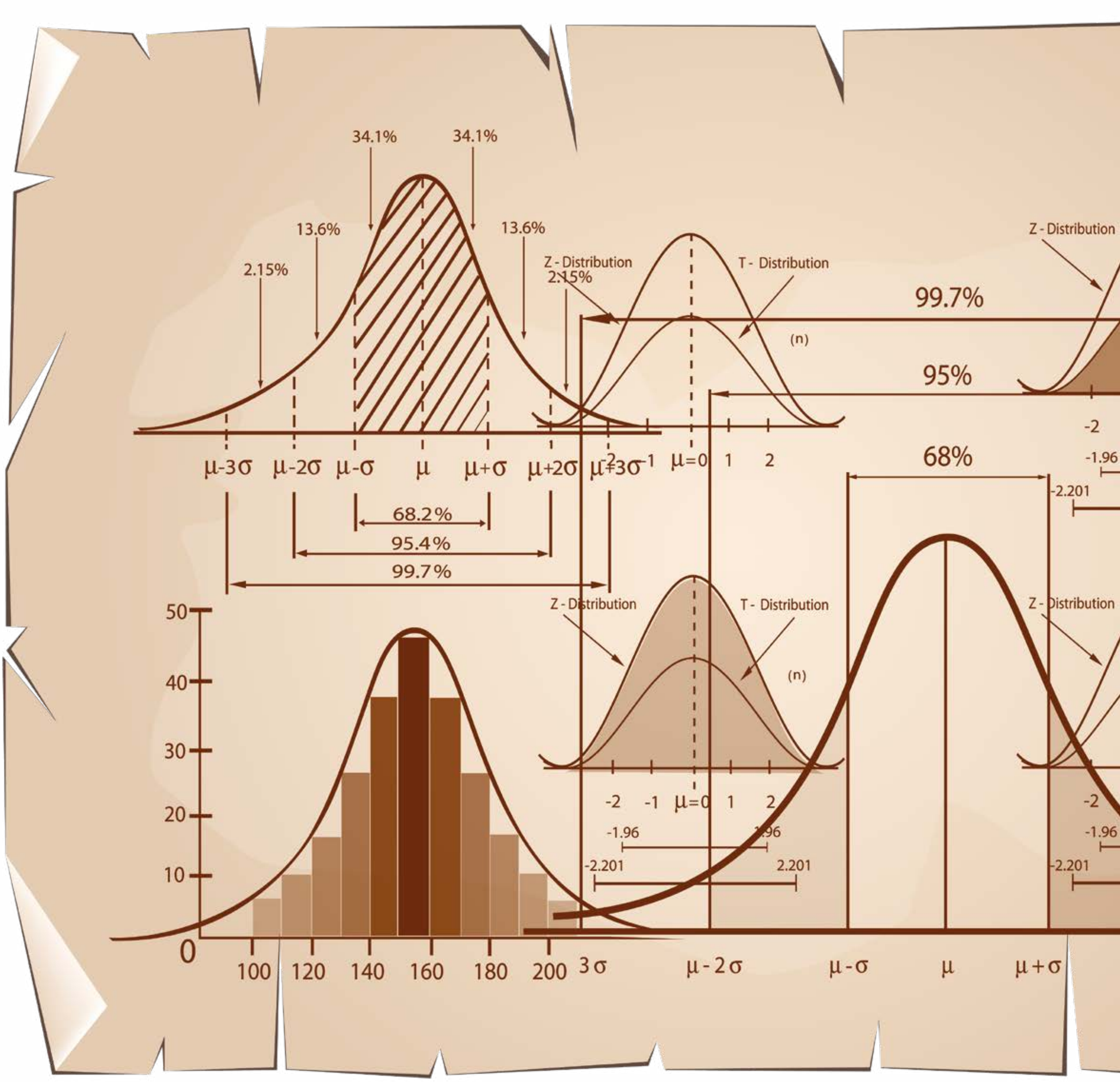


ABSTRACT

The statistical processing of the measurement results of the short-circuit impedance of 1175 HV and EHV transformers, performed in 1983, is described. As feedback, recommendations were given to designers on the optimal choice of short-circuit impedance without the risk of unreasonable rejection of transformers during the testing phase. In the author's opinion, his recommendations have not lost their significance up to this day.

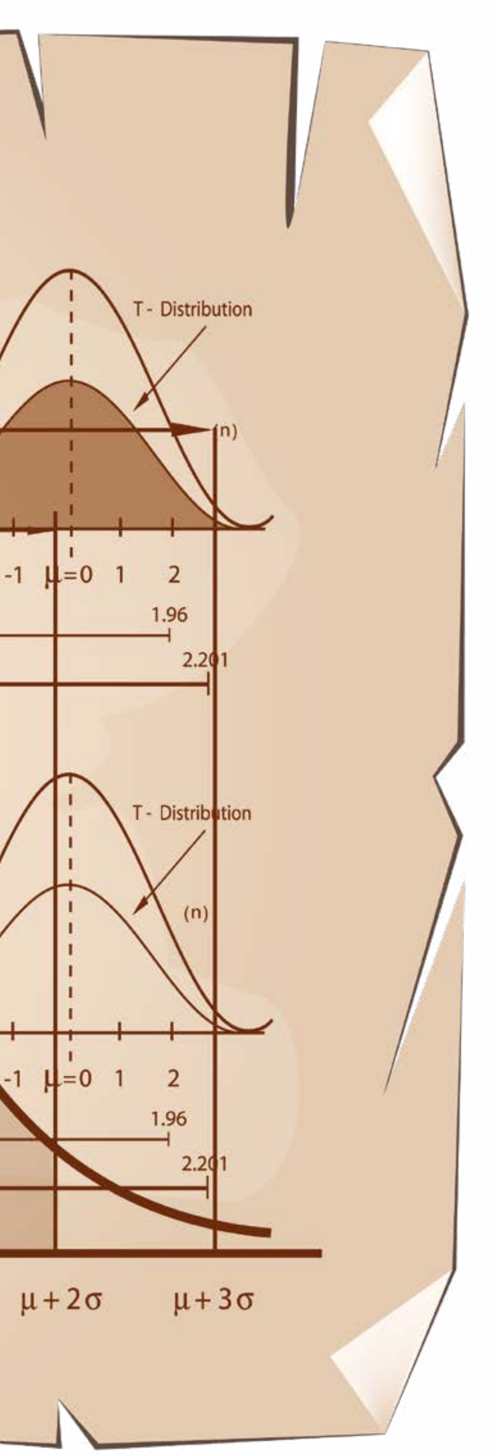
KEYWORDS:

power transformers, short-circuit impedance, statistical methods, testing, ZTZ

For the vast territory of the former USSR, hundreds and thousands of HV and EHV power transformers were manufactured, which in the 1980s were produced mainly in Zaporozhye (Zaporozhye Transformer Plant ZTZ, now ZTR), and to a fewer extent in Moscow and Tolyatti. At this time, ZTZ also significantly increased the production of transformers for foreign customers. Transformers have been supplied to many countries in Europe, Asia, Africa, South America. For example, 67

For the vast territory of the former USSR, hundreds and thousands of HV and EHV power transformers were manufactured, which led to the development of standard methods for controlling technological processes

Deviation of short-circuit impedance from specified design value



units of the identical autotransformer 267 MVA 500/230 kV were supplied to China, 39 units of autotransformers 200 MVA 220/110 kV were supplied to Bulgaria, etc.

This mass production of transformers has led to the use of standard methods for controlling technological processes in a series production environment. The study of the scatter of the characteristics of transformers measured at the test station by statistical methods made it possible to determine whether the deviation of the measured value of a particular transformer from the calculated value is random and acceptable or indicates a defect (for example, a significant increase in no-load current indicates poor assembly of core corners). The study also identifies weak links in production, including by analysing the measurement results (for example, no-load current and no-load losses at low voltage 380 V) after individual operations and technological cycles. In addition, the study clarifies if calculation methodology is reasonable and if the distribution of tolerances between calculation and production is within the expected ranges and if there is a need for the improvement of the design methodology. And finally, the results of the study can be used to compare the production technology levels of different transformer manufacturers (for example, in the 1980s, 110 kV transformers were produced at five factories).

Determination of the statistical distribution laws of the characteristics of power transformers is the first necessary stage of a statistical study. Usually, at ZTZ, the applicability of 4-5 statistical distributions was checked: normal Gaussian, normal logarithmic, asymptotic for maximum and minimum values, uniform. It was

Determination of the statistical distribution laws of the characteristics of power transformers was conducted, and several distribution functions were tested for different quantities

Developed methodology made it possible to apply the following statistical method – determining the permissible deviation of the impedance from the customer's requirement ε

found that Weibull's law governs the distributions of time to the breakdown of insulation during tests at the factory and during the running-in period in operation (the first part of the "life curve"), or the double exponential distribution is applicable. For the value of PD – the logarithmic-normal law can be used. For the no-load current and losses, for short-circuit impedance as well as load losses, including their additional losses and for the other measured values, the Gaussian normal distribution can be used. For example, the sharp-peaked normal distribution was calculated for the DC resistances of the LV windings with delta connection for one of the power transformers series. The reason turned out to be subjective errors of the testers (averaging the results). However, the error was later eliminated by adjusting the measurement process.

Many ZTZ developments on the assessment of the stability of the transformer production technology and on the "feedback" from testers to designers have not lost their significance to this day. In an effort to preserve knowledge and make it available to the younger generation of engineers, the author shares his experience on the issue raised in the title of the article. The applicability of Gauss's law for the distribution of the short-circuit impedance U_k has made it possible to use standard methods of information "extraction". For this, 12 samples of 110-500 kV transformers with a capacity of 6.3–400 MVA were examined (1175 pieces in total). It turned out that the U_k of all samples are within the tolerance of ± 10 % with large margins (for example, Fig. 1):

This made it possible to apply the following statistical method - determining the permissible deviation of the impedance from the customer's requirement ***ε***. The value of ε depends on the size of the series of the ordered transformers and can show the permissible relative number of transformers that can be rejected during tests ***q*** (Fig. 2):

An interesting fact has been established - the permissible value of ***ε*** increases with an increase in the transformer power.

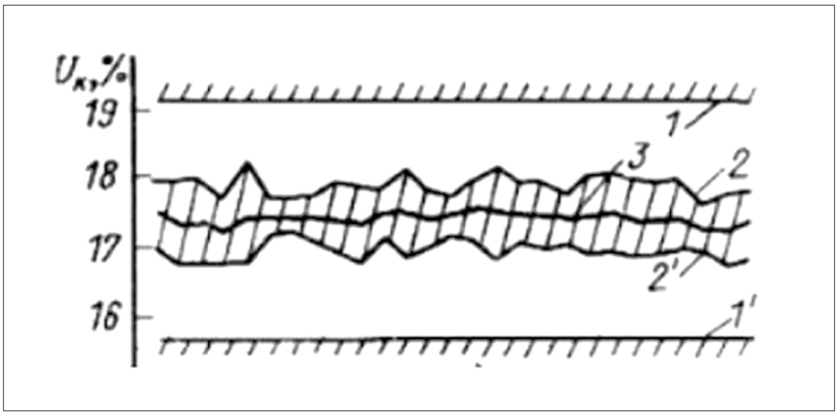


Figure 1. Accuracy diagram of the production of 10 MVA 110 kV transformers. Monitored parameter short-circuit impedance HV-LV

Specific recommendations were developed for the designers as to what value of $\boldsymbol{\varepsilon}$ at a given risk of unjustified rejection during testing $\boldsymbol{\alpha}$ can be used to optimise the transformer design (Fig. 3).

In Fig. 3, curves 1 and 3 represent the dependence of the calculated tolerance ε on the power of the nominal transformer $\boldsymbol{P}$ with a risk of a deviation of $\boldsymbol{\alpha}$ less than or equal to 0.135 % (that is, in a series of 1000 transformers, a 1⅓ of the transformer may be unreasonably rejected by the testing station), and the curves 2 and 4 are for the case when $\boldsymbol{\alpha}$ is less than or equal to 2.5 % (that is, 2.5 transformers can be unreasonably rejected in a series of 100 transformers). The results obtained were used in the development of new series of Soviet transformers.

Similar statistical studies of other characteristics made it possible to significantly improve the technical and economic indicators of Soviet transformers and increase their competitiveness in the world market.

Example 1. The designer was tasked with designing a three-winding transformer 10 MVA 115/38.5/LV kV for serial production in the amount of 100 pcs. Requirements are set for U_k to be 10.5 % for HV-MV mode and 6.5 % for MV-LV mode. Referring to Fig. 3, the designer can use the value $\boldsymbol{\varepsilon}$ = 3.5 % without unreasonable return from testing of suitable transformers. That is, to optimise the design, the designer can set the value U_k = 10.13 % (10.5 - 0.035 x 10.5) in the calculation program for the HV-MV mode and for the CH-LV mode, the value U_k = 6.73 % (6.5 + 0.035 x 6.5). Or set any other Uk values in the range (10.13 - 10.87) % for HV-MV and in the range (6.27 - 6.73) % for MV-LV.

Example 2. Let us show how to use curves 1 and 2 of Fig. 3 for the number of ordered transformers less than 100 pieces. Let the designer be tasked with developing an autotransformer 250 MVA 400/230/LV kV for delivery in the amount of 4 pcs. The requirement is set for the U_k value for the main mode HV-MV to be 13 %. Transfer curves 1 and 2 from Fig. 3 to the left of Fig. 4. For a power of 250 MVA (red vertical arrows in Fig. 4), we plot the dependence of $\boldsymbol{\varepsilon}$ on the number of transformers N (right side of Fig. 4).

Similar statistical studies of other characteristics made it possible to significantly improve the technical and economic indicators of Soviet transformers and increase their competitiveness in the world market

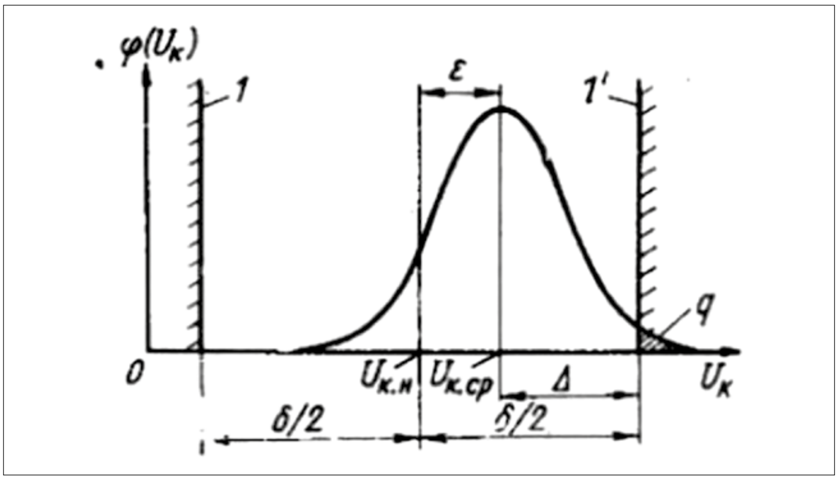


Figure 2. Normal distribution of short-circuit impedance when the mean value is shifted from the middle of the tolerance band. $\boldsymbol{\varepsilon}$ - permissible deviation of impedance from customer requirements, $\boldsymbol{q}$ – a relative number of unreasonably rejected transformers during testing

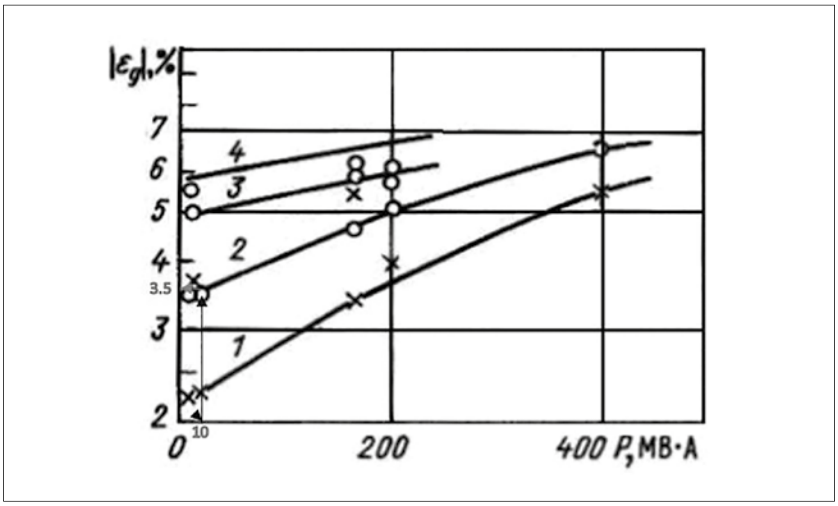


Figure 3. Dependence of the permissible design accuracy $\boldsymbol{\varepsilon}$ on the power of the projected transformer. Curves 1 and 2 refer to double-winding transformers and adjacent multi-winding transformer windings. Curves 3 and 4 refer to further pairs of windings of multi-winding transformers.

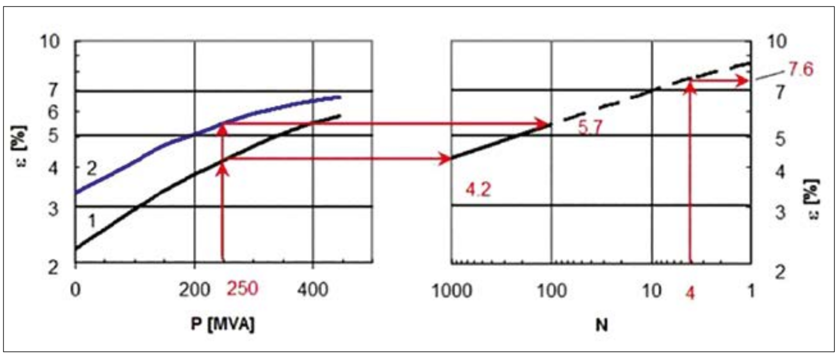


Figure 4. Determination of the permissible value $\boldsymbol{\varepsilon}$ = 7.6 for the main pair of windings of the designed autotransformer 250 MVA with the scope of supply N = 4 pcs.

For this, on the left side of Fig. 4, graphically determine the value **ε** = 4.2 for a series of 1000 pieces according to curve 1 and **ε** = 5.7 according to curve 2 for a series of 100 pieces. We transfer these values to the right and connect them with a solid line on the right side of Fig. 4. Then we extrapolate this straight line up to the value N = 1 (dashed line). Having designated the number of transformers equal to 4 on the abscissa axis of the right side of the figure, we determine **ε** = 7.6. That is, the designer can set the extreme values of U_k = 13.99 % (13 + 0.076 x 13) or U_k = 12.01 % (13 - 0.076 x 13) or any other values in the range (12.01 - 13.99) % in the calculation program with complete confidence that neither one in four autotransformers will not be unreasonably returned from the test station.

The author is not yet aware of such studies conducted in other factories, but this may be confidential information. However, the author is confident that methodology similar to the methodology based on Fig. 4 can currently be used for applications where the permissible tolerance is ± 10 %, e.g., see IEC table (Fig. 5). The author's confidence is based on the logical assumption that the technology of transformer production at other plants, to put it mildly, is not worse than the technology of ZTZ of the 80s.

The specified information can be used by customers when choosing the tender winner for the power transformers. It is recommended that the customer's representatives compare the required, calculated and measured values of the short-circuit impedance during the FAT and require the manufacturer to explain the reasons and the acceptability of these differences.

Conclusion

1. Curves of Fig. 4 can be applied at the present time in the design of power transformers for the purpose of their technical and economic optimisation in those factories where statistical studies of short-circuit impedance have not yet been carried out.
2. This article may be helpful for power transformer customers and their representatives, especially during remote FAT.

The described methodology can be used for the technical and economic optimisation of power transformers, especially in factories where statistical studies of short-circuit impedance have not yet been carried out

3. Short-circuit impedance for: – a separate-winding transformer with two windings, or – a specified first pair of separate windings in a multi-winding transformer a) principal tapping b) any other tapping of the pair	When the impedance value is ≥ 10 % ± 7,5 % of the declared value When the impedance value is < 10 % ± 10 % of the declared value When the impedance value is ≥ 10 % ± 10 % of the declared value When the impedance value is < 10 % ± 15 % of the declared value
4. Short-circuit impedance for: – an auto-connected pair of winding, or – a specified second pair of separate windings in a multi-winding transformer a) principal tapping b) any other tapping of the pair – further pairs of windings	± 10 % of the declared value ± 15 % of the declared value for that tapping To be agreed, but ≥ 15 %

Figure 5. Tolerances for short-circuit impedance according to IEC [2]

Bibliography

[1] V. V. Gurin, Statistical indicators of accuracy and stability of the short-circuit impedance of large power transformers, Elektrotechnika, No. 4, 1983 (in Russian)

[2] IEC 60076-1:2011 Power transformers - Part 1: General, https://webstore.iec.ch/publication/588

Author

Vitaly Gurin graduated from Kharkov Polytechnic Institute (1962) and graduated from school at the Leningrad Polytechnic Institute. Candidate of technical sciences in the Soviet scientific system (1970). For 30 years, he tested transformers up to 1.150 kV at ZTZ, including the largest one of that time in Europe, and statistically analysed the test results. For over 25 years, he was the Executive Director of Trafoservis Joint-Stock Company in Sofia (the diagnosis, repair and modernisation in the operating conditions of transformers 20 – 750 kV). He has authored about 150 publications in Russian and Bulgarian and is the main co-author of GOST 21023.