AUTOMATED INDUCTION THERMOGRAPHY OF GENERATOR COMPONENTS

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ABSTRACT. Using Active Thermography defects such as cracks can be detected fast and reliably. Choosing from a wide range of excitation techniques the method can be adapted to a number of tasks in non-destructive evaluation. Induction thermography is ideally suited for testing metallic components for cracks at or close to the surface. In power generation a number of components are subjected to high loads and stresses – therefore defect detection is crucial for a safe operation of the engines. Apart from combustion turbines this also applies to generators: At regular inspection intervals even small cracks have to be detected to avoid crack growth and consequently failure of the component. As an imaging technique thermography allows for a fast 100% testing of the complete surface of all relevant parts. An automated setup increases the cost effectiveness of induction thermography significantly. Time needed to test a single part is reduced, the number of tested parts per shift is increased, and cost for testing is reduced significantly. In addition, automation guarantees a reliable testing procedure which detects all critical defects. We present how non-destructive testing can be automated using as an example an industrial application at the Siemens sector Energy, and a new induction thermography setup for generator components.

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INTRODUCTION

Large scale generators convert mechanical into electrical energy and are a key component in power plants burning fossil fuels. At the plant of Siemens Energy (Charlotte, NC, USA) such generators are manufactured and also serviced.

A generator consists of a rotating part driven by the turbine – the rotor – and the stator, the non-rotating part. The rotor is formed by a large forged part with slits to accommodate the copper coils. To lock the coils into position so called rotor wedges are used (Fig. 1) – steel bars the size of a picket of a fence built from non-magnetic steel and coated with copper. During operation the rotor wedges are subjected to large mechanical forces. Defects in these components could lead to fatal consequences: Because of the large centrifugal force a wedge could break resulting in massive damage to the generator and the attached turbine.

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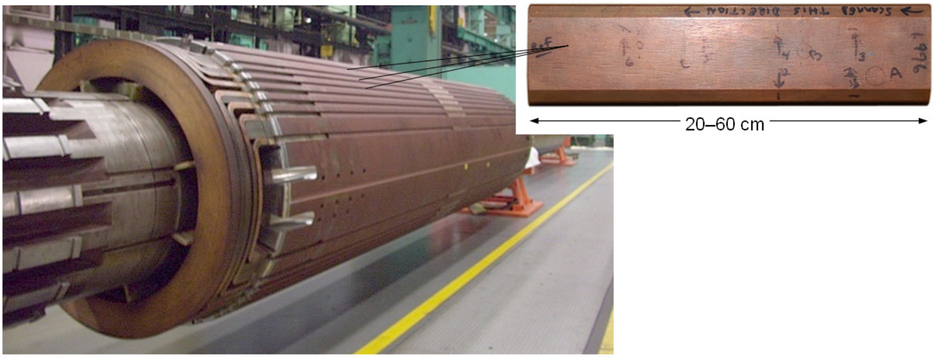

FIGURE 1. Photograph of a rotor – To cover one slit a number of rotor wedges are inserted in a row.

For this reason all rotor wedges have to be requalified for further use when a generator is serviced. Up to now fluorescent penetrant inspection was used to check the parts. This method proved to be very reliable but has also crucial disadvantages: The coating has to be removed before inspection, the manual FPI inspection process takes long and is operator dependant, and the reusable parts have to be recoated after the inspection. Because of this major drawback a more practicable inspection technique was needed.

Compared to penetrant inspection which only detects defects open to the surface thermography has the advantage of also detecting subsurface cracks. Therefore active thermography for inspecting rotor wedges was the ideal candidate as an alternative method which eliminates the non-value added steps such as stripping the coating and recoating afterwards.

PRINCIPLE OF OPERATION

Active thermography is able to detect defects fast and reliably. Unlike passive thermography additional energy is applied to the part under test using different excitation techniques. The distribution and the pattern of the heat diffusion can be interpreted to locate defects. The progress of active thermography in recent years was not only driven by the technology of the infrared cameras used to image the evolution of surface temperature but also the large number of excitation techniques available to choose from for a specific application [1,2,5,7].

Depending on the selected technique different kinds of defects can be detected or different parameters measured. For crack detection specifically also a range of excitation methods exist: Acoustic thermography was specifically developed for crack detection but also flying-spot laser excitation or induction could be used and have been evaluated for their applicability to rotor wedge inspection. Also standard eddy current techniques have been tried but lack the necessary sensitivity when applied to parts with highly conducting coatings such as copper.

To test for cracks in metallic parts of regular geometry – as is the case for the rotor wedges – induction thermography is ideally suited: The methods works completely non-contacting and imaging and a large amount of energy can be easily coupled into the part. To excite the part a coil induces a current within the part. The current in the part follows the coil but in opposite direction to the current in the coil. The penetration depth of the induced current follows the well-known laws for the skin effect:

$$s = \frac{1}{\sqrt{\mu_r \mu_0 \sigma \pi f}} \tag{1}$$

Here μ_r is the relative susceptibility, μ_0 the susceptibility of vacuum, σ the conductivity of the material and f the frequency of the current applied to the induction coil. Since rotor wedges are made from non-magnetic steel ($\mu_r = 1$) for a frequency of $f = 1.5$ kHz the resulting penetration length would be approximately $s = 10$ mm, for $f = 150$ kHz s would be 1 mm [3]. Since the coating is relatively thin (below 0.1 mm) a penetration depth of 1 mm is sufficient to find all relevant defects even below the coating. Besides, a higher frequency leads to a better coupling of the coil to the part and therefore more current is induced [8, 9]. Standard eddy current testing uses even higher frequencies and cannot achieve high sensitivity on coated parts.

The induced current heats the part but any defect such as a crack perpendicular to the path of the current results in a higher dissipation at the defect resulting in a locally higher amplitude and locally different time vs. temperature curve. The amplitude measured by the infrared camera primarily depends on the distance to the induction coil and the emissivity of the surface. By separating the time dependency of the surface temperature from the amplitude using pulse-phase analysis the influence of different surface conditions can be minimized [6].

Because of the fast heat diffusion in steel the surface temperature changes rather quickly. Therefore the time-temperature evolution has to be recorded with a high frame rate of the camera but on the other hand also results in a fast inspection time of less than 1 s per position.

AUTOMATION OF THE INSPECTION

The number of rotor wedges to be inspected depends on the size and the type of the generator. On average there are about 300 pieces per generator. The excitation using induction is restricted to small area of 2–3 cm around the coil therefore several shots are necessary to cover a part completely.

The inspection using induction thermography could in principle be performed using a handheld system. Such a system has already been built by Siemens in Munich [9]. Though a handheld device costs less compared to a full-fledged automated system, the overall cost of the inspection is nevertheless lower with automation since the time needed for inspection is reduced and throughput is increased. More or less as a “by-product” – the inspection process is more reliable because it automatically documents all results. Since the possible benefits of such a system clearly outweighed the cost a new system for automated inspection has been developed for use in the Charlotte plant.

Setup of the Inspection System

Figure 2 shows a view of the inspection system: Situated on the left hand side is the loading area where the rotor wedges are inserted before the inspection and removed afterwards. The part on the right hand side contains the induction coil and the infrared camera shielded from the infrared radiation of the surroundings and the inspector. The operator controls the system via computer from the display and keyboard mounted on a swivel arm.

FIGURE 2. View of the inspection system from the outside.

Central elements of the inspection system are the induction coil and the infrared camera. The coil is located horizontally above the part under test but close to the surface. The camera looks straight down onto coil and part (Fig. 3).

In order to record the fast heat diffusion in steel a high-speed camera is used that operates in the mid-wave range of the infrared (3–4 µm) and records up to 400 frames per second. The shielding around the camera reduces unwanted reflexes from the surroundings. The induction generator built into the system delivers electrical power into the coil of up to 10 kW. Similar generators are also used for induction heating in material processing but a custom computer controlled electronic circuit added to the inspection system can control the induction heating with millisecond precision. Because of the high current in the cable between induction generator and coil a transformer is built into the cable close to the induction coil. Generator, cable and coil are water cooled and can be switched on for extended periods of time allowing inspection of large parts without having to wait for the cool down of the equipment. In order to detect cracks independently of their orientation the current has to be induced in two directions perpendicular to each other. In this system the two sides of a triangular coil are used which form an angle of 90° to each other (Fig. 3).

Inspection Process

To requalify a part the upper and lower surface of the rotor wedges have to be inspected for cracks. In the inspection system this is done in two steps: The operator first places the part with the upper side facing up into the system and starts the inspection process. During the inspection the part is secured by a pneumatic fixture to a carriage and is moved under the induction coil either at constant speed or step wise depending on the chosen inspection program. After the run is completed the operator turns the part upside down and restarts the process. After finishing the resulting images are stored to hard disk and displayed to the operator who can now proceed to inspect the next part.

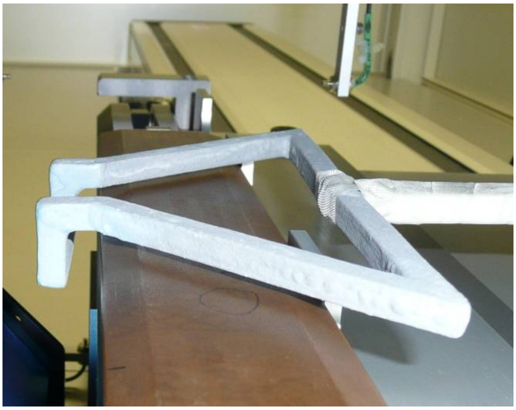

FIGURE 3. Part under test and induction coil.

In order to ensure constant sensitivity of the inspection a fixed distance between part and induction coil is necessary. Since the geometry of the rotor wedges differs depending on the generator type in length, width and thickness the fixture on top of the carriage can be adjusted with a micrometer screw on both sides. This eliminates not only adjustments of the coil but also focusing of the camera. Similarly a stop parallel to the rotor wedge can be adjusted to different widths. The length of the part is automatically accommodated using a pneumatic actuator with a long range. These manual adjustments only have to be done if the type of the rotor wedges changes. To prevent a crash between part and induction coil light barriers stops the motion of the part if the adjustments have not been done properly.

Depending on the mode of operation (constant speed or stepwise) the inspection of one part is completed in one to five minutes.

RESULTS

In order to test function and sensitivity of the system a rotor wedge was prepared with EDM notches of 3 mm length and 0.75 mm depth. The result image of an inspection of this reference wedge exhibits the characteristic pattern of ideal notches [4]: At the small sides spherical indication can be seen corresponding to area of higher current density. To prove that detection is independent of orientation notches in different directions turned in 45° steps are prepared (Fig. 4). A second test wedge was prepared identically to the reference wedge but coated: Due to the higher emissivity compared to the uncoated reference wedge the visibility of the indications was even higher.

The result of the inspection cycle is an image which displays the time-evolution of the surface temperature (phase image) in pseudo color. Figure 5 shows such an image for the case of a rotor wedge with natural defects (cracks). Compared to the artificial defects (notches) the indications are linear without a spherical indication at the end. Also visible in Fig. 5 is a comparison to penetrant inspection.

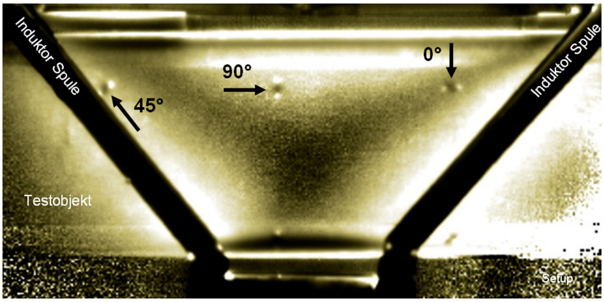

FIGURE 4. Reference wedge with artificial defects (EDM notches).

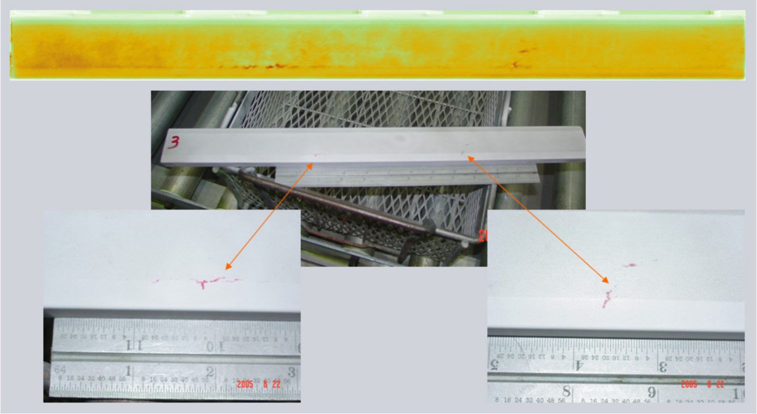

FIGURE 5. Rotor wedge with natural defects (cracks).

A comparison of induction thermography to the fluorescent penetrant inspection shows the superiority of the induction thermography to the traditional method for this application (Table 1). Despite the high investment cost for an inspection system using induction thermography the new method is more cost-effective. The cheaper inspection costs per part lead to a return-on-invest over the course of 1–2 years.

TABLE 1. Comparison of traditional and new inspection technique.

	Penetrant inspection	**Induction thermography**
Sensitivity	Very high	Very high
Investment costs	Low	High
Cost of operation	Medium	Low
Time for inspection	20 days	5 days
Preparation of inspection	Stripping of coating	None
Steps after inspection	Cleaning / coating (usable parts)	None
Operator dependent results	Image recording depending on operator	Image recording independent of operator
Environmental issues	Chemical waste	None
Automation	No	Yes
False Positives	Medium	Low
Archiving of data	Manual (camera)	Automatic
Statistical data	Manual	Automatic

In addition to the lower cost because of the eliminated process steps of stripping and recoating also the overall time for the inspection is considerably reduced. Without the stripping the full inspection process can now be completed in-house also reducing the lead time for inspection. Therefore the small time window for servicing a generator can be used more effectively allowing for more time for necessary repairs and manufacturing of replacement parts.

OUTLOOK

The presented project demonstrates how induction thermography can be applied in an industrial service and manufacturing environment. An inspection system has been developed and built for the inspection of rotor wedges for generators which is now in use on the shop level in the plant in Charlotte, NC, USA. The system is able to perform inspections either in a mode where the part is scanned at constant velocity or in the "traditional" stepwise induction thermography. The elimination of major steps before and after inspection resulted in considerable reduction of the time and cost of the inspection.

Even beyond the presented case induction thermography shows the potential for a broad spectrum of further applications. A major advantage compared to penetration testing is the possibility to also detect subsurface defects not open to the surface which is the key for inspecting coated components.

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