PERFORMANCE EVALUATION OF A CLASS F ELECTRICAL INSULATION SYSTEM FOR THREE PHASE INDUCTION MOTORS

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Îu scopul aprecierii cât mai exacte a performanţelor sistemului de izolaţie $A_{II}P_{GE}$ de clasă F, autorii prezintă o comparaţie între caracteristicile acestui sistem şi acelea a două sisteme de izolaţie similare, de clasă F, utilizate de companii de renume precum ANSALDO – Italia şi ELIN – Austria.

Sistemul de izolaţie $A_{II}P_{GE}$ aduce o contribuţie importantă la creşterea performanţelor motoarelor asincrone româneşti de 6 kV, cu puteri de până la 2500 kW şi la asigurarea unei durate de viaţă şi a unei fiabilităţi mai mari în comparaţie cu motoarele de acelaşi fel care utilizează vechiul sistem de izolaţie.

Avantajul – evident – al sistemului de izolaţie $A_{II}P_{GE}$ constă în aceea că este integral produs în România, acest lucru ducând la o reducere semnificativă a a costurilor de fabricaţie.

In order to assess the performances of $A_{II}P_{GE}$ class-F insulation system the authors present a comparison between the characteristics of this system and those of two similarly class-F insulation systems used by famous companies, ANSALDO-Italy and ELIN-Austria.

$A_{II}P_{GE}$ insulation system has an important contribution in improving the performances of Romanian 6kV induction motors with powers up to 2500 kW, and in assuring a long life and high operation reliability compared to the same kind of motors using the ancient insulation system.

Key words: insulation system, coil, formette, motorette, thermal endurance tests

1. Introduction

The candidate insulation system, symbolized by $A_{II}P_{GE}$, represents the outcome of the theoretical and experimental studies performed on seven types of class-F insulation systems, conceived by the authors for the stator winding of 6kV induction motors, the $A_{II}P_{GE}$ being the powerful tested insulation system [1–8]. These studies are a response to the needs of Electroputere Romanian Company.

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This company has decided to modify the range of the 6 kV induction motors, in order to provide a power up to 2500 kW, the main purpose being to put in use a powerful insulation system for the stator winding.

The $A_{II}P_{GE}$ insulation system uses a rectangular section copper conductor having rounded angles, glazed and supplementary isolated with two layers of impregnated fiberglass. The aligning process of the coil conductors was carried out by polymerizing the sheet‘s resin. This sheet was applied right on the conductors and on the right side of the coil, in a single layer. In the coils' main insulation manufacturing process, mica and epoxy resin based tapes and sheets were used, as well as polyester tapes and sheets. We have to add that all the materials mentioned above are made in Romania. The corona-protection was made using a conductive wrapping on the right side of the coils and a semi-conductive wrapping on the heads of the coils. All the $A_{II}P_{GE}$ coils were VPI impregnated in a no solvent GE 74023 thermo-hardening resin.

Compared to the ancient insulation system, the $A_{II}P_{GE}$ insulation system allows reducing the unilateral thickness of the coils' main insulation from 2 mm to 1.6 mm. Due to this fact, as well as due to its excellent properties and compared to the same kind of motors using the ancient insulation system [1, 3], the possibility to reduce both weight and size up to 15 % has been created. In order to ensure the quality level of $A_{II}P_{GE}$, candidate insulation system, the experimental results obtained using this system will be compared with those of two reference systems, tested the same way [6, 7].

Due to their excellent properties, we have chosen the ANSALDO-Italy and ELIN-Austria as reference insulation systems [9, 10]. More else, the long successful experience in on-line service activity proves their outstanding reliability.

2. Test models

In order to establish the characteristics of the three analyzed systems we have used the formettes for the $A_{II}P_{GE}$ and ANSALDO insulation systems and three motors of HKG 150 K04 type, with 1000 kW, 6 kV, 1500 rpm (labelled M_1, M_2, M_3), for ELIN system.

Electroputere Company manufactured 12 coils (of a real motor with 1000 kW, 6 kV, 1500 rpm), six with $A_{II}P_{GE}$ and the other with ANSALDO insulation system. The coils were released in groups of two same type coils, inserted (double-layer) into a slot simulator, in order to obtain a formette [6].

The formettes are test models, especially used for evaluation of insulation systems for windings [6].

Each coil had a different number punched on its upper part. This number represents the formette in which the coil was placed: 1, 2, 3 for ANSALDO coils, and 4, 5, 6 for $A_{II}P_{GE}$ coils.

3. Results and discussion

Several tests were performed on the manufactured models or motors, in order to make assessments on the performances of the analyzed systems.

Each value of presented characteristics, referring to a certain formette, indicates the medium average value calculated for the two coils of the same formette.

The main tests carried out are presented hereafter.

High voltage test of the main insulation

The rated withstand voltage of 13 kV has to be applied, for 1 minute, between coil terminals and earth.

All the three analyzed insulation systems passed this test.

Voltage test of the inter-turn insulation

The inter-turn insulation must support a voltage value $U_w = 1.3U_N/W$ (where U_N represents the nominal voltage and W, the number of the wires), applied during 5 minutes.

$U_w = 600$ V was chosen as test value.

All the three analyzed insulation systems passed this test.

Polarization index and absorption coefficient test

The values of the polarization index, K_p, and the absorption coefficient, K_{abs}, are given by the following relations:

$$K_p = \frac{R_{10}}{R_1}, \quad (1)$$

$$K_{abs} = \frac{R_1}{R_{15}}, \quad (2)$$

where:

R_{10} is the resistance of the insulation system measured 10 minutes after applying the voltage, in [Ω];

R_1 is the resistance of the insulation system measured 60 seconds after applying the voltage, in [Ω];

R_{15} is the resistance of the insulation system measured 15 seconds after applying the voltage, in [Ω].

If the polarization index, K_p and the absorption coefficient, K_{abs} have small values, the conduction is relatively high, generally due to humidity or to a great amount of conductive pollution in the insulation materials. On the other hand, if these coefficients have big values (greater than 2 and, respectively, 1.3) then the insulation is considered to be dry and in good state [1, 11, 12].

Figs. 1 and 2 indicate the values of the K_p index and respectively the values of the K_{abs} coefficient for $4A_{II}P_{GE}$, $5A_{II}P_{GE}$, $6A_{II}P_{GE}$ type of coils, and for the three ELIN motors, labelled M_1, M_2, M_3 [1, 12, 13].

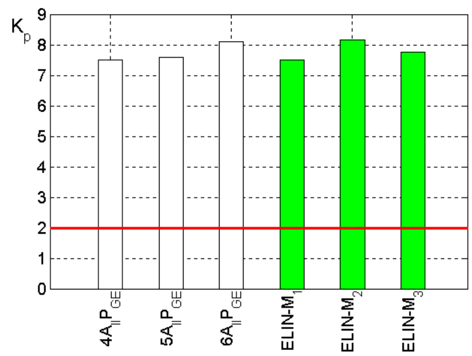

Fig. 1. K_p values for the $A_{II}P_{GE}$ type of coils and for the three ELIN motors (M_1, M_2, M_3).

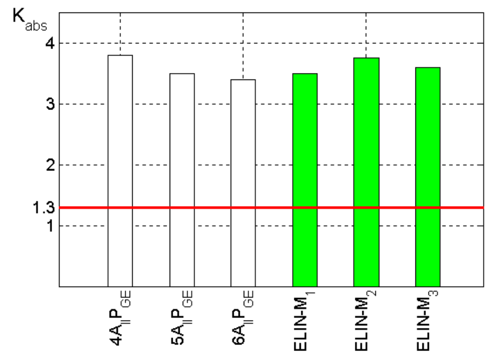

Fig. 2. K_{abs} values for the $A_{II}P_{GE}$ type of coils and for the three ELIN motors (M_1, M_2, M_3).

The polarization index K_p and the absorption coefficient K_{abs} don't give us any information about a particular malfunctioning of the isolation, but an overview on the general state of the insulation system. They don't allow a prediction of the failure risks.

By analyzing the two figures we have to point out that high and grouped values of K_p and K_{abs} were obtained for the two insulation systems.

Dielectric loss factor test

This is one of the most efficient tests in order to establish the quality of an insulation system.

A good insulation system should have a tanδ-U/U_N curve as linear as possible, where U/U_N represents the relative values of applied voltage. Its ionization threshold should be greater than its service voltage in order to avoid a premature wear.

Also, the asymptotes attached to both of the curve branches should make a small angle compared to the ionization threshold. A great angle means that a great number of air pockets are present in the insulation.

Fig. 3 gives the average values of tanδ, noted by A, corresponding to the relative applied tension $U/U_N = 0.2$, for all $A_{II}P_{GE}$ type of coils and for the three ELIN motors. A good insulation system corresponds to values lower than 0.04, limit given by international norms [14].

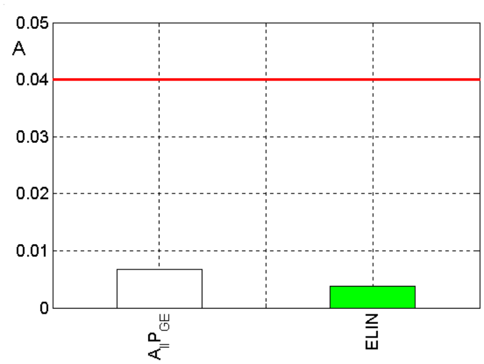

Fig. 3. A values for the insulation systems marked on the figure

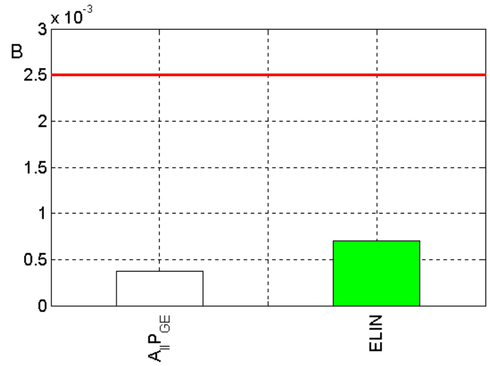

Fig. 4. B values for the insulation systems marked on the figure

Figs. 4 and 5 indicate the average values of B and C, calculated for all $A_{II}P_{GE}$ type of coils and for the three ELIN motors. B and C are given by [1, 11, 14]:

$$B = \frac{1}{2}\left(\tan\delta_{0.6} - \tan\delta_{0.2}\right), \tag{3}$$

$$C = \frac{1}{2}\left(\tan\delta_{0.8} - \tan\delta_{0.6}\right), \tag{4}$$

where: $\tan\delta_{0.2}$; $\tan\delta_{0.6}$; $\tan\delta_{0.8}$ represent the average values of $\tan\delta$ for all $A_{II}P_{GE}$ types of coils and for the three ELIN motors, at a relative tension applied (U/U_N) of 0.2; 0.6 and respectively 0.8.

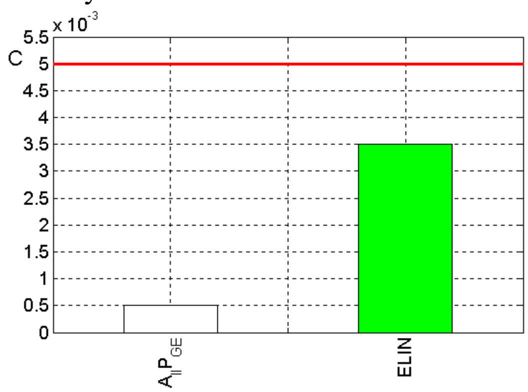

Fig. 5. C values for the insulation systems marked on the figure

To avoid ionization threshold before reaching the rated voltage, the insulation systems must encounter the following relations: $B \leq 2.5 \cdot 10^{-3}$ and $C \leq 5 \cdot 10^{-3}$.

Analyzing Figs. 3, 4 and 5 we notice very low values, either for A, or for B and C, in the case of $A_{II}P_{GE}$ and ELIN systems. So, the two tested insulation systems are efficient.

Fig. 6 indicates the tanδ-U/U_N variation for all the $A_{II}P_{GE}$ or ANSALDO coils and for the three ELIN motors [1, 9 and 10].

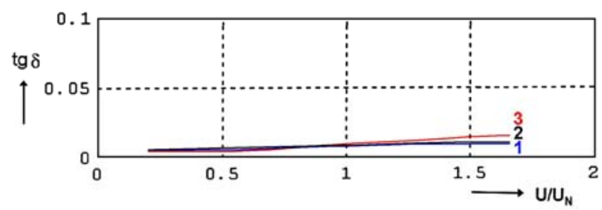

Fig. 6. Curves tanδ-U/U_N for the following insulation systems: 1-ANSALDO; 2-$A_{II}P_{GE}$; 3-ELIN

In this figure tanδ represent the medium average values for all similar types of coils or motors at different relative applied voltages. Fig. 6 shows that the three analyzed insulation systems present very little dielectric loss factor and very flat characteristics.

Insulation time factor test

The values of the insulation time factor, T_{10} are given by the following relation:

$$T_{10} = R_{10} \cdot T_{10}, \tag{5}$$

where R_{10} is the insulation resistance measured 10 minutes after applying the voltage, in [MΩ], and C_{10} is the electric capacity, in [μF].

T_{10} does not depend on the motor's size.

Values of T_{10} greater than 25000 seconds correspond to a good insulation system resistance [1, 9, and 11]. Fig. 7, gives us the values of T_{10} insulation time factor for the $A_{II}P_{GE}$ coils and for the three ELIN motors. Analyzing the figure, we notice that high and grouped T_{10} values were obtained for the $A_{II}P_{GE}$ and ELIN systems.

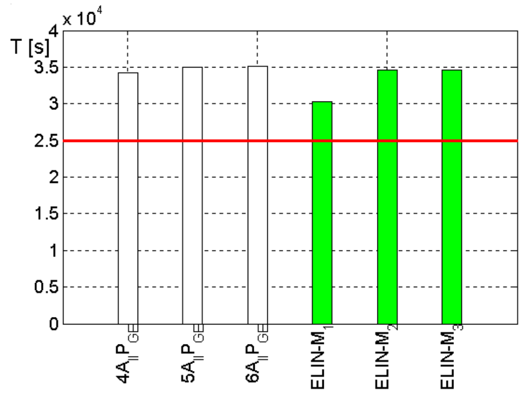

Fig. 7. T_{10} values for the $A_{II}P_{GE}$ type of coils and for the three ELIN motors (M_1, M_2, M_3)

Impulse voltage test

The tests were carried out on the coils grouped in the following formettes: 5, 6 for $A_{II}P_{GE}$ system and 2, 3 for ANSALDO system.

The level of 29 kV is based on a standard lightning impulse having a front time of 1.2 μs and a time to half-value of 50 μs [12, 15–17]. The level of 29 kV is obtained by application of the formula:

$$U_P = U_N + 5kV\,, \qquad (6)$$

where U_P is the rated lightning impulse withstand voltage (peak), given in [kV], and U_N is the rated voltage, given in [kV].

This step includes the impulse voltage test of the inter-turn insulation and of the main insulation.

This test was passed by all tested coils.

Breakdown voltage test

The test includes the following steps [2, 15, 16, 18]:

- the selection of the tested coils: we chose all the coils of type $A_{II}P_{GE}$ and ANSALDO;
- their thermal ageing: exposure to a temperature of 170° C for 28 days;
- their mechanical stress: endurance of an oscillation movement of 50 Hz with 0.3 mm amplitude;
- their moisture stress: exposure to a 95% humid environment during 48 hours at 25° C;
- the determination of the breakdown voltage of the main insulation.

The obtained results are presented in Fig. 8.

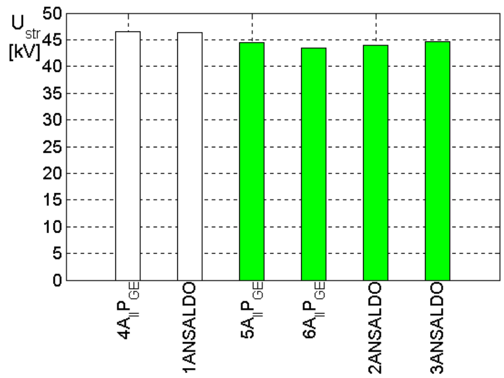

Fig. 8. Values of breakdown voltage for $A_{II}P_{GE}$ and ANSALDO type of coils

In this figure, the values of the breakdown voltage for the coils also tested with the impulse voltage are presented with green bars and for the other coils, with white bars.

The analysis of Fig. 8 shows that the impulse voltage test did not affect in a significant way the values of the breakdown voltage for the tested insulation systems. These tested systems were presented higher and approaching values for the breakdown voltage.

Evaluation of the thermal endurance

For this test, realized in our laboratories on the $A_{II}P_{GE}$ insulation system, were used parts of a real motor's stator called motorettes. The motorette contained 10 coils (Fig. 9).

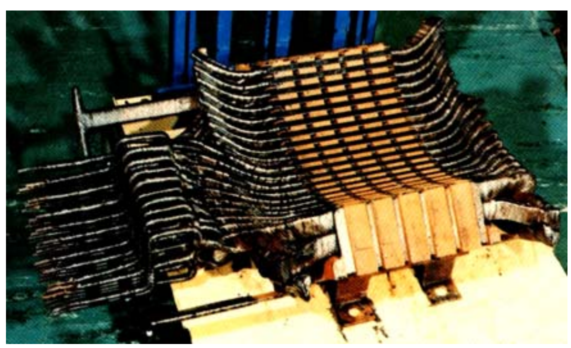

Fig. 9. Motorette designed for the evaluation of the thermal endurance of $A_{II}P_{GE}$ insulation system.

Three motorettes, corresponding to a different exposure-temperature (170°C, 190°C, 210°C), were manufactured for the $A_{II}P_{GE}$ tested system [1, 19].

The $A_{II}P_{GE}$ system was evaluated using the aging method by repeated cycles of heat, vibration, moisture and electrical stress [19, 20, 21]. Extensive experience with other tests of this general nature indicated that the most of the deteriorating effects of service can be reasonably approximated by such a sequence of exposures to high temperature, mechanical stress, moisture and voltage.

The voltage is applied in succession to ground after each and every exposure to moisture and between conductors for ten minutes, when the specimens are still in the humidity chamber exposed at approximately room temperature. Experience has shown that applying voltage during an extended time, in humidity conditions is necessary to detect failures. The ageing cycles repeat until the end point of insulation system life is established.

The thermal endurance graph for the $A_{II}P_{GE}$ tested insulation system is presented in Fig. 10.

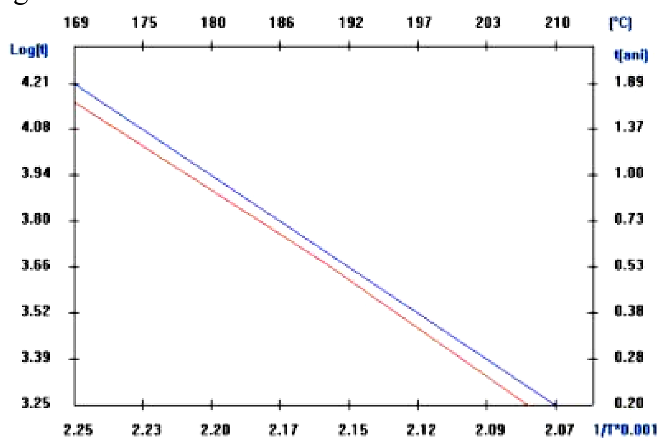

Fig. 10. Thermal endurance graph for the $A_{II}P_{GE}$ system

The abscissa contains the values of the time to failure (in hours) for each ageing temperature while the ordinate gives us the reciprocal thermodynamic temperatures.

This thermal endurance graph was acquired by means of statistical computing of the results [1, 20, 21], using a home developed Visual C++ 6.0 program [1].

From Fig. 10 we can observe a long life (around 28 years) at the optimal motor's temperature, a thermal index of 167°C, and an active energy E = 1.025eV, for the $A_{II}P_{GE}$ system. After the thermal endurance test the $A_{II}P_{GE}$ system was approved in the class-F temperature.

Fig. 11 indicates the life-curve of the MICASYSTEM-ANSALDO insulation system (obtained after similar tests), with a thermal index 166°C [10].

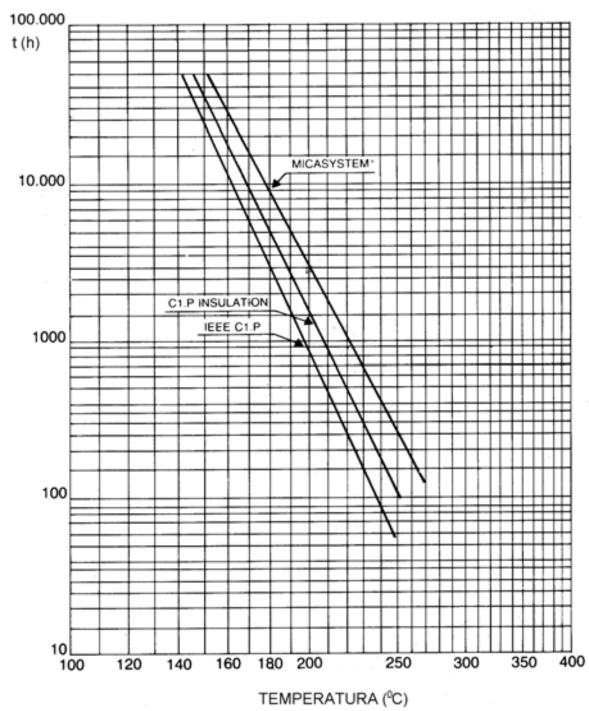

Fig. 11. Thermal endurance graph for the MICASYSTEM – ANSALDO system[10]

If we choose an ageing temperature of 180°C, the average life time for the systems $A_{II}P_{GE}$, and MICASYSTEM-ANSALDO are 9146 h and respectively 9890 h.

4. Conclusions

In this paper, comparative parameters are presented for the $A_{II}P_{GE}$, ANSALDO and ELIN electrical insulation systems. The analysis of the results allows us to conclude that:

• $A_{II}P_{GE}$ candidate system provides performances virtually identical with those of reference systems, ANSALDO and ELIN. In this kind of respect, we add that the $A_{II}P_{GE}$ system is economically efficient. In fact, the fabrication cost cutting brought by making in Romania the $A_{II}P_{GE}$ insulation system brings a lot more sense in using this Romanian made system rather than importing ANSALDO or ELIN systems.

• $A_{II}P_{GE}$ insulation system was approved in the class-F temperature, after the thermal endurance test. $A_{II}P_{GE}$ system being used in class-F and having an index temperature of 167°C, it means that it has a large thermal reserve, so a thermal stability that ensures superior reliability of the motor to normal operating temperature of 155^{o}C, while concurrently allowing it to withstand exposure to higher temperatures, short duration, on overload, without risk.

• The tests achieved in our laboratories show that $A_{II}P_{GE}$ insulation system presents the following excellent properties: high breakdown voltage of the main insulation; very high insulation time factor (more than 25000 seconds that means very high insulation resistance); non-susceptibility to ingress of humidity, due to very high K_p and K_{abs}; very little dielectric loss factor, tanδ, with very flat characteristic tanδ-U/U_N; long life and high operation reliability.

That is why the $A_{II}P_{GE}$ system is now used in all the windings of 6kV induction motors made by Electroputere Romanian Company. The $A_{II}P_{GE}$ insulation system allows reducing the unilateral thickness of the main insulation of the coils from 2 mm to 1.6 mm, compared to the ancient insulation system. Due to this fact as well due to its excellent properties, the company has now the possibility to reduce both weight and size up to 15 % compared to the same kind of motors using the ancient insulation system [1, 3].

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