Investigation of Thermal Instability Testing on Synchronous Generator Rotors using an Experimental Direct Mapping Method

A. Narain Singh, and W. A. Cronje
School of Electrical and Information Engineering
University of the Witwatersrand
Johannesburg, South Africa

W. Doorsamy
Dept. of Electrical and Electronic Engineering Technology
University of Johannesburg
Johannesburg, South Africa

***Abstract*— Utilities employ Thermal instability testing (TIT) for final acceptance testing after the construction and refurbishment of turbogenerator rotors. This type of testing is performed through two methodologies namely current injection and friction/windage in order to assess the thermal sensitivity of the machine's rotor. Although there are distinct differences between the two methods, no apparent preference is shown by service providers/OEMS globally. There is also no definitive evidence or standards that offer a comparison of the two methods and suitability assessment thereof. The presented research investigates these two methods of TIT for a synchronous generator rotor. An experimental setup with infrared thermography is employed to investigate the thermal behaviour of the machine's rotor for each of the test methods. Experimental results show that the thermal behavior of the generator rotor is significantly different for each methodology. It is also shown in this paper that contemporary TIT practice requires an augmented test methodology.**

Keywords—Thermal instability testing, turbogenerator, infrared thermography, direct thermal mapping

I. INTRODUCTION

There is broad variety of acceptance testing techniques available to service providers/utilities after the construction and refurbishment of turbogenerator rotors. The choice of technique depends on the component being tested, and complexity and cost of the test. Condition assessment of the rotor during the process of refurbishment or construction is imperative for identifying defects or faults before the generator unit is commissioned. This can improve the reliability and avoid the significant expense of failure and unplanned maintenance. Many diagnostic methods for synchronous generator units are available but these are usually limited to specific faults on the rotor – e.g. diagnosis of insulation defects or short-circuited windings [1, 2]. This paper focuses on a final acceptance test – i.e. Thermal Instability Testing (TIT) - used to assess the functionality of the complete rotor. TIT is generally performed at a dedicated balancing facility to assess rotor vibration under similar-to-operational conditions. Two different types of TIT test modalities may be used to evaluate generator rotors. The first type, Current Thermal Instability Testing (CTIT), is when the rotor is 'excited' using current injection and the second, Friction Thermal Instability Testing (FTIT), uses friction/windage. The most suitable test mode of TIT has not yet been determined due to a lack of knowledge perpetuated by deficiencies in related international standards; uncertainty with regards to the test procedures, and the high capital cost associated with suitable testing facilities for experimental purposes [3, 4]. In this paper, the thermal behaviour of a synchronous generator rotor undergoing TIT is investigated to gain a better understanding of each test mode. An analysis of the experimental results is presented together with a novel augmented test methodology that will assist with improving international standards relating to TIT of turbogenerator rotors.

II. SYNCHRONOUS GENERATOR MAINTENANCE

The fundamental design of generating units utilised worldwide have not changed significantly from the time of inception of the turbo generator. The horizontal mounted stator-rotor combination has become a staple in the generating fleets of many utilities. The ever increasing demand for cheaper, more reliable power has given rise to supply shortages in many countries. Utilities are struggling to meet these demands. Majority of the installed capacity are that of older units which are being driven harder, increasing the frequency for maintenance. Performing maintenance or refurbishment work on a generator rotor requires a thorough understanding of the failure modes which will determine what corrective action must be taken. For example, an intern-turn fault would only require a partial rewind while a cracked coil retaining ring would require replacement. During the refurbishment process a number of condition based tests are utilised to fault find and ensure quality.

A. Refurbishment Process

Rotor refurbishment methodology will differ with respect to design variations. A generic procedure is therefore not possible but the basic principles of refurbishment do apply. Different refurbishment options exist based on the condition of the rotor. A rotor may either undergo a component replacement; partial rewind or complete rewind.

1) Component replacement: Components may be replaced to improve material properties; fix defects related to design flaws or to comply with routine maintenance. Coil retaining rings are replaced to improve material properties and enhance reliability as newer materials are less susceptible to cracking and failure. Wedges may also be changed to improve material properties and adjust interference fits. Slip-ring assemblies as well as stalk bolts and main leads may also need to be replaced owing to failure or wear.

2) Partial rotor rewind: A partial rotor rewind refers to a small scale specialised repair on a specific area of concern on the rotor than can be very complex. It is performed to solve inter-turn faults; migrating insulation components; ground wall insulation breakdown; coil distortion and turn breaks. The repair procedure can range from replacing sections of insulation or replacing a number of copper turns or a whole coil (or number of coils) if necessary.

3) Complete rotor rewind: Complete rotor rewind takes place when the rotor winding has reached its end of life or when the failure experienced cannot be repaired performing a partial rewind or a component replacement. In the case where the rotor winding has reached the end of its design life the copper winding can be evaluated and reused if still in a good condition whereas the old insulation system is replaced [5].

B. Acceptance Testing

The ongoing cycle of component failure, repair and maintenance must be managed adequately to ensure security of the generating capacity of a utility. All refurbishment activities should not rely exclusively on the adroitness of personnel conducting the work. This needs to be supplemented with a testing regime that ensures the ultimate quality of the finished product. Being able to detect rotor faults during the refurbishment process goes a long way in ensuring reliability when the unit is commissioned. A number of tests have been devised over the years to be able to assist with rotor fault detection.

1) Insulation Resistance: The insulation resistance test is probably the most common diagnostic tool used to determine problems with the insulation system. It also provides assurance that subsequent high voltage testing can proceed without fear of insulation breakdown. A DC high voltage is applied between two conductors that are insulated from one another. This provides a measurement for the resistance of the insulation separating the conductors. The resistance for a perfect insulating material should be infinite but in practice this is not the case as the perfect insulator does not exist. A low resistance value would indicate a problem with the insulation system. Wet, contaminated or damaged insulation would yield a low insulation resistance.

2) Recurrent Surge Oscillograph (RSO): The RSO test can be used to detect inter-turn shorts, earth faults as well as any high resistance connections that may be present in the winding. The principal of this test relies on whether the terminals of the winding are electrically symmetrical. Any faults that exist in the winding will result in an asymmetry. Detection is made possible by injecting a steep fronted step voltage at each terminal. The return signals, when compared, should be identical for a fault free winding, while a difference would indicate a fault condition.

3) Winding resistance: The total series copper winding resistance of the rotor is measured. The test can detect inter-turn shorts, poor connections, incorrect connections as well as circuit discontinuities. The resistance value obtained is generally compared to a previously measured value for the same winding.

4) High voltage (HV) testing: AC, DC or VLF DC voltages can be applied to a rotor for HV testing. The purpose of the test is to determine if the winding assembly is capable of withstanding the rated operating voltage as well as any over voltages and transients that may occur during operation. If the insulation does not breakdown during the test then this is considered a successful result.

5) Non-destructive testing: The rotor steel body, wedges and coil retaining rings undergo a non-destructive examination to detect any material fatigue and cracking. A number of techniques are used: fluorescent dye penetrant, Eddy current and ultrasonic testing [6, 7].

III. THERMAL INSTABILITY TESTING (TIT)

TIT is performed on a turbogenerator rotor as a final acceptance test before it is dispatched to a utility’s power plant. The acceptance tests described in the previous section only target specific components of the rotor and do not guarantee acceptable function of the complete rotor. Only the harmonious functioning of all the different rotor components during operation indicates reliable refurbishment or construction. A principal indicator of thermal instability is unexpected rotor vibration as the field current is increased. Simply put, the rotor should be mechanically and electrically balanced to be deemed stable and acceptable for service. On the other hand, if the rotor is not balanced uneven loading will result in bowing of the shaft and an associated increase in the level of vibration. A rotor exhibiting excess vibration is declared unacceptable for operation and a fault investigation is initiated. The process of identifying the precise root cause of the instability is challenging due to the high number different possibilities and complex construction of the rotor. Thermal sensitivity/instability can be caused by short-circuited turns, movement of coils, inadequate cooling due to blocked ventilation slots, winding defects, variation in blocking distances, and ill-fitting body wedges [8, 9]. The current-vibration relationship makes the detection rotor thermal instability a straight-forward process, however the mode used to test this relationship is significant. This is because the rotor will only exhibit specific latent thermal sensitivity problems under suitable emulation of certain operational conditions. Three different modes or methods of TIT are in used in practice. The first test type of test is performed online once the rotor has been commissioned. The two other tests – i.e. FTIT and CTIT - are performed at a balancing facility after construction or refurbishment. Currently, there are no international standards relating to these TIT test modes or acceptance criteria for aforementioned current-vibration levels.

The exact procedure of each of these tests remains as confidential intellectual property of the OEM/Repairer or Utility performing the test [10]. Additionally, considerable capital investment is required to construct a balancing facility to perform TIT on a turbogenerator rotor. The test method ultimately determines if the rotor is acceptable for service and therefore has a direct bearing on warranties and associated profitability of the rotor construction or refurbishment. Hence, it is crucial to determine which method is most suitable for detecting thermal sensitivity on turbogenerator rotors.

IV. METHODOLOGY

A. Modes of TIT

Present knowledge of TIT modalities invokes the following pertinent questions:

- Is there a model-based approach, with the aid of simulation, to thermal sensitivity testing currently in practice?
- Which procedure is more suitable – i.e. Current (CTIT) or Friction (FTIT) method?
- What TIT criteria should be used for acceptance?

TIT is an online technique that is intended to mimic true steady state operating conditions and is currently the most effective method in detecting latent thermal instability of a turbogenerator rotor. However, this type of testing does have drawbacks. One such drawback is the potential to cause an increase in vibrations after completion of the test [11]. Therefore, TIT cannot guarantee that a refurbished/repaired or newly constructed rotor will perform as planned upon commissioning. The resulting corrective action usually implies decommissioning with the added costs of root cause identification, repair and testing. Simply put, this methodology is inherently unsuitable for testing of repaired or refurbished rotors and is more applicable to detecting vibrational problems that are experienced over the operational lifetime the rotor. The actual TIT modalities, CTIT and FTIT, are more critical in assessing the thermal sensitivity of rotor and determining if it is acceptable for dispatch and commissioning. These specific test modes are performed at the service provider's facility which is more equipped to carry out corrective measures and repeat testing at reduced cost. After a rigorous process consisting of repeated thermal balancing and electrical acceptance tests a commissioned rotor will undergo final online thermal balancing [12]. At this point, the problem arises of which mode of testing is most suited for detecting potential thermal sensitivity problems. This research proposes an experimental Direct Thermal Mapping (DTM) method to investigate the differences between the two modes of TIT and to augment the overall process.

B. Direct Thermal Mapping (DTM)

The presented DTM method captures and spatially maps the surface temperatures of the rotor. This is accomplished by transforming each of the temperature measurements and the corresponding physical coordinate into a 2D thermal map. The direct thermal map is essentially a measure and display of 3 parameters – i.e. two-value coordinates and a temperature, in the form of a 2D map. This type of representation is typically referred to as a heat map and consists of rows and columns which present parameter values in the form of a colour scale. This method is widely used in fields such as natural and biological sciences for presenting large amounts of data [13, 14]. DTM is used here to map the surface temperature of the rotor during operation and provide easy detection of thermal instability. The blocks of the thermal map characterises a physical portion of the rotor. This data is captured using an infrared camera (IR). The distance between the rotor and IR camera is directly determined by the physical size of the rotor surface area rotor that is captured.

C. Experimental Configuration

The test configuration used for the investigation consists of a rotor of a 20 kVA synchronous generator. The design of the experimental rotor follows that of a 600 MW turbogenerator rotor. Hence, it has 2-poles (3000 rpm at 50 Hz operation) with distributed-concentric field windings, damper bars, insulated pedestal bearings, and static outboard excitation (with shaft-mounted slip rings). The length of the experimental rotor is down-scaled from a traditional 600MW turbogenerator rotor by a ratio of 2:25. The following key aspects relating to TIT are investigated using the experimental configuration and DTM:

1. FTIT - DTM method is applied to rotor under condition of friction/windage.
2. CTIT – DTM method is applied to rotor under condition current injection.

Both of the aforementioned tests were carried out at operational speed – i.e. 3000 rpm. Firstly, FTIT was performed with only air friction/windage used to 'excite' the rotor. A time-based approach is used to evaluate the modes of TIT. Therefore, the tests are conducted over a suitably long period of time as to allow for the either operational temperature or a steady-state temperature to be reached. The duration of FTIT was eight hours with temperature readings taken at 30 minute intervals. In order to map the rotor temperatures, the speed of the rotor is reduced through controlling the prime mover (induction motor-variable speed drive set). The measurement process is conducted at a speed of 60 rpm to accommodate the infrared camera's maximum sampling frequency and yet still obtain maximum accuracy. The temperatures of the winding, enclosure and laboratory environment were also recorded. A direct thermal map of the surface temperatures of the rotor, after 8 hours of FTIT, is shown in Figure 1. This figure indicates that higher temperatures are experienced on the excitation (or non-drive) end of the generator rotor. The map also indicates a gradually decreasing temperature along the length of rotor. The excitation-end is at a significantly higher temperature that the drive-end of the rotor i.e. approximately 4°C at the end of the test. Although relatively small, this difference may be considered as significant in practice as it could well lead to thermal instability. Initially, it was suspected that the temperature gradient was due a problematic bearing or frictional losses due to interaction of the slip-rings and brush gear. Hence, the FTIT test was repeated after dissembling the brush gear to verify the source of the temperature difference.

Figure 2 shows the thermal of the surface temperatures of the rotor under FTIT when the brush gear has been removed. The previous trend of higher temperatures at the non-drive end is not found in this instance and more uniform temperature distribution observed consistently throughout the duration of the test. This result confirms that the interaction between the slip-rings and brush gear is responsible for introducing a significant temperature gradient along the length of the rotor. This is also an interesting result because the slip-ring connection is often used in practice as a point of winding temperature measurement during FTIT. The presented finding shows that this technique obtaining the winding temperature could be unsound as the interaction effect of the slip-ring and brush gear may potentially bias the measurement. The current TIT test mode or CTIT is performed with the rotor operating at 3000 rpm under current excitation at different levels. For the presented investigation, 4 current levels were selected according to the rating of the downscaled rotor as 5 A, 10 A, 20 A and 35 A. The test is conducted such that the filed current is increased to the maximum value with a settling time of one hour between each increment. DTM is performed at 10 minute intervals, more frequently than the previous FTIT to capture the higher rate of rotor heating. The process of mapping followed with CTIT is the same as the previous test. Figure 3 presents the results of the DTM for CTIT after 210 minutes for a current injection of 35 A. Large symmetrical rectangular areas indicate higher temperatures. The higher temperatures are indicative of the coils, and the faces of the rotor poles. Additionally, contrasting colours of the map make the inter-poles of the rotor clearly visible – i.e. areas of lower temperatures are darker. The resulting thermal maps of CTIT are substantially different from the maps obtained under both cases of FTIT. Figure 4 depicts how the rotor is mapped i.e. orientation, using the presented method.

V. RESULTS AND ANALYSIS

In order to analyse the thermal behavior of the rotor under the different test conditions the temperature recordings were extracted from each of the thermal maps obtained during the 3 different tests i.e. CTIT, FTIT with brush gear and FTIT without brush gear. These distributions are summarized in the form of a box plot in Figure 5. Figure 6 gives the mean of these distributions. The corresponding skewness and kurtosis plots are given in Figures 7 and 8, respectively. Skewness is essentially a measure of the distributions symmetry where 0 indicates a normal distribution, and negative and positive values indicate skewed to the left and right, respectively. The shape of the distribution and "tailedness" relative to a normal distribution is given by kurtosis – i.e. 0 kurtosis implies a normal distribution, higher values imply larger tails (or outliers) and lower kurtosis implies smaller tails (or a lack of outliers) [15, 16]. The resulting temperature distributions of the rotor undergoing FTIT resemble a normal distribution as the means, modes and medians are approximately equal. Examples of this are taken from the distributions obtained at180 min, 360 min and 480 min, as shown in Table I. Upon closer inspection, the FTIT results as given by Figures 6 and 7 shows that for the initial 200 mins the temperature distributions have a positive skewness (to the right) and kurtosis (towards leptokurtic or peaked distribution).

TABLE I. TEMPERATURATURE STASTISTICS FOR FTIT

Measurement Time (min)	Statistical Measure	Value (°C)
180	Mean	47.44
	Median	46.70
	Mode	46.70
360	Mean	59.15
	Median	58.90
	Mode	58.50
480	Mean	62.89
	Median	62.30
	Mode	62.70

These distributions deviate from normal and are representative of the uneven temperature distribution of the rotor during the initial stages of the test. The effects of the brush gear interaction are found to exacerbate this initial non-uniform heating – i.e. higher level of skewness and kurtosis. In both cases of FTIT the distributions tend to towards an approximately 0 skewness (normal distribution) and negative kurtosis (towards platykurtic or flat distribution). The overall results of the FTIT confirm that this TIT mode gradually heats the rotor to an approximately normal temperature distribution. Removal of the brush gear and repetition of the FTIT resulted in a more uniform distribution and approximately 0 kurtosis (mesokurtic or normality with fewer outliers). It is should be noted that the removal of the brush gear resulted in a significantly lower average surface temperature than with the brush gear (see Figure 6). Figure 2 shows that the total range of the rotor surface temperature is relatively insignificant at less than 2°C. Ultimately, the results indicate that FTIT will produce an approximately normal temperature distribution. The initial heating phase of the rotor under CTIT progressed at more rapidly than with the FTIT. Furthermore, the skewness (as shown in Figure 7) of the temperature distributions changes more erratically from positively skewed to 0 and then negatively skewed. This indicates the some components, such as the windings, are at a higher temperature than the rest of the generator after 210 min which results in outliers to the right of the distribution. The kurtosis measure of the distributions under CTIT (given in Figure 8) also changes from positive to 0 and then to negative indicating a shape transformation from peaked to normal to flat. Furthermore, these kurtosis values indicate there are a significant amount of outliers in the temperature distribution of the rotor undergoing CTIT. This behavior is also a result of the incremental changes in the current excitation during the test. The thermal map in Figure 3 shows that total range of the rotor surface temperature is very significant at approximately 17°C. The results obtained during this test show that the by exciting the field winding of the rotor the internal heat source (as opposed to external in FTIT) result in heterogeneous temperature distributions. This thermal behavior of the rotor during CTIT is due the various constituent materials heating at different rates. The averages of the temperature distributions under CTIT are substantially higher than both case of FTIT (see Figure 6). The summary box plot in Figure 5 gives a direct comparison of temperature distributions (at a specific time) of the rotor for the different test conditions.

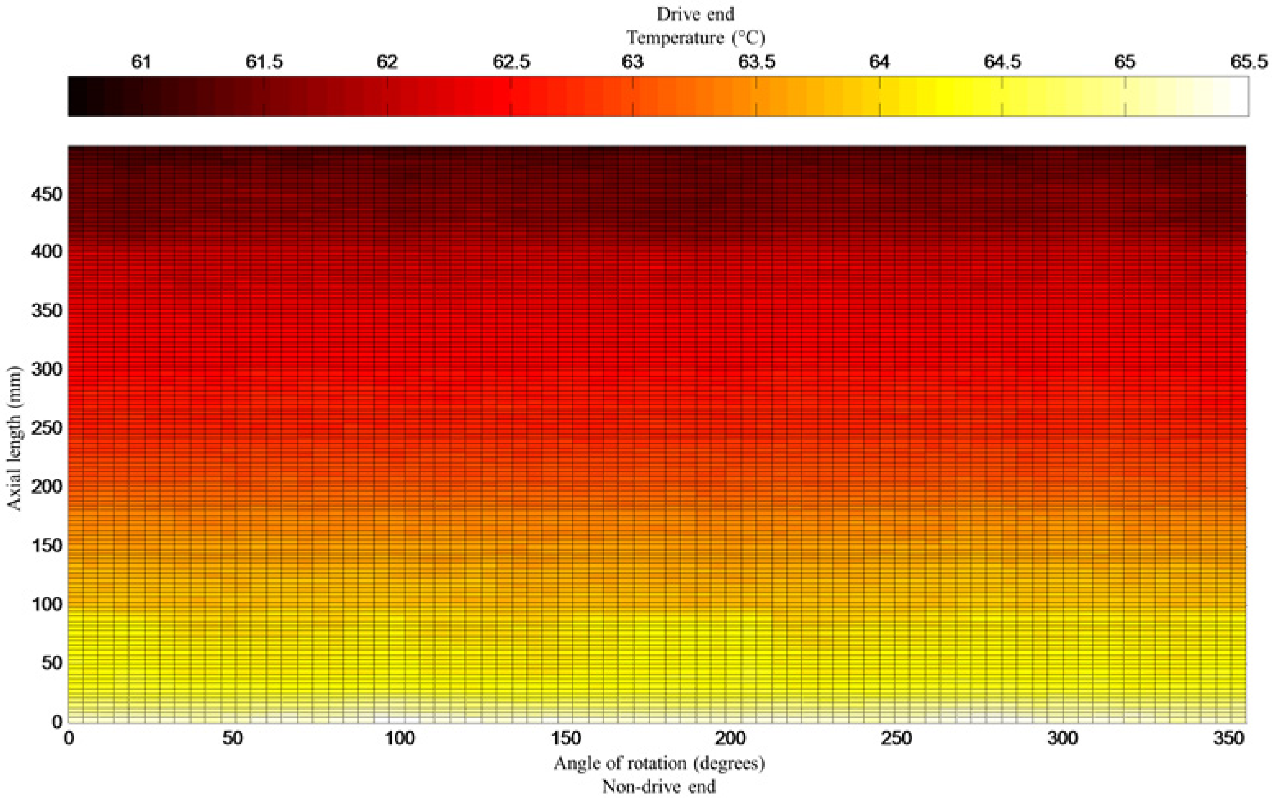

Fig. 1. A direct thermal map of the experiemental test rotor, with brush gear, after 480 minutes of undergoing FTIT.

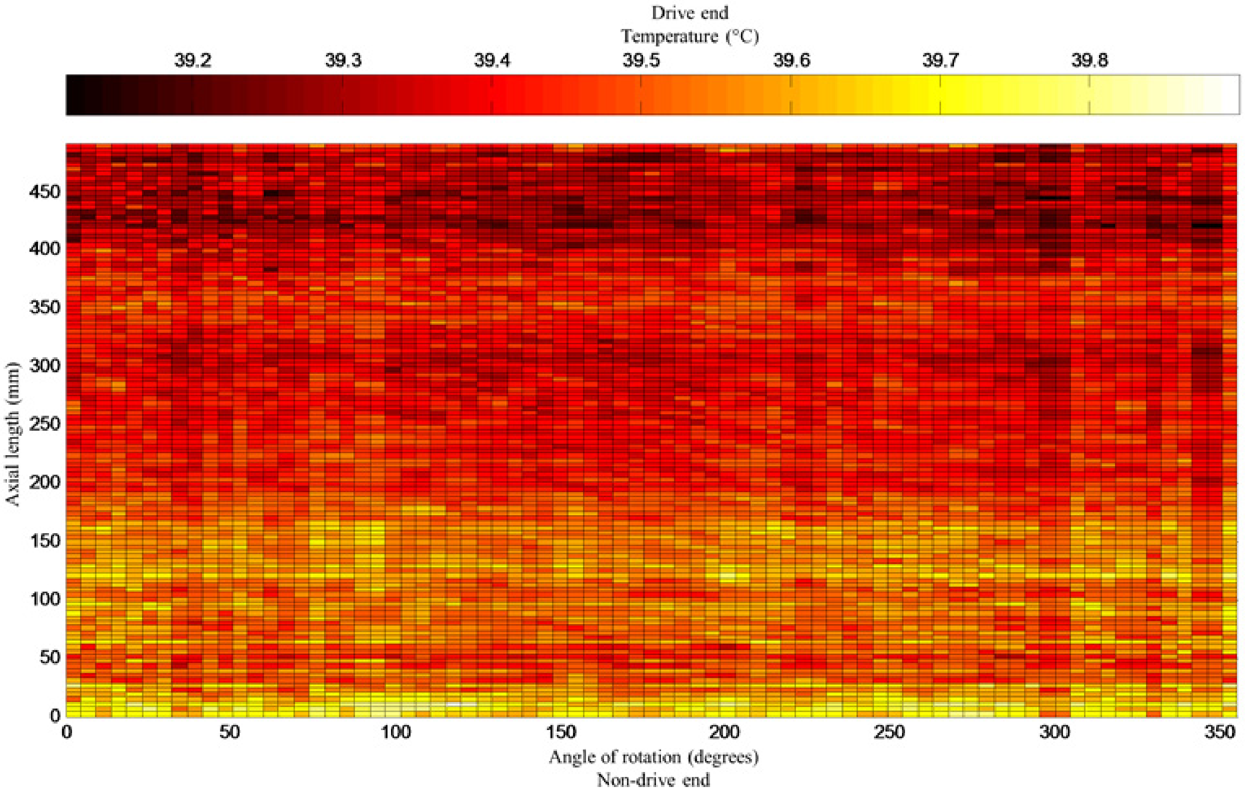

Fig. 2. A direct thermal map of the experiemental test rotor, without the brush gear, after 480 minutes of undergoing FTIT.

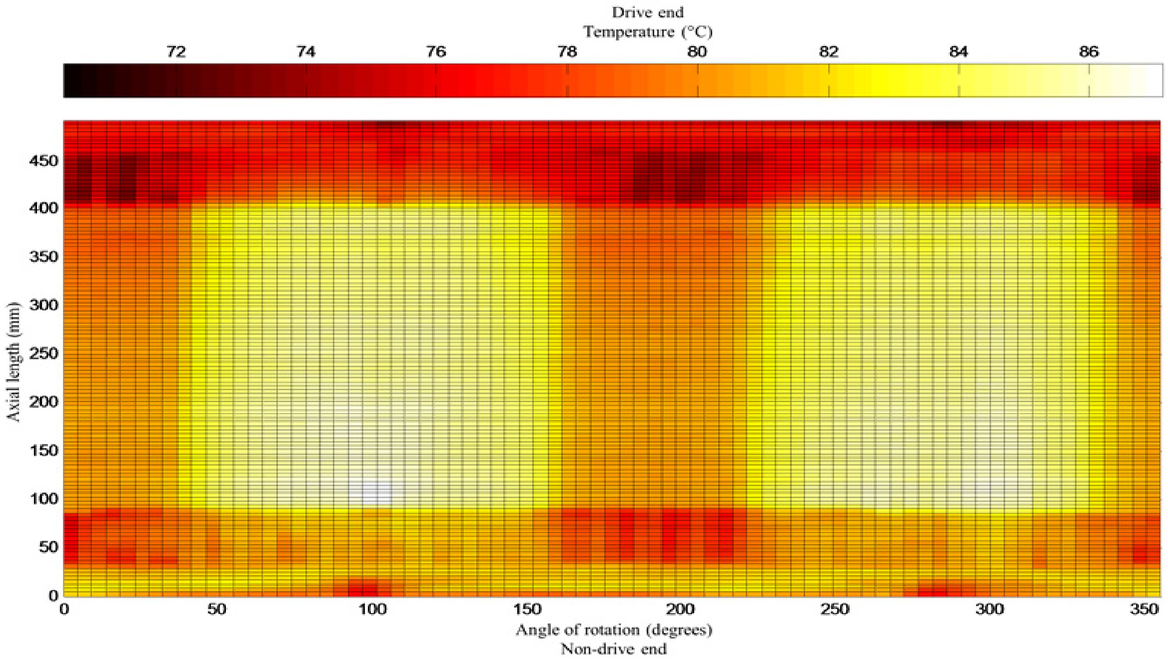

Fig. 3. A direct thermal map of the experiemental test rotor undergoing CTIT after 210 minutes of 35 A current excitation.

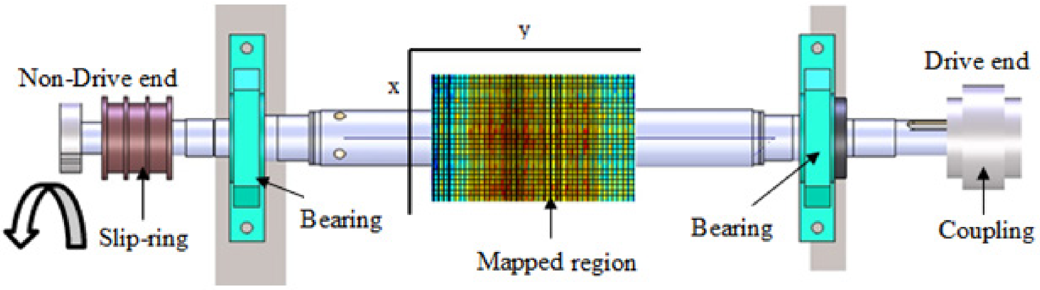

Fig. 4. Orientation of thermal map with repect to experimental rotor.

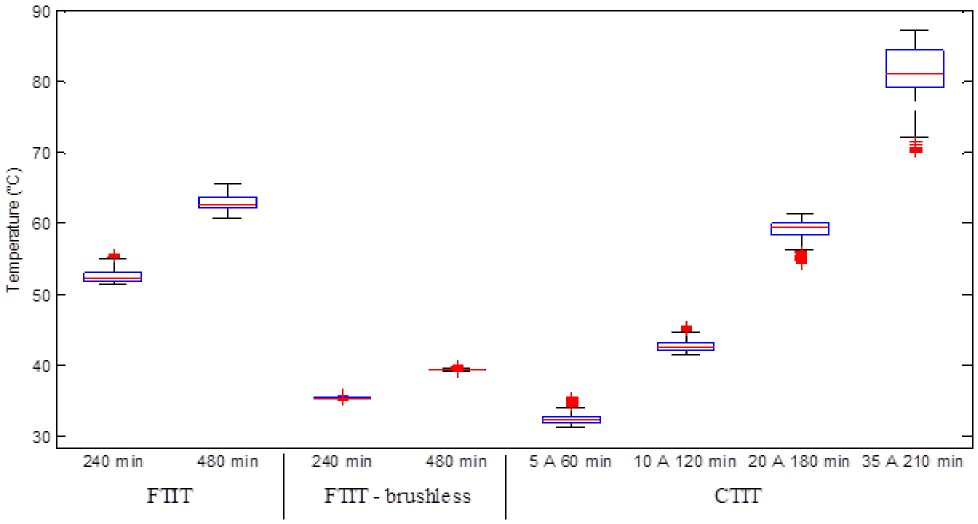

Fig. 5. Summary of the temperature distributions for experimental test rotor obtained from the direct thermal maps for each of the different conditions.

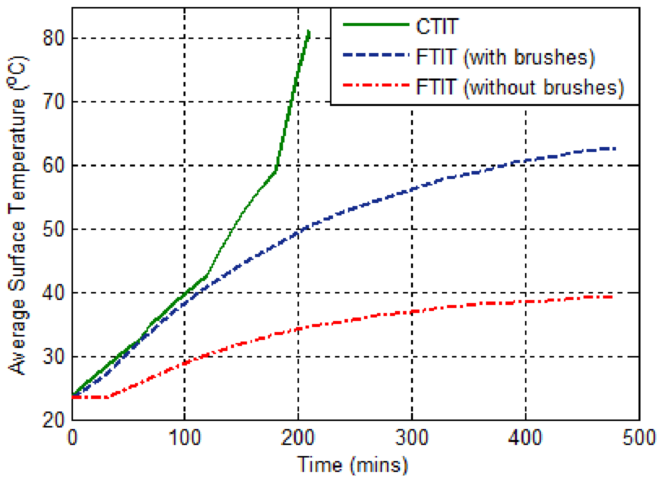

Fig. 6. Means for each temperature distribution of the experimental rotor for for the different test conditions.

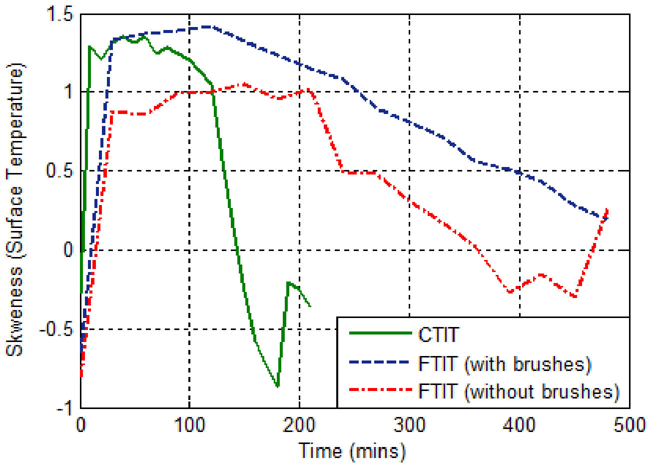

Fig. 7. The skewness each temperature distribution of the experimental rotor for the different test conditions.

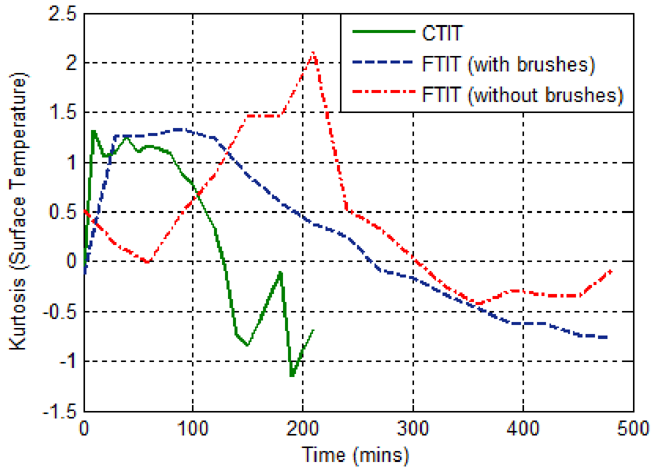

Fig. 8. The kurtosis of each temperature distribution of the experimental rotor for the different test conditions.

It is observed that the removal of the brush gear shows that the range and average of the rotor temperature distribution is considerably reduced. The range and average progressively increase for the case of CTIT. Hence, the influence of current injection in CTIT causes non-uniform heating of components of the rotor with many outliers. The results of the investigation show that the two modes of TIT are not interchangeable and further evaluation of each mode should be carried out in practice. Furthermore, the practice of measuring the rotor winding resistance via the collector assembly to estimate the temperature needs to be reconsidered. The bias introduced by the interaction of the slip-brush gear and slip-rings may be significant as this phenomenon introduces an asymmetrical temperature distribution along the length of the rotor. DTM enabled identification of this phenomenon and quantification of the extent of the resulting thermal gradient between the non-drive and drive-end of the rotor. Heating of the rotor during FTIT is gradual over a relatively long period of time because it is uncontrolled and strongly influenced by ambient temperature. Additionally, the initial temperature of the air surrounding the rotor, within the enclosure, and interaction thereof with the rotor determines the steady-state or maximum temperature. The maximum temperature and final average temperature of the FTIT test was significantly lower than CTIT. FTIT does not emulate the operating conditions or thermal behavior of a rotor in practice. Therefore, FTIT is not suitable for effective detection of thermal sensitivity or acceptance testing of the rotor. With CTIT, the heat source was the winding and therefore heat is transferred from the copper coils outwards through the rotor. It is also found that the different materials and complex nature of the construction of the rotor influences the transfer of heat - i.e. temperature of rotor components rises at different rates, during CTIT. In practice, only a few point measurements are taken on the rotor surface and the collector assembly, under the assumption of uniform temperature distribution, which are used to determine if the rotor is thermally stable. This methodology is not correct because the assumption of uniform heating does not hold for CTIT. DTM is more appropriate in the case of CTIT because a few point measurements will not suffice.

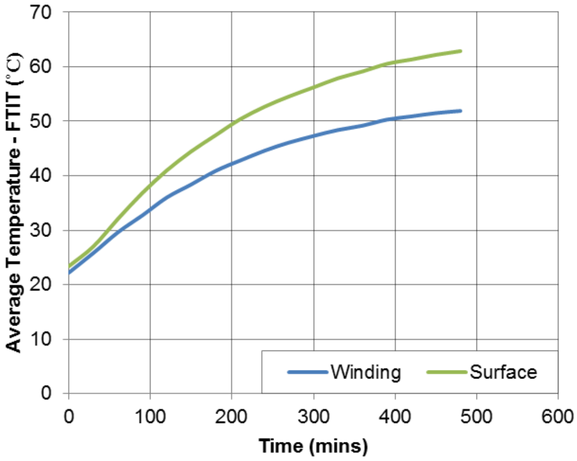

Fig. 9. Average surface temperates of the rotor compared to the winding temperature for the FTIT senario.

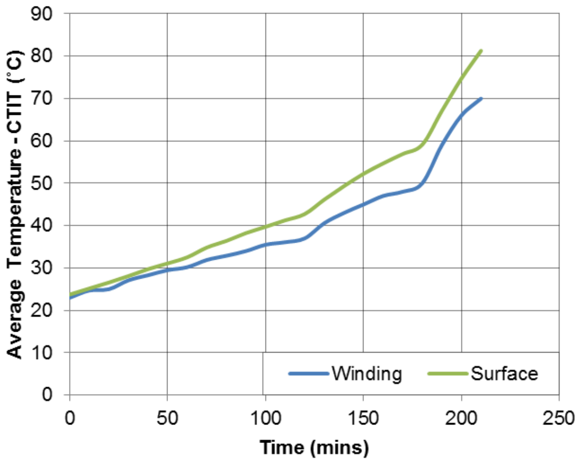

Fig. 10. Average surface temperates of the rotor compared to the winding temperature for the CTIT senario.

In addition to the applying the DTM method during CTIT and FTIT modes, the winding temperature was monitored via infrared sensors positioned on the rotor overhangs as this is the only area where the windings are clearly exposed. Figures 9 and 10 show results of these winding temperatures as compared to the average rotor surface temperature distributions recorded via DTM. It can be seen that the winding temperature is significantly different when compared to the surface of the rotor. Therefore, the use of the current and resistance of the winding to estimate the rotor temperature in practice is incorrect and these results confirm that this approach is inaccurate.

VI. CONCLUSION

In the presented research, the shortcomings of the contemporary TIT modes are presented and an augmented TIT methodology i.e. DTM is proposed. An experimental generator rotor was used to determine the differences between the two TIT modes namely CTIT and FTIT. Results of the investigation show there are significant differences in the thermal behavior of the rotor while undergoing each test. During FTIT the temperature distributions or the rotor follow a normal distribution while non-uniform distributions are exhibited during CTIT. Furthermore, the interaction of the brush gear and slip-rings are found to have a significant effect on the temperature distributions during FTIT. This interaction produces a temperature gradient along the length of the rotor from the non-drive end to the drive-end. This result requires further investigation on a large turbogenerator rotor as the observed temperature difference resulting from the phenomenon could potentially bais measurements conducted during TIT. FTIT differs from CTIT in that the results are more representative of ideal thermal response whereas the rotor exhibits more realistic thermal behavior during CTIT. The presented statistical measures show both quantitatively and qualitatively that the rotor's thermal behaviour is significantly different for each test condition. This detailed assessment and analysis of the rotor under each TIT mode is only possible through the DTM method. Although it is found that CTIT is more suitable to detecting thermal sensitivity than FTIT – it is necessary to augment the mode using DTM in order to reduce the uncertainty. Furthermore, this augmented method may contribute to better understanding rotor thermal sensitivity thus improving international standards relating to TIT.

REFERENCES

[1] E. A. B. Greg C. Stone, Ian Culbert, Hussein Dhirani, *Electrical Insulation for Rotating Machines*: John Wiley & Sons, INC, 2004.

[2] I. Kerszenbaum, "Inspection of Large Synchronous Machines," Piscataway, NJ: IEEE Power.

[3] "IEEE Guide for Operation and Maintenance of Turbine Generators," *IEEE Std 67-2005 (Revision of IEEE Std 67-1990)*, pp. 0_1-69, 2006.

[4] "IEEE Recommended Practice for Monitoring and Instrumentation of Turbine Generators," *IEEE Std 1129-1992*, pp. 0_1, 1992.

[5] J. Stein, "Main generator rotor maintenance," *EPRI Project Manager-Final Report*, 2006.

[6] G. Klempner, and I. Kerszenbaum, *Operation and Maintenance of Large Turbo- Generators*: John Wiley & Sons, INC, 2004.

[7] P. Tavner, L. Ran, J. Penman, and H. Sedding, *Condition Monitoring of Rotating Electrical Machines*: The Institution of Engineering and Technology, 2008.

[8] J. G. Paxton, "Turbine Generator Rotor Thermal Unbalance," *EPRI Proceedings: Utility Motor and Generator Predicitve Maintenance and Refurbishment Conference,* vol. EPRI TR-104625, pp. 112-116, 1994.

[9] R. J. Zawaoysky, and W. M. Genovese, *Generator Rotor Thermal Sensitivity – Theory and Experience,* GER-3809, GE Reference Library, GER-3809, 2001.

[10] B. Irwanto, L. Eckert, and T. Prothmann, "Thermal Unbalance Behaviour of Turbogenerator Rotors." pp. 2231-2242.

[11] Y. Yang, and Q. Zhao, "Generator thermal sensitivity analysis with Support Vector Regression." pp. 944-949.

[12] T. Kawurama, and E. Shoyama, "Latest Technology for Turbine Generators," *Hitachi Review,* vol. 27, pp. 367-372, 1978.

[13] C.-H. Chen, "Generalized association plots: Information visualization via iteratively generated correlation matrices," *Statistica Sinica,* vol. 12, no. 1, pp. 7-30, 2002.

[14] L. Wilkinson, and M. Friendly, "The history of the cluster heat map," *The American Statistician,* vol. 63, no. 2, 2009.

[15] A. Field, *Discovering statistics using IBM SPSS statistics*: Sage, 2013.

[16] R. M. Weiers, *Introduction to business statistics*: Cengage Learning, 2010.