TEST BENCH AUTOMATION FOR AGING AND PARTIAL DISCHARGE EXPERIMENTS IN HYDROGENERATOR STATORS

MATEUS G. SANTOS*, GERSON A. BRAULIO***, JOSÉ V. BERNARDES JR**, CREDSON SALLES**, JOSÉ R. C. MILANEZ*, EDSON C. BORTONI**, GUILHERME S. BASTOS *,

** Systems Engineering and Information Technology Institute, Federal University of Itajubá*

***Electrical and Energy Systems Institute, Federal University of Itajubá*

Av. BPS, 1303, Itajubá-MG, Brazil

**** CEMIG Geração e Transmissão*

Av. Barbacena, 1200, Belo Horizonte-MG, Brazil

E-mails: mateus.gabriel@unifei.edu.br, braulio@cemig.com.br, jusevitor@unifei.edu.br, jrcmilanez@unifei.edu.br, credson@lat-efei.org.br, bortoni@unifei.edu.br, sousa@unifei.edu.br

Abstract — This paper proposes the automation of a test bench for partial discharges measurement during thermal cycle tests with nominal voltage applied to hydro generator stator windings, allowing the simulation of simultaneous electrical and thermomechanical stresses. To that end, it is mandatory to identify a relationship between the internal and external winding temperatures since the voltage applied makes it impossible to insert sensors directly to the winding. It proposes the online reading of partial discharge during the entire test; in opposition to the common practice of reading the partial discharge data once before and once after the run of accelerated aging tests, such as the thermal cycle.

Keywords — Hydro generator stator, Partial Discharge test, Concurrent stator stress, Stator life cycle, Test bench automation.

1 Introduction

Partial discharges are small sparks that happens due to the electrical charges flow when a small gas rupture occurs. They normally occurs in small gaps on the electrical machines insulation when the incident magnetic field gets over the dielectric strength limits of the gas that fills those gaps.

Those discharges are only partial because there is an insulation material with a greater dielectric strength limit in series with the gaps. According to the standard (IEEE Std. 1434, 2000) partial discharges are incomplete electrical discharges between insulations or between insulation and conductor. In terms of power generators, that means that partial discharges can be defined as incomplete electrical discharges that occurs on the interior of stator windings only for generators of 2.3kV (two thousand and three hundred volts) or higher voltage.

The power generator partial discharges usually are intensified by different stresses (electrical, thermal, thermomechanical, amongst others) present on the operation of this kind of equipment (C.Stone, et al., 2014). Hence, the monitoring of partial discharges offers a diagnosis of generator's insulation condition, and the evolution of partial discharges can show that its insulation is degraded or aged due to the effects of multiple type of stresses present in the operation.

The online monitoring of partial discharges provides results that makes stator windings maintenance and repair activities easier to schedule and also data for the development of mathematical models to predict the remaining lifecycle of generators (Sumereder, 2008) .

According to statistical data, the insulation failures represents the majority of generator failures (Study Committee SC 11, 2003). Several different statistical analysis have been realized with data from generator units in operation leading to the conclusion that the generator lifecycle is directly related to the insulation lifecycle (I. J. Kokko, 2010; C.Stone, et al., 1988; Kelmann & Kaufhold, s.d.; Bartnikas & Morin, 2006).

The development of mathematical models able to predict and access the generator remaining lifecycle based on insulation status requires significant amounts of data. An efficient method to generate that data is the execution of aging tests in laboratories simulating the main stresses to machines insulation during its operation.

Electrical, thermal, mechanical and thermomechanical are the main stresses related to electrical machines insulation, but performing aging experiments with only one kind of those stresses occurring on the winding don't produce the same aging and degradation as the normal operation where all stresses occur simultaneously (Bartnikas & Morin, 2006). Therefore the development of multiple stresses aging experiments are proposed to better simulate what occurs during the electrical machine operation (Bartnikas & Morin, 2006; Morin & Bartnikas, 2012.).

The thermal cycle experiment realized in this work is standardized (IEEE Std. 1310, 2012). The thermomechanical effect that electrical machines are subjected to is simulated in a stator winding through the repetition of its heating and cooling cycles, however, differently of what the standard suggests, this experiment was proposed with nominal voltage also applied to the winding. Therefore both electrical and thermomechanical stresses are simultaneously present on the winding, enabling the monitoring of its partial discharge during the whole experiment.

This paper presents the development of an automatic workbench that allows the realization of said experiments with minimal operator interaction while registering several different data from the experiment for posterior analysis, in order to model stator winding's partial discharge behavior throughout its aging in operation.

In relation to the structure of this paper, chapter 2 is about the software and equipment used to collect and manage experiment data. Their configuration are presented in chapter 3. A preliminary experiment is shown in chapter 4, leading to a mathematical relation between internal and external winding temperature. Chapter 5 presents the adjustments made to allow the execution of the thermal cycle with nominal voltage applied experiment and some results obtained at UNIFEI's High Voltage Laboratory.

2 Instrumentation and data management

To analyze the impact of simultaneous stresses on the winding partial discharges the proposed experiment suggests the online monitoring of those discharges during its realization, therefore several data also must be monitored during its realization:

2.1 Partial discharge and applied voltage

Partial discharges, the main study object of this experiment, are monitored using the partial discharge monitor Haefely Test AG, Model DDX 9121b, presented in figure 1. This monitor has a coupling capacitor of 1nF, model 9230 with 100kV maximum voltage and a partial discharge calibrator model 9520, with discharge band from 1pC to 50nC.

Furthermore, the coupling capacitor works as voltage divider and allows the monitor software the capacity of also registering the voltage applied to the winding, besides the partial discharge data.

Figure 1. Partial discharges monitor and its components

2.2 Temperature on winding surface

In the thermal cycle experiment, the internal winding temperature must vary between 40ºC and 155ºC, so it is mandatory to monitor that temperature. However, considering the simultaneous applied voltage it is not feasible to drill the winding to measure the internal temperature, therefore it must be obtained indirectly.

Thus, a FLIR thermal camera model AX8 was used to monitor the temperature in the winding external surface.

Figures 2a e 2b presents the camera and one snapshot taken with it, respectively:

a) b)

Figure 2. Thermal camera and one of its snapshots

Since the camera can only read the external surface temperature, some experiments were executed without voltage application using a drilled winding that allowed the use of thermocouples to read the internal temperature, in order to obtain a mathematical relation between the internal and external surface temperatures.

2.3 Induced current

To produce the heating of the winding it is necessary to induct a current in it, and it is important to monitor that current in order to assure the heating occurs accordingly to the standard and making adjustments speeding up or down the heating as needed.

Three equipment are used to measure the induced current: a TC (current transformer) 0-2500A:0-5A, a current transducer 0-5A:4-20mA and a Fieldlogger module for data acquisition and registering, presented respectively on figures 3a, 3b and 3c.

a) b)

c)

Figure 3. Equipment for measurement and collection of induced current data.

2.4 Environmental condition

In order to observe if environmental conditions effectively affect the winding, environmental temperature, humidity and dew point are monitored using a sensor model T3511 from Comet Sensors presented on figure 4.

Figure 4. Sensor T3511.

2.5 Communication and data availability

The partial discharge monitor is able to communicate with a computer through its native software that is used to calibrate the monitor (the calibrator induces a known electrical signal and the monitor is then calibrated around that signal), start and finish data collection, monitoring of measured values, and data export to text files with formats such as ".csv".

Other equipment allows the communication and have their data available through Modbus TCP/IP protocol. Obs.: the TC and current transducer only convert the induced current from 0-1000A to 4-20mA, sending these converted values to the Fieldlogger which finally makes them available for Modbus reading.

In order to enable the communication via Ethernet TCP / IP, a 24-port PoE (Power over Ethernet) switch was installed on the outside bench of the test cell.

2.6 Data storage and management

The PI (PI System), a data infrastructure system developed by OSISOFT, is used to store, manage and visualize the data. It centers data from different sources, allowing the association of each monitored variable to elements that makes easier the comprehension of the monitored plant and the visualization of its data.

The PI functioning can be roughly divided in three different levels:

1) Interfaces: they read the data from different data sources (usually sensors), associating a timestamp with it and then send them to the server. There are several different interfaces, one for each protocol or type of data source.
2) Server: it has two great blocks: PI Data Archive, a temporal database that stores the values (tags) sent by the interfaces and the PI AF (PI Asset Framework) that allows the organization of such tags in elements that make it easier for users to view, use and comprehend that data.
3) Visualizing tools: they allow the access and visualization of data through different platforms such as MS Excel plug-ins, Web pages, etc.

In this experiment 3 different interfaces were used: PI Interface for Modbus Ethernet ReadOnly, PI Interface for Modbus Ethernet ReadWrite and PI Interface for UFL (interface used to read text files with ".csv" format).

The university works with PI System since 2016 and the PI dedicated infrastructure is located at the university datacenter allowing continuous and reliable data collection.

3 Experiment configuration

In order to perform the experiments, the equipment and PI interfaces were configured as shown in the following subsections, resulting in the workbench final configuration which its schematic is presented on figure 5

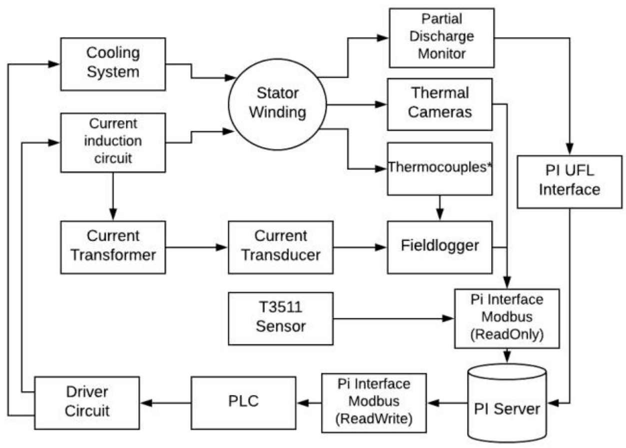

Figure 5. Final workbench schematic.

3.1 Experiment equipment configuration

Some equipment, other than instrumentation ones, are also used to ensure the proper functioning of the experiments.

In opposition to what standard IEE std 1310 suggests, the thermal cycle experiment will be done with nominal voltage applied to the winding, in order to allow registering the partial discharge evolution during the whole experiment.

The test winding is wrapped with a conductive layer (aluminum foil) all along its rectilinear stretch and connected to the ground point. This way the applied voltage lies between the conductor and the grounded conductive layer that electrically represents the generator stator. The potential difference lies completely in the test winding solid insulation allowing the online monitoring of partial discharges through the coupling capacitor, during the whole experiment.

Another circuit is necessary to apply current to the stator winding. Therefore, a variable autotransformer powering a group of inductors and an isolated cable (where the current is induced) inserted through the inductors were used. The isolated cable is connected to the winding terminals, transmitting the induced current to the winding that heats progressively, enabling the heating cycle to occur.

A cooling system consisting of a wind blower connected to an open flexible folding tube, directing the blower's air to the winding. This way, whenever the cooling system is on, a great amount of air is directed to the winding, speeding up its cooling cycle.

The thermal cycle is completed after a heating cycle and a cooling cycle are done, and another heating cycle is about to begin.

Figure 6 shows a winding positioned on four isolating supports, wrapped by a conductive layer; the connection between the winding and the coupling capacitor; the connection between coupling capacitor and partial discharge monitor through a 50Ω coaxial cable; the medium voltage cable with the muffle connected to the industrial frequency voltage source. All these equipment and connections form the voltage applying circuit.

Figure 7 shows the circuit that induces the current for the winding: a cable with XLPE insulation for current induction; four current inductors connected in parallel configuration, and a variable autotransformer (VARIAC) with industrial frequency and adjustable voltage between 0 and 240V.

Then, figure 8 shows the cooling system composed by the wind blower that uses a Three phase induction motor with 0,75 HP and the open flexible folding tube that directs the air to the winding as can be seen on figure 6.


Figure 6. Voltage applying circuit


Figure 7. Current induction circuit


Figure 8. Cooling system

In order to monitor the temperature and accordingly control the current induction circuit and the cooling system, the Exsto module XT136 was used. Figure 9 shows the module and the connections used on the experiment.

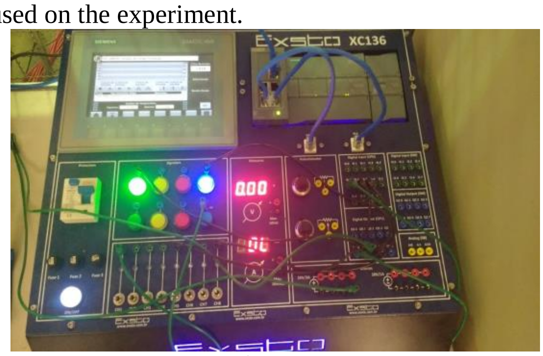

Figure 9. PLC module for controlling the experiment.

This module counts with PLC Siemens S7-1200 (CPU 1214C DC/DC/DC), 8DI/8DQ expansion card, 5-port Ethernet switch, HMI KTP700 basic and several connectors, switches and LEDs for ease of access and integration.

The PLC programming was done using ladder logic. The software communicates with the Fieldlogger or PI through Modbus Ethernet to acquire the temperature readings, calculates the average and when that average reaches the limits upper or lower, it activates the correspondent system: the cooling system when it reaches the upper limit, and the current induction circuit when it reaches the lower limit.

An HMI interface was developed for experiment operation and it is shown on figure 10.

Figure 10. HMI interface screen.

Since the PLC must command the power of inductors or the cooling system accordingly to the temperature, a digital out was used. However, the PLC digital out can provide 24Vdc and the inductors must be powered with 220Vac (for the current induction circuit) or 380Vac (for the cooling system). Therefore, it was necessary to design a drive circuit with contactors and timer relay, shown on figure 11.

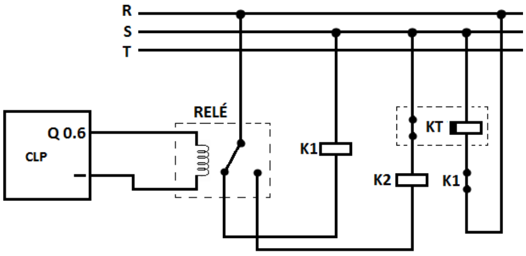

Figure 11. Drive Circuit - Command

The PLC digital out was connected to a 24Vdc relay coil, capable of driving up to 250Vac. The relay normally closed contact was connected to the coil of K1 (the three phase contactor for cooling system powering), its normally open contact was connected to the coil of K2 (two phase contactor for current induction system powering) and finally the relay common contact was connected to a phase (R). The normally closed contact of KT (safety timer relay) was connected to the second coil terminal of K2, no connection was made using its normally open contact, and its common contact was connected to a different phase (S). A normally close contact of K1 was connected to a phase (R) and to KT's coil. The remaining contacts of coils K1 and KT were connected to a different phase (S). Finally, the normally open contacts from K1 and K2 were respectively connected to the cooling system and current induction circuit, and corresponding phases as shown in figure 12.

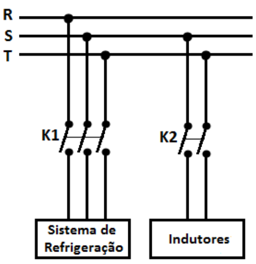

Figure 12. Drive circuit – Actuators powering

In this configuration, when the PLC out is off (logic value 0) the cooling system is active. When the PLC out is on (logic value 1) the K1 coil has its power cut. KT is powered (KT is configured to 1h period, and works as a safety timer for the heating cycle interrupting the circuit after one hour in case the system loses the command signal). In addition, so is K2 coil, powering the inductors and keeping them on, until the upper temperature limit is reached or the heat safety timer ends.

3.2 Data acquisition and storage configuration with PI

In this project, PI collects and centers the data from different equipment using proper interfaces according to the data source protocols.

The partial discharge monitor software makes its data available through ".csv" format text files with UCS-2 coding, through export request made by the user. Therefore, a mouse macro software was used to start the monitor software, recall the last calibration, start the data acquisition, wait thirty minutes, end the data acquisition, save the test and export the ".csv" report file. Such sequence of actions is repeated forty eight times adding to twenty-four hours of operation. Some user ought to start the macro every twenty-four hours in order to collect all the experiment data.

The PI interface for UFL is only able to read files with UTF-8 coding, therefore, a PowerShell script was developed. The script monitors the folder where the ".csv" files are exported, and every time an UCS-2 file is created, its content is copied to a new corresponding UTF-8 file. After the copy, the UCS-2 file is deleted and the UTF-8 file can be read by the PI interface for UFL.

In order to configure the UFL interface, a configuration file is created containing the folder path to the files to be read, its nomenclature standards, the format and location of the information that must be extracted, and also which tags must be updated with the extracted values.

For the partial discharges monitor the relevant information are: 1) The data capture start date – which identification occurs searching the character "-" in specified positions on the lines of the file. 2) The time offset between the reading and the data acquisition start. 3) The value Q(peak) [pC] – equivalent to Qm (magnitude of partial discharges).

. 4) The RMS voltage applied to the winding. 5) The discharge pulses rate – equivalent to NQN (partial discharge total activity). The identification of all items, except for item 1, is done using the file indentation.

After extracting the values, the writing of the tags Qm, TensãoRMS and NQN is done using the values for those data in addition to the timestamp that is a composition between the data acquisition start date and the reading time offset from the start.

Once the file is totally read, the interface changes the file name so it doesn't read the same file twice, and after some while it deletes old files that have already been read.

In relation to the other equipment, the Modbus interfaces (two Modbus Ethernet interfaces are used: ReadOnly – that only reads data from equipment; and ReadWrite – that writes data in specific PLC registers) are configured using the IP addresses of those that must be read, the ports used in communication (Modbus usually uses port 502). Besides that, it is also necessary to configure the interface to operate as a Windows service and create scan classes – that determines the time interval between readings of the data source for all tags configured for such scan class.

Table 1 presents the IP address of each equipment and the number of tags created for each one of them.

Table 1. Equipment IP addresses and tag number

Equipment	IP address	Tags
Partial discharges Monitor	200.235.76.123	03
Thermal Camera	200.235.77.70	21
T3511 Sensor	200.235.77.74	03
Fieldlogger	200.235.77.76	12
PLC	200.235.77.79	05
Network Switch	200.235.77.80	-

In order to configure the tags in the PI, the PI System Management Tools (PI SMT) software is used. It is necessary to identify the interface used and its instance using the fields "Point Source" and "Location1". Specify the source equipment Modbus ID with field "Location2". Define the Modbus function and the data type to be read at "Location3". Choose the scan class on "Location4". Provide the Modbus register equipment address corresponding to the data to be read through "Location5". Finally, the equipment IP address is set on field "Instrument Tag".

With the correct configuration of the interface and the tags, the Modbus interface will be able to collect, format and send the data to the PI server, allowing the monitoring of the data during the experiment, as well as the visualization and analysis of the data in posterior phases of the project.

Obs.: More details about the interfaces Modbus, its configuration and its tags can be found in (OSISOFT, 2016).

4 Preliminary experiments and its results.

In order to verify the existence of a mathematical relation between the internal and external surface of the winding insulation, it was proposed the realization of preliminary experiments. These experiments would be done using a winding to be discarded, with no voltage applied, so it could be drilled, allowing the use of thermocouples to acquire its internal temperature and its comparison with the external surface temperature obtained by the thermal camera.

The thermal camera requires points over surfaces with high emissivity in order to realize correct readings of the temperature on that surface. Therefore, five points were chosen along the side of the winding monitored by the camera, such points were wrapped with insulating tape (it has emissivity index close to 1). Using the camera web interface five monitoring boxes were created, each one containing only one of the points wrapped with insulating tape. The camera provides readings of the maximum, minimum and average temperatures read on the box area.

In order to the thermocouples readings be as close as possible to the readings done by the camera the drillings for its installation were done in the points covered with insulating tape.

To read the data from the thermocouples, each one of them were connected to five different analog inputs of the Fieldlogger configured as Thermocouple K. The current transducer was also connected to a Fieldlogger analog input, configured as 4-20mA current input. The camera readings were always available through Modbus TCP/IP and the use of the Fieldlogger made the thermocouples and current transducer readings available through Modbus too.

All the readings were sent and stored on the PI server. Furthermore, the PLC was programmed to read the temperatures of each thermocouple and use it to control the experiment as explained on session 3.1 of this paper.

The induced current was set to 600A and some heating and natural cooling (without the use of the cooling system) cycles were realized. It can be noted on figure 13 that the cycle times were very different for the heating and cooling cycles. The experiment standard says that the heating and cooling cycle times must be close from one another and they have a temperature variation rate between 1,5^{0}C and 3,5^{0}C per minute. Hence it was decided the use of the cooling system to accelerate the cooling cycle and the reduction of the induced current to deaccelerate the heating time in order to meet the standard requirements.

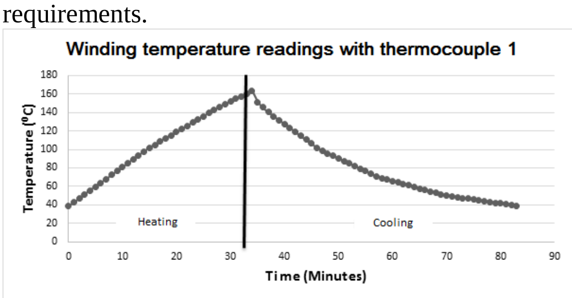

Figure 13. Thermocouple 1 readings for 1 thermal cycle.

After the heating and cooling times were adjusted, several cycles were realized, in order to analyze the variation of the temperature behavior during the experiment.

Considering that the distance between the different reading points is small (around 30cm) concerning heat propagation, a uniform variation of the temperature in those five points is expected. That can be verified by the graphs on figures 14 and 15.

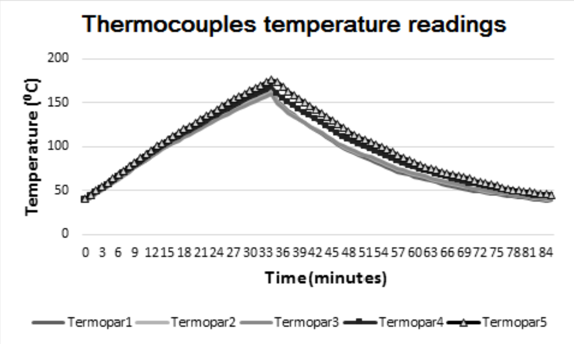

Figure 14. One thermal cycle reading by all thermocouples.

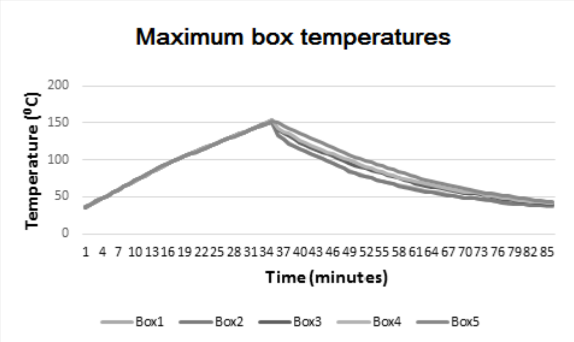

Figure 15. Maximum temperatures at the five monitored boxes during a thermal cycle.

Therefore, it was chosen the use of the average thermocouple temperature and the average of the boxes maximum temperatures. Figure 16 presents a graphical comparison of those averages, as well as the difference between then (delta), and it is possible to observe that the delta varies a lot according to the temperature, but has small variation between different thermal cycles.

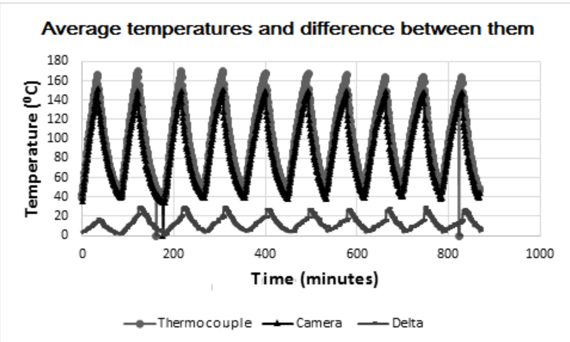

Figure 16. Comparison between average temperatures obtained

With the data of several thermal cycles, it is possible to identify the time where the heating and cooling cycles ended and then compare the maximum and minimum temperatures obtained by the camera and thermocouples, and the difference between them on those points. This information allows the identification of surface temperatures corresponding to internal temperatures of 40^{0}C and 155^{0}C. Tables 2 and 3 compare the internal temperatures (thermocouple) and at external surface (camera), as well as the difference between them (delta) at the cycle end times for heating and cooling.

It is possible to see that the average temperature at the end of the cycle presented only 5^{0}C to the 40^{0}C target, the delta also presented a 5^{0}C variation. Therefore, to achieve the internal 40^{0}C target, it is necessary that the surface temperature readings are equal to 35^{0}C.

Considering the heating cycles, the error to the target was always around only 0,5^{0}C, therefore, to find the external surface corresponding to the internal temperature of 155^{0}C, it is enough to use only the delta (around 15^{0}C).

Table 2. Cooling cycle end times

Cooling			
Cycle end Time	**Thermocouple**	**Camera**	**Delta**
16-feb-18 11:10:17	42,68982	39,79946	2,890359
16-feb-18 12:38:00	43,8972	38,34757	5,549628
16-feb-18 14:11:13	42,79444	39,23395	3,56049
16-feb-18 15:40:09	44,74939	39,38378	5,36561
16-feb-18 17:14:13	43,06484	38,81601	4,248834
16-feb-18 18:38:10	47,54771	41,24996	6,29775
16-feb-18 20:02:00	44,81488	39,02382	5,791061
16-feb-18 21:24:14	46,44759	41,13007	5,317521
16-feb-18 22:49:46	44,29579	40,54376	3,752026
17-feb-18 00:12:00	46,09599	39,43432	6,661666
Average	44,63976	39,69627	4,943495

Table 3. Heating cycle end times

Heating			
Cycle end time	**Thermocouple**	**Camera**	**Delta**
16-feb-18 10:15:10	155,141	141,7434	13,39763
16-feb-18 11:41:25	155,0252	136,0973	18,92789
16-feb-18 13:16:30	155,2739	138,0295	17,2444
16-feb-18 14:44:53	155,0615	138,0957	16,96576
16-feb-18 16:18:18	155,4462	137,7332	17,71306
16-feb-18 17:51:05	154,8871	139,706	15,18109
16-feb-18 19:17:00	155,4285	140,3953	15,03315
16-feb-18 20:43:26	155,4088	140,8044	14,6044
16-feb-18 22:05:01	155,4391	141,1161	14,323
16-feb-18 23:29:30	154,8928	142,1631	12,72967
Average	155,2004	139,5884	15,61201

Considering the heating cycles, the error to the target was always around only 0,5^{0}C, therefore, to find the external surface corresponding to the internal temperature of 155^{0}C, it is enough to use only the delta (around 15^{0}C).

This way it is possible to use external surface temperatures of 35^{0}C and 140^{0}C as equivalents to internal temperatures of 40^{0}C and 155^{0}C, respectively. Therefore, these can be used as lower and upper limits of operation on the experiment with applied voltage.

5 Thermal cycle with nominal voltage applied experiment

Since in the applied voltage experiment the temperature can only be read on the external surface using the camera, the relation obtained on section 4 is used to infer the internal temperature.

This way the PLC will need the temperatures read by the camera to control the experiment, however, the Modbus address mapping of AX8 cameras is done with 6 digit addresses, making the direct communication between PLC and camera impossible. A PI interface for Modbus Ethernet ReadWrite was used as solution, it will write the maximum box readings in five PLC registers (one for each camera box), every time the PI receive a new value for the tags monitoring the boxes.

With all adjustments done it is possible to realize the thermal cycles with applied voltage experiment monitoring the partial discharge.

Currently an experiment is being realized and the figure 17 presents a part of the results relating the temperature on the external surface with the partial discharge magnitude.

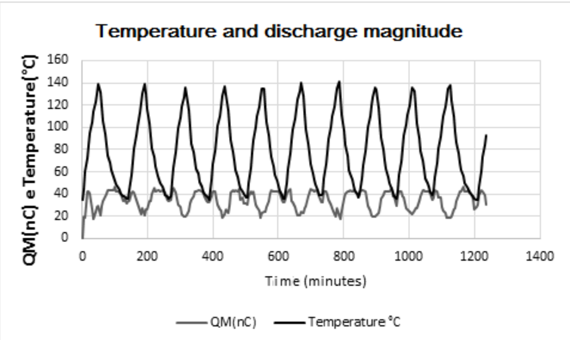

Figure 17. External surface temperature and partial discharge magnitude.

6 Conclusion and future work

With all equipment and software properly installed and configured, it was possible to perform preliminary experiments and verify that there is a relation between the external surface and internal temperatures during the thermal cycle (the difference starts at 5ºC when the internal temperature is 40ºC and it steadily grows up to 15ºC when the internal temperature is around 155ºC).

Such relation allows the realization of thermal cycle with applied voltage experiments as proposed. The test bench works properly in an automated way, allowing the online and remote monitoring of the experiment using the PI System.

Future work consists in the development of notification systems through e-mail or cell phones messages to inform the operation status of the test bench and the analysis of the obtained data with the progressive aging of the winding.

Acknowledgments

The authors are grateful to CEMIG for the partnership and all the support on the project "Proposal for an Approach to Diagnosis and Evaluation of Generators' Life", which this work is part of, as well as OSISOFT for the partnership and support in the issues related to the PI System.

References

Bartnikas, R., & Morin, R. (2006). Analysis of multistress-accelerated aged stator bars using a three-phase test arrangement. IEEE Transactions on Energy Conversion.

C.Stone, G., Culbert, I., A.Boulter, E., Dhirani, H., & C.Stone, G. (2014). Electrial Insulation for Rotating Machines. New Jersey: IEEE PRESS.

C.Stone, G., Lloyd, B., Sedding, H., & Gupta, B. (1988). The Ability of Diagnostic Tests to Estimate The Remaining Life Time of Stator Winding Insulation. IEEE Transactions on Energy Conversion.

I. J. Kokko, V. (2010). Electrical Ageing in Lifetime Estimation of Hydroelectric Generator Stator Windings. XIX International Conference on Electrical Machines.

IEEE Std. 1310. (2012). IEEE Recommended Practice for Thermal Cycle Testing of Form-Wound Stator Bars and Coils for Large Rotating Machine. New York: IEEE Power and Energy Society.

IEEE Std. 1434. (2000). IEEE Guide to the Measurement of Partial Discharges in Rotating Machinery. New York: IEEE Power Engineering Society.

Kelmann, F., & Kaufhold, M. (s.d.). Evaluation Analysis of Thermal Ageing in Insulation Systems of Electrical Machines - A Historical Review. IEEE Transactions on Energy Conversion 2010.

Morin, R., & Bartnikas, R. (2012.). Multistress Aging of Stator Bars in a Three-Phase Model Stator Under Load Cycling. IEEE Transaction on Energy Conversion.

OSISOFT. (2016). PI Interface for Modbus Ethernet PLC 4.2. San Leandro: OSISOFT.

Study Committee SC 11, E. (2003). Hydrogenerator Failures - Results of the Survey. CIGRE.

Sumereder, C. (2008). Statistical Lifetime of Hydro Generators and Failure Analysis. IEEE Transactions on Dielectrics and Electrical Insulation.