SUMMARY:
The generator market is concerned with the long-term reliability and cost performance of power plants. While our 250-MVA class air-cooled turbo-generator with an ‘Inner Cooler Ventilation System’ has an efficiency over 98.8%, its temperature was within the class-B limitation with the actual insulation of a class F unit. We therefore evaluated its potential by placing more than 1000 temperature and ventilation sensors in a test generator. This paper discusses the results of those measurements of the air gap ventilation, stator strand temperature, and rotor winding temperature. Measurement of the highest temperatures was assured by embedding thermocouples, optical temperature sensors, and resistor temperature detectors in the rotor and stator windings. The optical temperature sensors were installed in the stator strands. The air flows measured in the air gap and the temperatures measured in the rotor, stator, and air gap were all similar to those calculated using design programs, and all the temperatures measured under full-load conditions were well below the limits for class B insulation.

KEY WORDS:

Introduction
The increasing output range of modern turbo-generators has made the influence of unscheduled outages a major concern for utility companies, since the cost of an unexpected generator failure might be 10 times the cost of scheduled repair work [1]. A study considering the total cost performance of generators—including initial, running, and unexpected costs—showed the advantage of air-cooled generators [2], and our 250-MVA class generator equipped with ‘Inner Cooler Ventilation System’ was put on the market in 2002. It has an efficiency of over 98.8%, almost as high as that of hydrogen-cooled generators[3]. A number of factors affect the lifetime performance of generators, and every aspect of our generator’s performance must be evaluated. Anything that has the potential to affect
operational life must be observed and tested. In the work reported here, we therefore measured the highest operating temperatures the unit experiences so we could establish the upper range of generator operating durability.

1. Measurements

1.1 Sensor Position
We began this evaluation by identifying critical points in the generator. The selection of the critical features of an air-cooled turbo-generator was based on our design calculations and our experience with other generators. Operating temperature affects the long-term reliability of any generator, and key factors determining the temperature of an air-cooled generator are the amount and distribution of air flow.

Over 1000 ventilation and temperature sensors were placed in the generator: 77 in the air gap, 166 in the field coil, 48 in the end of the stator, and 800 elsewhere. Some of these measurement points are shown in Fig. 1.

1.2 Measurement of air flow
We concentrated on flow and temperature distribution in the air gap because calculations had shown that the amount of air flow there is critical. The temperature there becomes high because air has a small heat capacity and there are various heat sources, such as the stator core, the rotor surface, and exhaust gases. The air flow and temperature distribution in this region are quite complicated.

An example of an anemometer setting is shown in Fig. 2. This figure shows the stator bore without a rotor. In the actual test stand, the rotor was put into place without anemometers. Then Pitot tubes with five holes as anemometers were inserted through the ventilation ducts. These tubes measured the velocity and direction of the main stream. Each anemometer could be slid in a radial direction to allow the main stream distribution to be evaluated at various depths in the air gap. The flow in the cross section of the air gap was calculated by summing up the measured ventilation distribution.

The total flow in the generator was measured at the main coolers, where 48 sensing points were set immediately downstream from each cooler. Comparing the heat exchanged at the coolers with the air temperature rise in the generator also gives a rough figure for the flow quantity.

Fig. 1. Points of measurement on 250 MVA generator.

Fig. 2. Anemometers in air gap.
1.3 Measurement of temperature

Usually, the resistor temperature detectors (RTD) embedded in top and bottom coils are the only way to detect the temperature of the stator coils. The data provided by RTDs can be used to evaluate the average temperature of the coil strands.

Temperature sensors are not usually embedded in field windings. Instead, their resistance calculated from the field current and the field voltage is compared with a reference resistance, and this value is converted to the average temperature of the windings. In most cases, the field current under a 3-phase short-circuit condition is the maximum value at the shop. The temperature under a full-load condition is then estimated by extrapolation.

From these measurement, we are able to estimate average temperatures of windings but not the highest. And the generator reliability is often related to the highest temperatures.

To directly measure the highest operating temperatures the unit is subject to, we embedded detectors on the stator and the rotor windings. The placement of temperature sensors in the stator end windings is illustrated in Fig. 3. In this region, many spacers between coils cover the surfaces. And the thick insulation on the series loop connection also complicates temperature distribution. Non-electrical temperature sensors had to be used there because the stator windings carry a high voltage. Optical sensors were therefore attached to the strands while the test generator was being manufactured, before the strands were insulated. An embedded temperature sensor is shown in the lower left corner of Fig. 3. In total, there were more than 100 measuring points in the stator to locate the highest temperatures.

Fig. 4 shows the bundles of thermocouples for rotor windings during installation. A total of 166 temperature sensors were placed in and out of the slots. This number was enough to measure the temperature distribution in the axial direction of each turn. Therefore, the maximum temperature could be precisely determined. The test was conducted under full-load conditions by electrically connecting the generator to a load machine with larger output range (Fig. 5). Although extrapolation procedure of rotor temperature has been verified by standards, we further investigated its accuracy by full-load field current.
Temperature calculation
A large network analytic calculation method was developed before the generator was designed. It included an air flow calculation, a stator temperature calculation [4], and a rotor temperature calculation. The stator and the rotor thermal networks are shown in Figs. 6 and 7. As illustrated in fig. 6, the actual configuration of the strand transposition in the slot area is taken into account. In the network, the stator coil bars, core, air gaps, air ducts, and all components, including stator wedges and ripple springs, have also been taken into consideration. The network begins with the series connection components and expands to the center point in the axial direction. The boundary conditions are air temperatures such as those at the fan outlet, inner cooler outlet, and rotor outlet, and the input losses are core loss, circulating current loss, eddy current loss, and mechanical losses. All these losses are located in this model according to calculated distribution.

The rotor network contains all the rotor components, including the shaft and a retaining ring. Although the conductors are directly cooled by air, wedges, creepage blocks, and other components act on the temperature significantly. While the rotor temperature in this configuration is not really affected by the stator, the stator temperature is influenced by the rotor because the outlet air on the rotor has to go through the stator ducts.

**Fig. 6.** Thermal network for calculation of stator temperatures.

**Fig. 7.** Thermal network for calculation of rotor temperatures.
Evaluation of measurements

Measured and calculated air flows in the air gap are illustrated in Fig 8, where positive flow values represent air heading toward the stator center from the left side of the part and negative flow values represent air heading in the opposite direction. The measured ventilation distribution showed good agreement with the calculated design values. The flow in the stator ducts was calculated from the measured stator core and coil loss distributions and measured temperature rise. And the accuracy of measurements in the air gap was checked by comparing the air flow in the air gap with that in the ducts. These evaluations confirmed the design accuracy. The calculated and measured temperature distributions in a stator coil and the air gap under short-circuit conditions are shown in Fig. 9, where 0 on the horizontal axis represents the core end and 1.0 represents the center of the generator. The 1.0 at the vertical axis is the calculated maximum temperature. In both the coil and the air gap, the calculated and measured temperatures show good agreement. This accuracy also applies to open-circuit condition, and mechanical loss (no-load no-voltage) condition. From this result, we can say the design tool is accurate enough for routine design.

Calculated strand temperature distributions in the stator coils under full-load conditions are shown in Fig. 10. Even the highest strand temperature is well below the limitation of the class B insulation. The temperature map calculated for stator coils are shown in Fig. 11. Although conventional temperature calculations locates the highest temperature at the innermost position of the top coil, our calculation shows that the highest temperature does not necessarily lie at the position. This distribution is due to the circulating current loss in the strands. Both from the calculations and measurements, the highest temperature had a wide margin relative to the class B temperature limitations. This assures good long-term reliability.
The measured and calculated temperature distributions of the field windings are shown in Fig 12. Here, 0 on the horizontal axis represents the slot end and 1.0 represents the center of the generator. Under no-load, short-circuit, and full-load conditions, the highest of the 166 measured temperatures was at the slot end. Fig. 13 shows the field current dependability of the highest temperature. Even in the rated field current, the temperature was well below the limitation of the class-B insulation. These measurements were also used to check the validity of the short-circuit test, and it was found that the rotor temperatures measured under short-circuit conditions can be extrapolated to the temperatures under full-load conditions with sufficient accuracy. This is true for the average temperatures as well as the highest temperatures.

Conclusion
The highest temperatures measured in the stator and rotor windings temperatures had a wide margin relative to the class B temperature limitations, which assures the long-term reliability of the generator. The measured temperatures were close to the temperatures calculated using design programs and confirmed that the actual performance of the 250-MVA class air-cooled generator is satisfactory.

References