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A NUMERICAL METHOD FOR 3D-DESCRIPTION OF SCATTERED CHARACTERISTIC AGING DATA FROM MULTISTRESS AGED XLPE-CABLE INSULATION

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ABSTRACT

In the field of state estimation and insulation characterization of electrical equipment for power systems the main tasks for research work are actually represented by the development of diagnostic measuring techniques including appropriate data evaluation procedures, and tools for remaining life estimation. On the basis of experimental data yield by several diagnostic measurements on multistress aged XLPE-cable insulation in this contribution a numerical procedure is presented, which is intended to used as an analytical method for the description of the life volume for electrical equipment. By application of multivariate interpolation techniques from the field of scientific visualization a life volume based on experimental values from accelerated aging tests up to 1 year and simulated data with a maximum aging duration of 10 years is determined. The accuracy of this method is checked by comparison of the resulting simulated data and further experimental values, which were not included in the modelling procedure.

KEYWORDS

Numerical modelling, 3D scattered data, multistress aged XLPE-cable insulation, life volume

INTRODUCTION

XLPE is employed widely as insulating material for power cables predominantly owing to ecological and economical reasons. Especially good experiences in service and enhanced manufacturing procedures enable the use of XLPE as insulating material for high voltage and extra high voltage cables. For receiving a deeper understanding of the actual insulation state of the operating resource the comprehension of aging mechanisms resulting from multistress operating conditions, which are mainly characterized by the simultaneous presence of electrical and thermal stress, constitutes an essential task. Due to direct interaction between the aging factors synergic effects arise, and will affect the aging mechanisms however. For evaluation of the impact of interacting aging factors on the insulation condition suitable preferable non-destructive diagnostic techniques with derivable meaningful quantities are needed. The improvement regarding the sensitivity of well known diagnostic parameter and the development of new aging markers are still in an ongoing process [1], [2].

In addition most current efforts in the prediction of the remaining life of polymeric cable insulation are directed towards accelerated destructive aging tests, and the determination of the time to failure. This approach is applied for a long time, and leads to the development of some phenomenological aging models [1], [2]. These models are mainly based on thermodynamic relationships, though it should be noted that the basis for thermodynamics is strongly influenced by probability considerations. Therefore the relation between aging rate and life time is under discussion, and different approaches relating to this point exist. Moreover the impact of empirical experience on the adjustment of free equation parameters has to be taken into consideration when the gained results are compared with the data from other procedures [2].

With regard to the outlined focus in this contribution a different approach is presented, which is free from thermodynamic relationships, and not restricted to a specific measuring or testing procedure.

EXPERIMENTAL PRELIMINARY WORK

At the beginning of this research work an extensive laboratory aging course on full-sized XLPE-model cables with high voltage insulation quality and reduced insulation thickness was carried out with different combined electric field strengths, conductor temperatures, and test durations. The maximum aging parameters ranged between 20 °C...130 °C, 0 h...8760 h, and 0 kV/mm...52 kV/mm. After fixed time steps up to one year experimental investigations on different aged cables were performed. The tests consist of destructive and non-destructive methods, which are described in detail in [3] and [4]. The results obtained by diagnostic techniques like isothermal depolarisation current measurements or unilateral low-field nuclear magnetic resonance measurements provide suitable parameters to characterize synergic phenomena within the insulation morphology resulting from interacting aging factors. However the sensitivity of these techniques is observed for the applied aging parameter range, and stress conditions above aging thresholds discussed in relevant literature [1], [5].

Besides aging markers gained by non-destructive measurements classical insulation characterization was performed by destructive tests in order to determine the residual electrical strength of different aged XLPE-model cables too. Thus a proposed structure for a clear reference of every experimental data point in 3D space stretched up by the aging parameters electric field strength, conductor temperature, and test duration is summarized in Table 1.

Table 1: Summary of data structure for scattered data modelling of aging markers in 3D

x_i	y_j	z_k	G_{ijk}	method
coordinate			attribute	
ϑ_a	t_a	E_a	$E_{r,\,bd}$	residual electrical strength
ϑ_a	t_a	E_a	τ_i	isothermal depolarisation current
ϑ_a	t_a	E_a	T_2	nuclear magnetic resonance

This type of data structure constitutes in the field of numerical mathematics an extension of normal 2D matrices, and will be named as multidimensional array. In this approach the attribute is a scalar value. In general also vectors are possible. A spatial imagination of the used data structure can be taken from Figure 1.

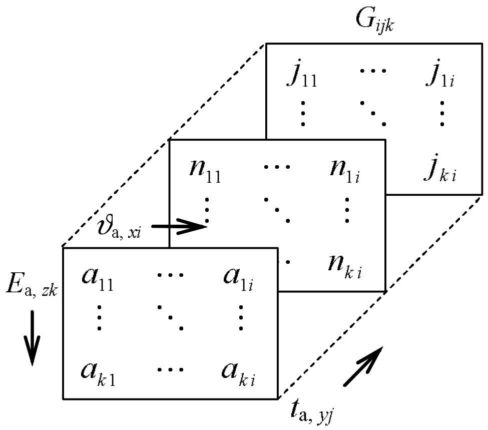

Figure 1: Multidimensional array structure for 3D scattered data with scalars

MULTIVARIATE SURFACE APPROXIMATION

For estimation of remaining life of solids the surface of a life volume represents a restricted area which has to be calculated with most available accuracy. Since in case of generally time and sample restricted aging programs the characteristic aging data were usually scattered in 3D. Therefore multivariate interpolation methods from the field of scientific visualization in computer graphics, which deal with surface-on-surface or function-on-surface problems e. g., can be a helpful approach to achieve approximations of surfaces with high precision.

In this work at first two different interpolation methods for scattered data points in 2D were compared to gain more supporting values for the applied multivariate procedure creating a surface with minimized interpolation error. The calculation of area was done by application of multivariate approximation techniques based on RBF. This method enables the estimation of areas on the basis of volumetric data points. The main advantage of this procedure constitute the fact that any information concerning the kind of connection between the data values is necessary. Therefore the assumption of fitting parameters in the usually formed equations for life time calculation can be avoided. In the context of this paper a description of relevant equations of RBF is too extensive, so that some fundamental references for that purpose can be referred to [6], [7], [8], and [9].

However a short sketch of the main steps is described in the following. It is looked for an approximation function with a partly deviation from the actual value of the function. Every data point will be related to a RBF, which uses the data value as a centre and calculates the distance of every other possible value by euclidean norms. The approximation function constitutes the weighted sum of the RBF, and the weighting coefficients will be got by solving a linear system of equations. A survey of relevant RBF used in the above mentioned literature is summarized in Table 2.

Table 2: Summary of relevant RBF in the field of multivariate approximation techniques ($c > 0$)

radial function $\varphi(r)$	type
$\varphi(r) = r$	linear function
$\varphi(r) = \sqrt{r^2 + c^2}$	multiquadrics
$\varphi(r) = \left(\sqrt{r^2 + c^2}\right)^{-1}$	inverse multiquadrics
$\varphi(r) = r^3$	cubic function
$\varphi(r) = r^2 \log r$	thin plate spline
$\varphi(r) = e^{-\left(r^2/c^2\right)}$	gaussian

In pre-investigations with a fixed interpolation method for additionally supporting data points a good applicability of the gaussian RBF was found. The criterion of assessment was used by minimizing the interpolation error, which was calculated by the difference of the data points and the corresponding values of the surface totally. The only free parameter in RBF is *c*, which can be considered as a smoothing parameter. The impact of the chosen *c* value on the approximation precision was investigated, and the corresponding results can be depicted from Figures 2 and 3.

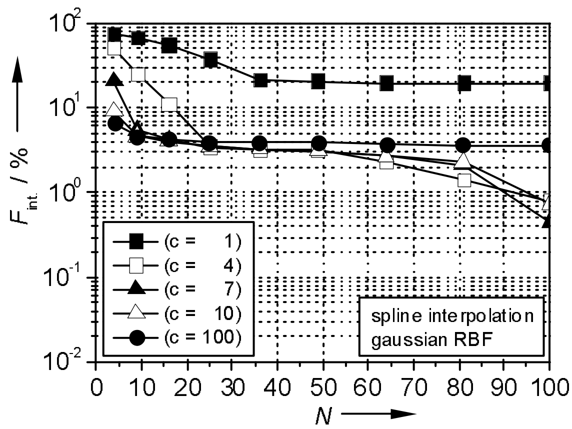

Figure 2: Interpolation error $F_{int.}$ with supporting values by spline interpolation and calculation of area by gaussian RBF for different *c* in dependence of the number of RBF *N*

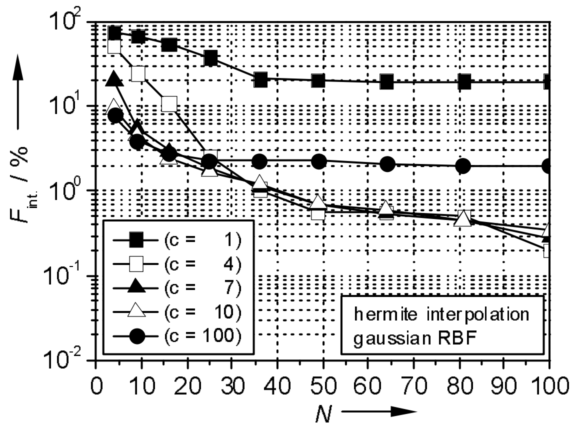

Figure 3: Interpolation error $F_{int.}$ with supporting values by hermite interpolation and calculation of area by gaussian RBF for different *c* in dependence of the number of RBF *N*

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The limits for c between 1 and 100 are sufficient compared with literature data. From the results it is apparent that a selection of $c = 7$ and $N = 50$ constitutes a good compromise between calculation time and accuracy.

With the chosen parameters and RBF in the following the comparison between the two interpolation methods was continued. Figure 4 shows the calculated surface with additional supporting values by hermite interpolation. Experimental data points are represented by black filled circles, and supporting data is displayed by open circles. The maximum aging time was 5000 h. Further by gray filled circles some single data points are visualized, which were not involved in the calculation procedure. It is obvious that these data exhibit more or less deviation compared with the surface data. However the aging duration for the additional values were 2000 h and 8760 h, and logarithmic scaling of time axis should be regarded.

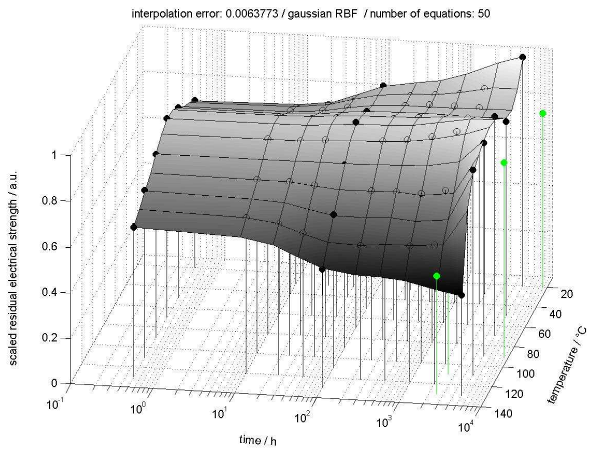

Figure 4: Calculated surface with gaussian RBF based on data points from experiments and additional values by hermite interpolation

In Figure 5 the corresponding surface with supporting data by spline interpolation is shown.

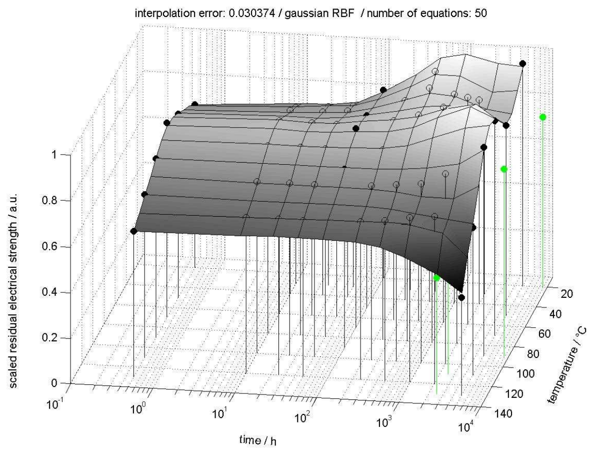

Figure 5: Calculated surface with gaussian RBF based on data points from experiments and additional values by spline interpolation

From Figure 5 it can be seen that the calculated surface is more smooth compared to that in Figure 4, but a clear difference concerning the interpolation error is also obvious. This finding can be traced back to the stronger oscillating behaviour of splines in case of less scattered data. For further verification of the correct selection regarding the interpolation method, spline and hermite interpolation for additional supporting data were conducted, and application of different RBF leads to approximation of the surface. It is apparent from Figure 6 that hermite interpolations demonstrate a clearly better approximation precision than spline interpolation. The difference between various RBF is small.

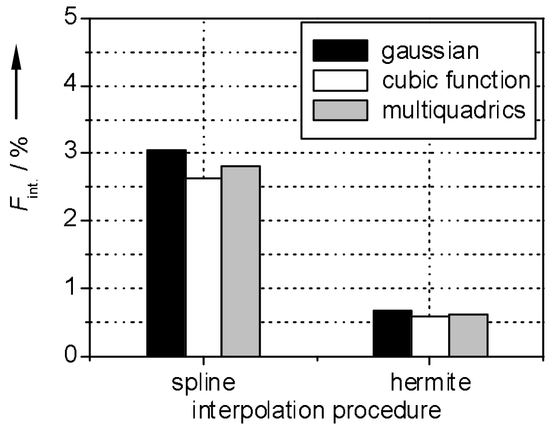

Figure 6: Interpolation error $F_{int.}$ with supporting values by spline or hermite interpolation and calculation of area by different RBF ($c = 7$, $N = 50$)

VOLUME DETERMINATION BASED ON DELAUNAY TRIANGULATION

Using the already described data structure (Table 1) a further technique from the field of scientific visualization in computer graphics was applied in order to model the life volume below the approximated surface. Therefore a procedure is necessary, which enables the numerical calculation of values on a defined subdivision of the treated space. For scattered spatial data an optimal basis for interpolation on an irregular triangular mesh is represented by *Delaunay* triangulations, because always a global optimal solution will be generated [10]. In Figure 7 the working method of *Delaunay* triangulations is displayed on the basis of example data.

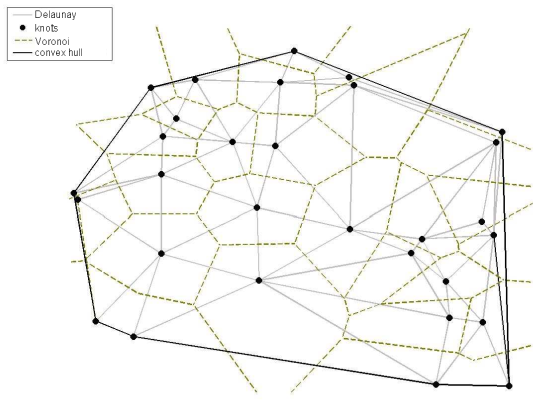

Figure 7: Schematic representation of *Delaunay* triangulation

It can be seen that all data points, which are referred as knots are sited inside the convex hull describing the smallest convex polygon. Therefore the solution of a *Delaunay* triangulation is unambiguous. Moreover an inherent problem of this interpolation methods is obvious. Linking additional data points to an already existing triangulation result in a loss of clarity, and suitable techniques for minimizing interpolation errors have to be applied. Incremental inserting algorithm as described in [11] and [12] offer efficient calculation codes for new triangulations. New knots of triangles can be situated inside or outside of existing triangulations, and in case of outside positioned knots special programming like [13] can be used to construct further triangulations in peripheral regions of the data. However the technique described in [13] is frequently applied even though in practical applications often an user intervention is necessary for acceptance of evaluated values.

To avoid this action regarding the evidence and self-working of calculation programs for triangulations with data points outside the convex hull additional values used in this work were generated by application of the method by *Montefusco* and *Casciola* [14]. With it extension data represents together with original values the basis for triangulation calculations, and extrapolation of knots outside the convex hull is infirm. Extension data will be determined on the basis of *Shepard* algorithm, which is basically characterized by application of weighted averaging of adjacent knots. Using the outlined method for extrapolation of life volume data in the following results for two different cases are displayed. In Figure 8 the outcome on the basis of aging data with durations of maximal 5000 h is visualized taking into account some programming hints in [15].

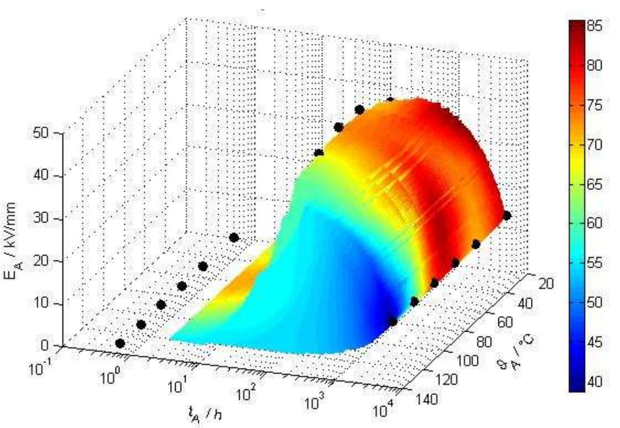

Figure 8: Calculated life volume of XLPE-cable insulation with interacting aging factors as electrical field strength, temperature, and duration; the scaling bar indicates the expected residual electrical strength after aging with a grid resolution of 5.5 °C, 2 h, and 0.5 kV/mm

It can be depicted from the graphic that especially in the proximity of the experimental data values with comparatively short aging times no calculation of life volume data is possible. This fact will most probably caused by non converging calculation procedure. It can be reduced by rising the corresponding resolution steps in time direction. But due to logarithmic scaling the calculation of additional data will bring about a strong increase in the required calculation time.

For evaluation of the calculation accuracy comparisons of separate data points concerning the residual electrical strength were done. The experimental values with t_a = 2000 h used therefore were not included in the calculation procedure. The deviation of measured and calculated values ranges between 6 % and 10 %. However it should be reminded, that the displayed experimental data consists of *Weibull* nominal values including 95 %-confidence intervals. Assessing the comparatives a trend towards lightly higher values by the calculation procedure can be stated.

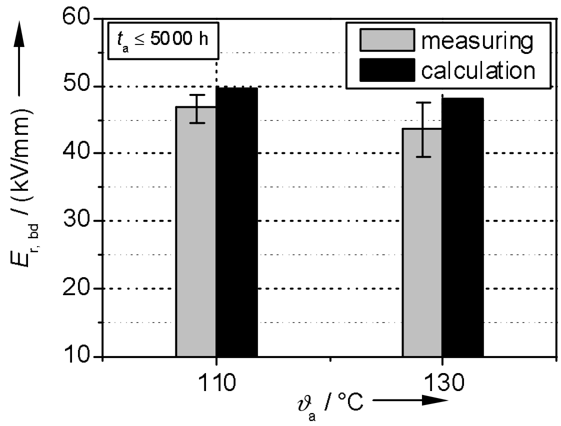

Figure 9: Comparison between experimental and calculated residual electrical strength of XLPE-cable insulation after aging course for selected aging temperatures ϑ_a (E_a = 13.1 kV/mm, t_a = 2000 h)

For further evaluation of the calculation precision resulting from the described method for life volume modelling simulated aging data by application of *Montefusco* and *Casciolas'* procedure with a maximum aging duration of 10 years was used. Figure 9 summarizes the corresponding results.

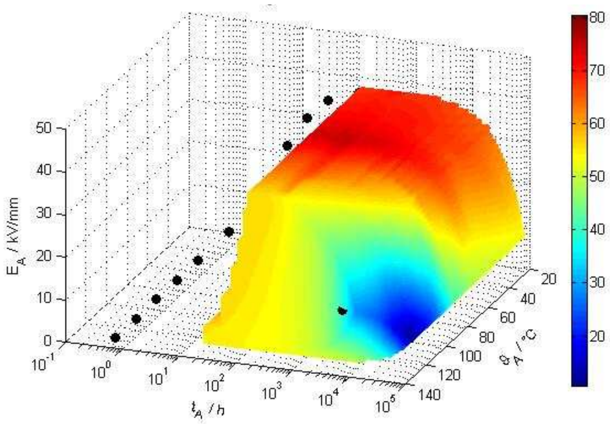

Figure 10: Calculated life volume of XLPE-cable insulation with interacting aging factors as electrical field strength, temperature, and duration; the scaling bar indicates the expected residual electrical strength after aging with a grid resolution of 5.5 °C, 17.5 h, and 1 kV/mm

As compared with Figure 8 the same phenomena near the area with low aging times is visible. In case of distinct longer aging duration an increase in time resolution appears unsuitable, and therefore the grid resolution was adapted correspondingly. Since every data point influences the values of adjacent data a postponement of the calculated residual electrical strengths compared to the data shown in Figure 8 is obviously. The shift will be clearly reduced in case of more additional supporting and experimental data points. With regard to the calculation precision again experimental data which were not included in the calculation procedure were compared with simulated values (Figure 11).

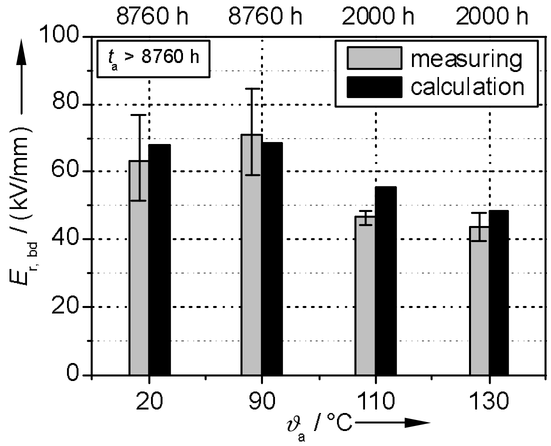

Figure 11: Comparison between experimental and calculated residual electrical strength of XLPE-cable insulation after aging course for selected aging temperatures ϑ_a and aging times t_a (E_a = 13.1 kV/mm)

It can be seen from Figure 11 that in the lower range of the applied aging temperatures the calculated data were not considerably different from the experimental values. The deviations range between 4 % and 7 %. Moreover the calculated results are clearly within the 95 %-confidence intervals. In case of higher aging temperatures the differences increase up to maximal 18 % for ϑ_a = 110 °C. Since the data basis for the calculation procedure is different to that for the results presented in Figure 9 due to additional supporting data and the availability of more data points for longer aging durations the calculation precision for longer times is enhanced. Moreover the grid resolution in time direction is increased because of the overall calculation time. This fact will be reflected in higher deviations between measured and calculated values for shorter times.

CONCLUSIONS

For modelling the life volume of multistress aged XLPE-cable insulation a numerical method consisting of two steps is proposed. The essentials of the technique are based on calculation procedures with multivariate interpolation methods from the field of scientific visualization in computer graphics. It turned out that the procedure considers the properties of sparse scattered 3D data in a suitable manner, and that the calculation accuracy is justifiable at the expense of additional calculation time. Additional supporting values can be used to increase the precision, and the calculation of residual electrical strength becomes comparable to measured data.

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GLOSSARY

EPR: Ethylene propylene rubber
RBF: Radial basis function
XLPE: Cross-linked polyethylene