the phenomenon of the damper bar that lies in the leeward side of the poles prone to failure, taking the eddy current density distribution as the research point, some researches are made. In the paper, a 24 MW bulb tubular turbine generator is taken as an example. The reasons that cause the asymmetric distribution of the eddy current in damper bars are analyzed, and the key influence factors are determined. The asymmetric mechanism of the eddy current densities in damper bars is revealed through further studies. Above all, the following conclusions are obtained:

1) When the generator is operated at rated condition, the eddy currents of the damper bars display periodic variation with the rotation of the generator rotor, and the fluctuation period of the eddy currents of damper bars is completed in a cycle of 40/3 ms. Although the eddy current of the far right damper bar is not always the biggest among the three damper bars, the valid value of it is the biggest in the mass. The valid values of eddy currents in the three damper bars are, from left to right, 397.5 A, 278.1 A and 462.8 A.
2) The cogging and armature reaction are the main factors to affect the asymmetrical distribution of the eddy current in damper bars. In essence, the magnetic field distribution of the generator is changed by the cogging and armature reaction. The stronger the magnetic field intensity around the damper bars, the more eddy current generated in the damper bars.
3) The eddy current of the damper bar that lies in the leeward side of the pole is obviously increased when the damper bar is located at the boundary of the cogging. Influenced by the armature reaction, the magnetic field is offset to the right side of the pole. It makes the distribution acreage and intensity of the eddy current on the far right side damper bar obviously increased.

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