Calculation of Temperature in a Large Turbine Generator with Multilayer Roebel Transposition Coils
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I. INTRODUCTION

Recent market trends require highly efficient and reliable turbo generators. In 2001 the inner cooling ventilation system (ICVS) made it possible to make highly reliable 250MVA 50Hz air-cooled turbine generators with an overall efficiency of 98.8% [1]. To further increase efficiency, we have been developing design tools that can be used to improve ventilation and loss distribution, reduce temperatures, and better control vibration [1][2]. Our main concerns were the vibration, mechanical, and stray-load losses in two-pole commercial turbine generators and the higher temperatures due to these losses.

Generators with larger ratings use hydrogen or water or both as cooling media. The configuration of indirectly hydrogen-cooled machine is similar to that of air-cooled machines, so the calculation tools and technologies developed for air-cooled generators can basically be used with only slight modification. But because the cooling mechanism is different in water-cooled generators, some fundamental modification of the design tool was needed.

The coil in a water-cooled generator has hollow strands through which water, introduced from the coil end, flows and cools the strands directly. A water-cooled coil usually has four or more stacks (rows) of strands, while a hydrogen-cooled or air-cooled coil usually has two rows and is cooled indirectly by coolant via the ground insulation. Because the cooling capability of water is much larger than that of air or hydrogen, the heat load on the coils cooled by air or hydrogen is smaller than that on water-cooled coils. The process producing electrical losses therefore differ between water-cooled coils and air-cooled or hydrogen-cooled coils, so we needed to modify the design program to handle a larger number of rows, direct cooling, and the different mechanism of loss generation. Part of this modification has already been reported [3].

Calculating loss requires temperature determination because the resistance of conductors changes with their temperature. In other words, loss distribution and therefore temperature distribution, depends on the initially determined temperature. But the initial temperature is usually set to a specific value, so little attention has been paid to the initial temperature distribution. The temperature and resistance of conductors in actual generators, however, are neither uniform nor constant, and the initial temperature determining resistance should therefore be an important factor to consider when predicting the actual loss and temperature distribution.

In the work reported in this paper, the program reported in Ref. 2 was modified to handle a water-cooled generator that has four rows of strands in a coil. The relations between armature winding temperature and loss are discussed here with particular regard to 220MVA-class air-cooled generators and 500MVA-class water-cooled generators.

II. TEMPERATURE CALCULATION

A. Loss and Temperature

Temperature calculation for a generator requires estimation of the coolant flow and of losses such as friction and ventilation loss, iron loss, armature direct loss, field direct loss, and stray load loss. All losses should be taken into account when calculating the temperature rise of the coils in an air-cooled generator because they all affect the temperature. The mechanical loss in a hydrogen-cooled generator is much smaller than that in an air-cooled machine because compressed hydrogen has a large heat capacity and low viscosity. The influences of losses other than armature direct loss or a part of the stray load loss are even smaller in a water-cooled generator because the strands covered with thermal and electrical insulation are directly cooled by water.

In this paper all the above losses are taken into an account even for water-cooled generators because any of these losses may have at least a small influence on the temperature rise. Of course, the principal losses that determine coil temperatures are the direct loss and the stray load losses generated in the coil. Temperature distribution has to be determined because resistance varies with temperature. A specified temperature is usually used for loss calculation, but the temperatures in the armature coils are not actually uniform. In the work reported here the fine temperature distribution for loss calculation was determined by iteration of the calculation flow shown in Fig. 1. By virtue of incorporating the
fig. 1. Flow of temperature calculation for armature coils.

calculated temperature calculation into the resistance determination, an uncertain boundary condition vanishes. The calculation was iterated until the temperature at each location reached a constant value.

B. Temperature dependence of losses in armature coils

Figure 2 shows strands in a transposed coil. A stator coil is composed of numbers of strands and circulating current loss is minimized by arranging the vertical location of each strand according to the axial position. Magnetic fluxes (or induction) crossing the strands are canceled within the stator core but unequal fluxes at both ends causes circulating current within strands. For example, the different leakage fluxes $\Phi_1$ at coil end 1 and $\Phi_2$ at coil end 2 induce a voltage between strand 1 and strand $k$, and this voltage causes circulating currents. Fluxes also induce local eddy currents within single strands, and these eddy currents depend on the local temperature. The mechanisms of circulating current and eddy current are shown on the right-hand side of Fig. 3. The circulating current between strand 1 and strand $k$ depends on sum of the resistances of strand 1 and strand $k$. When the average temperature of strand $k$ is $t_k$, the resistance of strand $k$ is calculated by the following formula:

$$R_k = R_{k0} \frac{235 + t_k}{235 + t_0},$$  (1)

where $k$ is the strand number, $R_k$ is the resistance ($\Omega$) of strand $k$, $R_{k0}$ is the resistance ($\Omega$) of strand $k$ at $t_0$, $t_k$ is the average temperature ($^\circ$C) of strand $k$, and $t_0$ is the reference temperature ($^\circ$C).

The eddy current induced within a single strand depends on the local resistance in the corresponding location. To handle the average and local temperature, the idea of segmentation is used in the loss calculation. The segmentation for temperature distribution is shown in Fig. 3, where $i$ represents axial position and $k$ represents the strand number. The electric resistivity of strand $k$ at position $i$ is calculated by the following formula:

$$\rho_{ki} = \rho_0 \frac{235 + t_{ki}}{235 + t_0},$$  (2)

Where $i$ is the axial position, $k$ is the strand number, $\rho_{ki}$ is the resistivity ($\Omega$ m) of strand $k$ at position $i$, $\rho_0$ is the resistivity ($\Omega$ m) of the strands at the reference temperature $t_0$ ($^\circ$C), and $t_{ki}$ is the temperature ($^\circ$C) of strand $k$ at position $i$.

The average temperature of strand $k$ is calculated by using the following formula:

$$t_k = \frac{1}{n} \sum_{i=1}^{n} t_{ki},$$  (3)

Where $n$ is the total number of axial segments.

fig. 2. Arrangement of strands in a transposed stator coil.

fig. 3. Segmentation for temperature distribution in a stator coil.
After the eddy current and circulating current are calculated, the corresponding loss distribution is calculated with the local temperature. The total loss distribution is obtained by summation of circulating current loss, eddy current loss, and direct loss.

C. Temperature calculation

The temperature calculation uses thermal network analysis. Figure 4 shows an example of an actual configuration of a stator of a water-cooled generator and the corresponding network for temperature calculation. A coil has four rows of strands, each two of which constitute a subcoil and are transposed separately. Cooling water flows into the hollow coils at the end part. The network takes into consideration the stator coils, cooling water, core, air gap, air ducts, and all the other components, including the stator wedges and ripple springs. We take into account the actual configuration of the strand transposition in the slot area. The complete network shown in Fig. 5 begins with the series-connected components and expands to the center point in an axial direction. With all the losses in the generator taken into consideration, the temperature distribution can be calculated. Here the thermal element connecting the coil and the water is drawn larger for better understanding.

III. CALCULATION RESULTS

Figure 6 shows the history of the initial temperature rise in the loss calculation for a 220MVA-class air-cooled generator. For the first step, the calculation of the electrical resistance is based on a uniform temperature of 115°C. In the second and later steps the initial resistances are determined by the temperature distribution calculated in the former steps. The temperature rise shown in this figure is the averaged value along the entire length, but the loss is actually calculated with complicated model. The temperature rises of the top and bottom coils were both constant after the first iterative calculation, and the final temperature rise was roughly 80% of the initial value that was used for initial loss calculation. The traces of loss breakdown are shown in Fig. 7, where 1.0 pu represents the total loss of top coil calculated in step 1. Though the final temperature rise was only 80% of the assumed value, total loss remained nearly constant and the deviation from the first step was less than +1%. The value for the top coil was +3%, while that for bottom coil was -2%. According to the temperature decrease, the direct loss decreased because the resistance decreased. The eddy current and circulating current, on the other hand, increased. Because the bottom coil had smaller eddy currents, the total of these losses for the final step was smaller than the initial value. These calculation results show that generators with a configuration similar to that of 220MVA air-cooled generators do not require accurate resistance determination for temperature calculation, since direct loss counterbalances stray load loss.

Figures 8 and 9 shows the history of initial temperature rise and calculated losses for a 500MVA-class water-cooled generator. The initial uniform temperature for the first step is 95°C. Two or more iterative calculation were needed for convergence to constant values. In this generator the temperature rise and the loss decreases step by step. Though circulating and eddy current losses increase because the temperature decreases, the decrease of direct loss dominates the total loss. The use of water, which has a cooling capacity greater than that of air, enables the use of coils with a smaller cross section. This reduces the percentage of eddy current loss and circulating current loss, leaving the tendency to be determined by the direct loss. The deviation of the converged total loss was -10% of the first step. This means that the loss and temperature of water-cooled generators cannot be estimated without
accurately determining temperature used for calculating the resistance.

Figure 10 shows the calculated temperature distributions in a 500MVA-class water-cooled generator. The upper part of this figure shows the temperature map seen from the side of row 1, while the lower part shows the temperature map seen from the side of row 4.

Both of them are an identical stator coil view from the coil end and water inlet side, and the temperature is higher on the side of row 1.

The temperature is at the central axis of generators. 1.0 pu represents the maximum calculated temperature within the entire length in step 1. Rows 1 and 2 constitute a subcoil and are transposed with regard to each other. Rows 3 and 4 constitute another subcoil and are also transposed. But these
subcoils are not transposed with regard to each other, and the radial components of magnetic fluxes cross between these subcoils. This causes circulating current between the two subcoils, and the subcoil made up of rows 1 and 2 has larger losses at higher temperatures. Each coil shows twisted stripes along the axis. The colder strands are hollow conductors that are directly cooled by water, and the hotter strands are solid strands that are cooled through the thin insulation between them and hollow conductors. Current and temperature distributions at the core center are shown in Fig. 11, where 1.0 represents the direct current. The currents in rows 1 and 2 are larger than those in rows 3 and 4, and the largest current is roughly 3 times the smallest current. This current distribution explains why the temperature of rows 1 and 2 is higher than that of rows 3 and 4.

The temperature distribution is more uniform than the current distribution even though loss is proportional to the square of the current. The difference between the maximum temperature and the average was only 4 K. The thin insulation between strands averages the temperature distribution. Extrapolating this maximum temperature to the entire length of the generator gives a maximum temperature of 76°C at the outlet. This temperature is well below the limit for water-cooled coils.

IV. CONCLUSION
We have developed sophisticated design tools to handle Roebel transposition coils with more than four stacks of strands and have investigated the relation between the temperature distribution and loss in stator coils. We found that the initial temperature affects neither the loss nor temperature of an air-cooled generator but does affect the loss and temperature of a water-cooled generator. For a 500MVa-class water-cooled generator, the actual loss was only 90% of that calculated with a constant temperature of 95°C. Though the maximum value of strand current is three times of the minimum value, the temperature deviation from the average at the core center is no more than 4 K and the maximum temperature at the outlet remains 76°C, which is well below the limit for water-cooled coils.

V. REFERENCES