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Testing of Insulation Systems in Accelerated Aging Conditions

Slaven Nađ, Josip Treger, Stjepan Car

Summary **— The paper describes the testing procedure of the insulation system of electrical rotating machines with form-wound windings in accordance with the standards IEC 60034-18-31 and IEC 60034-18-42. Testing is based on a comparison of reference insulation system which has given satisfactory service experience and candidate insulation system which is intended to be used instead of existing insulation system. To prove or disprove the reliability of candidate systems in reasonable time, the accelerated aging test is carried out, considering various factors that reduce the life of the insulation system in greater or lesser extent: heat, exposure to mechanical vibrations and moisture (according to IEC 60034-18-31) and voltage (according to IEC 60034-18-42). In order to save materials and easier handling of test samples, tests are carried out on reduced models of coils (so-called formette coils) that are placed in frames imitating the stator core. The purpose of the test is to verify the potential contributions of a new impregnating resin, as well as the addition of nanoparticles in a new impregnating resin in a condition of increased voltage stress due to machine connection to the grid via frequency converter. In addition to the test procedure, the paper presents the results obtained so far.**

Keywords **— insulation system, electrical rotating machines, form-wound winding, thermal classification, life curve, formette**

I. Introduction

As a part of research project named "Development of submerged aggregate for small hydroelectric power plant with low water head" launched in 2020 in Končar – Generators and motors, investigation of generator insulation system, which is vital part of submerged unit, is taking a place. Overall insulation system of generator is consisting of mica-based mainwall and inter-turn insulation. The voltage stress control system is performed in two variants: with just a conductive slot-part layer or with both a conductive slot-part layer and a semi-conductive layer in the end-winding region. Conductive layer is based on glass fabric impregnated with an electrically conductive varnish, while semiconductive layer consists of polyester fabric, impregnated with a silicon carbide. Rated voltage is 690 V. Due to fact that generator is connected to grid via frequency converter with impulse repetition rate 2 kHz and impulse rise time equal 0,12 µs, insulation system will be exposed to higher voltage stress in comparison with insulation system of directly grid connected generator. In order to ensure capability of withstanding higher voltage stress and better thermal conductivity of insulation system, new polyamide-based impregnating resin is applied as well as the addition of nanoparticles in new impregnation resin [1], [2]. Main purpose of this research is to determine the influence of those two new elements to the insulation system lifetime comparing existing end new insulation system. To achieve reliable results of comparison in reasonable time, accelerated aging tests are performed with purpose to consider factors which can reduce the lifetime of insulation systems in a greater or lesser extent: heat, mechanical vibrations, humidity (in accordance with IEC 60034-18-31 standard) and voltage (in accordance with IEC 60034-18-42 standard).

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II. Thermal Evaluation and Classification of Insulation Systems

A. Introduction

Thermal evaluation and classification of insulation systems is carried out in accordance with IEC 60034-18-31:2012 [3] and some practical solutions form [4]. Object of testing is insulation systems with form-wound windings used in rotating electrical machines in conditions of accelerated thermal ageing. Test procedure is based on comparison between existing insulation system, which gave reliable service life (so-called "reference insulation system") and new insulation system which is intended to replace the existing insulation system (so-called "candidate insulation system"). Reference and candidate system are compared under the same test conditions.

Testing is performed on coils with shorten slot-part (so-called "formette coils" – figure 1) which are inserted in special frame (so-called "formette frame") which simulates stator core. Formette coils with formette frame constitute the test object - formette.

Fig. 1. Coil with shorten slot part – so-called "formette coil"

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In this specific case, test object consists of 5 complete formette coils and 8 half-formette coils (coil legs with shorten slot part) which is intendent to fill the empty upper/lower layers as shown on picture 2. All provided test procedures are performed on complete formette coils which are not electrically connected between themselves. Purpose of half-formette coils is to provide fixture of complete formette coils and imitation of real condition in stator core.

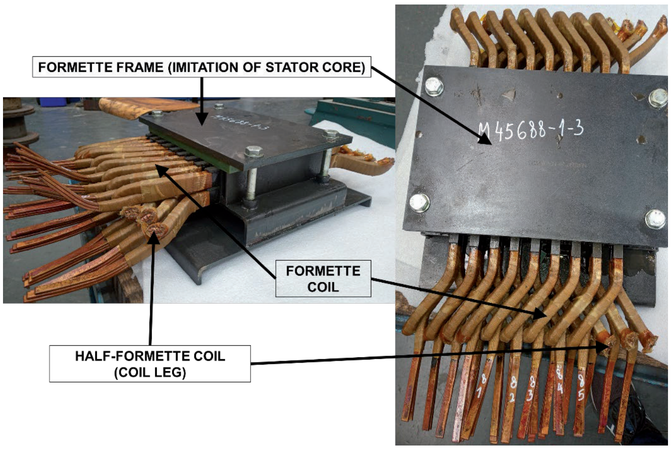

Fig. 2. Test object (formette) and its main parts

Sequence of test procedure is shown on figure 3. At the beginning of test procedure, first step is so-called "zero-cycle" or "initial diagnostic cycle" which has a purpose to determine initial state of insulation system. It considers test of mainwall and inter-turn insulation which is following with informative tests (measuring of capacitance, insulation resistance and possible occurrences of partial discharges). After successful implementation of zero-cycle, next step is cycle which consist of series of sub-cycles: thermal aging, informative tests (measuring of capacitance, insulation resistance and possible occurrences of partial discharges), mechanical stress, exposure to moisture and diagnostic sub-cycle (voltage withstand test of mainwall and inter-turn insulation). The specified cycle is repeated until insulation breakdown on all formette coils is recorded in diagnostic sub-cycle, which means end of testing. Insulation system is intended for thermal class H (180 °C).

Thermal evaluation and classification of insulation systems will be carried out on 6 different insulation systems shown in table 1. Insulation systems 1 and 2 are references, while systems 3-6 are candidates.

TABLE I:

INSULATION SYSTEMS PREPARED FOR TESTING

No.	Voltage stress control system	Impregnating resin	Insulation system
1	Only conductive	Existing	Reference
2	Conductive and semiconductive		
3	Only conductive	New	Candidate
4	Conductive and semiconductive		
5	Only conductive	New + nanoparticles	Candidate
6	Conductive and semiconductive		

B. THERMAL AGEING

Sub-cycle of thermal ageing is conducted at three different temperatures. For thermal class H, in accordance with standard [3], temperatures are following: 200 °C, 220 °C and 240 °C. Thermal aging time is reverse proportional to aging temperature. From proposed interval following aging times are chosen:

- 29 days for temperature 200 °C
- 8 days for temperature 220 °C
- 2 days for temperature 240 °C

Each of the listed insulation systems in table 1 is tested at the three specified temperatures with the corresponding exposure time using one test object (formette coils + formette frame) per temperature and per insulation system, which means that a total of 18 test objects - formettes required for testing.

An oven (figure 4) is used to heat the test objects in a way that all parts of the insulation system are equally exposed to the selected aging temperature, which was controlled on the oven control device screen during the entire exposure time and was kept at a

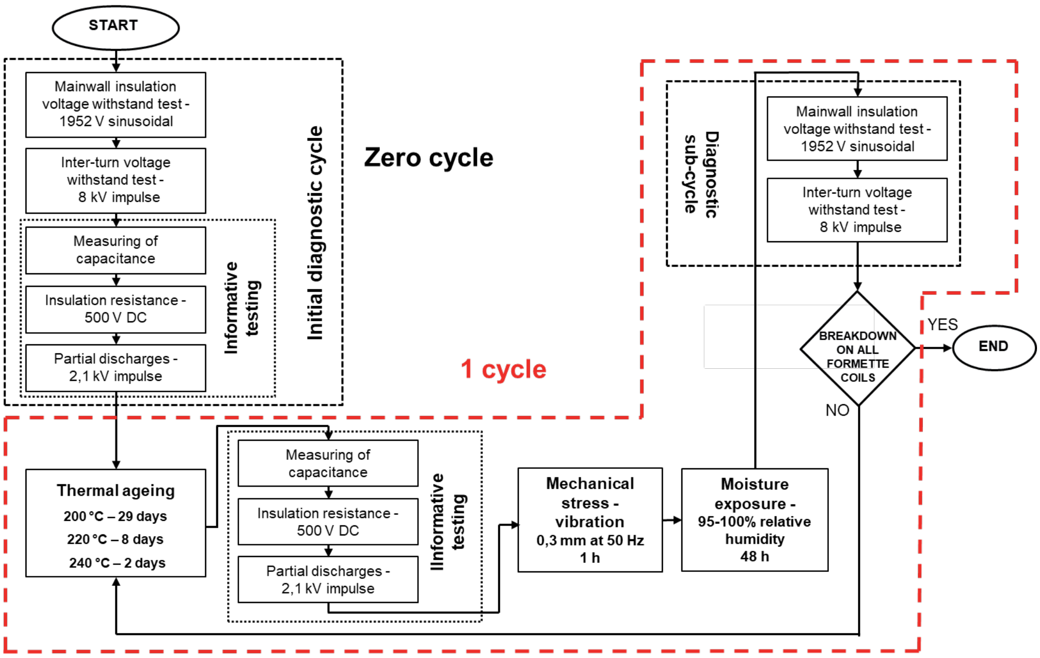

Fig. 3. Sequence of test procedure for thermal evaluation and classification of insulation systems

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constant interval of ± 3 K.

The sub-cycle of thermal aging of the test objects begins when the calibrated temperature detector reaches the aging temperature, while the end of the cycle represents turning off the oven and opening the door to cool the test objects to the ambient temperature. After cooling down the test objects, a sub-cycle of informative tests follows.

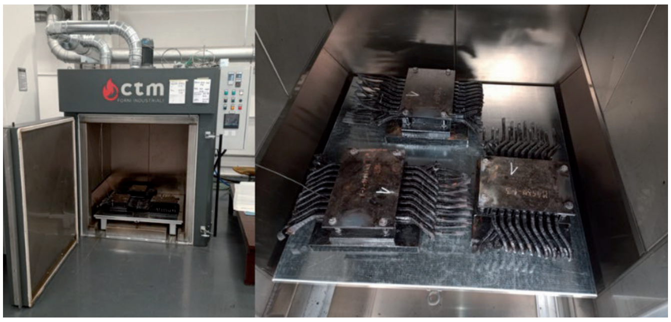

Fig. 4. Oven for thermal aging (left) and test objects inside of the oven (right)

C. Informative tests

Non-destructive informative tests are carried out after the thermal aging sub-cycle. They consist of the following tests:

- Measuring of insulation resistance 500 V DC, according to standard [5]
- Measuring of capacitance
- Partial discharge measurement with impulse voltage 2,1 kV according to standard [6]

D. Exposure to mechanical vibrations

After conducting informative tests, the test objects are exposed to mechanical stress at room temperature without applying voltage.

Each test object is mounted on a horizontal shaking table (figure 5) and subjected to oscillation at 50 Hz. The movements of the vibrating table are in the direction normal to the plane of the test specimens so that the coil ends will vibrate radially, which is consistent with the end winding forces that typically occur on an actual rotating machine. The peak-to-peak vibration amplitude value is about 0,3 mm.

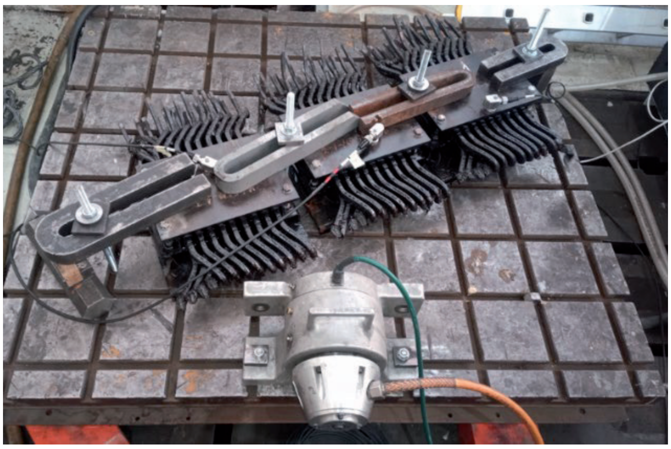

Fig. 5. Horizontal shaking table with test objects

E. Exposure to moisture

After mechanical conditioning, test objects are exposed to moisture. A visible and continuous moisture deposit is achieved by enclosing the test object in a condensation chamber (figure 6). Each test object is exposed to moisture for 48 hours, with temperature range 25°C ± 10°C. According to IEEE standard [7] which deal with the same test, the requirement for relative humidity is 95-100 %.

Fig. 6. Condensation chamber with (left) and without (right) cover

F. Diagnostic sub-cycle

Diagnostic sub-cycle is based on elevated voltage withstand tests which are used for check condition of the specimens and to determine the end of test life. The test is performed immediately after the end of the moisture exposure cycle, while the test objects are still wet.

Each part of the insulation system is tested separately to identify location that may contain cracks and/or separation of layers caused by thermal aging and mechanical stress. The voltage was applied as follows:

- Between the test specimens and the frame - **test of mainwall insulation** - voltage waveform: sinusoidal, amplitude: 1952 V, frequency: 50 Hz, duration: 1 min
- Between turns of test specimen - **inter-turn insulation test** - voltage waveform: impulse, amplitude: 8 kV, impulse rise time: 0,2 ± 0,1 μs, duration: 1 min

After completion of diagnostic sub-cycle, one complete cycle ends and the next one begins in the same sequence of sub-cycles: thermal aging, informative tests (measuring of capacitance, insulation resistance and possible occurrences of partial discharges), mechanical stress, exposure to moisture and diagnostic sub-cycle (voltage withstand test of mainwall and inter-turn insulation) until a breakdown is determined on all formette coils that consist one test object, which designate the end of the test.

G. First results

Since this is a long-term testing, only part of the results is available. Thermal aging at the highest temperature (240 °C) started first, because it takes the shortest time. Despite that fact, the test on highest temperature is still ongoing, and the results obtained so far are shown in table 2. The change of capacity and insulation resistance through the cycles measured as part of informative tests is shown in figures 7 and 8. Partial discharges with impulse voltage of 2,1 kV were not recorded in any cycle.

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Table II:

The results of thermal ageing carried out so far at 240 °C

No.	Total completed cycles	The number of cycle in which the failure was recorded					90% - CONFIDENCE LIMIT OF FAILURE OCCURRENCE					
		No. of formette coil					5% - value		MEDIAN		95% - value	
		1	2	3	4	5	*No. of cycles*	*Hours*	*No. of cycles*	*Hours*	*No. of cycles*	*Hours*
1	**21**	20	19	21	19	20	19	912	**20**	**960**	20,8	998,4
2	**21**	21	21	21	19	18	18,2	873,6	**21**	**1008**	21	1008
3	**21**	15	21	21								
4	**21**					18						
5	**18**	18	18	18	18	18	18	864	**18**	**864**	18	864
6	**20**	20				17						

Testing at the highest temperature (240 °C) was completed for insulation systems 1, 2, and 5 because breakdown occurred on all formette coils. Failure is determined on each formette coil separately, so table 2 shows the median and 90% confidence limit of failure occurrence for each insulation system. According to the test results obtained so far, insulation system 1 (reference) and insulation system 5 (candidate) can be tentatively compared. Comparing their confidence intervals and medians (table 2), it is evident that the reference insulation system (No. 1) withstood more cycles of exposure to heat compared to the corresponding candidate system (No. 5), but for a final conclusion, test needs to be carried till the end, which means breakdown of all formette coils of insulation systems 3, 4 and 6. After that, it is necessary to carry out the same test for lower temperatures (220 and 200 °C) with appropriate thermal aging times and make a mutual comparison of the corresponding reference (1 and 2) and candidate insulation systems (3-6).

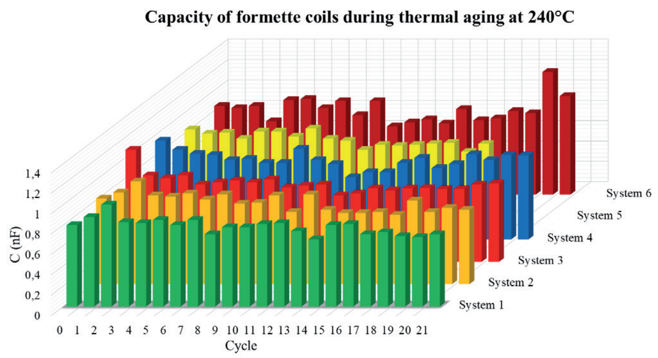

Fig. 7. Change of formette coils capacity during thermal aging cycles implemented so far at 240 °C

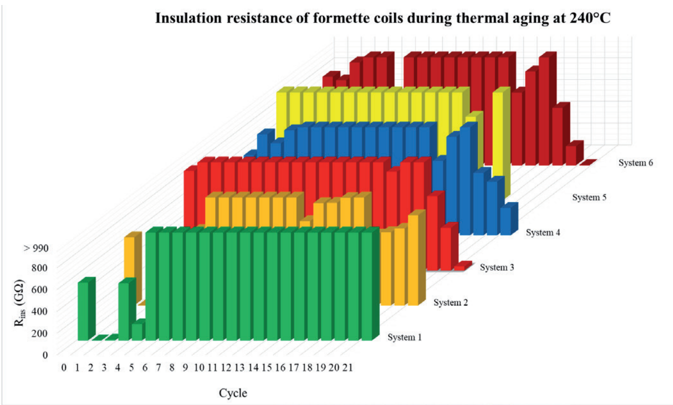

Fig. 8. Change of formette coils insulation resistance during thermal aging cycles implemented so far at 240 °C

If the insulation systems capacity (determined as the median of five formette coils for each system) is observed during the thermal aging cycles (Figure 7), a slight drop in capacity can be observed as the cycles progress. A similar occurrence happens with the insulation resistance, which is also represented by the median of five formette coils per insulation system. At the very beginning, the resistance is lower, after which it reaches a level that exceeds the measuring range of the instrument (indicated in Figure 8 with > 990 GΩ). This phenomenon can be attributed to the additional curing of the insulating layers during heating to a temperature higher than the temperature class. Around the fifteenth cycle, the majority of insulation systems experience a drop in resistance. That tendency continues in the following cycles, and the final result is the breakdown of certain formette coils.

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III. Testing of Insulation Systems According to Standard IEC 60034-18-42

A. Introduction

Standard [8] and its amendment [9] define the necessary voltage tests for the qualification of the partial discharge resistant electrical insulation systems used in rotating electrical machines fed from voltage converters. The standard includes the testing of three basic elements of the insulation system: mainwall insulation, inter-turn insulation and voltage stress control system (so-called conductive and semi-conductive layers). Similar for the previous group of tests, formette coils with associated formette frames (so-called test objects) are used, whereby the execution of the formette coils and frame is adapted to the needs of the individual test.

Mainwall insulation test consists of the life curve reconstruction using voltage aging. In the case of inter-turn insulation, the presence of partial discharges when exposed to impulse voltage is checked and, if necessary, the life curve is reconstructed, also using voltage aging. Voltage stress control system is tested using a combination of sinusoidal and impulse voltage, and the presence of partial discharges and possible damage is checked after the test.

The purpose of those voltage tests is to determine the level of resistance of the insulation system to the occurrence of partial discharges and to associate corresponding IVIC (Impulse Voltage Insulation Class) class. According to simulated operating conditions of the voltage converter, the test parameters were adapted for testing in accordance with the IVIC 5.

As in the previous case, the test is carried out on 6 different insulation systems, which are shown in table 1.

B. Mainwall insulation test

The test is carried out on coil legs with a shortened slot part (so-called „half-formette coils“) that are inserted into formette frame, imitating the presence of a stator core. According to the amendment [9] for testing the mainwall insulation, the test object consists of a frame with two slots filled with four half-formette coils (Figure 9). The half-formette coils are connected in parallel that each is exposed to an equal voltage, while the formette frame is grounded.

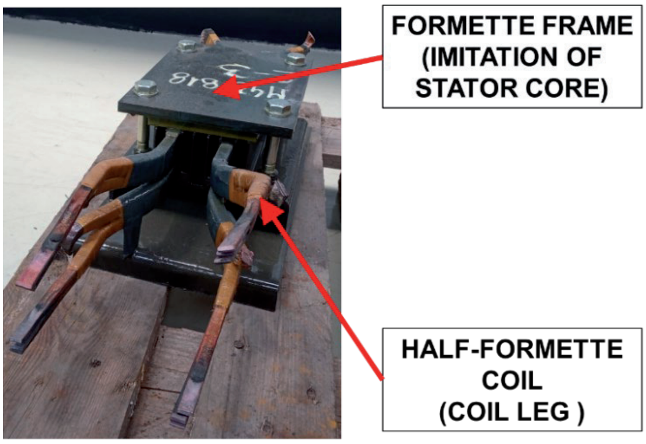

Fig. 9. Parts of formette for mainwall insulation test

The purpose of testing is to determine the electrical life curve of the mainwall insulation of both systems (reference and candidate) and compare their life curves in a way that the candidate system can be qualified. The reconstruction of the life curve is done under conditions of accelerated voltage aging, while the voltage levels are determined using the life curve of the mainwall insulation given in annex E of the standard [8], considering the IVIC 5 classification. According to the requirements stated in standard [8], it is necessary to choose at least three voltage levels, whereby the predicted average time to failure at the highest voltage level should be around 50 h, and at the lowest voltage level it should be over 5000 h. Taking in consideration that requirements voltage levels were calculated and are listed in table 3. The voltage has a sinusoidal waveform.

Table III:

Test voltage levels for reconstruction of mainwall electrical life curve

Predicted average time to electrical failure	Peak to peak test voltage
50 h	11,58 kV
2500 h	7,83 kV
5000 h	7,31 kV

According to table 3, insulation system 1 was subjected to the highest test voltage with an expected time to failure of 50 h. However, named insulation system has lasted 860 hours without electrical breakdown so far, and the test is still ongoing. This phenomenon indicates that the mainwall insulation of system 1 exceeds the IVIC 5 classification and that it can potentially be assigned a numerically higher IVIC level. Therefore, for the expected time to failure of 50 h, it is necessary to select a higher test voltage. In addition, it can be assumed that the initially selected amount of voltage (11.58 kV) will result in a failure time that is in the middle of the interval [50, 5000] h. Remaining insulation systems (2-6) will be tested after the completion of insulation system 1 testing.

C. Inter-turn insulation test

The inter-turn insulation is tested with an impulse voltage in accordance with standard [6], and the possible presence of partial discharges is determined. Since the mentioned test was already carried out as part of the zero or initial diagnostic cycle (informative tests) within the Thermal evaluation and classification of insulation systems (chapter 2.A), and according to the standard [8] the test objects are equal to the test objects shown in Figure 2, the results were taken over from that test. During the test, the presence of partial discharges was not found on any of the insulation systems, therefore the inter-turn insulation is considered qualified, which means that the test of the inter-turn insulation was successfully carried out.

D. Test of voltage stress control system

Testing of the voltage stress control system consists of three cycles: exposure to impulse voltage at the beginning and at the end of test and exposure to sinusoidal voltage. The test parameters are listed in Table 4.

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Table IV:

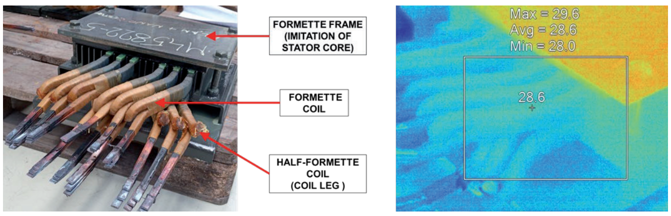
Parameters for voltage stress control system testing

Cycle	1	2	3
Duration	100 h	1000 h	100 h
Voltage waveform	Impulse	Sinusoidal	Impulse
Peak to peak test voltage	$1{,}3 \cdot U_{j\,max} = 1430\ \mathrm{V}$	$1{,}3 \cdot U_{pg} = 2860\ \mathrm{V}$	$1{,}3 \cdot U_{j\,max} = 1430\ \mathrm{V}$
Frequency	2 kHz	50 Hz	2 kHz
Impulse rise time	0,12 μs	-	0,12 μs

Acceptance criteria [8]: There are no partial discharge activity visible to the unaided eye in a darkened room or with a UV detector during the final stage of testing with impulse voltage. There is no visible (to the unaided eye) outer surface damage of the voltage stress control system (conductive and semi-conductive layer) in the endwinding region.

For testing the voltage stress control system, the test object consists of 3 formette coils, 6 half-formette coils and a formette frame with 9 slots as shown in Figure 10 on the left. The three slots inside the frame remain unfilled, while purpose of half-formette coils is to provide fixture of complete formette coils and imitation of real condition in stator core. Half-formette coils are not exposed to the test voltage.

Fig. 10. Parts of formette for voltage stress control system test (left) and



temperature distribution of insulation system 1 formette at the beginning of testing (right)

Additionally, the test object is inspected with a thermal camera at the beginning and at the end of the test to determine the possible presence of temperature increase, and to detect possible damage more easily on the conductive and semi-conductive layers. For now, the first test cycle of the voltage stress control system (impulse voltage exposure) has been successfully carried out on insulation system 1. At the very beginning of the test, the initial heating of the conductive and semi-conductive layers was determined with a thermal camera (Figure 10 right). The second test cycle (exposure to sinusoidal voltage) is currently underway. The testing of the other insulation systems (2-6) follows after the successfully completed testing of the insulation system 1.

Conclusion

The paper describes the construction of test objects and procedure for testing insulation systems under conditions of accelerated thermal and voltage aging in accordance with the relevant IEC standards. Due to the duration of the study, only the partial results are listed. Thermal aging for the highest temperature has been completed for half of the intended insulation systems. The first results indicate a slightly higher endurance of the reference systems compared to the candidate systems, but for concrete conclusions it is necessary to carry out the test till the end. Informative tests performed during thermal aging (slight drop in capacity and insulation resistance) correspond to the progressive degradation of the insulation system caused by delamination and the accumulation of moisture between the insulation layers. The mainwall insulation voltage test, according to the first results, indicates a slightly higher voltage endurance of insulation system 1 compared to IVIC classification 5, but for final conclusion the test should be completed. The inter-turn insulation, from a voltage endurance perspective, is considered qualified, while testing of the voltage stress control system is ongoing.

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