Abstract

In the stator windings of large rotating machines such as the turbogenerators and the hydrogenerators, the conductor bars are divided into strands to reduce the eddy current loss due to the leakage magnetic flux which are mainly induced inside the slot. Moreover, in the case of the strands which are shorted in the most end of the stator bar, inter-strand circulating current is induced due to the leakage flux and it causes additional heating. Therefore the strands are usually transposed in the stator core region and sometimes in the end region in the generators of large output. In order to enhance the efficiency of the generator and/or to avoid the additional heating, it is important to evaluate the loss in each part of the machine and the circulating current loss should also be calculated precisely to evaluate the effect of transposition.

In this paper, magnetic field analysis method using multi-slice finite element method is proposed to calculate the circulating current in the stator bar which includes strands transposed in the coil end region. Then circulating current loss analyses of transposed stator bars are performed and the effect of the transposition is discussed for some variations of transposition. The end transposition “90-360-90” is the most effective for the coilend internal leakage flux and circulating current loss increase for “0-360-0” case is reduced to around 3/5 by the coilend transposition and it is around the same level as “0-450-0” case.

Key words : Strand transposition, Stator winding, generator, Circulating current, Generator, Finite element method, Electromagnetic field analysis

1. Introduction

Recently, in the view of reduction of environmental impact, burden, requirement for enhance the efficiency of power systems, as well as power generators. In order to investigate high efficiency machines, it is important to predict the losses precisely. Especially, on the stray load loss, which was originally the unknown loss, it has been getting clarified that it is composed of the eddy current loss in the various conductive structures, additional resistance loss in the coil bars and so on.

In the large rotating machines, such as the turbogenerators and the hydrogenerators, the conductors of the armature windings generally consist of double layers of half coils (Tari, et al., 1977) including mutually insulated conductor strands which are transposed(Roebel,1915). In the case that the strands are shorted at the both ends, electromotive force arises due to the difference of the induced voltage by the interlinkage flux and it leads to the circulating currents between the strands. On the evaluation of this circulating current, some works have been published(Takahashi, et al., 2002, Ide, et al., 2003, Kometani, et al., 2003), and the authors have also presented analysis methods and application to
the reduction of the circulating current loss (Tokumasu, et al., 2003, Fujita, et al., 2009).

As for the transposition measures of the strands, transposition in the coilend region has been known as well as the transposition only in the active part of the stator core slot but many of the literature deal with only the transposition in the active part. Therefore, the authors have developed an analysis method of the circulating currents in the transposed coil bars in the coilend region modifying the method without the transposition in the coilend region. In this paper, the developed analysis method using multi-slice finite element method is presented and some examples of investigation on variations of transposition are described.

2. Stator winding and strand transposition

2.1 Stator winding

In the large rotating machines, such as the turbogenerators and the hydrogenerators, the conductors of the armature windings generally consist of double layers of half coils, which are connected to the corresponding half coils. Fig.1 (a) illustrates a typical cross section of the stator coils. It is composed of layers of mutually insulated conductor strands to reduce eddy current loss. As the strands are shorted at the both ends, electromotive force arises when the induced voltage by the interlinkage flux differs in each strand. Then circulating currents are induced between the strands which lead to additional losses. In order to eliminate such losses, the strands are commonly transposed as shown in Fig.1(b).

The conductors are wound and treated by insulating tapes, through which coils are cooled in the indirect cooling type generators. The design of the generators must be careful to keep the temperature limit of the insulating material not to be damaged.

2.2 Circulating current

The classification of the loss in the armature winding is presented in Fig.2. First, the loss is classified in the dc resistance loss and ac loss. The ac loss consists of eddy current loss, inter-strand circulating current loss, and inter-circuit circulating current loss in the windings in parallel. The magnetic flux which causes the inter-strand circulating current loss, which is mainly dealt with in this paper, is also divided into slot flux in the core region and coilend flux. Furthermore, the coilend flux is categorized into coilend internal flux and coilend external flux. Figure 3 shows schematic diagrams of these fluxes and coil strands. The coilend external flux can be divided into two components of direction, transverse and vertical to the coil height direction. Recently, according to the advance of analysis methods and the computer performance, many researches have been published on its quantification.

2.3 Strand transposition

Figure 4 illustrates the strand transposition of the stator conductor bar. Figure 4(a) to (c) present the strands which are transposed only in the active part in the core region, namely not transposed in the coilend part. The 360 degree
transposition includes the strands which rotate in one cycle in the active part. Similarly, in the 450 degree transposition, the strands rotate in one and a quarter cycle, and the 540 degree transposition one and a half cycle (Ringland and Rosenberg, 1959).

The interlinkage flux in the active part is cancelled when the core is uniform and the strands are transposed as mentioned above. But the voltage induction by the interlinkage flux in the coilend part is doubled in the 360 degree transposition that leads to the circulating current. To improve this, the 450 and 540 degree transposition are aimed to reduce the voltage induction in the coilend part.

As denoted in the caption of the Fig.4, the transposition configuration is expressed arranging the angle in a coilend part, an active part and another coilend part as “0-360-0”, “0-450-0”, and “0-540-0” respectively for the 360, 450, and 540 degrees in the active part without coilend transposition. As shown in Fig.4 (b) to (c), the transposition pitch in the border zone of the active part is the half of the other part for “0-450-0” and “0-540-0” transposition.

Figure 4(d) illustrates an example of the transposition in the coilend parts (Sequentz, 1973). The strands are 90 degree transposed in each coilend part as well as 360 degree transposition in the active part so as to reduce the voltage induction. This type of transposition is expressed as “90-360-90” in this paper.
3. Analysis method of circulating current

3.1 Circulating current by slot flux

As the magnetic flux can be treated to have only transverse direction component, assuming the permeability of the core around the slot as infinite, the circulating current due to the leakage flux in the active part is calculated by solving the network equations on the strand currents considering the interlinkage flux in the slot (Fujita, et al., 2009).

Here, detail explanation on the circulating current due to slot flux is omitted because the leakage flux in the slot region is cancelled in the cases dealt with in this paper. However, when the interlinkage flux is not balanced by uneven ventilation duct arrangement, distribution of the core space factor and irregular strand transposition, the voltage induction should be evaluated (Fujita, et al., 2005).

3.2 Circulating current by coilend flux

If the complicated structure of the stator coilend and the clamping flange to fasten the laminated core is strictly considered, 3D analysis is required to calculate the inter-strand circulating current due to the coilend flux. However, dealing with the leakage flux classified by the cause of circulating current, 2D electromagnetic analysis can be applicable around a single coil bar.

On the 2D FE analysis using the magnetic vector potential, constrains can be applied to the eddy currents utilizing the indefiniteness of the potentials. Hereby the circulating currents in the multi conductors can be analyzed using the network theory (Nakata, et al., 1980, Tokumasu, 1986).

In the case without coilend transposition, as is shown in Fig. 5(a), two coilend regions are discretized separately and analyzed simultaneously imposing the condition that the circulating currents in the corresponding strands are the same. Here, taking into account the strand impedance in the active part and the inter-strand mutual inductance as an external admittance matrix, the finite element analysis and the network analysis can be done at a time (Tokumasu, et al., 2003).
The functional is shown in Eq. (1) where $Y_{kl}$ is the admittance matrix corresponding to the strand impedance in the active part.

$$
\chi = \int \left\{ \frac{\left( rotA \right)^2}{2\mu} + \frac{\omega \sigma}{2} \left( A - \sum_k \beta_k \frac{C_k}{L} \right)^2 \right\} dSL + j\omega \sum_{k,l} Y_{kl} C_k C_l
$$

(1)

To calculate the circulating currents due to the internal coilend flux, total current of the coil bar is given. On the other hand, to calculate the circulating currents due to the external coilend flux, total current is set to zero and the external field obtained from other analysis is given as boundary conditions.

In this method where the interaction between the strand currents in the coilend region is included in the FE analysis, it is not necessary to calculate the inter-strand mutual inductance in the coilend region (Takahashi, et al., 2002). The inter-strand mutual inductance in the active part can be obtained easily from the positional relation of strands.

Furthermore, in the analysis considering the coilend flux, the strand is approximated as step-wise configuration and each step is expressed as a layer of sub-region “Coilend 1-k”($k=1,2,...,n$) shown in Fig.5 (b). For the other side of the coilend sub-region, the same approximation is applied. In each sub-region, a constraint condition is imposed that the strand current is the same in corresponding strand and the entire region is calculated in all the analysis sub-regions simultaneously.

4. Circulating current analysis on a hydrogenerator

4.1 Analyzed machine

Here, as an example of application to a power generator, 30MVA class hydrogenerator, whose frequency is 60Hz, is analyzed. The machine includes double layer of stator bar in a slot and the coil bar is composed of 2 columns and 13 rows of flat square strands.

4.2 Analysis condition

The transposition angle analyzed in this paper is “0-360-0”, “0-450”, “0-540-0”, and “90-360-90”. As for “90-360-90” transposition, the strand location is moved in 7 rows and the exact angle is 97 degrees in the coilend part. Figure 6 presents an example of finite element mesh for the analysis without coilend transposition. In the analysis of coilend transposition, the analysis region includes 7 sub-regions for one coilend side, namely 14 sub-regions for entire model.
An ac analysis is performed using a complex analysis. For the analysis of coilend internal leakage flux, the load current is set to the real part and for the analysis of coilend external leakage flux, the external magnetic flux is set to the real part. Then the current vector is summed considering the phase difference as a post processing. Figure 6 (b) illustrates an enlarged view of the mesh around the coil bar and the strand number is marked in the figure.

4.3 Analysis results

4.3.1 Magnetic flux density distribution

Figure 7 displays examples of real part of the flux distribution and these flux line presents the flux source leading to the circulating current. Figures correspond to (a) coilend internal flux, (b) coilend external flux in the transverse direction and (c) coilend flux in the radial direction, respectively. As these distributions are almost the same for each of the transposition condition, Fig.7 shows the flux lines only for the “0-360-0” case.

Corresponding to the flux source shown in Fig.7, the imaginary part of the flux line distribution is displayed in Fig.8 to Fig.10 for the one side of the sub-region. For the case of “0-540-0”, the results are not presented because the flux line distribution of the internal flux case becomes the same as the one of “0-360-0” and for the external flux case, the circulating current becomes zero.

In the case of “0-450-0” presented in Fig.9, the location of the strand is rotated in 45 degrees in the coilend part against the “0-360-0” case and therefore the flux lines are rotated correspondingly. The flux distribution in the sub-region in the opposite coilend side is not shown but it shows bilateral symmetry distribution to the figures in Fig.9.

Figure 10, the case “90-360-90”, shows that the flux lines are rotated as the strands change the position rotationally. These figures of flux line distribution show that the circulating currents are simulated validly.

4.3.2 Strand current distribution

Figure 11 presents the strand current distribution normalized by the averaged load current of each strand. As shown in Fig.11 (a), the distribution of the circulating current due to the coilend internal flux for “0-360-0” and “0-540-0” coincides with each other. This means “0-540-0” transposition does not reduce the voltage induction due to the coilend internal flux. On the other hand, “0-450-0” and “90-360-90” transpositions are able to reduce the circulating current due to the coilend internal flux and the end transposition is the most effective for this flux.

As for the circulating current due to the coilend external flux in Fig.11(b), “0-540-0” is the most effective and “0-450-0” and “90-360-90” cancel the voltage induction partially.

On the circulating current due to the radial flux shown in Fig.11(c), though the distribution of the circulating current does not differ so much except the “0-540-0”, the current magnitude is smaller than other cases and the effect on the total circulating current is not so remarkable.
Fig. 7 Magnetic flux line distribution (real part).

Fig. 8 Magnetic flux line distribution in the case of 0-360-0 transposition (imaginary part).

Fig. 9 Magnetic flux line distribution in the case of 0-450-0 transposition (imaginary part).

Fig. 10 Magnetic flux line distribution in the case of 90-360-90 transposition (End-external flux, imaginary part).
4.3.3 Strand loss distribution

Figure 12 presents the distribution of the total circulating current loss in the strands in which the circulating current of each cause is combined considering the phase difference. The vertical axis is the ratio to the average dc resistance loss in the strand in per unit (PU) expression. As shown in the figures, there is a strand where the loss is about 5 PU, which might affect local temperature rise of the strand.

In the “0-540-0” case, the strand loss is the most averaged and in other cases, there are strands whose strand loss are less than 1 PU. Furthermore, it can be said that by the coilend transposition, the peak loss value is reduced to around half of the “0-360-0” case.

4.3.4 Circulating current loss increase

Figure 13 displays the loss increase in the coil bar for each cause of circulating current. In the figure, the loss increase, when the circulating current due to each cause is summed to the load current, is normalized by the loss due to the averaged load current. As shown in the figure, the loss increase due to the coilend external flux is dominant in this machine. As for the total circulating current, the loss for “0-360-0” case is reduced to around 3/5 by the coilend transposition and it is around the same level as “0-450-0” case. Considering that in the case of “0-450-0” and “0-540-0” the transposition pitch in the border zone of the active part should be half of the other part, the coilend transposition is one of the effective solutions of loss reduction.
5. Conclusion

As described above, magnetic field analysis method using multi-slice finite element method is proposed to calculate the circulating current in the stator bar which includes strands transposed in the coil end region. Then circulating current loss analyses of transposed stator bars are performed and following results are obtained:

- With the proposed analysis method, effect of the strand transposition can be evaluated by the circulating current analysis categorizing the magnetic flux which induces the inter-strand voltage.
- As the reduction measure of the circulating current, the “0-540-0” transposition is the most effective for the coilend external leakage flux, and the end transposition “90-360-90” for the coilend internal leakage flux.
- The circulating current loss increase for “0-360-0” case is reduced to around 3/5 by the coilend transposition and it is around the same level as “0-450-0” case.

Nomenclature

- \( A \) magnetic vector potential [Tm]
- \( \mu \) permeability [H/m]
- \( Ice \) circulating current [A]
- \( \sigma \) conductivity [S/m]
- \( Y_{kl} \) admittance matrix [S]
- \( \omega \) rotational speed [rad/s]
- \( \beta_{ia} \) cut-set matrix on voltage [-]
- \( \chi \) functional [-]
- \( C_k \) coefficient on terminal voltage [Vs/m]
- \( L \) conductor length [m]

References

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