DEGRADATION OF STATOR INSULATION OF HIGH-VOLTAGE ASYNCHRONOUS MACHINES IN GAMMA AND NEUTRON RADIATION FIELD

by

Nenad M. KARTALOVIĆ [1*], Bojan M. JOKANOVIĆ [2], Milan Z. BEBIĆ [2], and Djordje R. LAZAREVIĆ [3]

[1] Electrical Engineering Institute "Nikola Tesla", University of Belgrade, Belgrade, Serbia
[2] Faculty of Electrical Engineering, University of Belgrade, Belgrade, Serbia
[3] Nuclear Facilities of Serbia, Belgrade, Serbia

This paper presents the results of an examination of function stability of high-voltage asynchronous motors exposed to ambient strain caused by combined neutron and gamma radiation. This problem appears in practice when a high-voltage asynchronous motor is used in nuclear power plants where it can be exposed to this type of ambient strain. The failure of the engine's operation under such conditions may have unexpected consequences. As more than 50 % of failure (malfunction) of high-voltage asynchronous motors is caused by damage to stator insulation, the focus of the paper was on testing the effects of combined neutron and gamma radiation on stator insulation. The tests were carried out under well-controlled laboratory conditions on samples taken from both new and used factory coil windings. Two-layer samples were used to record partial discharge threshold voltage and breakdown voltage. By comparing the experimentally obtained results with the applicable mathematical-statistical procedure, an estimate was made of the aging acceleration of stator insulation and the time duration of reliable operation of high-voltage asynchronous motor was determined by lifetime exponent.

Key words: high-voltage asynchronous machine, stator insulation, aging of stator insulation, neutron radiation, gamma radiation

INTRODUCTION

Production, partial transmission and electricity consumption nowadays cannot be conceived without electrical machines. Electrical machines have gained such broad application thanks to their simple construction, design, maintenance and high reliability in operation.

The existing efforts in the development and production of electrical machines are reflected in the increase of unit power obtained from the same dimensions of active material (every 15 years the unit strength nearly doubled). Such significant advance was considerably contributed to by general technical development, but primarily by the development of insulation materials in terms of their dimensional reduction and improvement of their dielectric characteristics. It is believed that it is possible to produce an asynchronous motor of up to 100 MW. Such large units (and often smaller ones) are installed at vital spots in hydro, thermal and nuclear power plants.

Any unplanned outage from the operation of such capital units causes unpredictable consequences, and the costs incurred can exceed by several times the value of the electrical machine itself. This means that at the present stage of development it is necessary to find the optimum between the tendency to use more (load) active material in the electrical machine and to provide sufficient duration of their reliable exploitation.

Based on the data available in the literature, it is evident that the most common source of electrical machine failure is the insulation of the stator. Accordingly, the efficiency, reliability and lifetime of an electrical machine can be improved most effectively by the development of testing methods and by close monitoring of the condition of stator insulation. In this sense, it is necessary to develop a method for efficient monitoring of insulation state while in operation, as well as a method for prediction of this state by laboratory tests on comparable models [1-3].

---

* Corresponding author; e-mail: nenad.kartalovic@gmail.com

STATOR INSULATION OF HIGH-VOLTAGE ELECTRICAL MACHINE

The stator insulation of an electrical machine consists of grooved supports with previously formed coil windings of a particular shape incorporated into it, fig. 1. The coil winding insulation is the basis of stator insulation [4, 5]. The coil winding insulation is mostly influenced by the technological process of its manufacturing [6, 7].

The technological process of coil winding manufacturing proceeds in the following steps: 1– formation of coil winding body, 2 – stretching of coil winding, 3 – fixing of the conductor, 4 – isolating of the conductor, 5 – forming of a multilayer conductor, 6 – pressing and polymerization of the multilayer conductor, 7– forming of the
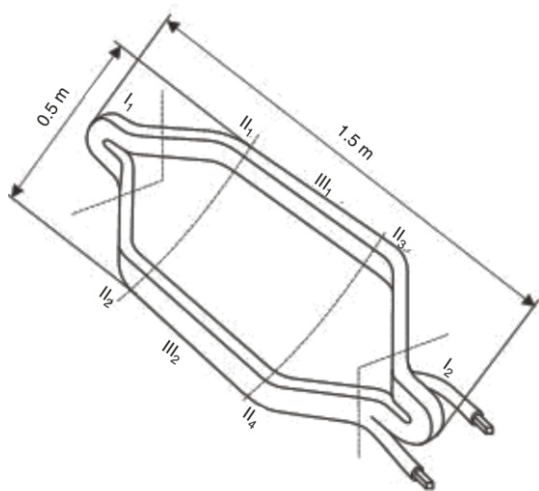

Figure 1. High-voltage asynchronous motor winding (zones I, II, III marked)

final appearance of coil winding, 8 – external isolating of the obtained coil winding. Figure 2 shows the cross-section of a completed coil winding.
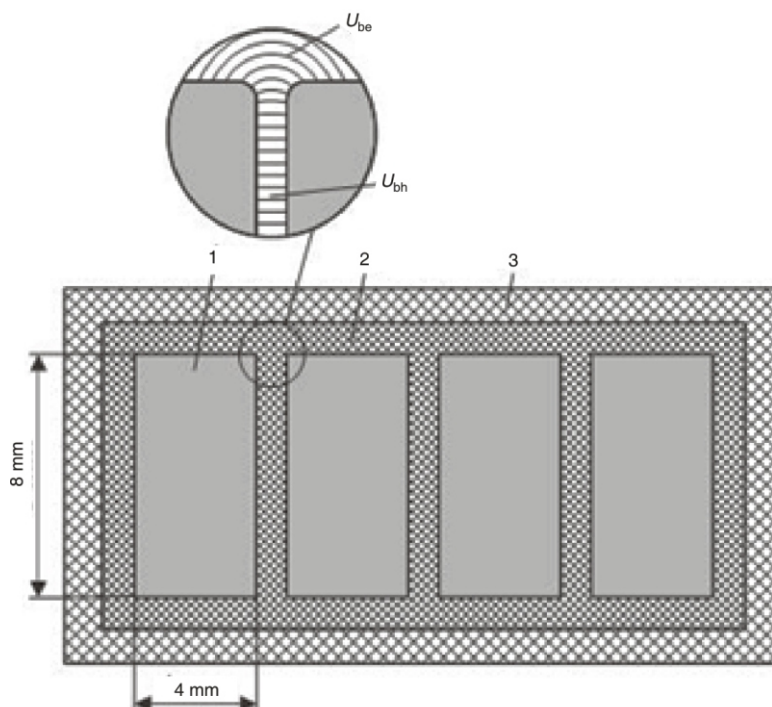
During the manufacturing of coil winding, its lifetime is mostly affected by the insulation of the conductor. The commercial name for this type of insulation is lacquer-glass-glass-lacquer (LGGL). Although this insulation can be exposed to a voltage of a few hundred volts in operation, and its breakdown voltage is close to ten kilovolts, the breakthrough of this insulation is nevertheless the one that causes most frequent failures of electrical machines while in operation. The insulation system weakens due to the aging of the material especially by strain during operation [8, 9].

STRAIN TYPES OF STATOR COIL WINDING INSULATION DURING EXPLOITATION

The most important types of strain are: thermal, voltage, mechanical, ambient, and combined. In practice, as a rule, the strain is always combined. Due to the complexity of the interaction (synergy) of these strains, it is not possible to provide a universal method for testing the insulation, nor is there a way to determine its lifetime. In practice, partial impact analysis is used most often to determine the impact of a strain type. This simplified method of testing makes the process practical and significantly less expensive, but it has a negative effect on the accuracy and completeness of results [10,11].

In this paper, the focus was on ambient strain, more precisely, on one of its forms – the influence of nuclear (neutron) radiation on the stator insulation of an electrical machine. Cases where the effects of neu-

Figure 2. Coil winding cross-section of a high-asynchronous machine stator (1 – copper conductor, 2 – inner LGGL insulation, 3 – outer mica-resin-polyester insulation); U_{be} is the edge breakdown voltage and U_{bh} is the central breakdown voltage

266

N. M. Kartalović, *et al.*: Degradation of Stator Insulation of High-Voltage ...
Nuclear Technology & Radiation Protection: Year 2019, Vol. 34, No. 3, pp. 264-271

tron influence on an electrical machine can be expected are rare but the effects of neutron radiation on insulation can be catastrophic in the event of machine failure while in operation. Specifically, electrical machines operating in nuclear power facilities are subjected to a particularly strict monitoring system since their failure could endanger the safety of the whole nuclear plant and thus lead to undesirable consequences. It should be emphasized that the likelihood of such an occurrence is extremely small especially with the new generation of nuclear plants.
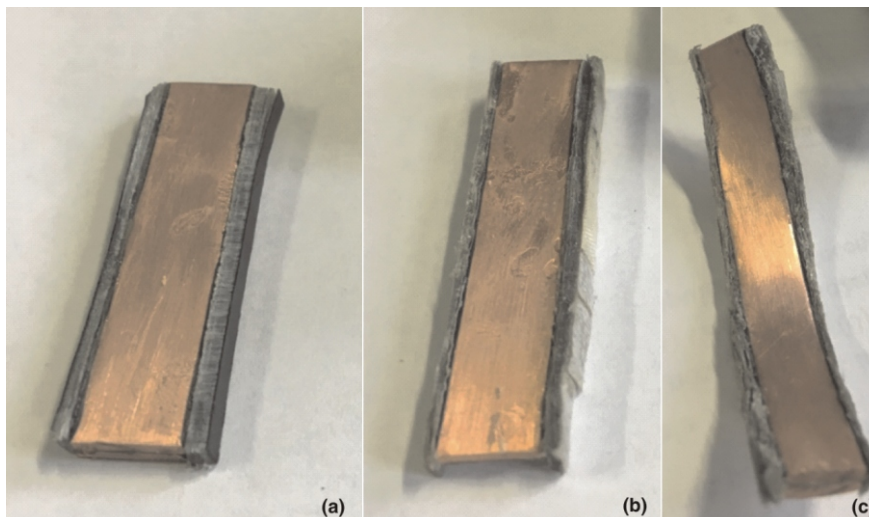
EXPERIMENT

The tests were carried out in a field of neutron and gamma radiation on both new and used samples in order to predict the condition of coil winding insulation of a high-voltage machine. New samples were taken from new coil winding in zones I, II, and III, fig. 3. Used samples were taken from the same coil winding zones but after they had spent one, two, five, eight, and ten years in operation. The samples were taken by extracting a portion of coil winding from which a dou-

ble-layer sample was made (copper-insulation-copper), fig. 4. Fifty identical samples of each type were taken (*i. e.*, from zones I, II, and III). The identity of the samples was verified by measuring the tangent of the loss angle and applying the *h*-test (statistical uncertainty of 5 %) on the obtained results [12-14].

The samples thus obtained, in groups of 50, were exposed to radiation from a Ra-Be neutron source (according to information from the certificate of Amershaw company, with the activity of 18.5 GBq and neutron intensity of $7.3 \cdot 10^6$ ns^{-1}) for 5 days. Together with the tested samples, a gold foil was installed to determine induced efficiency. Subsequently, by using the averaged effective cross-section for neutrons in gold, the neutron flux was determined. In parallel with the experiment, the same flux was determined by Monte Carlo simulation. Good agreement was obtained within the range of 1.5 %. The absorbed dose of neutron and gamma radiation was determined by simulation based on the neutron flux obtained by Monte Carlo simulation. Table 1 presents data on the absorbed dose of neutron and gamma radiation of individual parts of the sample and the average absorbed dose for the whole insulator [15, 16].
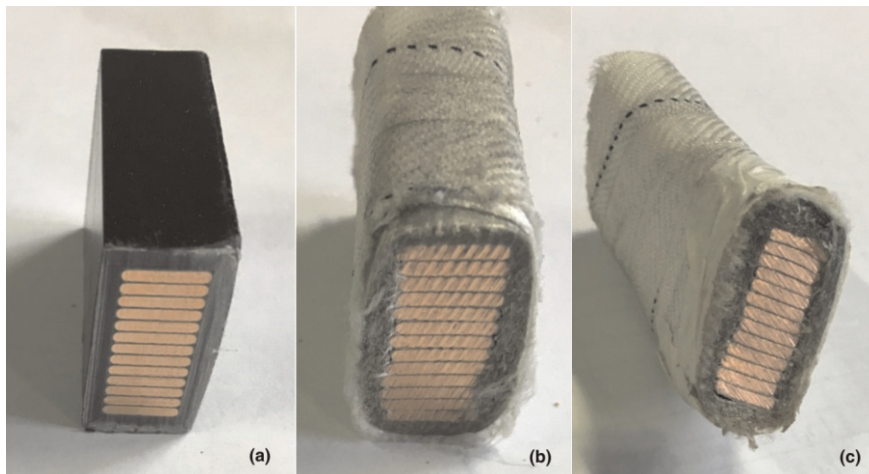
Figure 3. Samples taken from a new coil winding; (a) zone I, (b) zone II, (c) zone III

Figure 4. Double-layer test samples

N. M. Kartalović, *et al*.: Degradation of Stator Insulation of High-Voltage ...
Nuclear Technology & Radiation Protection: Year 2019, Vol. 34, No. 3, pp. 264-271

267

Table 1. Absorbed dose of neutron and gamma radiation

Number of experiments	Neutron flux [$cm^{-2}s^{-1}$]	Absorbed dose [Gy]	
		Neutrons**	Gamma radiation***
1	$1.62 \cdot 10^5$(3 %*)	5.16 (3 %)	1033.1 (0.50 %*)
2	$6.17 \cdot 10^4$(3 %)	1.55 (3 %)	252.4 (1.00 %)
3	$3.50 \cdot 10^4$(3 %)	0.70 (3 %)	98.2 (1.50 %)

* the percentages in parentheses are the total measurement uncertainty, while with the absorbed dose of gamma radiation they are only the statistical uncertainty of Monte Carlo;

** the value of absorbed dose of neutron radiation was obtained as absorbed energy from neutron by using the Monte Carlo program MCNP-5, after experimental validation for neutron flux (it was assumed that the difference between the measured and simulated neutron flux is not greater than 1.5 %);

*** the value of absorbed dose from photon of gamma radiation was obtained as absorbed energy from photon in the insulator by using the Monte Carlo program MCNP-5 with ^{226}Ra chain in equilibrium and for the activity ^{226}Ra of 18.5 GBq (according to the certificate of Amershaw company)

On irradiated and non-irradiated samples, the following insulator characteristics were measured: tgδ – tangent of loss angle, R_1 and R_{10} – insulation resistance 1 minute and 10 minutes after ac voltage load, respectively, U_{pt} – ac voltage of partial discharge threshold, and U_{db} – ac breakdown voltage. Based on the measured values, it was determined as follows: s – polarization index (the ratio of insulation resistance R_{10} after 10 minutes of ac voltage load and R_1 after 1 minute of ac voltage load), k – the coefficient of proportionality between the value of ac breakdown voltage and the ac voltage of partial discharge threshold and r – lifetime exponent [17, 18]. The tangent of loss angle was measured according to standards IEC 60502-2 and IEC 60250. The insulation resistance was measured according to standard IEC 60270. The ac breakdown voltage was measured by a modified standard [19, 20]. Figure 5 shows test circuit for testing samples with ac voltage. The method of raising voltage was used to determine the lifetime exponent [21, 22]. All measuring procedures for the acquisition of measured

values were fully automated. The experiments were carried out under well-controlled laboratory conditions. The combined measurement uncertainty of any measurement procedure was not greater than 5 % [23-25].
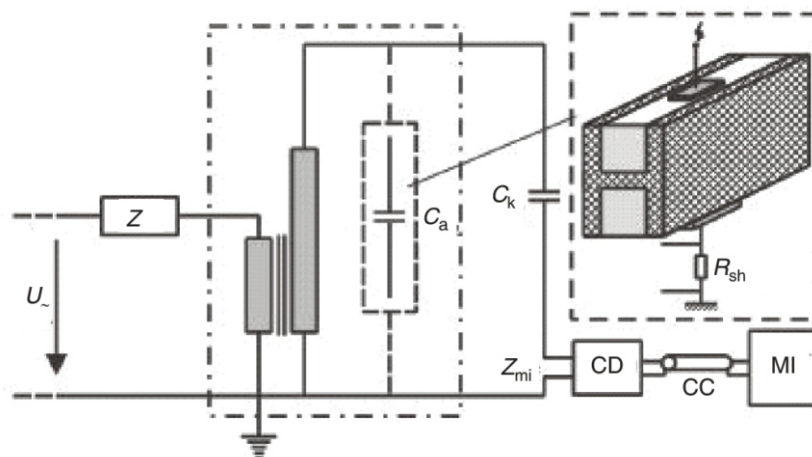
The obtained statistical samples of 50 randomly measured values were processed as follows: dubious measurement results were rejected by using Chauvenet's criterion; all pertaining random variables of a single statistical sample to a unique statistical sample were checked by U-test; random variables of each statistical sample were tested by χ^2 – test and Kolmogorov test on affiliation to Gauss (Normal) distribution, 3-parameter Weibull distribution and to the double exponential distribution, and the first, second and third moment of statistical distributions from obtained statistical samples were determined by the method of moments [26-28].

LIFETIME AND LIFETIME EXPONENT

The insulation capabilities of inorganic and organic insulating materials vary greatly in terms of time dependence. In the case of inorganic insulating materials, there is little (or no) dependence of insulating abilities on time. In the case of organic insulating materials (which are increasingly used) there is a pronounced dependence of insulating abilities on time. The dependence of insulating abilities on time is described by the characteristic of lifetime, *i. e.*, by the dependence of breakdown voltage on breakdown time.

In order to determine the lifetime characteristic, it is necessary to know the statistical distributions of random variables breakdown time and breakdown voltage. In order to obtain a reliable characteristic of lifetime, the statistical samples of the variables breakdown time and the breakdown voltage must meet the strict requirements of *t*-distribution. It has been determined that the cumulative frequencies and functions of the derivative of random variables breakdown time and breakdown voltage can be successfully described by the distribution of extreme values. The 3-parameter

Figure 5. Test circuit for testing double-layer samples with ac voltage ($U_\sim$ – high-voltage supply, Z – filter, C_a – test object, C_k – coupling capacitor, Z_{mi} – measuring instrument input impedance, CD – coupling device, CC – connecting cable, MI – measuring instrument, R_{sh} – grounding shunt)

268

N. M. Kartalović, *et al.*: Degradation of Stator Insulation of High-Voltage ...
Nuclear Technology & Radiation Protection: Year 2019, Vol. 34, No. 3, pp. 264-271

Weibull distribution is the most appropriate for this class of problems [29-31].

To obtain the characteristics of lifetime (*i. e.*, the distribution functions of breakdown time and breakdown voltage), it is necessary to form a statistical sample of n values of random variable breakdown time (obtained by constant voltage U_{d1}).

The empirical function of breakdown time distribution, is described by Weibull distribution

$$F(t_d, U_{d1}) = 1 - \exp\left[-\left(\frac{t_d}{t_{d63(U_{d1})}}\right)^{\delta_t}\right] \quad (1)$$

where t_d is breakdown time, t_{d63} is 63 % quantile of breakdown time and δ_t is the third parameter of the Weibull distribution (the so-called Weibull exponent).

The lifetime characteristic is constructed by using selected quantiles of this distribution. It has been established that the lifetime characteristic is a straight line on a double-logarithmic scale [32, 33]. For each order of quantile p of breakdown time, the lifetime characteristic is described by the following

$$U_{dp} = k_{dp} t_{dp}^{1/r} \quad (2)$$

where U_{dp} is the breakdown voltage of quantile order p, t_d – the breakdown time, k_{dp} – the constant that characterizes the geometry of the structure, and r – the lifetime exponent dependent on insulating material. Deviations from the straight line of the lifetime characteristic point out to a change in the mechanism of aging.

If, by analogy with eq. (1), we adopt the Weibull distribution

$$F(U_d; t_{d1}) = 1 - \exp\left[-\left(\frac{U_d}{U_{d63(t_{d1})}}\right)^{\delta_U}\right] \quad (3)$$

for breakdown voltage U_d with a fixed breakdown time t_{d1}, then for the same probabilities $F(t_d; U_{d1}) = F(U_d; t_{d1})$

$$U_{d63}(t_{d1})[t_{d1}]^{\delta_t/\delta_U} = U_{d1}[t_{d63}(U_{d1})]^{\delta_t/\delta_U} \quad (4)$$

According to lifetime law, given that the exponent r is applicable to all quantiles, a relation between the Weibull exponent for the breakdown time and the breakdown voltage and the lifetime exponent can be obtained by eq. (2)

$$r = \frac{\delta_U}{\delta_t} \quad (5)$$

As stated, the statistical samples of random variables breakdown time and breakdown voltage, required to determine lifetime characteristics, are determined by the experimental method of constant voltage. The disadvantage of constant voltage method is that it is time-consuming. In order to speed up ob-

taining of results, it is possible to apply an experimental method by increasing voltage. The results obtained by the method of the increasing voltage can be transformed into the results obtained at constant voltage [32]. This is achieved by entering the used rates of increasing voltage U into U_d – t_d diagram. The optimum lines passing through the points thus obtained can be interpreted as characteristics of the lifetime obtained by the method of the increasing voltage.

In order to determine the relation between the test results obtained by increasing voltage and those at constant voltage, the method of damage accumulation is used. Damage accumulation is characterized by the development of irreversible destruction of the solid body structure by the magnitude of *relative consumption of lifetime*

$$l_{\Delta U} = \frac{t_b}{t_d} \quad (6)$$

where t_d is the breakdown time and $t_b < t_d$ is the duration of insulation strain. By applying eq. (2) for any quantile p, the following is arrived at

$$t_b = k_{dp}^{-r} l_{\Delta U} (U_b)^{-r} \quad (7)$$

For the known values of lifetime exponent r, eq. (7) enables conversion of pairs of strain values (U_b, t_b) to equivalent strains (U_b^*, t_b^*), *i. e.*, strains with the same lifetime consumption

$$t_b^* = t_b \left(\frac{U_b}{U_b^*}\right)^r \quad (8)$$

This is due to the fact that a strong electrical strain of short duration can cause the same insulation damage (the same lifetime consumption) as a weaker strain with long duration.

If the lifetime model is applied to the whole test with increasing voltage (U_{ds}, t_{ds}), the breakdown time and the breakdown voltage, analogous to eq. (8), can be calculated for equivalent testing with constant voltage (U_{dk}, t_{dk}). If $U_{dk} = U_{ds}$ the following applies for any quantile

$$t_{dk} = \frac{t_{ds}}{r+1} \quad (9)$$

and if $t_{dk} = t_{ds}$

$$U_{dk} = \frac{U_{ds}}{\sqrt[r]{r+1}} \quad (10)$$

RESULTS AND DISCUSSION

Table 2 presents the measurement results of tangent of loss angle, tgδ, polarization index, s, coefficient of proportionality, k, and lifetime exponent, r; depending on the received dose of neutron and gamma radiation. The parameter of the presented results is the time duration of the coil winding in the electrical machine from which the samples were taken, or more specifically, tab. 2 shows the measurement results of new samples and samples used for 10 years.

Table 2. Dependence of; (a) tangent of loss angle, tgδ, (b) polarization index, *s*, (c) coefficient of proportionality, *k*, and (d) lifetime exponent, *r*, on the received dose of neutron and gamma radiation

Absorbed dose [Gy]		tgδ, zone I		tgδ, zone II		tgδ, zone III	
Neutrons	Gamma	New	Used	New	Used	New	Used
0	0	5.3	5.6	5.1	5.4	4.8	5.3
0.7	98	5.7	6.1	5.6	5.8	5.1	5.5
1.55	259	5.8	6.2	5.9	6.3	5.7	6.4
5.16	1033	6.1	6.5	6.0	6.4	5.9	6.8
(a)							

Absorbed dose [Gy]		*s*, zone I		*s*, zone II		*s*, zone II	
Neutrons	Gamma	New	Used	New	Used	New	Used
0	0	4.08	3.78	4.35	3.90	4.40	4.29
0.7	98	3.96	3.52	4.15	3.81	4.28	4.14
1.55	259	3.72	3.28	3.90	3.73	4.05	3.91
5.16	1033	3.41	3.02	3.62	3.45	3.92	3.68
(b)							

Absorbed dose [Gy]		*k*, zone I		*k*, zone II		*k*, zone III	
Neutrons	Gamma	New	Used	New	Used	New	Used
0	0	6.31	5.35	6.41	5.65	7.43	6.75
0.7	98	6.01	5.00	6.10	5.32	7.21	6.58
1.55	259	5.87	5.72	5.95	5.28	7.05	6.32
5.16	1033	5.32	5.15	5.53	5.01	6.87	6.12
(c)							

Absorbed dose [Gy]		*r*, zone I		*r*, zone II		*r*, zone III	
Neutrons	Gamma	New	Used	New	Used	New	Used
0	0	12.2	11.2	12.6	11.6	12.8	11.7
0.7	98	11.9	10.9	12.1	11.2	12.6	11.4
1.55	259	10.6	9.8	11.7	11.0	12.1	11.2
5.16	1033	10.1	9.5	10.8	9.6	11.8	10.8
(d)							

Based on the results shown in tab. 2, it can be seen that neutron + gamma radiation has much greater influence on the dielectric characteristics of the LGGL coil winding stator insulation of high-voltage asynchronous machines. By comparing these results with the corresponding results obtained by irradiation of LGGL insulation by gamma radiation only [34] insulation of the same samples by other, standard, ambient strains, it can be concluded that neutron radiation has the most destructive effect on the coil winding stator insulation of high-voltage asynchronous machines. This influence is particularly related to the accelerated aging process and the inhomogeneity of the aging mechanism.

CONCLUSIONS

The examination of the influence of neutron + gamma radiation on the stator insulation of high-voltage asynchronous machine has shown that the presence of neutron component in radiation significantly accelerates the degradation processes of LGGL insulation. This occurs most likely due to direct interaction with the structure of the lacquer and glass, which leads to cleavage of their macromolecules. Such a process is significantly more efficient than the impact of solely gamma radiation which interacts with the system of electrons, or that of electrons. In most common conditions under which high-voltage asynchronous machines operate, there is no probability of their being in the field of neutron radiation. However, if such a possibility does occur, operation failure of such machines can have catastrophic consequences, so in that case the insulation condition of their stator should be controlled more frequently and it is necessary to take into account the possibility of their much shorter lifetime (*i. e.*, they need to be overhauled and replaced more often, and the replaced high-voltage asynchronous machines should be treated as radioactive waste).

AUTHORS' CONTRIBUTIONS

The experiments were carried out by the all authors. Also, all the authors analyzed the results and

270

N. M. Kartalović, *et al.*: Degradation of Stator Insulation of High-Voltage ...
Nuclear Technology & Radiation Protection: Year 2019, Vol. 34, No. 3, pp. 264-271

participated in preparation of the final version of the manuscript.

REFERENCES

[1] Vereb, L., *et al.*, The Influence of the State of Inter-winding Insulation on the Tendency of Normal Voltage Increase in high-voltage Asynchronous Machines, *Proceedings*, 9th International Symposium on high-voltage Engineering, Graz, Austria, 1995

[2] Vereb, L., *et al.*, Prospects of Constructing 20 kV Asynchronous Motors, *IEEE Transactions on Dielectrics and Electrical Insulation, 16* (2009), 1, No. 4784574, pp. 251-256

[3] Vereb, L., *et al.*, Effect of Insulation Construction Bending on Stator Winding Failure, *IEEE Transactions on Dielectrics and Electrical Insulation, 14* (2007), 5, pp. 1302-1307

[4] Vereb, L., *et al.*, The Inter-Winding Insulation and Tendency of Nominal Voltage Increase in high-voltage Asynchronous Machines, *Proceedings*, Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), Atlanta, Geo., USA, Annual Report, 1998, pp. 542-545

[5] Jeftenić, I., *et al.*, Aging of Stator Coil Interconductor Insulation of high-voltage Asynchronous Motor, *IEEE Transactions on Dielectrics and Electrical Insulation, 25* (2018), 1, pp. 352-359

[6] Rajović, Z., *et al.*, Influence of SF_6-N_2 Gas Mixture Parameters on the Effective Breakdown Temperature of the Free Electron Gas, *IEEE Transactions on Plasma Science, 41* (2013), 12, pp. 3659-3665

[7] Fort, E. M., Pietsch H. E., Aging of Insulation by Thermal and Electrical Stresses, *Proceedings*, Electrical/Electronics Insulation Conference, Boston, Mass., USA, IEE Publication No. 75 CH 1014-0-EF54, 1975, p. 143

[8] Steinmetz, C. P., Lamme, B. G., Temperature and Electrical Insulation, *AIEE Trans., 32/I* (1913), p. 79

[9] Montisinger, V. M., Loading Transformers by Temperature, *AIEE Trans., 49* (1930), p. 776

[10] Dakin, T. W., Electrical Insulation Deterioration Treated as a Chemical Rate Phenomena, *AIEE Trans.* (1948), Part 1, p. 67

[11] Osmokrović, P., *et al.*, Reliability of Three-Electrode Spark Gaps, *Plasma Devices and Operations, 16* (2008), 4, pp. 235-245

[12] Dorsch H., Overvoltages and Insulations Design for Three-Phase High-Voltage Applications (in German), Siemens – A. G. Berlin

[13] Lazarević, Z., *et al.*, A Novel Approach for Temperature Estimation in Squirrel-Cage Induction Motor Without Sensors, *IEEE Transactions on Instrumentation and Measurement, 48* (1999), 3, pp. 753-757

[14] Brancato, E. L., Insulating Aging a Historical and Critical Review, *IEEE. Trans Electrical Insul., EI-13.* (1978), 4, pp. 308-317

[15] Marjanović, N. S., *et al.*, Simulated Exposure of Titanium Dioxide Memristors to Ion Beams, *Nucl Technol Radiat, 25* (2010), 2, pp. 120-125

[16] Vujisić, M., *et al.*, Simulated Effects of Proton and Ion Beam Irradiation on Titanium Dioxide Memristors, *IEEE Transactions on Nuclear Science, 57* (2010), 4 PART 1, No. 5550408, pp. 1798-1804

[17] Osmokrović, P., *et al.*, Investigation of the Optimal Method for Improvement of the Protective Characteristics of Gas-Filled Surge Arresters – With/Without the Built-In Radioactive Sources, *IEEE Transactions on Plasma Science, 30* (2002), 5 I, pp. 1876-1880

[18] Stanković, K. D., Perazić, L. S., Determination of Gas-Filled Surge Arresters Lifetime, *IEEE Transactions on Plasma Science*, *99* (2018), Oct., pp. 1-9

[19] Stanković, K. D., *et al.*, Statistical Analysis of the Characteristics of Some Basic Mass-Produced Passive Electrical Circuits Used in Measurements, *Measurement: Journal of the International Measurement Confederation, 44* (2011), 9, pp. 1713-1722

[20] Schwab, A. J., High-Voltage Measurement Techniques, M.I.T. Press, Cambridge, Mass., USA, 1972

[21] Kartalović, N., *et al.*, The Effect of Gamma Radiation on the Stator Insulation of Rotating Electrical Machines, *Radiation Effects and Defects in Solids*, (2019), On-line first, https://doi.org 10.1080/ 10420150.2019.1651727

[22] Vujisić, M., *et al.*, Comparison of Gamma Ray Effects on Eproms and e^{2}proms, *Nucl Technol Radiat, 24* (2009), 1, pp. 61-67

[23] Stanković, K., Osmokrović, P., The Model for Calculating the Type a Measurement Uncertainty of GM Counters from the Aspect of Device Miniaturization, *IEEE Transactions on Nuclear Science, 61* (2014), 3, No. 6819052, pp. 1316-1325

[24] Osmokrović, P., *et al.*, Determination of Pulse Tolerable Voltage in Gas-Insulated Systems, *Japanese Journal of Applied Physics, 47* (2008), 12, pp. 8928-8934

[25] Vujisić, M., *et al.*, A Statistical Analysis of Measurement Results Obtained from Nonlinear Physical Laws, *Applied Mathematical Modelling, 35* (2011), 7, pp. 3128-3135

[26] Lončar, B., *et al.*, Radioactive Reliability of Gas Filled Surge Arresters, *IEEE Transactions on Nuclear Science, 50* (2003), 5 III, pp. 1725-1731

[27] Hauschild, W., Mosch, W., *Statistical Techniques for High-Voltage Engineering*, IEEE Power Series, 13, Peter Peregrinus Ltd., London, UK, 1992

[28] Kartalović, N. M., *et al.*, The Determination of the Mean Value of the Non-Homogenous Background Radiation and the Measurement Uncertainty Using Welch-Satterthwaite Equation, *Nucl Technol Radiat, 32* (2017), 4, pp. 371-374

[29] Osmokrović, P., *et al.*, Stochastic Nature of Electrical Breakdown in Vacuum, *IEEE Transactions on Dielectrics and Electrical Insulation, 14* (2007), 4, pp. 803-812

[30] Tomić, L. D., *et al.*, Probability Density Function Estimation of a Temperature Field Obtained by Pulsed Radiometric Defectoscopy, *Measurement: Journal of the International Measurement Confederation, 46* (2013), 8, pp. 2263-2268

[31] Vulević, B., Osmokrović, P., Evaluation of Uncertainty in the Measurement of Environmental Electromagnetic Fields, *Radiation Protection Dosimetry, 141* (2010), 2, pp. 173-177

[32] Delaere, K., *et al.*, Influence of Rotor Slot Wedges on Stator Currents and Stator Vibration Spectrum of Induction Motors: A Transient Finite Element Analysis, *IEEE Trans. Mag., 39* (2002), 3, pp. 1492-1494

[33] Osmokrović, P., *et al.*, The Validity of the General Similarity Law for Electrical Breakdown of Gases, *Plasma Sources Science and Technology, 15* (2006), 4, pp. 703-713

[34] Jokanović, B., *et al.*, The Influence of Combined Strain and Constructive Solutions for Stator Insulation of Rotating Electrical Machines on Duration of their Reliable Exploitation, *International Journal of Electrical Power & Energy Systems, 110* (2019), Sept., pp. 36-47

N. M. Kartalović, *et al*.: Degradation of Stator Insulation of High-Voltage ...
Nuclear Technology & Radiation Protection: Year 2019, Vol. 34, No. 3, pp. 264-271

271

Ненад М. КАРТАЛОВИЋ, Бојан М. ЈОКАНОВИЋ, Милан З. БЕБИЋ, Ђорђе Р. ЛАЗАРЕВИЋ

ДЕГРАДАЦИЈА ИЗОЛАЦИЈЕ СТАТОРА ВИСОКОНАПОНСКИХ АСИНХРОНИХ МАШИНА У ПОЉУ ГАМА И НЕУТРОНСКОГ ЗРАЧЕЊА

У раду је приказано испитивање стабилности функције високонапонског асинхроног мотора изложеног амбијенталном напрезању комбинованог неутронског и гама зрачења. Ова проблематика долази до изражаја у пракси када се високонапонски асинхрони мотор користи у нуклеарним постројењима у којим може бити изложен овоме типу амбијенталног напрезања. Испад из рада мотора у таквим условима може да има несагледиве последице. Како више од 50% кварова високонапонског асинхроног мотора долази услед оштећења изолације статора, у раду је испитивано дејство комбинованог неутронског и гама зрачења на изолацију статора. Испитивање је рађено у добро контролисаним лабораторијским условима на узорцима узетим са фабричких навоја (канура) и то нових и коришћених. На двослојним узорцима је сниман напон прага парцијалног пражњења и пробојни напон. Поређењем експериментално добијених резултата одговарајућим математичко-статистичким поступком урађена је процена убрзања старења изолације статора, а преко експонента века трајања одређено је време поузданог рада високонапонског асинхроног мотора.

Кључне речи: високонапонска асинхрона машина, изолација статора, старење, неутронско
зрачење, гама зрачење