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Thermographical analysis of turbo-generator rotor

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ABSTRACT

Refurbished or newly constructed utility-scale turbo-generator rotors requires stringent acceptance testing before commissioning and subsequent operation thereof. Conventional methods of testing are inadequate in detecting and locating thermally induced problems. This paper presents a thermographic method for carrying out thermal instability testing of generator rotors. An experimental setup is used to map the thermal distribution of the generator rotor. Implementation and testing of the method is carried out in a laboratory setting using a down-scaled turbo-generator rotor.

1. Introduction

Modern large turbo-generator rotors are predisposed to thermal sensitivity owing to their complex design, material composition and operating requirements. Manufacturing and refurbishment techniques introduce component variations which cause most rotors to exhibit some level of thermal sensitivity [1,2]. Thermally induced vibration in generator rotors is by far the most difficult problem to diagnose and correct. Symptoms may be a bowed shaft and a vibration signature linked to the excitation current, but the possible underlying causes are numerous. It is especially difficult to physically determine mechanically dynamic or electrical causes of the thermal imbalance without excitation. A thorough inspection and methodical overhaul of the rotor in search of anomalies will require the rotor to be separated from the stator. Since the exact conditions that cause the thermal unbalance are not acting on the rotor, physically identifying the anomaly is impracticable. This phenomenon is commonly referred to as thermal instability/sensitivity. Conventional balancing techniques and acceptance tests are not suited to detect and correct such problems [3].

This paper presents a method for detecting thermal instabilities on newly built and refurbished rotors using thermographic analysis. Through directly mapping the thermal distribution of the surface of generator rotor, the method offers the possibility of localising the root causes of existing instabilities. The initial concept and preliminary results of the direct thermal mapping of a turbo-generator rotor was first presented in [4]. The presented research build on this with substantial improvements to technique, and gives detailed description of the methodology together with results obtained from implementation and testing in a laboratory setting.

2. Contemporary thermal analysis of generator rotors

Electrically induced unbalance typically manifests from the thermal behaviour of the rotor. As the rotor is excited by an increasing current, the copper winding will rise in temperature. The increasing temperature naturally causes the copper to expand within the slots and overhang area, but not in proportion to the expansion of the steel rotor forging, as the coefficient of expansion of copper is nearly twice that of steel. The expanding copper will exert axial forces on the other components of the rotor – slot contents, body wedges, blocking and coil retaining ring assembly [5]. The heat generated within the winding will also be conducted through the steel body and dissipated by the cooling medium. If this heat transfer process continues symmetrically along the body of the rotor, a thermal unbalance will not be experienced. However, if the heat transfer process or coil forces occur asymmetrically, an unbalance will be experienced, resulting in the bowing of the rotor body. The severity of the thermal bow will determine the amplitude of the vibration experienced at the bearings [6]. If the vibration levels exceed the operating limits of the rotor, this can result in failure and the loss of generating capacity.

Thermal Instability Testing (TIT) is common practice for major utilities and is performed at specially designed balancing facilities or in situ to determine the thermal behaviour of rotors [7]. TIT is generally performed after any major refurbishment work which has been conducted on the rotor i.e. rewind, slot liner replacements, major overhaul, retaining ring replacement etc. [8]. Two main testing methods are used worldwide: (1) Direct current injection into the rotor winding – i.e. Current thermal instability testing (CTIT) and, (2) Windage or friction heating – i.e. Friction thermal instability testing (FTIT). Different

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utilities prefer specific tests based on their own propriety experiences. The variations in methodology and lack of published data supporting either of the aforementioned tests create uncertainty as to which test is able to best detect any latent thermal imbalances within the rotor assembly.

The detection of rotor thermal sensitivity does not rely on any thermal characteristics measured during testing but rather on vibration monitoring. A thermal bow associated with thermal sensitivity is detected via vibration data. Vibration data analysis is currently the most widely used method for detecting problems with turbo-generator rotors [9], however it does not directly assist with locating the problem area. Solutions to the problem generally involve a compromise balance for minor imbalances or a full strip down for fault detection and repair for a major imbalance. Typical test procedures do not adequately consider thermal characteristics of the rotor. Rotor winding temperature may be determined using the following formula:

$$T_{\text{Hot}} = \left[\left(\frac{R_{\text{Hot}}}{R_{\text{Cold}}}\right)(234.5 + T_{\text{Cold}})\right] - 234.5 \quad (1)$$

where T_{Cold}, reference temperature value; R_{Cold}, winding resistance at the reference temperature; R_{Hot}, winding resistance at the testing point, and 234.5, thermal conductivity of copper.

In solving this equation, it is necessary to be aware of sources of uncertainty. Uncertainty can be categorised as either epistemic or aleatory [10]. Aleatoric uncertainty is characterised by the lack of predictability or intrinsic randomness of a phenomenon; epistemic uncertainty is characterised by a deficit of knowledge. This approach requires that resistance and physical temperature measurements be known at a specific current and voltage level to obtain a reference value. Subsequent temperature rises can be calculated by utilising the rotor resistance measurement. The resistance measurement needs to be accurate and can be significantly affected by inaccuracies and errors in voltage and current readings [11]. This form of temperature monitoring is relatively basic, as it does not account for hot spots within the winding but rather the average rotor winding temperature. Furthermore, this method does not indicate the temperature of the rotor's other extremities such as the shaft, coil retaining rings, or rotor surface [12]. The uneven thermal profiles of all of these components can lead to thermal instability. This drawback undermines the reliability of this model as a means to determine rotor thermal characteristics. It best serves to indicate average temperature while performing TIT. Epistemic uncertainty is a feature of modelling methods such as presented in [13], which arises due to the simplifying assumptions required for constructing a model of a complex turbo-generator rotor. Accurately determining the thermal characteristics of the entire generator rotor body would be invaluable in determining the differences between FTIT and CTIT through a more practical method that is not influenced by epistemic uncertainty.

3. Use of infrared (IR) sensors

The shortcomings of contemporary methods for thermal analysis of turbo-generator rotors must be overcome to improve acceptance testing processes. Rotor telemetry systems have been devised to monitor rotor ground faults and temperature measurement and have improved significantly over the past decade. Temperatures are monitored by installing resistance temperature detectors (RTDs) within the rotor winding slots and under the coil retaining rings. The connections are wired to an antenna mounted on the rotor body. The antenna transmits the digitised temperature values to a data acquisition unit external to the generator [14]. This method is dependent on the number of RTDs installed for accurate measurement of the thermal distribution of the rotor. Hot spot detection may still be a challenge depending on the RTD layout. Furthermore, this method requires significant modifications to the rotor insulation system to facilitate the installation of the RTDs and routing of the connections, which will involve substantial rotor disassembly. The invasive nature of the process would lead to further design variations that could affect rotor operation and thermal performance. Therefore, this method of temperature detection is ruled out for the experimental setup.

The widespread use of infrared thermography within the electrical industry has been commonplace for a number of years [15–18]. This non-contact, non-invasive method produces reliable and accurate results for fault finding and trouble shooting. Temperature measurements are made possible by detecting the radiant flux of an object; a temperature output is calculated through a calibration algorithm. Also referred to as a radiation thermometer, many varieties are available on the market today, from thermal imaging cameras to singular probes. Devices are able to measure a wide variety of temperature ranges and can operate at high speeds, making this approach an ideal choice for the proposed approach [19].

4. Thermal mapping

The presented method of data capture is in the form of a matrix of temperature values corresponding to the physical mapping of the surface of the generator rotor. This method transforms these temperature measurements and physical coordinates into a 2-D heat map. Simply put, the direct thermal mapping method present the 3-D temperature data (of the rotor surface) as a 2-D heat map. A heat map consists of a number of rectangular rows (angular position) and columns (axial length) that represent data values against a colour scale (temperature). This is a widely used method to display large matrices within many different fields such as natural sciences and biological science [20,21]. The experimental setup is able to capture surface temperature measurements together with physical coordinates that is used to create a heat map for easy interpretation and analysis of the thermal behaviour of the rotor under different thermal instability tests such as FTIT and CTIT. Furthermore, the rotor surface temperature map assists with root cause analysis and fault finding because it can be used to physically locate irregularities on the rotor.

4.1. Data capturing

Data acquisition is facilitated via two streams. The data from the IR camera and proximity probe interface is captured via a data-acquisition unit linked to a computer utilising proprietary software from the IR camera manufacturer known as Optris PI Connect. The winding, ambient, and enclosure temperatures are captured via a separate unit linked to a computer. All data is time stamped to facilitate data synchronisation. An overview of the experimental layout and data acquisition is shown in Fig. 1.

4.2. Generating a thermal map of the rotor

The initial step in constructing the heat map is to define the IR camera resolution pixel size that will correspond to the physical portion of the rotor to be measured. The distance of the IR camera from the test object (rotor) determines the size of the measurement pixel and therefore the map resolution. The further away the IR camera is from the test object, the larger the pixel size. The pixel size is also dependant on the optical lens fitted to the IR Camera.

A 20 kVA mini-rotor (shown in Fig. 2) designed to mimic a 600 MW turbo-generator rotor is used for validation and testing of the presented thermal mapping method (constructional details given in Table 1). A keyphasor probe is also utilised to determine the angular position of the mini-rotor. This is achieved with the aid of a fixed collar with a machined notch and a proximity probe. An output is received when the notch passes the proximity probe and indicates when one revolution has passed. The output from proximity probe is measured in synchronism with rotor mapping in order to determine when the entire surface of the