ANALYSIS OF THERMAL INSTABILITY TEST METHODOLGIES FOR SYNCHRONOUS GENERATOR ROTORS

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Abstract: Thermal instability testing (TIT) is utilised by service providers as a final proving test during the construction, repair and overhaul of large turbo-generator rotors. This test is typically performed using two methodologies – i.e. current injection and friction/windage methods – to evaluate the thermal sensitivity of the generator rotor. Although these methods are distinctly different – service providers/OEMS worldwide show no preference towards a methodology and there is no substantiating evidence or international standards which provide insight into which method is most suitable. This paper investigates these two methods of TIT for synchronous generator rotors. A specialised experimental configuration utilising infrared thermography is used analyse the thermal behaviour a synchronous generator rotor under different test conditions. Experimental results indicate that there are substantial differences in the behaviour of the rotor under the two different methodologies and that an augmented test methodology is required to improve TIT.

Key words: Thermal instability testing, synchronous generator rotor, infrared thermography.

1. INTRODUCTION

A wide range of testing and evaluation techniques are utilised by service providers during the construction, repair and overhaul of large turbo-generator rotors. These techniques vary in purpose, complexity and economic considerations. The ability to timeously identify problems during the overhaul/repair/construction process is the fundamental purpose of performing condition assessment. This proactive approach eliminates the possibility of the finally commission generating unit failing during operation i.e. increasing reliability of trouble free operation. Although many diagnosis techniques are used, these are generally specific to different components of the turbo-generator rotor, for example tests that evaluate the insulation or detect inter-turn shorts [1, 2].

This paper investigates a final proving test - known as Thermal Instability Testing (TIT) - that is performed to evaluate the rotor functionality in its entirety and is typically used to evaluate the rotor vibrational behaviour under close to operating conditions (3000 rpm) within a specialised balancing facility. The potential capabilities and usefulness of evaluating a turbo-generator rotor by performing TIT has been recognised, however there exists two distinctly different testing modes that can be employed. The rotor under test can either be ‘excited’ using current or friction/windage referred to as Current Thermal Instability Testing (CTIT) and Friction Thermal Instability Testing (FTIT), respectively. The mode that is best suited to TIT is yet to be determined and it is hindered by complexities surrounding the lack of international standards; unclear testing procedures; limitations of testing facilities; high capital cost of required testing facilities as well as testing interpretation [3, 4]. The presented research investigates the thermal behaviour of a synchronous generator rotor during the aforementioned TIT to analyse, compare and better understand each of the TIT methods.

2. THERMAL INSTABILITY TESTING (TIT)

A Thermal instability test is performed as the final proving test prior to the rotor being dispatched to the generating station. The previously described rotor acceptance tests are limited to target specific areas of the rotor but do not prove that the rotor can function as a whole. All the different components must be able to function homogenously during operation to be considered refurbished and reliable. In essence, thermal instability occurs when a change in the field current causes a corresponding change in vibration levels. A rotor that is both mechanically and electrically balanced - is stable and fit for service. Conversely - if a rotor is unbalanced - the resulting uneven loading will lead to bowing of the rotor shaft and increased vibrations. High vibrations result in the rotor being unfit for service and a process of fault finding needs to be followed as the causes of thermal instability are difficult to pinpoint. Thermal sensitivity/instability can be commonly caused by shorted turns, coil movement, blocked ventilation slots or inadequate cooling, non-uniform winding, distance blocking variations, ill fitted body wedges or tight rotor slots [5]. Detection as to whether a rotor is thermally sensitive is straight forward in a sense, as the relationship between the current and vibration levels are indicative enough. The methodology by which this relationship is monitored though is pertinent. Being able to create the specific operating conditions for the rotor to be able to exhibit a latent thermal sensitivity problem is important.

Three methods of Thermal Instability Testing (TIT) exist. The first test is an online test that is performed after the rotor has been commissioned. The remaining two tests are performed within a balancing facility that is capable of either performing a FTIT or CTIT. Facilities that can perform a CTIT can also generally perform a FTIT as well but not vice versa. It should be noted that no international standard exists for the testing methodology or acceptance criteria for vibration limits when performing TIT. The methodologies by which these tests are performed remain undisclosed as they form part of the intellectual property of the OEM /Utility/Repairer that performs the test [6, 7]. The matter is further compounded by the large capital investment required to possess a balancing facility capable of performing TIT. Interpretation and the methodology by which the test is performed will determine whether a rotor is fit for service or not. This can have significant consequences in terms of warranties and profitability associated with the rotor being refurbished/overhauled. It is therefore pertinent to determine which method best suits the detection of rotor thermal sensitivity.

3. COMPARISON OF TIT METHODS

The current knowledge base regarding TIT raises the following questions:

- Is a simulated approach being performed in a balancing facility suitable for thermal sensitivity testing?
- What procedure should be followed to perform the testing? CTIT or FTIT?
- What acceptance criteria should be used?

Currently, the available information disallows conclusive answers to the above questions. Online thermal instability testing is the technique that best suits the detection of a rotor latent thermal instability as it offers true steady state operation conditions. Online thermal instability testing can however also be destructive, resulting in increased vibrations after the test has been completed [8]. Online thermal instability testing does not afford the Utility the peace of mind that a repaired/overhauled generator rotor is fit for service prior to commissioning. Any remedial action necessary comes at a high expense of decommissioning, fault finding, repair and retesting. This methodology is thus not suited for the testing of repaired/overhauled rotors but is best suited to vibration problems that are experienced during the lifetime of the operation of the rotor. The reliability sought to be able to determine whether a rotor has a thermal sensitivity problem prior to the rotor being dispatched to site and commissioned lies with CTIT and FTIT. These tests are performed at the repairers' facility where any remedial action can be performed in house and retested conveniently at a lower expense. A rigorous testing process is followed with multiple thermal balances, frequent electrical testing and inspections. The process is concluded with a final thermal balance that is performed on-line after the rotor has been commissioned [9]. The difficulty again arises as to which method would be best suited to detect a thermal sensitivity problem. This research investigates the differences between CTIT and FTIT by utilising an experimental Direct Thermal Mapping Method.

3.1 Direct Thermal Mapping

The presented method for data capture is in the form of a matrix of temperature values corresponding to the spatial mapping of the surface of the generator rotor. This method transforms the temperature measurements and physical coordinates into a 2-D thermal map. Simply put, the direct thermal mapping method presents the 3-D data (temperature and surface area of the rotor) as a 2-D colour map (commonly referred to as a heat map). The map consists of a number of rectangular rows and columns that represent data values against a colour scale. This method has been widely used to display large matrices within many different fields such as natural and biological sciences [10, 11]. Ultimately, the method maps the temperature distribution of the rotor and outputs the data as a thermal map for easy interpretation and instability detection. Each block within the thermal map represents a measurement pixel of the IR camera and each pixel of the IR camera represents a physical portion of the rotor. The distance of the IR camera from the rotor determines the physical size of the area that is sampled.

3.2 Experimental Testing

The experimental test setup uses a mini-rotor rated at 20 kVA that is designed to mimic a 600 MW generator rotor – i.e. two-pole 3000 rpm, 50 Hz, distributed and concentric field windings, damper bars, insulated bearings, mono-block milled shaft with slots and shaft-mounted slip rings. Scaling is based on the length of the rotors thus the mini-rotor is down-scaled approximately to the ratio 2:25 when compared to a conventional 600 MW rotor. Two principle aspects are investigated in order to evaluate the different aspects related to TIT:

1. Mapping the rotor under the effects of friction to evaluate FTIT.
2. Mapping the rotor under current excitation to evaluate CTIT.

FTIT was performed under the influence of air friction/windage while the rotor was operated at 3000 rpm. The test was run for eight hours and readings taken every 30 minutes. A time based evaluation approach was followed owing to the nature of the heating mechanism. During the temperature mapping process, the rotor speed decreased via controlling the speed of prime mover (induction machine). Rotational speed is decreased to 60 rpm during the capture process with consideration of the maximum sampling rate of the camera. During this process surface mapping, winding temperature, enclosure temperature as well as ambient temperature is recorded. Figure 1 illustrates a thermal map of the rotor surface after 480 minutes. A trend is observed where the average horizontal temperature distribution showed that higher temperatures were being experienced towards the non-drive end of the mini-rotor. The temperature gradient is clearly observed on the thermal maps and the trend is consistent throughout the test. The drive-end of the mini-rotor operated at a significantly lower temperature. The temperature difference between the drive and non-drive ends varied by up to 4°C throughout the testing procedure. This is significant as even the slightest differences in temperature can lead to thermal sensitivity. The cause of this was suspected to either be related to bearing losses or rub at the non-drive end or that the slip-ring brush gear interaction generating heat due to frictional losses. To determine the origin of the temperature gradient the brush gear assembly was removed and the test repeated.

The thermal map of the rotor surface after 480 minutes with the removal of the brush gear is shown in Figure 2. No trend was observed where the average horizontal temperature distribution showed that higher temperatures were being experienced towards the non-drive end of the mini-rotor. A near uniform temperature distribution could be clearly observed on the thermal maps and the trend was consistent throughout the test. The results obtained showed that the brush gear slip-ring interaction introduced an additional thermal component that effected the rotor surface thermal distribution. The thermal losses experienced by the brush gear slip-ring interaction were able to heat the rotor body to a higher temperature as well as at a higher thermal rate per hour. The gradient observed was proven to be due to this interaction. This finding is of significance as during factory acceptance testing where FTIT is performed the winding temperature is measured via the slip-ring connection. The phenomena experienced could negatively affect the outcome of the test by not proving to be a true reflection of the thermal performance of a rotor while undergoing FTIT.

CTIT by definition requires the testing to be conducted during current injection. The mini-rotor was operated at 3000 rpm and excitation applied at different levels as per conventional thermal instability testing based on the rating of the mini-rotor - 5 A, 10A, 20 A and 35 A . A dwell time of one hour was observed at each current level and mapping was performed after every ten minutes. Sampling was carried out more frequently as opposed to FTIT as heating of the rotor was anticipated to occur at a higher rate under current injection. Mapping and parameter recordings were obtained in the same manner as that of FTIT. A rectangular symmetrical area of a higher temperature could be observed on all the thermal maps throughout the test. These areas of high temperature were identified as the pole faces and associated coils. A large scale high resolution thermal map is presented in Figure 3 where the temperature distribution can be observed in detail. The higher temperatures of the poles can be clearly observable as well as the inter-pole areas being represented as the darker areas of the distribution at lower temperatures. This observation differs greatly from that of FTIT.

4. ANALYSIS OF RESULTS

Figures 4, 5, 6 and 7 give the experimental results obtained for FTIT, including and excluding the brush gear effects, as well as for CTIT in terms of the mean surface temperature, and skewness and kurtosis of the temperature distribution for each measurement. A box plot of the selected distributions is given in Figure 4. The skewness indicates the asymmetry of the temperature distribution. A value of 0 indicates a symmetrical distribution. A positive value indicates skewness to the right and a negative value to the left. Kurtosis is a measure of the shape of the distribution i.e. the measure of the “tailedness” of a distribution as comparted to a normal distribution. A normal distribution has a Kurtosis of 0, high values indicate heavy tails or the presence of outliers while lower values indicate light tails or the absence of outliers in a data set [12, 13].

The distribution of the FTIT scenario indicates the mean, median and mode are close to resembling a normal distribution – being equal. For example at 180 minutes the values are 47.44, 46.70 and 46.70; at 360 minutes the values are 59.15, 58.90 and 58.50. Upon further analysis of the initial four hours of FTIT the distribution was skewed to the right with positive Kurtosis values indicating a leptokurtic distribution i.e. a peaked distribution with outliers. This shift from a normal distribution indicates the heating phase of the mini-rotor surface during the test. The influences of the slip-ring brush-gear interaction as observed within the thermal maps contribute to this trend. As the effects of the slip-ring brush-gear interaction normalise during the concluding four hours of the test the skewness of the distribution tends to become closer to a normal distribution (0) while the Kurtosis becomes negative or platykurtic, indicating a flattening out of the distribution. Large differences could be observed between the hottest and coolest part of the mini-rotor rotor surface – by up to 5 °C. From these observations it can be inferred that this method of performing thermal sensitivity testing produces a slow, more uniform temperature distribution on the surface of the mini-rotor. Once the brush-gear was removed the resultant distributions indicated a uniform distribution with the mean, median and mode being virtually identical throughout the testing. A positive skewness was observed for a large duration of the test which later approached 0 then proceeded to be slightly negatively skewed. The Kurtosis values were close to zero indicating a mesokurtic distribution i.e. normality with no outliers. The effects of the removal of the brush-gear are quite significant as this test did not reach the high temperatures experienced in scenario 1. Smaller differences could be observed between the hottest and coolest part of the mini-rotor rotor surface – by up to 2 °C. A close to normal distribution of temperature along the surface of the mini-rotor can be expected for this mode of testing.

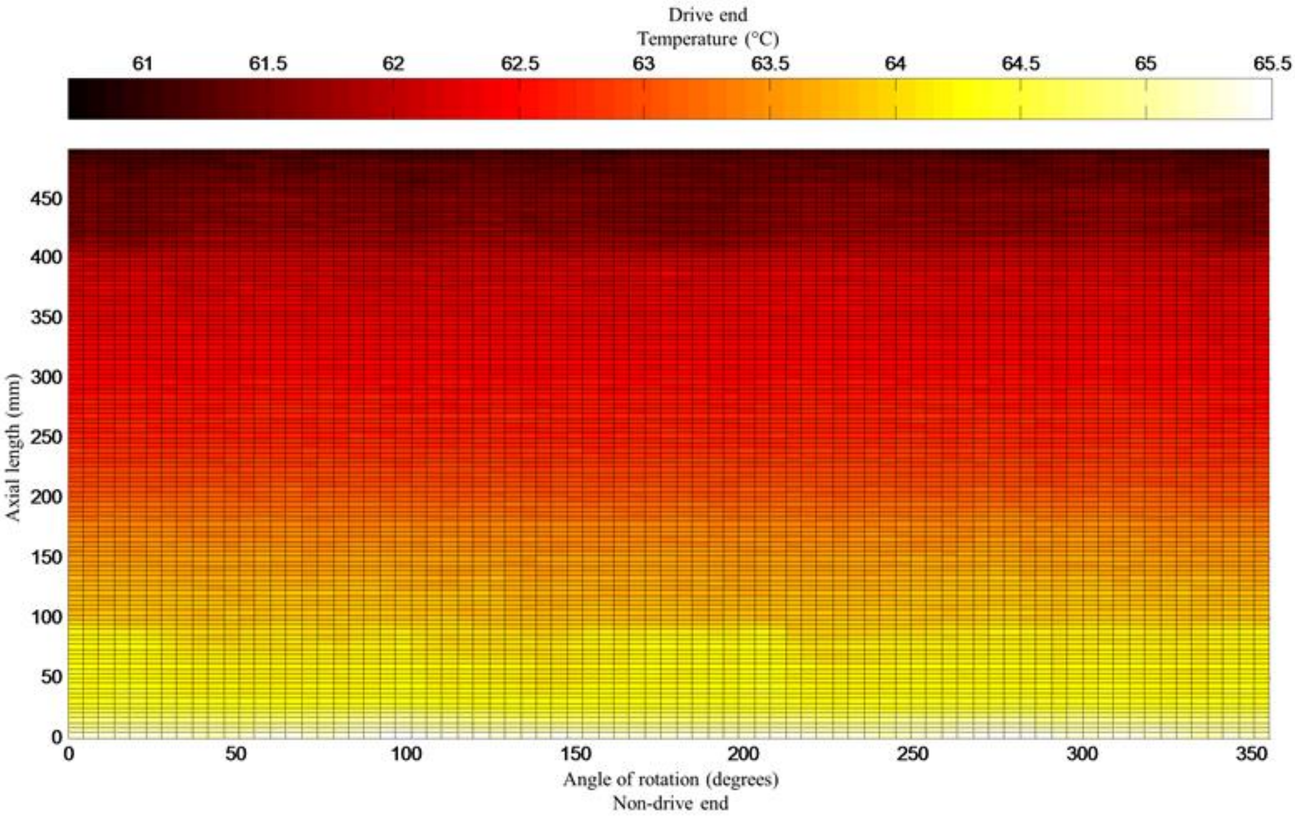

Figure 1. Thermal map of rotor for obtained under FTIT, including brush gear, after 480 mins.

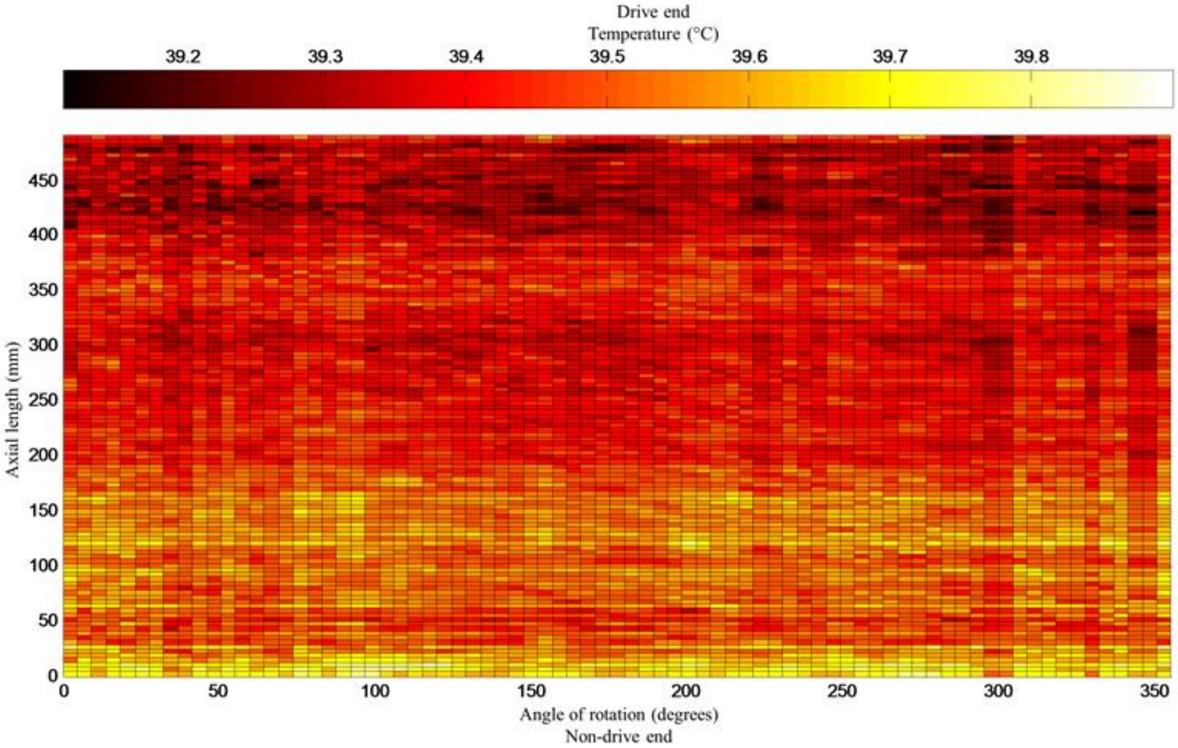

Figure 2. Thermal map of rotor for obtained under FTIT, excluding brush gear, after 480 mins.

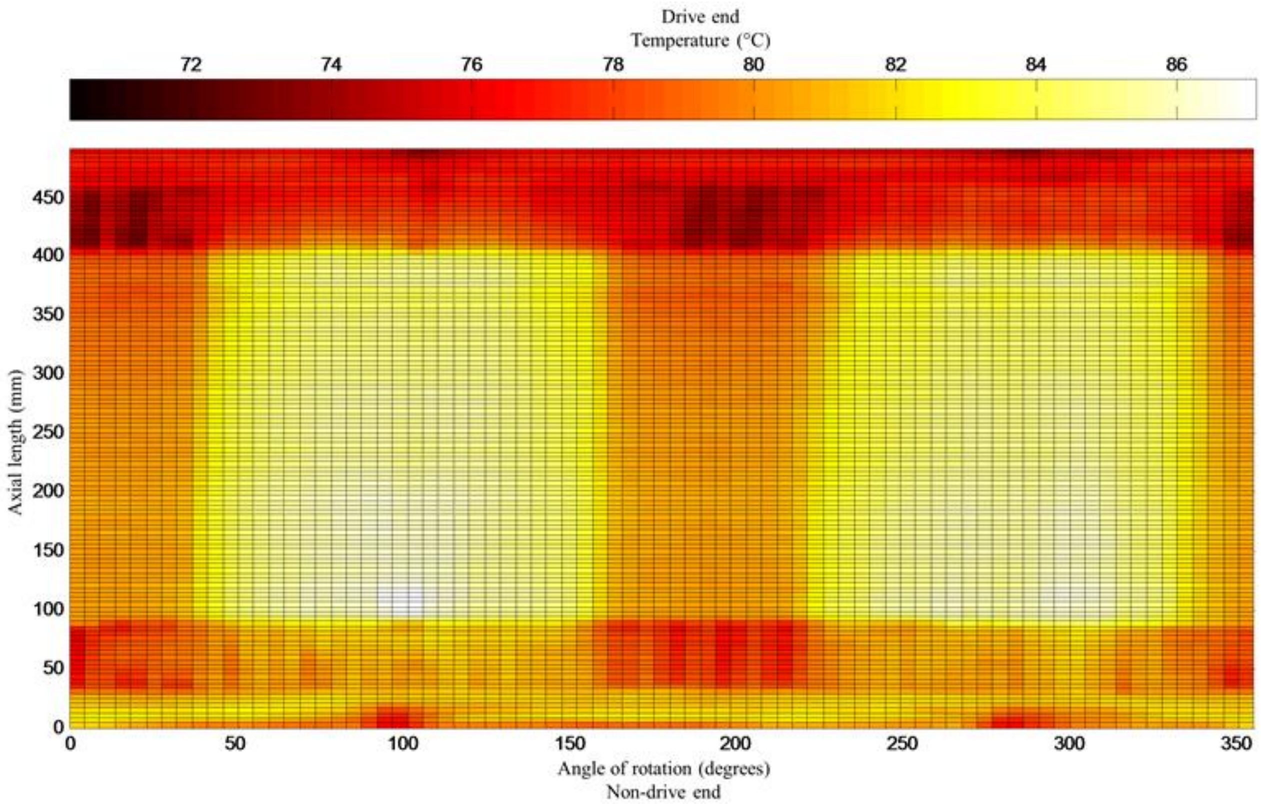

Figure 3. Thermal map of rotor for obtained under CTIT with a current injection of 35 A after 210 min.

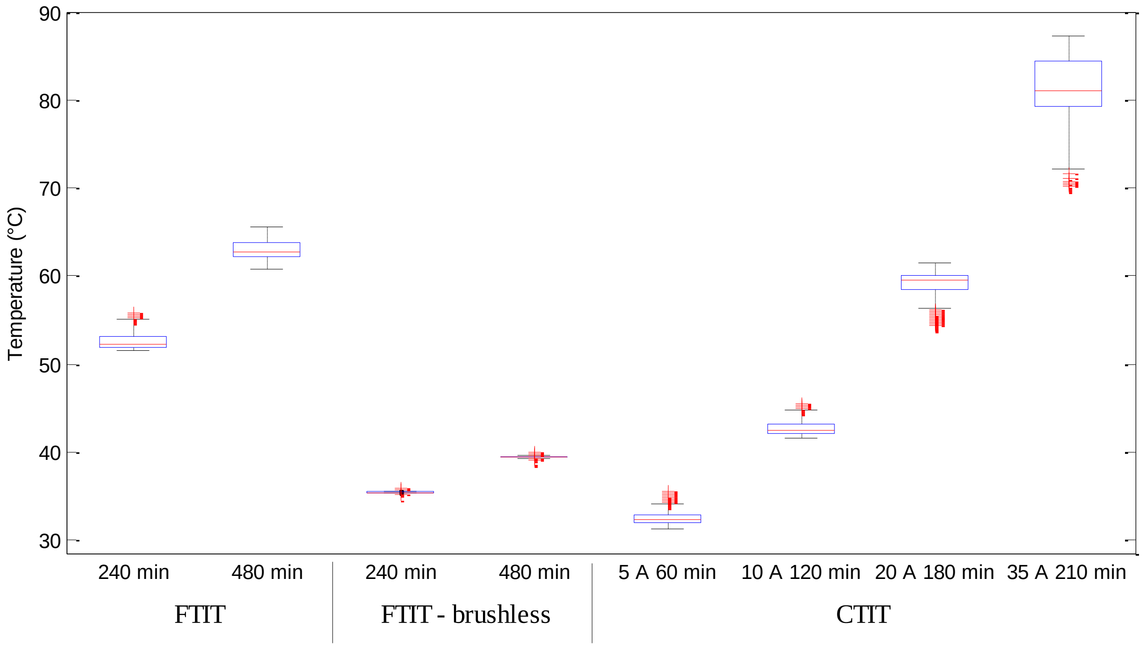

Figure 4. Box plot of selected surface temperature distributions of generator rotor obtained under the three different experimental test conditions

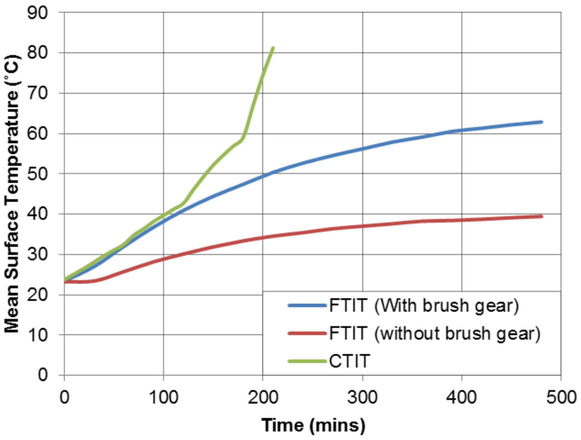

Figure 5: Mean surface temperatures of generator rotor obtained under the three test conditions.

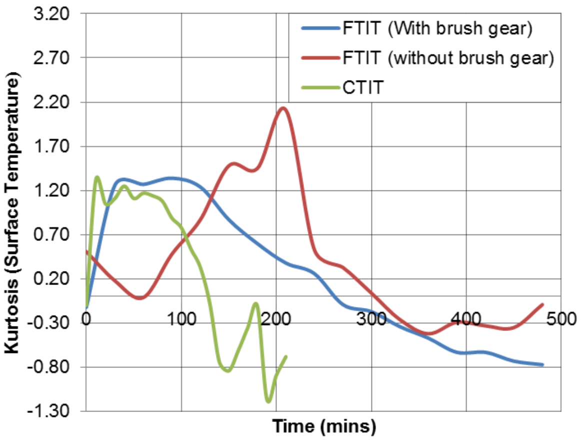

Figure 6: Skewness of surface temperature distributions obtained under the three different test conditions.

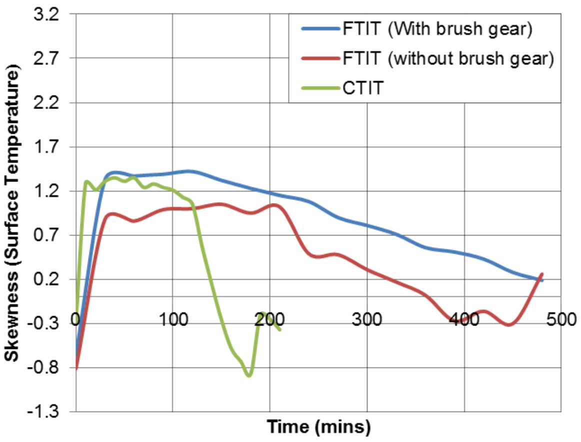

Figure 7: Kurtosis of surface temperature distributions obtained under the three different test conditions.

For the CTIT scenario the mean, median and mode throughout the test are close to being equal or representing a normal distribution. As the test progressed and the current values increased the skewness changed from being highly skewed to the right, approaching 0 then proceeding to become highly skewed to the left. The Kurtosis followed the same trend with initially being leptokurtic then mesokurtic and finally platykurtic. The Kurtosis values indicate the presence of significant outliers throughout the test. The effect of a changing current source can be attributed to this behaviour. Large differences could be observed between the hottest and coolest part of the mini-rotor rotor surface – by up to 17 °C. These observations show that the winding as a heat source produces temperature profiles that are not homogenous throughout the mini-rotor surface. The non-homogenous (heterogenous) thermal nature of the rotor is due to the various materials constituting its construction and when excited the materials undergo heat transfer at different rates. An overall higher mean temperature is achieved during CTIT as compared to the previous scenarios.

The TIT data is summarised as a series of box plots in Figure 4. FTIT shows a contracted distribution with the absence of significant outliers. A further contraction is observed once the brush-gear is removed showing a normal distribution. CTIT on the other hand shows a large distribution of values with significant outliers. The testing methods differ significantly with CTIT showing a more realistic (large range) distribution as rotors are operated under the influence of current as opposed to friction.

The mode in which TIT is being performed globally requires a re-evaluation based on the results obtained. The effects of the slip-ring brush-gear interaction for the friction scenario created an additional heating component leading to asymmetries in the thermal distribution. A discernible thermal gradient was created with the non-drive end operating at a higher temperature. The effect of the collector assembly was quantified by executing the test with the brush-gear removed. During conventional FTIT the winding temperature is determined by measuring the rotor winding resistance which can only be achieved via the collector assembly. The collector assembly has been found to be a major contributor to the rotor heating as compared to friction alone. Furthermore, heating via friction was found to be slow, uniform and uncontrolled. FTIT is greatly influenced by ambient temperature and the interaction with the experimental setup. This influences at what point the equilibrium or maximum temperature is reached which is significantly lower than that of CTIT. In essence FTIT supports the assumption that a generator rotor, during operation, heats up uniformly and is able to provide that heating mechanism. This instead of evaluating the actual thermal behaviour of the rotor it is able to create the ideal heating conditions as to how a rotor should behave thermally. The FTIT scenario does not present the actual thermal behaviour of a rotor during operation and cannot be effectively used for generator rotor thermal sensitivity evaluation.

The results observed for CTIT differed in contrast to FTIT. The influence of the collector assembly was also apparent in the CTIT scenario but was insignificant as CTIT depends of there being a pathway to inject current into the rotor. The temperature rise for CTIT is achieved via current injection thus the winding temperature initially rises and heat is dissipated from the winding outward. The composition of the rotor greatly affects that manner in which heat is distributed i.e. the heat distributes thought the different materials at different rates. This is more representative of a rotor during operation. The winding temperature is ascertained utilising a numerical calculation which is reliant on accurately measuring the physical winding temperature, current, voltage and winding resistance at a reference instant. The subsequent temperature value can be calculated by utilising the rotor resistance measurement at any given time and current level. However, the winding is not physically exposed for the temperature measurement to be taken thus the rotor body temperature is sampled in several areas and then averaged as an assumption that the winding is at the same temperature. This is not a particularly sophisticated procedure to determine the winding temperature especially for a test that requires a high degree of accuracy to evaluate thermal sensitivity.

This shortcoming is evident as the results for CTIT show a wide range of temperatures being experienced on the rotor surface during testing. To assume a normal distribution and then iterate temperature values for subsequent current levels introduces an inaccuracy of the actual temperature of the winding as well as the temperature distribution of the mini-rotor surface. Differences between the temperatures of the winding as compared to the mini-rotor average surface temperature are illustrated in Figure 8. The winding temperature was captured directly from the winding surface. The relationship between the average surface temperature and direct winding temperature support the narrative that current CTIT modes are not being conducted accurately. The temperature concerning the winding and surface can differ by up to 11 °C. This is a phenomena that is also prevalent for FTIT as illustrated in Figure 9.

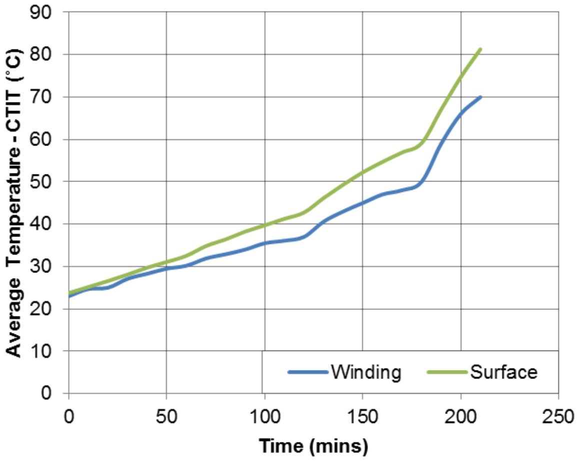

Figure 8: Surface and winding temperatures obtained during CTIT.

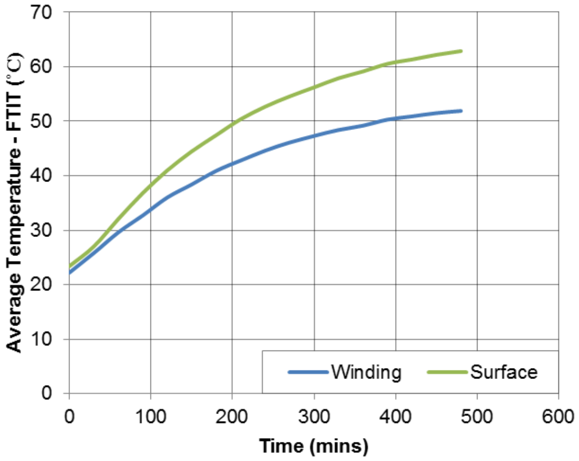

Figure 9: Surface and winding temperatures obtained during FTIT.

The results observed for CTIT were indicative of the manner in which a rotor would behave during operation. Contemporary CTIT modes need to be augmented with the direct mapping method to ensure an accurate approach to thermal sensitivity testing. The analysis conducted strongly supports an augmented CTIT as a preferred method to test for rotor thermal sensitivity.

5. CONCLUSION

The differences between contemporary TIT methods have been highlighted via the direct thermal mapping technique. The method of FTIT has been found to exhibit an even, symmetrical heating along the rotor surface. As opposed to CTIT indicating a non-uniform thermal distribution across the rotor surface where symmetrical areas of high temperature are observed.

The collector assembly losses have also been found to effect the thermal distribution of the rotor. A noticeable thermal gradient was observed with higher temperatures being experienced at the non-drive end of the rotor for both FTIT and CTIT. This phenomenon will warrant further investigation as slight changes in thermal distribution can affect rotor thermal sensitivity.

From observations, it can be said that utilising CTIT as a method to detect rotor thermal sensitivity is favoured. FTIT created a testing environment that simulated the ideal thermal distribution of a rotor as opposed to CTIT which exhibited a more realistic representation as rotors operate under current injection. However, the method must be augmented to include the direct thermal mapping process to improve testing procedures and accuracy. This will lead to increased rotor reliability and reduced uncertainty on the part of service providers.

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