Verifying ventilation flows

An innovative technique using a hot-film anemometer has been developed for measuring the flow distribution through generator rotors. **By W. Ray Laster and George W. Sanford**

When designing large air-cooled generators with the highest efficiency, engineers need to know the total flow rate to the rotor as well as the flow distribution to ensure there are no local hot spots. However, gaining an understanding of generator ventilation has been hampered by a lack of experimental data on rotating machines. Furthermore, while the axial flow distribution along the rotor body can be estimated using standard techniques, such methods average the flow in the circumferential direction.

To overcome these limitations, engineers at Westinghouse Electric Corp.'s Power Generation Technology Division in Orlando, Fla., have developed a novel technique for measuring airflow through each vent hole. The technique uses a hot-film anemometer—a velocity-measurement device with a very-high-frequency response—to measure such flows separately while the rotor is spinning at a rated speed of 3,600 rpm.

This technique can also be used to verify the integrity of the manufacturing process by enabling engineers to identify and address problems with the circumferential flow, and thereby achieve a sufficient flow area for ventilation in all parts of the rotor. Previously, the only way to identify such problems was to measure discrete temperatures during a running test, which is prohibitively expensive and time-consuming for use in production testing. In addition, this approach can be used only after the rotor has been designed and manufactured. By contrast, the hot-film anemometer technique can be performed as part of the factory rotor balance without adding significant cost to the generator.

This technique played an important role in optimizing the Westinghouse air-cooled generator (WESTAC), an efficient, low-cost unit for use with combustion and small steam turbines. WESTAC's state-of-the-art ventilation system reduces overall ventilation flow by 50 percent compared with previous air-cooled models. Engineers achieved the reduction by adopting an axially cooled stator core that improves the ventilation of the field winding by allowing the air gap to be used exclusively for rotor discharge air. This results in a lower back-pressure in the gap, which increases field-winding airflow and eliminates the need for radial vents in the stator core.

The hot-film anemometer technique also has been used to verify the ventilation of each generator rotor during season and balance before installation. In effect, the technique helped engineers get the WESTAC design right the first time, cutting time to market.

Detecting Flow Disturbances

Most air-cooled generators rely on a radial-vent scheme for rotor cooling. Airflow is provided by a single blower, located on the turbine end of the machine, that draws cooling air through the rotor and the stator. In addition, there is considerable self-pumping through the rotor because of the difference in the radius between the air inlet and exit passages on the rotor.

In the radial-vent scheme, air enters the rotor through axial channels at each end of the rotor that feed a series of radial channels formed by punching slits through the copper conductors at regular intervals along the rotor's length. These slits exit the rotor into the air gap through holes in the rotor blocking and wedging. Airflow through these radial passages effectively cools the rotor. Accordingly, the flow through each of these radial vents must be uniform to

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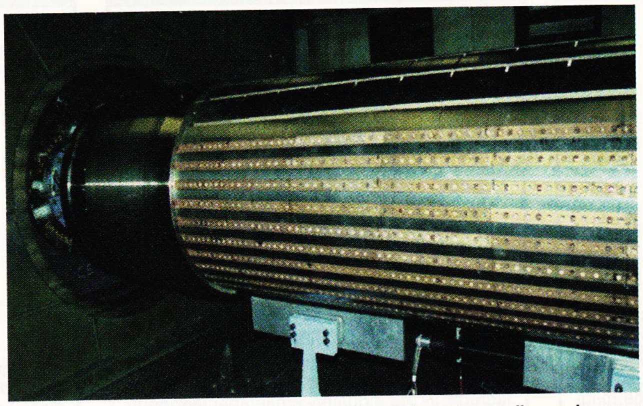
ensure that no local hot spots exist on the rotor.

A typical air-cooled generator has 24 axial channels, each of which feeds 28 radial vents in the rotor. Clearly, measuring at each of the resulting 672 ventilation holes individually is impractical. The key to overcoming this limitation was the use of hot-film anemometers with frequency responses as high as 175 kilohertz. Since the frequency at which a ventilation hole passes a fixed location in space for a typical radial path rotor is approximately 2.5 kilohertz, these devices are sufficiently sensitive to detect flow disturbances due to flow exiting the ventilation holes as they pass a stationary sensor. This technique is unique in that it uses the high-frequency response developed to study the structure of turbulent fluctuations in highly turbulent flows and applies that response to the analysis of a rapidly varying transient flow.

The sensor for the hot-film anemometer is a 0.5-micrometer-thick, 1.25-millimeter-long nickel film deposited on a 3-millimeter-long, 70-micrometer-diameter quartz fiber. The constant-temperature anemometer consists of a Wheatstone bridge and a servo amplifier. When subjected to fluid flow, there is an instantaneous heat loss from the nickel film because of convective heat transfer, which reduces the sensor's temperature and resistance. The output of the servo amplifier is the voltage change required to restore the sensor to the original temperature. With the aid of a linearizing circuit, this signal is converted such that it is directly proportional to flow velocity.



The hot-film anemometer technique helped optimize rotor cooling and ensure against manufacturing defects during final balance of the WESTAC rotor.

The sensor is placed close to the surface of the spinning rotor, and the velocity is measured with a hot-film anemometer. The sensor must be placed as close as possible to the rotor surface because the magnitude of the velocity disturbance caused by the vent holes decreases significantly as the probe is moved away from the surface.

Furthermore, the measured velocity contains a circumferential velocity component due to the rotor peripheral velocity and a radial velocity component due to the flow exiting the vents. These components must be separated if the rotor flow is to be accurately determined.

In a typical rotor, the peripheral rotor speed can be seven times greater than the flow through the ventilation holes. Because the hot-film anemometer probe is directional, orienting the probe so that it is perpendicular to the axis of rotation has proven to be an effective way of eliminating rotor peripheral-velocity effects. In such an orientation, the probe is relatively insensitive to the peripheral velocity. To remove random fluctuations due to turbulence, the signals were averaged over several cycles. The resulting transient signal consists of a series of sharp peaks corresponding to the flow exiting each vent hole.

The technique proved invaluable in the design of WESTAC, which features a single blower on the turbine end of the rotor. There, the blower hub and fluted shaft accelerate the flow to the rotor rotational velocity before entering the rotor. On the exciter end of the rotor, nothing is available to accelerate the flow before it enters the rotor. An analysis performed using the Fluent computational-fluid-dynamics code from Fluent Inc. in Lebanon, N.H., showed that the circumferential flow distribution through the rotor on the exciter end of the initial WESTAC design would be significantly nonuniform. An experimental means was needed to confirm this analysis.

The one way of doing this at the time was to measure the temperatures during a full-generator test, which provides an indirect measurement of the rotor flow only, is expensive, and can be performed only after the rotor has been designed and manufactured. Devised by engineers to overcome these shortcomings, the hot-film anemometer technique proved to be much less expensive since it could be performed in parallel with the final balance of the rotor. It can also identify problems several months earlier in the design process.

Tests were performed on the rotor in the factory spin bunker during the final balancing and testing stage. Output was linearized such that 1 volt equals 20 meters per second. These measurements were obtained with a hot-film probe 100 mils from the rotor surface. Each vent hole is represented by a sharp spike in velocity. The smaller velocity signal following the peak represents the wake region at the trailing edge of the hole. The rotor that was tested contained 12 vent holes between each pole region. The flow rate exiting the ventilation holes is the integrated velocity over the area of the vent hole.

Vent-exit velocities through the radial-vent rotor were obtained by integrating the anemometer signal across each hole and averaging the hole velocities in the circumferential direction. As expected, the flow was greatest toward the center of the rotor and dropped toward the ends. These results were in close agreement with the design calculations.

Having verified the nonuniformity empirically, engineers corrected the problem by installing guide vanes on the exciter end inlet to the rotor inlet region. The anemometer test was repeated with the guide vanes in place, which improved the flow distribution and provided a small increase in flow to the rotor's exciter end.

At the end of testing, the prototype WESTAC rotor was disassembled and rewound. During disassembly, two ventilation passages were seen to be about 50 percent blocked with insulation. Evidence of the blockage was clearly provided by the anemometer signal. After having identified and addressed these problems, engineers completed the design without incurring a delay in the schedule. ▪