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Statistical methods for appraisal of quality of stator winding insulation of big rotating machines

J.Bezděkovský, P.Krupauer
Department of Stator Winding and Insulation Design
Edvarda Beneše 39, 30100 Plzeň
E-mail: jbezdekovsky@sem.fki-et.com, pkrupauer@sem.fki-et.com

Anotace
Pro vyhodnocení životnosti statorové izolace se používá mnoho statistických metod. Naměřená životnostní data lze proložit životnostní křivkou – můžete to být přímka nebo obecně mocninná funkce. Zajímá nás jak sklon přímky, tak i posunutí. Z proložené přímky se snažíme predikovat životnost izolačního systému pro požadované elektrické namáhání a pro požadovanou tloušťku izolace. V úvahu přichází rozdělení pravděpodobnosti s použitím Gaussova, Weibullova a Studentova rozdělení v systému mezioperačních zkoušek. Ověřujme normalitu (a lognormalitu) porovnáním s distribuční funkcí na pravděpodobnostním papíře nebo zkoumáme oprávněnost použití Gaussova či Weibullova rozdělení pomocí Anderson-Darlingova testu. Odhad parametrů Gaussova a Weibullova useknutého rozdělení metodou věrohodnosti při napěťových zkouškách.

Annotation
There are used many different statistical methods for evaluation of lifetime endurance of stator winding insulation. It is possible to interlace the measured lifetime data by a lifetime curve – it can be a line or generally a power function. We are interested in grade of the line and shift of the line. From the interlaced line we try to predict lifetime of the insulation system for required electrical stress and for required insulation thickness. We come into issues about probability distribution with using Gauss, Weibull and Student distribution in system of interoperate tests. We check the normality (log normality) comparing distribution function on the probability paper or alternatively validity of using Gauss or Weibull distribution by Anderson-Darling test. Parameters estimation of Gauss and Weibull cut distribution with method of likelihood by voltage test.

INTRODUCTION

One possibility how to test insulation quality is to do Voltage Endurance tests on real bars with cured insulation. It means to measure the time to a breakdown by applying of specific voltage. More often it is to do the endurance tests at the ambient temperature (on air or in oil bath). Consequently for valuating of lifetime from values measured at different voltage levels there are used some statistical methods. We are interested in the mean value of measured time, but more we are interested in the dissipation which is more important to be analyzed.

LIFETIME CURVE AND STATISTICAL DISTRIBUTION

During design of insulation system that fulfils the requirement for working stress 3.3 kV/mm, there was a need to use some statistical methods. This demand led to develop own software in Brush SEM. This software extended the verification of reliability from technological-production point of view. The lifetime test is a significant test. On the logarithmic time axis we display the measured times to breakdown at different voltage levels. We interpolate the measured data by a line. We are interested in the grade of line and the shift. From the interpolated line we try to predict the lifetime of insulation system for selected working stress and for measured thickness of insulation tube. The lifetime data have been collected for many years. It is possible to compare the lifetime curves (lines) among each other and it is possible to design the insulation system with higher working stress. Before using a CNC taping there was used a machine taping. Results of voltage endurance tests made by machine taping on real bars were often with big dissipation and low mean value. After establishing of CNC taping, it was managed to stabilize the dissipation, to increase the reliability and to extend the time to breakdown. By using machine taping we have reached the working stress 3.3 kV/mm. However the results from CNC taping show that it is possible to go at higher working stress.

During evaluation of collected lifetime data, we compare whether the measured data fulfill the KEMA and IEEE 1043 Standards. The KEMA standard says that the insulation system must withstand the voltage exposition $3 \cdot Un$ [kV] for 10 hours and $2 \cdot Un$ [kV] for 1000 hours. The IEEE 1043 Standard says that the insulation system must withstand voltage exposition $2 \cdot Un+2$ [kV] for 400 hours. These two standards are basic quality indicators of the tested insulation system.

For creating a reliable lifetime curve it is necessary to do the voltage endurance tests at 4 (or more) voltage levels and to measure 4 (better more) samples at each voltage level. The lifetime of insulation at any electric stress can be displayed by an empirical formula at probability level P=0.5 (see Fig. 1). With using of Student distribution that works with number of measured samples and dissipation, this line is then recalculated for the probability level P=0.99 or P=0.999. Using of the Student distribution is suitable for files with few samples.

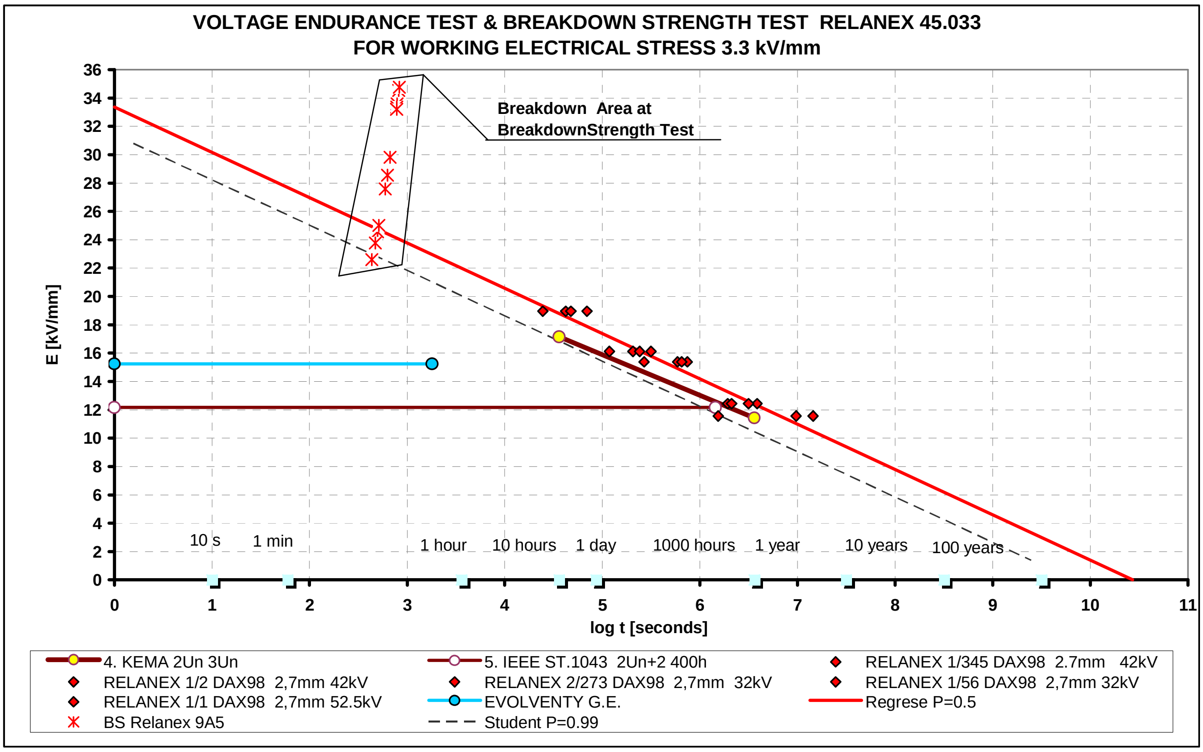

Fig. 1 Different voltage levels – interpolation in axis E(log t), way of approximation-recalculation by Student – KEMA – IEEE

By such tests it is suitable to use some statistical methods for evaluation - for example processing of values with cut selection that can gain a trustworthy estimation of parameters already during lifetime test. We work with a cut selection, where the extremes of likelihood function are searched by method of the biggest likelihood. In BRUSH SEM a software has been developed working with a model of the Normal distribution and after an inspiration from a customer even with the two-parametric model of the Weibull distribution. The programs for both models allow parameter estimation of Normal and Weibull two-parametric distribution.
A usage of the distribution is shown in following real example, when some samples have not been broken down yet:

Nominal Voltage Un = 15kV; Voltage Endurance Test 32kV; IEEE 1043 (400 hours)

Hours	356.1	489	550.5	594.3	663
Status	Break down	Break down	Break down	Break down	Break down

Hours	710.5	710.5	710.5	710.5	710.5
Status	Running	Running	Running	Running	Running

For this example there were predicted parameters of the Normal distribution : $\mu = t_{str}$ = 699.3 hours; sigma (σ) = 202.9 hours.

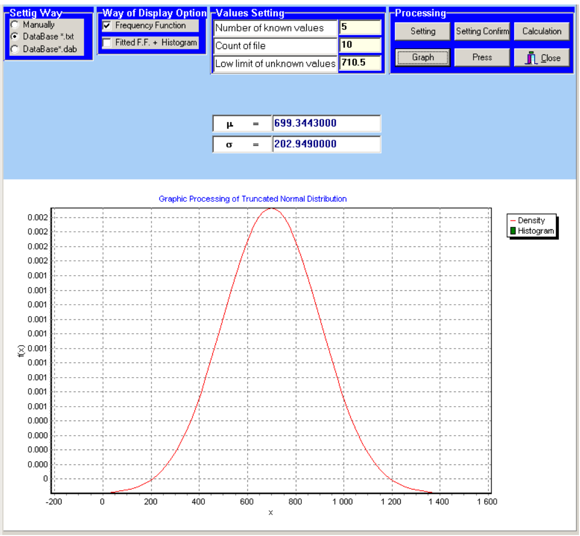

Fig. 2 Graphic processing of truncated Normal distribution

The program working with model of Weibull two-parametric distribution calculated following parameters: t_{str} = 699.8 hours; σ = 203.35 hours (see fig. 3). In the output section of the display there are other obtained parameters (shape and scale factor) of Weibull distribution.

The correspondence of the estimated mean value and dissipation (for Normal distribution and Weibull distribution) was very good. The Weibull distribution with parameter m=3.8 is very close to the Normal distribution. Possibility parameter estimation of the Weibull distribution by this program led to an endeavor to explore possible connection of shape and scale factor on the load intensity. To qualify other technical-production coherencies connected with the dissipation of these parameters.

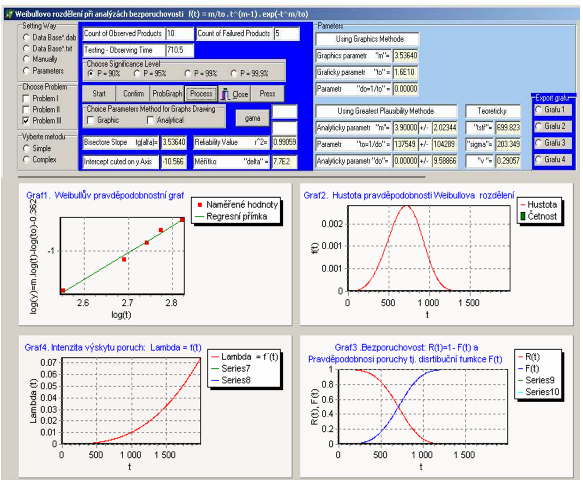

Fig. 3 $X_{str}=t_{str}$=699.8 hours; sigma = 203.35 hours for Weibull model

For confirmation of the dependence of the "m" parameter there were used some data from lifetime tests and the gained dependence m=f(E) proved the decreasing trend for increasing electrical stress – see Fig.4.

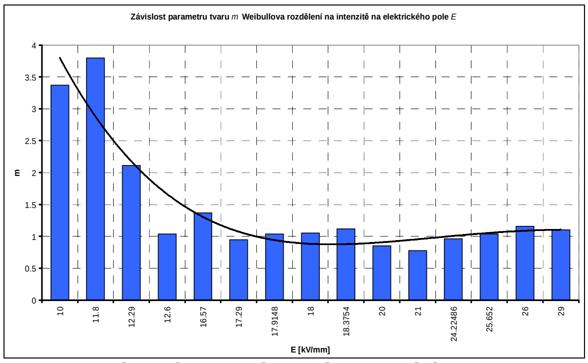

Fig. 4 Relation between electrical stress and shape parameter "m" of the Weibull distribution

Higher values of the "m" parameter around value 3.4 (for lower electric stress) evoke the possibility of Normal Distribution. So the general idea is being confirmed that the "m" parameter is established by a design – here for insulation thickness for the specific working stress. The validity of using Weibull distribution gives an important tool about good conformity of the dissipations that indicate the homogeneity of the file. Big dissipation of the parameter scale value D(d) by acceptable dissipation of the shape parameter D(m) shows evidence about file homogeneity from the technical-production point of view. Otherwise if the parameter D(d) is low and parameter D(m) is high, then the supposed Weibull model is not suitable.

From the requests for checking of measured data terminated a need to test the kind of distribution (Normal or Weibull). A software has been developed working with Anderson-Darling test (for files with few samples) of Normal and Weibull distribution. The software can display the graphs in normal and lognormal axis in the probability paper – see Fig. 5 and Fig. 6. The analysis of the dissipation has always been a very important factor for assessment of quality and reliability in Brush SEM (in department of Stator Winding and Insulation Department).

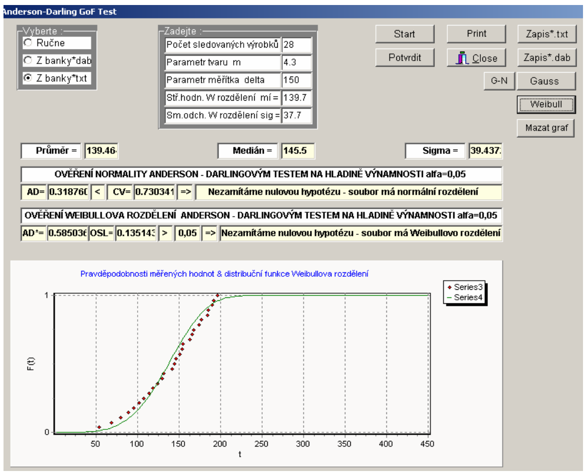

Fig. 5 Distribution function of Weibull distribution

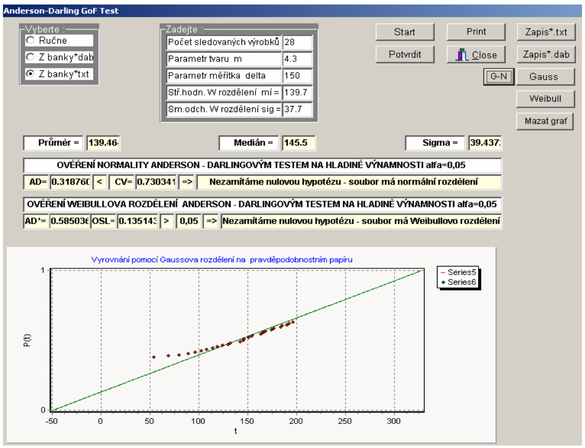

Fig. 6 Distribution in the probability paper

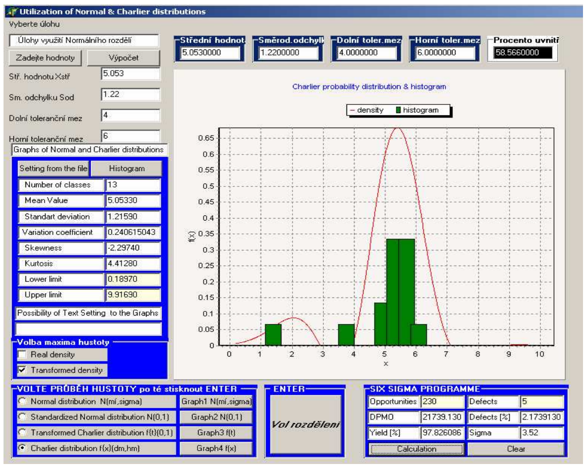

Fig. 7 Illustration of Normal and Charlier distribution

For these purposes it is especially suitable to work with the Charlier distribution. In the first approximation it is possible to consider the Normal distribution as the 1st member of the general valid Charlier distribution with other parameters (kurtosis and skewness). This distribution is expressed by rank of sequence derivation of probability density of Normal distribution. It is obvious that this approximation is very raw, a software has been developed which is able to display Charlier distribution. This Charlier distribution gives us a conception of the real behavior of the probability density. This software can check the suitability of the model distribution, but even to say something about the character of the tested file on the base of the shape of the distribution. The software works with a created database of the distribution function of the Normal distribution. The software is able to solve often "fractile" exercises – it means to find percentage of subjects being in (or outside) toleration limits and to find these limits. The software is able to solve exercises connected to this distribution and the software can work as a 6-sigma calculator.

CONCLUSION

Monitoring of results from dielectric tests of winding in production praxis is an typical example of work with files with lower number of samples. And this requires a slightly distinctive approach for statistical evaluation. Mentioned methods respect this approach for evaluation of lifetime tests and respect work with data form view of dissipation analysis. It is also possible to gain a trustworthy interpretation by low number of samples.

In BRUSH SEM (in Stator Winding and Insulation Department), usage of statistical methods has always had large tradition and signification during monitoring of quality and reliability. Now the praxis is enriched by graphical outputs from programs – some of them were shown as an example in this paper.

References

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