# Lifetime Extension of the High Voltage Asynchronous Machine in Relation to the Voltage Endurance Test

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**Research Article**

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## Abstract

The aim of the study is to achieve a simple, reliable and significant lifetime extension of the high voltage asynchronous machine in relation to the voltage endurance test. In order to achieve this goal, the focus was on achieving a longer-lasting and more stable insulation of the stator package of an asynchronous machine. Longer-lasting and more stable insulation of a stator is achieved by reinforcing the weak points on its prefabricated multiturn coils. These reinforcements were performed with standard insulating materials that are used for the production of the prefabricated multiturn coils (because of the fact that there is no data regarding the long-term behavior of new materials that show some better properties in laboratories, but only during short-term tests). With such reinforced weak spots on the basis of prefabricated models, they were made by the classical procedure with the use of standardized tools. In order to track the effects of the improvement of the insulation characteristics of a stator, an algorithm was developed based on the law of the increasing probability and on the determination of lifetime curves to the voltage endurance test. The lifetime curves were determined by the method of increasing voltage with the transformation of the obtained results to the corresponding results by the constant voltage method. The applied algorithm that was formed for the purpose of this study, had been verified with statistical reliability of 95 %. The combined measurement uncertainty of the measurement procedure was about 5 %.

## I. Introduction

Thermal and mechanical aspects of high voltage asynchronous machines' failure are certainly dominant, but voltage effects (partial discharge and breakdown voltage) also affect the failure [1–3]. The present study is mainly related to the aging process of high voltage asynchronous machines, along with the possibility of their lifetime extension concerning the voltage endurance test. The aging process of high voltage asynchronous machines usually takes place in the insulation system of the stator [4], which leads to their decommissioning. According to data from the literature and experience of repair shops, over 50% of the failures of high voltage asynchronous machines occur due to unplanned shortening of the lifetime of prefabricated stator multiturn coils' insulation [5, 6]. Such events are very unfavorable for the users. Therefore, this study aims to consider the technical/technological procedures of lifetime extension of the stator insulation system of high voltage asynchronous machines concerning the voltage endurance test.

## Ii. Industrial Production Of Prefabricated Multiturn Coils

II. Industrial Production Of Prefabricated Multiturn Coils
Prefabricated multiturn coils, as independent components of the stator, could have different shapes, while their fundamental characteristics and technological manufacturing process remain very similar. In the experimental part of this research, the prefabricated multiturn coils have been used. The shape of the prefabricated multiturn coil is a very common type used in engineering practice. The properties of the prefabricated multiturn coil and changes during the exploitation concerning the voltage endurance test of an asynchronous machine predominantly depend on the technological process of their production and

the applied materials. When considering the possibility of an extension of prefabricated multiturn coils' lifetime, it is necessary to consider improvements in the process of their production rather than using new materials as the long-term behavior of the new materials is insufficiently known.

The first step of production consists of wrapping a thin copper conductor with lacquer-glass-glass-lacquer insulating tape (two folded strips wound at an angle of 45º). Thereafter, an ellipsoidal structure is formed from the insulating thin copper conductor. The main insulation is then applied to the flat part of the ellipsoidal shape that will be placed in the slots of the stator package. The main purpose of the main insulation that is placed on the slot area of the coil is to provide mechanical strength in contact with the stator package where electrodynamic forces and mechanical vibrations occur. An important feature of the main insulation is that it should be homogeneous, compact, and should not contain air bubbles. After applying the main insulation, the ellipsoidal contour is pressed and bent to give it a final shape, which consists of two coil slots area and two so-called multiturn coil end winding.

Figure 1 shows the drawing and two photographs of the end-winding of the prefabricated multiturn coil (the end winding of the prefabricated part of the high voltage asynchronous machine has suffered double and single bending stresses).

The end-winding of the prefabricated multiturn coil is insulated with a tape that is either porous or impregnated with resin (mica tape is most often used). The multiturn coil end-winding must be compact, as in this way resistance to moisture and mechanical stresses is achieved. Thereafter, the obtained prefabricated multiturn coil is once again insulated and the final shape is formed (Fig. 2). In Fig. 2, the Roman numerals I and II are used to indicate the parts that suffered bending stress, called the end-winding of the prefabricated multiturn coil while the numeral III indicates the parts called the slot area of the coil (III) that did not suffer the stress caused by bending, during the formation of the prefabricated multiturn coil. In addition, during the exploitation of the end-winding coil, vibrations cause abrasion of the insulation and damage to the copper conductor. These two phenomena increase the occurrence of partial discharge and insulation breakdown [7].

To fill the air space between the prefabricated multiturn coil (i.e., the main insulation) and the slot of the stator sheet-metal package, an impregnating agent is used. The impregnating agent is, most frequently, an impregnating resin because it does not contain solvents like varnishes (lacquers) do. The end-winding of the prefabricated multiturn coil is also impregnated and subsequently baked with a complete multiturn coil for polymerization.

# Iii. Experiment

Different types of stresses (thermal, mechanical, voltage, humidity) and the aging of the prefabricated multiturn coils of high voltage asynchronous machines caused by those stresses, are evenly distributed across the multiturn coils due to symmetry [8–10]. This means that the examination of one multiturn coil from the aspect of parameters that affect aging, according to the law of the probability of increase, corresponded to the aging of the stator's insulation system [11].

Excluding the effects of standard exploitation and ambient conditions, a parameter that affects the aging of the multiturn coils is a partial discharge. Ultimate voltage aging, i.e., the end of life of the multiturn coil, happens with its breakdown. On the other hand, the test of aging over breakdown voltage is economically unprofitable and can be completely replaced by the test of partial discharge threshold because there is a unique linear physical relationship between the two quantities, expressed by a quantity called the coefficient of proportionality [12].

The idea of the experimental procedure was to make certain (not significant) modifications to the observed weak insulation points of commercially prefabricated multiturn coils, thus extending their lifetime. In addition to commercial multiturn coils, all the components from which the multiturn coil is made were available for the experiments, as well as all the necessary devices for making the prefabricated multiturn coils. Based on such available components and devices, prefabricated multiturn coils of the same shape as the multiturn coils illustrated in Fig. 5 (100 pieces) were produced with certain changes which, based on previous tests, were expected to extend the lifetime of the prefabricated multiturn coils, as well as the lifetime of the high voltage asynchronous machine itself.

It should be emphasized that, after the changes in the process of making commercially prefabricated multiturn coils, the procedure for obtaining an improved prototype was continued with the standard procedure. It should also be mentioned that the changes made for the formation of prototypes 1, 2, and 3 were additive, i.e., prototype 2 also contained changes made to prototype 1, and prototype 3. Prototype 3 also contained changes made to prototypes 1 and 2. Thereby, not only identical technological procedures but also the same insulating and conductive materials were used. This is important to point out because the chemical industry offers new materials with better properties, according to the results of laboratory tests for this application. However, there is no experience in their long-term operation, for which high voltage asynchronous machines are produced. In addition, the experiments were performed with standard materials and with standard procedures for the production of prefabricated multiturn coils. The reason for such a procedure is due to the lack of experience with the long-term behavior of the prefabricated multiturn coils made using new materials. This does not exclude the use of new materials in the future.

To measure the threshold of partial discharge and the breakdown voltage a professional instrument manufacturer HIOKI was used, equipped with appropriate software for these measurements. According to the manufacturer's instructions, measurements were performed at frequencies of 0.1 Hz and 50 Hz. The obtained results did not differ statistically (although it was expected that measurements at 50 Hz would lead to irreversible changes in the coil insulation during the measurements). The presented results refer to measurements obtained with a frequency of 50 Hz. The IEC 60270 standard was used to measure the partial discharge threshold voltage and the breakdown voltage for the voltage endurance test. The measurements were performed under strictly controlled laboratory conditions so the aging of the tested samples was exclusive due to stress. During the measurement of the partial discharge and the breakdown voltage, the measuring instruments were placed in the 100 dB protection cabin. The cabin was galvanically separated from the rest of the measurement system. The combined measurement uncertainty of the procedure was less than 5% [13–15].

First measurements were performed on two statistical samples of one hundred values of random variables partial discharge threshold voltage, and breakdown voltage for the commercially prefabricated multiturn coil. As it will be seen, the lifetime of the stator insulation has been proven to be dominated by a statistical sample of a random variable partial discharge threshold voltage. At the same time, the most accurate lifetime curves were obtained by measuring the breakdown voltage and breakdown time by constant voltage experiments. Having all this in mind only random variables of partial discharge threshold voltage and the ordered pair (breakdown voltage, breakdown time) were measured.

The statistical samples of 100 random variables ordered pair (breakdown voltage, breakdown time) of the commercially prefabricated multiturn coil and the prototypes 1, 2, and 3 were experimentally determined. The measurements were performed with increasing voltage, and then the obtained results were transformed into the results that would be obtained by the measurement with constant voltage (under the same conditions). The results obtained in this way made it possible to determine cumulative probability curves on the Weibull paper and duration curves with arbitrarily determined probability quantiles. However, the first step regarding mostly experimentally determined statistical samples was their statistical analysis to determine the cumulative probability and the lifetime curves.

The experimentally obtained results were treated as follows: 1 – The rejection of all the doubtful results using Chauvenet's criterion. 2 – The results obtained for one statistical sample were tested for belonging to a single sample using the U-test. 3 - Using the graphical test, $\chi 2$-test (Chi-Square test), and Kolmogorov test, the affiliation of random variables of each statistical sample to the Normal distribution, Weibull distribution, exponential distribution, and double exponential distribution was tested. The distribution that was determined as the most probable (i.e., had the least statistical uncertainty) determined the parameters by the moment's method and by the maximum likelihood method. It should be emphasized that the chosen test distributions (other than the Normal distribution) were the extreme value distributions and were chosen as such due to the nature of the quantity under the test. Namely, insulation damage resembles an extremely weak point and according to that logic, a random variable related to insulation weakening belongs to extreme random variables. This point is confirmed by the fact that all measured random variables belonged to the Weibull distribution (which is the basis for all the other extreme value distributions).

It should be emphasized that all the prototypes, together with the commercially prefabricated multiturn coil, were subjected to an additional experiment. Namely, the commercially prefabricated multiturn coil and all the prototypes were tested at the same time on the standard etalon oscillator table at a frequency of 100 Hz for 250 hours. These tests made sense to determine whether, after the changes that were made during the prototype construction, there was increased sensitivity of the prefabricated multiturn coil at the frequency to which it is exposed during exploitation. The only noticeable effect of oscillations occurred in the case of prototype 3, in which there was a reduction in the occurrence of partial discharge in a zone I compared to zones II and III (Fig. 2). In the case of prototypes 1 and 2, no changes in the effect of oscillations were observed compared to commercial types.

An experiment was also performed to record the position of the corona formation at a partial discharge threshold voltage. This experiment was performed with 100 commercially prefabricated multiturn coils and with 100 prototypes 1, 2, and 3 each. This experiment was performed in a darkened room individually on each of the 100 commercially prefabricated multiturn coils and prototypes. For each of these types of multiturn coils, the location of the first partial discharge was recorded with the HikVision instrument with the addition of a sensitive trigger system and a fast camera. In this way, it was possible to reliably determine in which of the zones I, II, or III (Fig. 2) of the prefabricated multiturn coil or prototype the breakdown is initialized by detecting the partial discharge threshold voltage. This realization was needed to interpret the observed effects related to the extension of the lifetime of the prototypes.

## Iv. Results And Discussion

The comparison of statistical samples of 100 random variables unambiguously indicated that the results of the experiment for determining the statistical sample of a random variable ordered pair (breakdown voltage, breakdown time), obtained by the constant voltage method, should be used to determine the lifetime curve. In this paper, however, the method of experimental determination of the statistical sample of a random variable ordered pair (breakdown voltage, breakdown time) was performed using the method of increasing voltage. This was done for a purely practical reason even though the constant voltage method is superior to this goal (the scientific reasons would be, theoretically speaking, absolutely satisfied if the measurement was performed by the constant voltage method, but such an experiment would last for decades and, worst of all, would not give the accurate results due to natural aging of measuring samples which would further lead to the synergy of the two mechanisms of aging). The same procedure was used for the measurement of the partial discharge threshold voltage. The difference in the obtained results was within the extended combined measurement uncertainty. Such a result is completely satisfying for engineering practice.

Figure 3 illustrates a cross-section of the multiturn coil with an extracted part showing the conductor edges. In the extracted part, the electric field was calculated (and drawn) by the electric charge simulation method. Figure 3 shows that the sharp edges of the conductor are significantly increasing the value of the electric field in the insulator between the conductors, which can lead to an earlier and more intense occurrence of a partial discharge. For this reason, the edges of the conductors of the prototype are rounded.

The prototype of the prefabricated multiturn coil with rounded edges was completed by the standard procedure and named prototype 1. In the following procedure, the relevant features of prototype 1 were compared with the commercially prefabricated multiturn coil, from the aspect of aging. Figure 4 shows the cumulative curves of a statistical sample of 100 random variables breakdown voltage for a commercially prefabricated multiturn coil and a prototype with rounded edges, i.e., prototype 1, on the Weibull probability paper. The cumulative curve shown in Fig. 4, for both the commercially prefabricated multiturn coil and the prototype 1, belongs to the complex probabilities of the additive type.

In the Table 1 are given the results obtained by thermal imaging observation and by simultaneous measurement of the partial discharge threshold voltage of a commercially prefabricated multiturn coil.

TABLE I

Results Obtained by Thermal Imaging Observation And by Simultaneous Measurement of the Partial Discharge Threshold Voltage of A Commercially Prefabricated Multiturn Coil

| Zone | I | II | III |
|---|---|---|---|
| Partial discharge occurrence | 50 | 40 | 10 |
| Value of the partial discharge threshold voltage [kV] | 14–24 | 16–24 | 25–30 |

The complex probability shown in Fig. 5 consists of two Weibull probabilities (or even three if cumulative lines are considered with extremely little statistical uncertainty). This result is easy to explain based on Table 1, which shows the zone of partial discharge threshold occurrence. A huge number of breakdown threshold occurrences take place in the end winding (zone I) of prototype 1 and this number differs by less than 10% compared to a commercially prefabricated multiturn coil. Based on that, it can be concluded that the appearance of the partial discharge threshold originates in the multiturn coil end winding due to the damage to the interconductor insulation that is caused by the technological manufacturing process, and not due to the sharp edges of the conductors. The sharp edges of the conductor affect the value of the partial discharge threshold voltage of the multiturn coil, but in all its zones equally (meaning zones I, II, and III). This interpretation is unambiguously confirmed by the results given in Table 1 which are obtained by locating the place of occurrence of the partial discharge threshold. The main result of this part of the experiment is that in Fig. 5a significant increase (about 20%) of the breakdown voltage for prototype 1 is observed. This change leads to an extension of the 63% lifetime curve that is obtained by the measuring method with increasing voltage and later transformed (reduced) to the measuring method with constant voltage by about 17%, Fig. 6 (the 63% lifetime curve was determined by the method given in the appendix).

Continuation of the improvement of prototype 1 of the prefabricated multiturn coil was the double insulation of the conductors with rounded edges using lacquer-glass-glass-lacquer insulation (to reduce partial discharge), i.e., the formation of the prototype 2. After the formation of the prefabricated multiturn coil 2, a new statistical sample of 100 random variables breakdown voltage was recorded. A similar level of increase was obtained when determining the statistical sample value of the partial discharge threshold for prototype 2 in comparison to prototype 1. Figure 6 shows the cumulative curves of the statistical samples of random variables breakdown voltage for the commercially prefabricated multiturn coil and prototype 1 and prototype 2 on the Weibull probability paper.

Based on this result, it can be concluded that the reinforcement of lacquer-glass-glass-lacquer insulation does not significantly contribute to the extension of the lifetime of the prefabricated multiturn coil. The extension of the lifetime of prototype 2 compared to prototype 1 was within the limits of the combined measurement uncertainty.

Since the end winding of the prefabricated multiturn coil suffers significant mechanical stresses due to oscillations (and in practice also significant ambient stresses), to extend its lifetime (from the aspect of failure caused by partial discharges and voltage breakdowns) the special attention is paid to the insulation of the multiturn coil end-winding. This was especially interesting also because during the technological process the multiturn coil end-winding suffers from double and single bending stresses. On that occasion, the lacquer-glass-glass-lacquer insulation becomes thinner and may crack, as already mentioned. For this reason, prototype 3 was made for which additions and improvements to the insulation were aimed at insulating the multiturn coil end-winding.

First of all, in the phase of formation the prefabricated multiturn coils in the future zones I and II (i.e. future end-windings), 6 conductors of the same shape and parallel to the main conductor were added (3 on each side of the main conductor). The thickness of the added conductors was 10% of the thickness of the main conductor. The added conductors were galvanic connected with the main conductor to the top of the future zone I and to the end of the future zone II. The galvanic connection of the added conductors was done by hard soldering. After hard soldering, the places of galvanic connections are polished to a high gloss. After galvanic connection, the additional conductors are insulated with the double lacquer-glass-glass-lacquer (the insulation of the same thickness as the main conductor where the insulation of the connection position of the main conductor and the additional conductors is especially strengthened). Further shaping and isolation of the prefabricated multiturn coils was completed as previously described. The installation of prototype 3 did not require any changes to the stator package. Figure 7 shows the end-winding of the prototype 3.

Thereafter, the five-fold conductor was pressed. Certainly, this operation was performed in zones I and II of the conductors and was not an easy task to perform in the given conditions. The technological process was continued in a standard way. After obtaining the final shape, the end-winding of the prototype 3 is additionally insulated with a porous strip that is made of natural fibers and mica, impregnated with resin, and additionally exposed to high temperature to achieve the polymerization of the resin. Subsequently, prototype 3 was finalized by the standard procedure. With prototype 3, 100 random variables breakdown voltage were measured (by increasing voltage method transforming the results to those that would be obtained by constant voltage method). Figure 8 illustrates the cumulative curves of the statistical sample of the random variable breakdown voltage for commercially prefabricated multiturn coil, prototype 1, prototype 2, and prototype 3 on the Weibull probability paper.

Figure 8 shows that prototype 3 has a higher breakdown voltage value of about 35% compared to the commercially prefabricated multiturn coil. This result can be explained by the fact that the cumulative distribution of the random variable breakdown voltage is no longer a combined additive type. Namely, the finishing touches to the end-winding of the prototype approximately equalized the partial discharge threshold voltage (and thus the breakdown voltage) in zones I, II, and III, as shown in Table 2. At the same time, this equalized the value of the breakdown voltage along with the entire prototype and eliminated all the weak points of the insulation of the end-winding of prototype 3. This proves that the described constructive changes during the formation of prototype 3 achieved homogenization of the entire prefabricated multiturn coil insulation. The consequence of the homogenization of the insulation of prototype 3 is the extension of its service lifetime by 35% compared to the commercial prefabricated multiturn coil in relation to the voltage endurance test, which is inferred from Fig. 7. Figure 9 shows the 63% lifetime curve of the commercially prefabricated multiturn coil, prototype 1, prototype 2 and prototype 3.

TABLE II

Results obtained by thermal imaging observation and by simultaneous measurement of the partial discharge threshold voltage of the prototype 3

| Zone | I | II | III |
|---|---|---|---|
| Partial discharge occurrence | 38 | 34 | 28 |
| Value of the partial discharge threshold voltage [kV] | 178–35 | 23–33 | 29–33 |

# V. Conclusion

By comparing the obtained values of the partial discharge threshold and the lifetime for commercially prefabricated multiturn coils and prototypes 1, 2, and 3, it can be concluded that prototype 3 is by far the best. Prototype 1 had a significant increase in the partial discharge threshold and the extension of the lifetime. Interestingly, the reinforcement of the interconductor insulation does not give any noticeable improvements (prototype 2). It is shown that the reinforcement of the interconductor insulation has no significant effect on the slot area of the prefabricated multiturn coil, unlike the effect in the zone of the end-winding of the prefabricated multiturn coil.

Namely, it has been observed that increasing the number of lacquer-glass-glass-lacquer interconductor layers does not contribute to improving the insulation characteristics of prefabricated stator multiturn coils of high voltage asynchronous machines, and neither contribute to the extension of the lifetime. Accordingly, we can conclude that the technological process of double and single bending during the formation of the end-winding of the prefabricated multiturn coil creates approximately the same number of damages to the lacquer-glass-glass-lacquer insulation. Naturally, if the number of insulation layers were to increase significantly (20–30), there would certainly be a significant reduction in the partial discharge threshold voltage (which has been confirmed experimentally). However, at the same time, there would be a significant change in the dimensions of the high voltage asynchronous machine, which could not be justified by the reduction of the partial discharge threshold voltage.

However, the change in the structure of the conduction system of the multiturn coil end winding and the introduction of additional (independent, interconductor insulation) cause a significant extension of the lifetime of the prototype 3. This can be explained by the damage that occurs during the formation of the multiturn coils. Such an explanation is confirmed by the fact that subsequent reinforcements of the multiturn coil end winding significantly reduce the partial discharge threshold voltage and prolongs the lifetime.

The obtained results also show that the weakest zone of the prefabricated stator multiturn coil is its ends (end-winding), i.e., both multiturn coil end windings (in Fig. 2 marked by I and II). It happens because the technological process in these zones causes bending and damaging of the insulation, and thus the electric field between the conductor stops being homogeneous. In addition, as the end windings of the prefabricated multiturn coil are outside the slots of the stator package, it is more exposed to mechanical and ambient stresses. The general conclusion would certainly be that by improving construction and by better insulation of the multiturn coil end windings, as performed on prototype 3 (or similar) of the stator prefabricated multiturn coils, it would be possible to increase the lifetime of high voltage asynchronous machines. It is important to emphasize that the changes made during the production of prototypes did not cause the slightest change in the aging mechanism of the obtained prototypes concerning the commercially prefabricated multiturn coil, which is concluded based on the linearity of the lifetime curves for commercially prefabricated multiturn coil and all tested prototypes.

# Declarations

**Conflicts of Interest:**

The authors declare no conflict of interest.

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# Figures

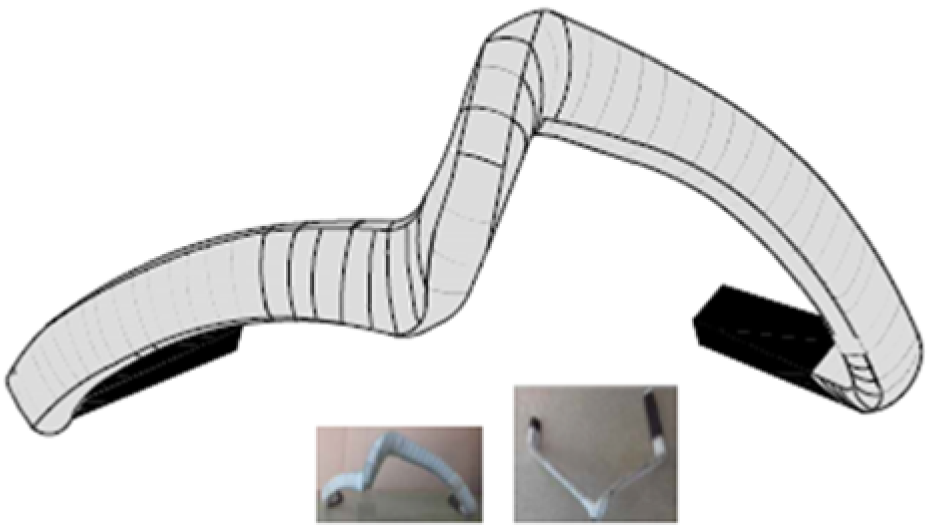


**Figure 1**

Prefabricated multiturn coil end-windings.

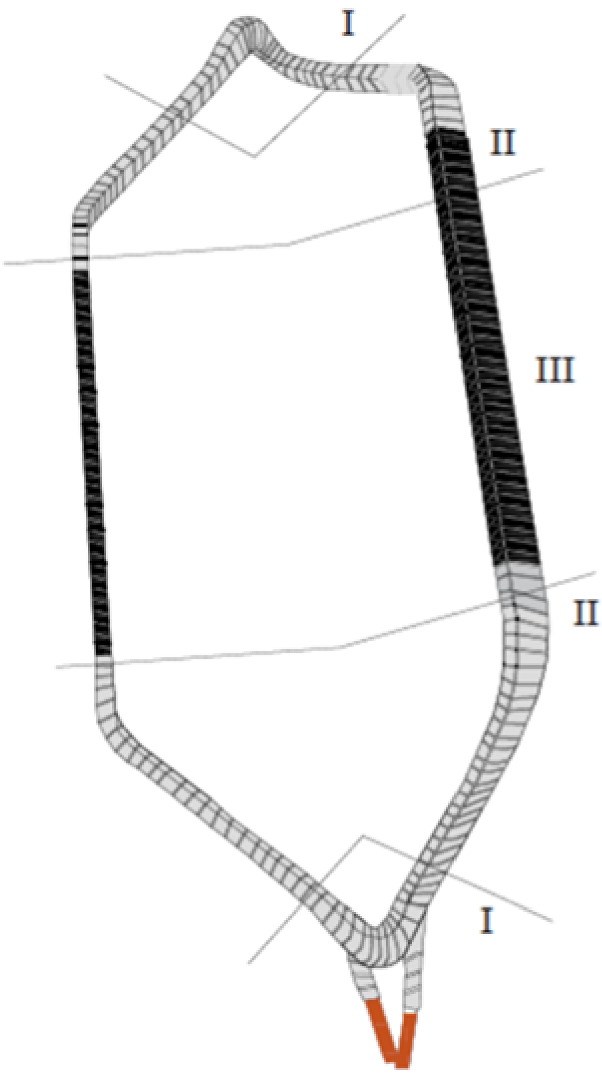


**Figure 2**

The final shape of the prefabricated multiturn coil with designated zones I, II, and III.

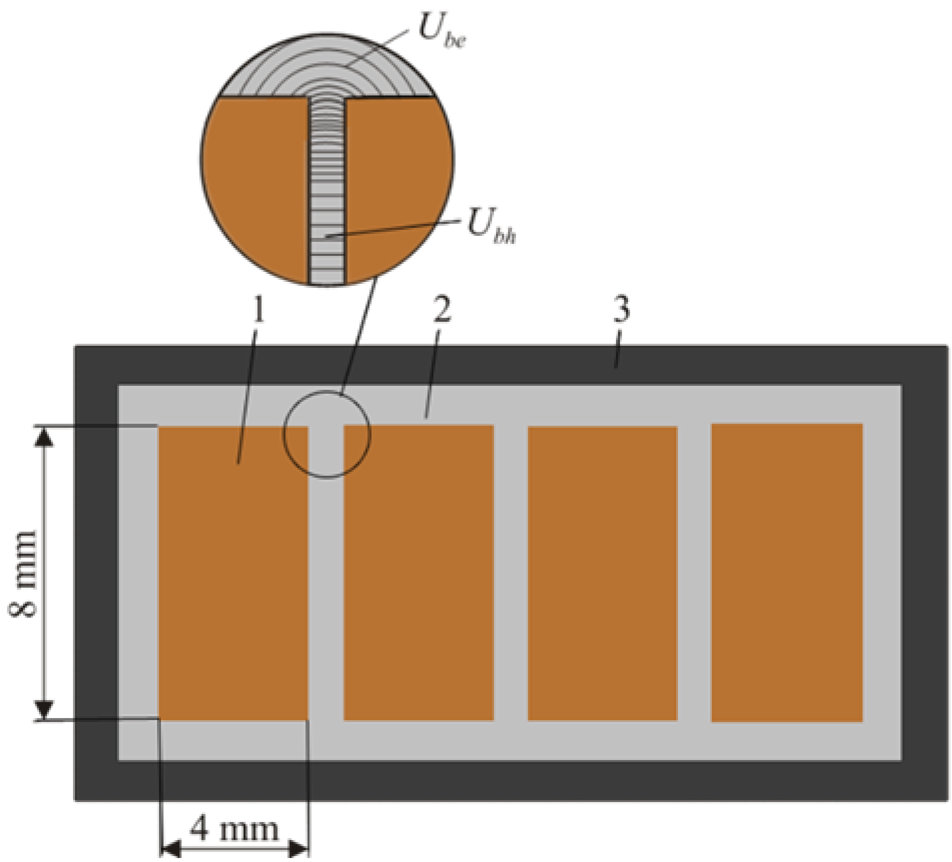



**Figure 3**

Cross-section of the slot area of the coil with an extracted part along the edge of the conductor (in which the electric field between the two conductors is calculated using the electric charge simulation method and drawn according to the standard); 1 - Conductor, 2 - Lacquer-glass-glass-lacquer insulation, 3 – Main insulation.

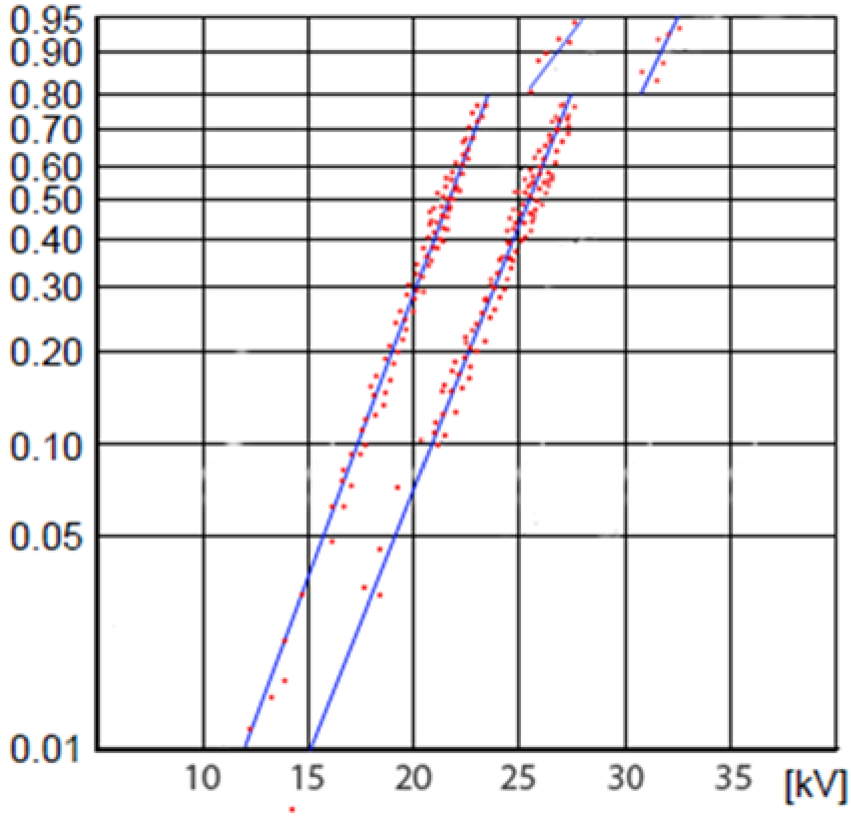



**Figure 4**

Cumulative curve of the statistical sample of 100 random variables breakdown voltage for both commercially prefabricated multiturn coils and the prototype 1 (from left to right).

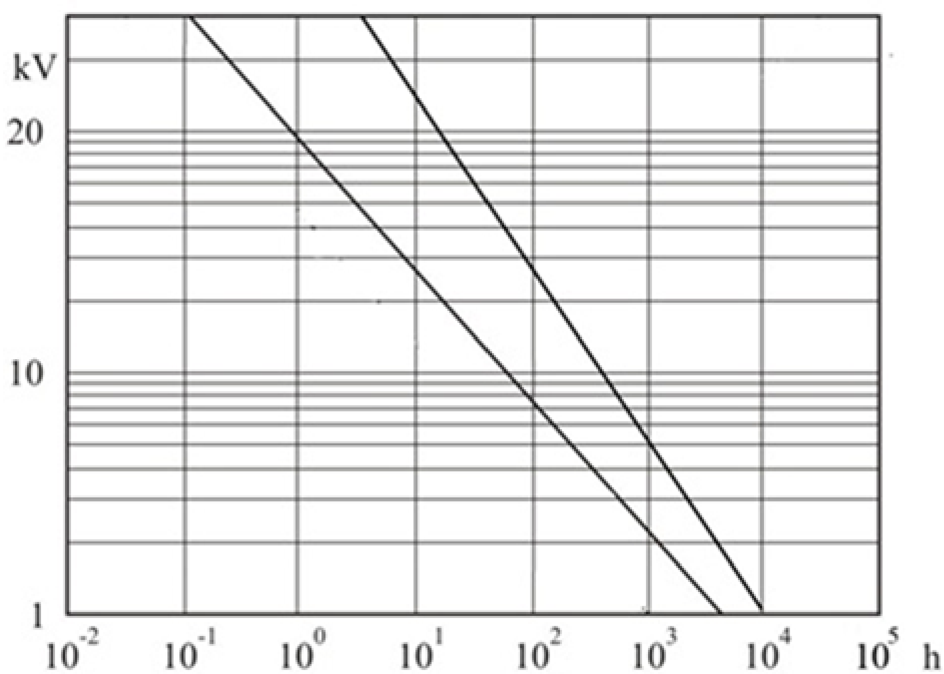



**Figure 5**

Breakdown 63 % lifetime curves for the commercially prefabricated multiturn coil and the prototype1 (from left to right).

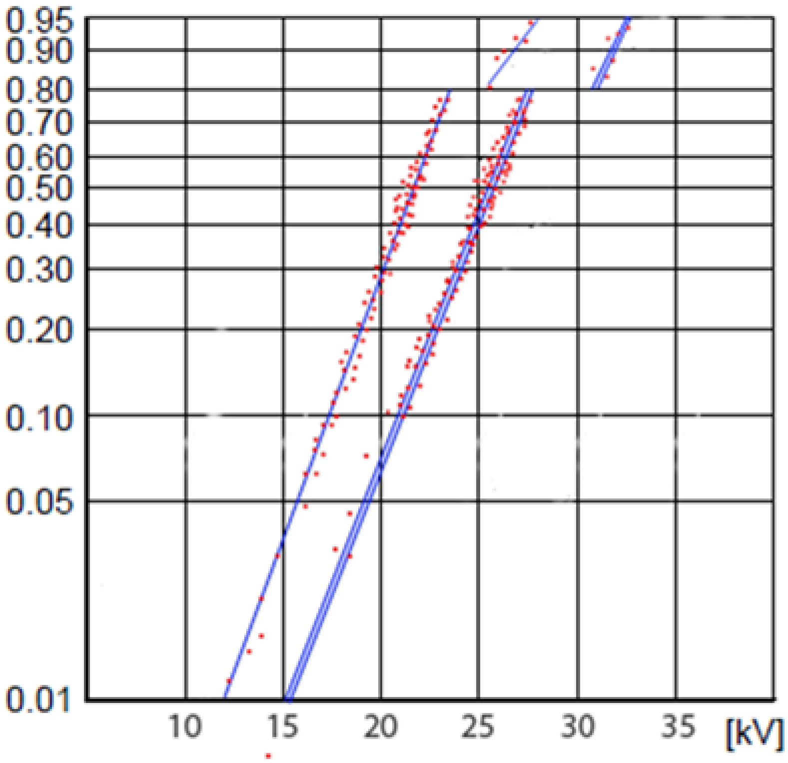



**Figure 6**

Breakdown cumulative curve of the statistical sample of 100 random variables breakdown voltage for commercially prefabricated multiturn coil, prototype 1 and prototype 2 (from left to right).

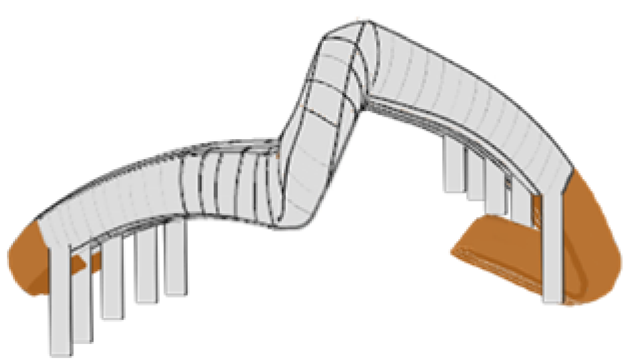


**Figure 7**

Modified multiturn coil end winding structure of the prototype 3.

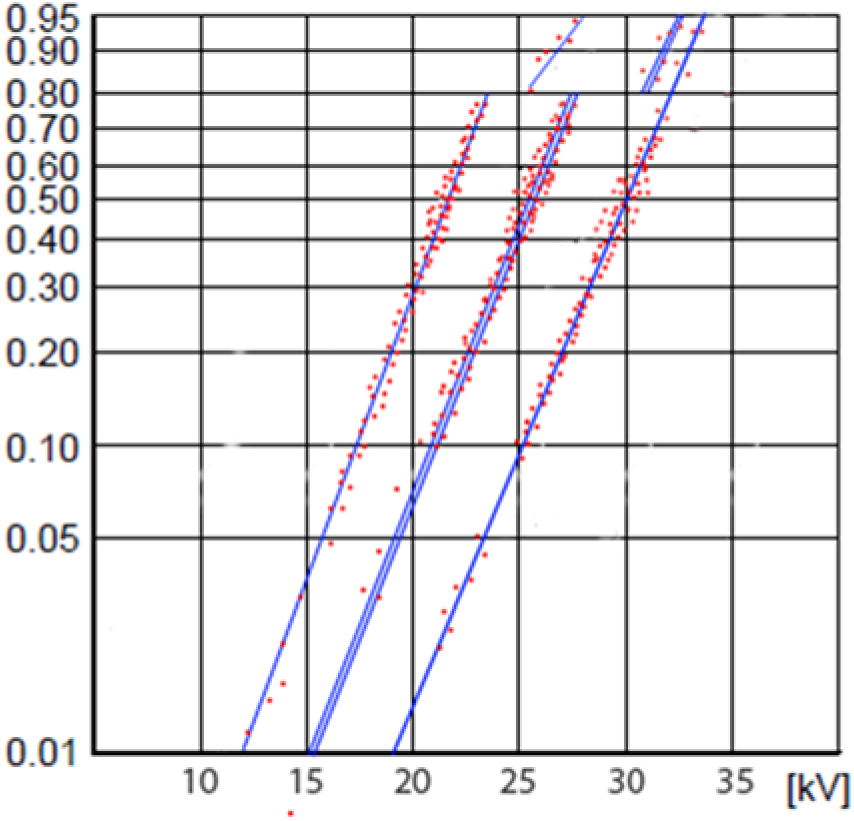
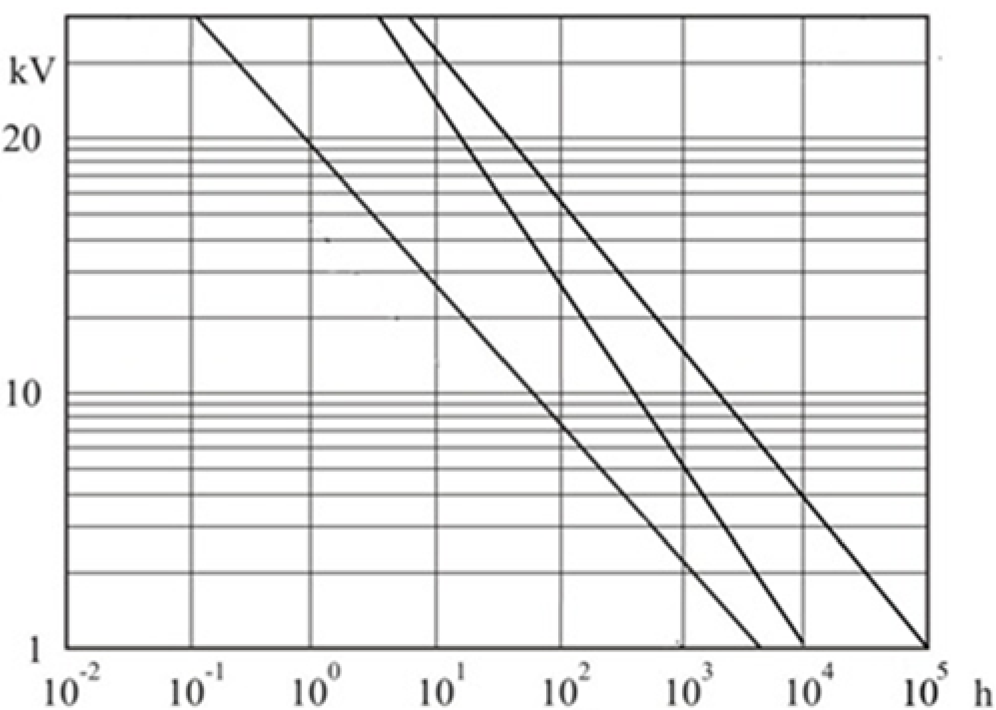



**Figure 8**

Breakdown cumulative curve of the statistical sample of 100 random variables breakdown voltage for the commercially prefabricated multiturn coil and prototypes 1, prototype 2, and prototype 3 (from left to right).



## Figure 9

Breakdown lifetime curves for the commercially prefabricated multiturn coil and prototype 1, prototype 2, and prototype 3 (from left to right).