Prediction of Lightning Impulse Voltage Induced Breakdown in Vacuum Interrupters

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ABSTRACT

A concept to predict the Lightning Impulse Voltage (LIV) breakdown probability of medium voltage Vacuum Interrupter (VI) tubes has been developed and tested for the first time employing the Voltage Holding Prediction Model (VHPM) originally formulated at Consorzio RFX. The VHPM is capable to calculate the Weibull breakdown probability curve of any multi-electrode multi-voltage system insulated in vacuum under dc voltage. Even though the possibility to employ the VHPM in the prediction of voltage breakdown under LIV conditions is not straightforward, the potential benefits of the VHPM usage in VI tube technology with regard to development, design and testing at medium and high voltage levels, strongly recommend the assessment of VHPM under LIV conditions. The paper aims to describe the methodology adopted to identify experimentally the VHPM parameters to be employed in such a novel application to assess its prediction capability. The measurements have been done in the Siemens Berlin VI tube factory test stand for LIV, compliant with the IEC standard. Different vacuum tube types manufactured by Siemens were investigated. The main difficulty was to obtain, with such a test bed, voltage breakdown distributions well fitted by a Weibull Distribution - upon which the VHPM is based – primarily due to the difficulty to reach a well-defined end of the conditioning test sequence preceding the relevant voltage breakdown test sequence suitable to be analyzed by the VHPM. Nevertheless, the VHPM prediction resulted in reasonable agreement with the measured probability curves. Finally, investigating VI tubes with spiral-type Radial Magnetic Field (RMF) contacts, characterized by a geometry strongly deviating from axial 2-D symmetry, the first implementation of a full 3-D version of the VHPM has been tested.

Index Terms — **Electric breakdown, Probability, Prediction methods, Weibull distributions, Electrostatic analysis, Vacuum interrupters, Impulse testing.**

INTRODUCTION

The dielectric stress properties of vacuum interrupters (VIs) under lightning impulse voltage (LIV) conditions are critical key features of reliably operated medium- and high-voltage vacuum switches [1]. For applications involving a rated voltage level of 145 kV (rms) for example [2], impulse voltage amplitudes of up to 650 kV have to be withstood to comply with the basic insulation level requirements (BIL 1.2/50 µs). A model-based prediction of voltage breakdown characteristics

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of VI designs would make laborious and expensive development tests unnecessary.

A promising theoretical method to predict the breakdown probability for the complex electrostatic system of contact electrodes and metal vapor shields/walls in a VI is the Voltage Holding Prediction Model (VHPM). The model was developed at Consorzio RFX for multi-electrode multi-voltage configurations insulated in vacuum [3] and was applied successfully to the full-scale prototype MITICA [4] of the neutral beam injector at ITER for plasma heating and current drive. The applied statistical approach in terms of the VHPM triple product $W = E_C\, U\, E_A^{2/3}$ (U is the peak LIV; E_C, E_A are the local electric fields at cathode and anode), from which the overall breakdown probability is calculated as Weibull cumulative probability distribution, has the advantage to assign to a given electrostatic configuration a unique probability versus voltage curve. Thus, any variation in the design of a vacuum switch tube is associated with its breakdown curve, allowing efficient VI optimization processes.

Though the VHPM originally had been developed for dc voltages on basis of the Cranberg-Slivkov clump theory, a critical review [5] found that also a photoelectric-cascade mechanism can lead to a formulation of voltage breakdown in terms of a triple product $W = E_C^{\lambda}\cdot U^{\nu}\cdot E_A^{\gamma}$. This finding justifies the application of the VHPM also to electron initiated breakdown mechanisms that are primarily responsible for voltage breakdown during the fast rise of a LIV impulse.

This work focuses on systematic LIV experiments (up to 250 kV, positive and negative polarity) carried out in the Siemens VI factory on medium-voltage vacuum tubes manufactured by Siemens. The study is aimed at validating the VHPM under well-controlled conditions. After a short sketch of the experiments in Section 1, the basis of the VHPM method and its application to the VI configuration with LIV features well-known from the experiments is described in Section 2. The applicability of the model on LIV conditions is discussed, and the experimental and simulation results are compared. In Section 3, a test of the predictive capability of the VHPM by means of a tube configuration with unknown voltage breakdown characteristics is presented. A brief description of the VHPM implementation in a three-dimensional geometry and its application to a tube type with radial magnetic field (RMF) contacts produced by Siemens, therefore characterized by ageometry with strongly 3-D features, is described in Section 4. The findings are finally summarized in Section 5.

1 EXPERIMENTAL SETUP AND CONDITIONS

The vacuum switch tubes under investigation were medium-voltage VIs coming from the regular tube production of Siemens. Figure 1 shows a half-plane sectional drawing of the tube. The disks of the AMF contact system are made of arc-melted CuCr, the contact pieces and contact stems of oxygen-free copper. The alumina ceramic insulators (green parts in Figure 1) are sealed with the central tube wall, the end caps, and the vapor shields inside the tube; the end caps and the bellows (at the movable stem) are made of stainless steel. The smaller vapor shields are electrically connected with the end caps and thus with the fixed and the movable contact system, respectively. The larger vapor shields are electrically connected with the tube wall that lies on floating potential (purple parts in Figure 1).

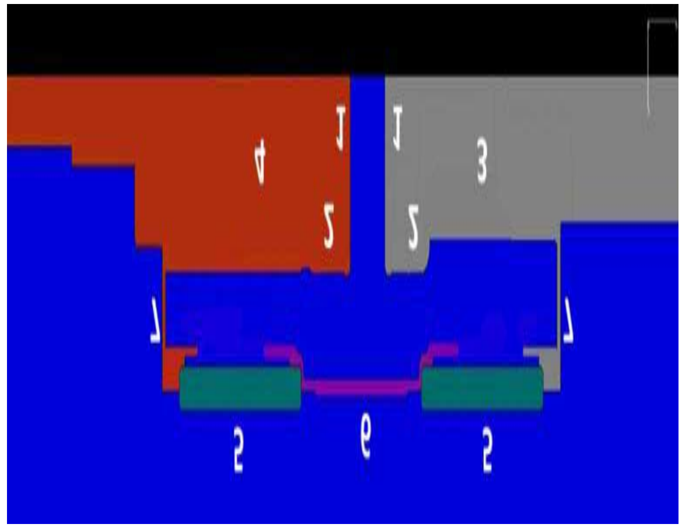

Figure 1. Half-plane sectional drawing of the vacuum tube design. 1: contact disks, 2: contact pieces, 3: fixed contact stem, 4: movable contact stem with shielding of bellows, 5: ceramic insulators, 6: tube wall with vapor shields, 7: end caps with vapor shields.

All test tubes were manufactured in accordance with the Siemens standards referring to surface finishing, evacuation procedure, heat treatment, and measurement of the inner pressure. The tubes were conditioned directly after the manufacturing process by application of power frequency (50 Hz) alternating voltages to guarantee the same initial conditioning status for each test tube.

The experiments were carried out in the Siemens tube factory in Berlin. Impulse voltage amplitudes up to 250 kV were generated with positive and negative polarity with respect to earth potential using a setup similar to the electrical circuit for impulse voltage tests described in [6]. The peak voltage was reached 2 µs to 6 µs after trigger time t=0, in single cases after 8 µs. The back tail of the impulses had a time constant of approx. 50 µs. Thus the shape of the LIV impulses complied with the basic impulse level requirements (BIL 1.2/50 µs). The impulse voltage was applied to the movable VI contact (orange parts in Figure 1); the fixed contact was held at earth potential (grey parts in Figure 1). To ensure that breakdowns will only occur inside the test tube, the VI tubes were placed in a container filled with insulating fluid (FC-40).

Two VI configurations have been employed in the experimental campaigns: (1) One with 10 mm gap for the VHPM application study described in Section III; (2) another with enlarged gap (15 mm) for the VHPM prediction test described in Section IV. The LIV test procedure is described in detail in the respective sections. In short: It comprises the initial test sequence called “conditioning region”, which is characterized by a stepwise voltage increase, and the final test sequence called “voltage breakdown region”, which is evaluated for the statistical analysis.

2 VHPM IMPLEMENTATION AND APPLICATION

3.1 VHPM DESCRIPTION

The VHPM method is based on the same probabilistic approach followed by the Failure Analysis Theory [7]. It associates the breakdown probability of a system to the physical mechanism underlying the clump induced breakdown, through the fundamental assumption that the number n of microparticles per square meter that potentially can produce a breakdown is a monotonic function of the triple product W. A functional dependence described by the Weibull's distribution is then assumed:

$$n(W)=\left(\frac{W}{W_0}\right)^m \tag{1}$$

where W_0 and m are the parameters depending mainly on material and surface treatments. The overall breakdown probability has then the following expression [3]:

$$P=1-e^{-\int_A n\cdot dA} \tag{1}$$

where the surface integral is evaluated along the cathode areas. Therefore, assumed to know the Weibull m and W_0 parameters, the overall breakdown probability depends on the distribution of the triple products W across the electrodes. This is determined by the solution of the electrostatic problem on the particular geometry, which is carried out by means of a finite element code and the subsequent trajectories calculation of negative particles moving from the cathode to the anode. This allows to associate to each element of the cathode of area A_i, the electric field on that element $E_{c,i}$, the electric field on the corresponding element of the anode $E_{a,i}$ linked through the trajectory and the voltage U_i in between. Thus the integral in equation (1) reduces to the sum of the following contributions:

$$\left(\frac{E_{c,i}\cdot U_i\cdot E_{a,i}^{2/3}}{W_0}\right)^m\cdot A_i \tag{2}$$

We use the commercial FEM code Comsol for the 2-D case and an efficient custom code, called CAFE [8], for the solution in 3-D, as better described in section 4.

The trajectories are calculated through a procedure which relies on the idea that the particle move through adjacent elements of the domain between the electrodes, avoiding the standard integration of particle motion equations by a common Runge–Kutta scheme [9]. The procedure is based on the adoption of first-order elements, which implies a uniform electric field E inside the generic element and thus a charged particle moving over it is subjected to a uniformly accelerated motion. Therefore, the overall trajectory corresponds to a piecewise parabolic curve.

3.2 APPLICABILITY ON LIV CONDITIONS

The VHPM has been developed to predict the voltage breakdown probability of multi-electrode multi-voltage systems insulated in vacuum under dc voltage conditions and under the hypothesis that the breakdown is determined by the value of W = E_C U $E_A^{2/3}$, that comes from the Clump model proposed by Cranberg and modified by Slivkov [10]. Actually, the W triple product - with a different formulation - can be derived [5] also from the emission of electrons from the cathode, so that the VHPM has the potential to be applied in the case in which the breakdown initiator are not the clumps but are the electrons. The conditions of LIV tests of VIs require to evaluate which is the prevailing breakdown mechanism, by an estimation of the maximum ratio of mass on charge $(m/q)_{MAX}$ for a particle causing the breakdown. The knowledge of the breakdown time τ_B and of the LIV peak voltage U_B allows estimating $(m/q)_{MAX}$ according to equation (3) if the breakdown occurs as "early breakdown", i.e. *during* the rise time of the LIV, which represent the great majority of cases.

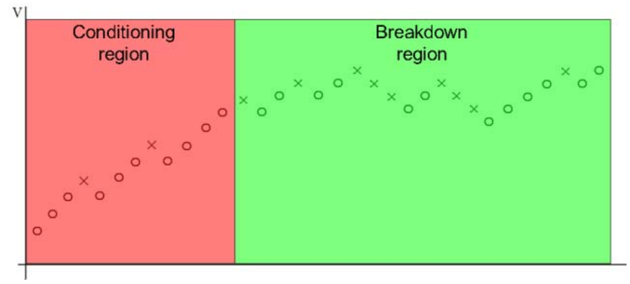

Figure 2. Sequence with "conditioning region" and "voltage breakdown region".

Table 1. Characteristic m/q values [kg/C].

electron	proton	Slivkov (clump model) [10]	**m/q_{max} (eq.4)***	Direct measure Texier [11] (clump model)	Direct measure Chatterton [12] (clump model)
$0.6\cdot10^{-11}$	$1.0\cdot10^{-8}$	2.0	**0.01**	3.0 ÷4000	0.2÷9.0

$$\left(\frac{m}{q}\right)_{MAX}=\frac{U_B\cdot\tau_B^2}{6\cdot d^2} \tag{3}$$

Table 1 compares the m/q values, reported in literature and measured with different techniques, with those derived by equation (3) inserting the parameters of our experimental campaigns.

In our campaigns, the characteristic breakdown time is the rise time of the applied LIV to the peak of the voltage (τ_B = 6 µs; U_B = 180 kV); the gap length is of the order of 10 mm, thus the m/q ratio of the particle inducing breakdown should not exceed 0.01 kg/C.

Some percent of the overall number of breakdowns in our campaigns occur during the falling tail of the LIV after the voltage peak, i.e. at some tens of microseconds. For these "late breakdowns" the maximum m/q ratio is estimated by an equation different from equation (3) and the ratio exceeds unity. Comparing the values reported in Table 1 with our experiments, the late breakdowns are fully compatible with the clump mechanism, but for the more frequent early breakdowns, the dimension of the particles would be lower than one tenth of the smallest particle measured by Chatterton. Thus it seems reasonable to consider that the prevailing mechanism of early breakdown is electron emission. Anyhow, in absence of a reliable formulation of the triple product W for the electron emission, the classical W formulation of the triple product for the clump-induced breakdown has been retained.

Basically, the VHPM is first used to derive the W_0 and m parameters of the Weibull distribution by fitting the experimental distribution of breakdown voltages obtained from the tube model under test with the Weibull distribution. The procedure to obtain the sequence of breakdown voltage data is indicated in Figure 2.

The voltage breakdown events considered for the statistical analysis are those obtained at the end of the conditioning phase (green area, characterized by increasing trend of the voltage holding capability); the method to obtain a statistical distribution of breakdown voltages is the stepwise application of voltage with steps of 5 kV each. It must be underlined that this value is set manually, and the actual voltage has a certain degree of uncertainty (±2 kV). The voltage is increased until the breakdown is reached (crosses, x); then the applied voltage is decreased with the same step amplitude, until the breakdown no longer occurs (circles, o); then the voltage is increased, again.

The probability of breakdown P_j is obtained from the set of the breakdown voltages V_j (j=1… N) arranged in ascending order ($V_j < V_{j+1}$) by using the ranking estimator reported in equation (4).

$$P_j = \frac{j-0.5}{N} \qquad (4)$$

The values of W_0 and m are obtained with the best fit technique consisting in minimizing the mean square error between the measured and calculated distribution.

3.3 APPLICATION TO VACUUM INTERRUPTER

The breakdown distribution of the VI configuration (Figure **1**) under investigation has been derived from LIV experiments carried out on a set of four vacuum tubes, coming from the same production batch; two have been subjected to positive polarity pulses and the other two to negative polarity pulses. Figure 3 shows the individual test sequences displaying the voltage data as function of the progressive number of applied pulses for a contact gap of 10 mm. The peak voltage of a pulse in case of "no breakdown" is displayed in green, the voltage value in case of "breakdown in front or on top of the pulse" is displayed in red. The approach to acquire the experimental data is in accordance with the procedure described in section 3.2 and visualized in Figure 2. Voltage steps of 5 kV are imposed in the power supply. However, the green points (no breakdown) presented in Figure 3 (and in Figure 4, see below) refer to the actual measures and thus show voltage differences for two adjacent tests that are characterized by a test-specific uncertainty and a deviation of ±2 kV with respect to the 5 kV steps.

The data inside the square boxes have been considered to belong to the above mentioned "breakdown region", i.e. the

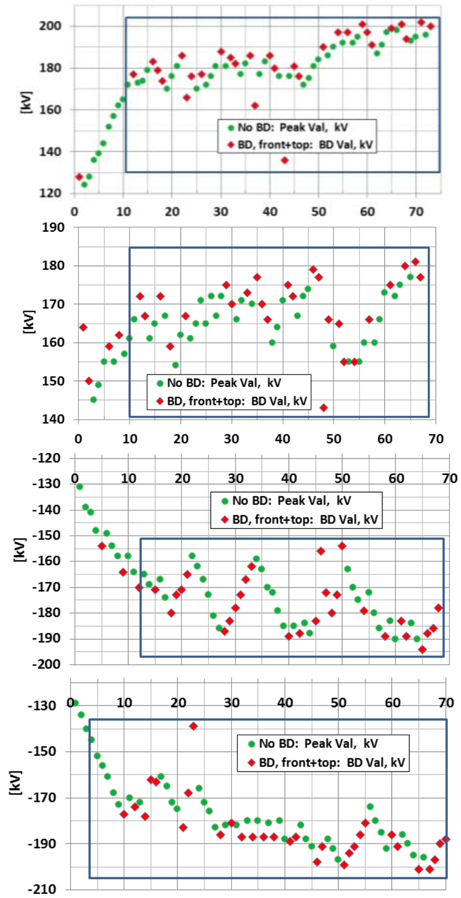

Figure 3. Plot of experimental data for VIs with numbers A, B (1st and 2nd diagram, positive polarity) and VIs with numbers C, D (3rd and 4th diagram, negative polarity); Gap=10 mm; peak voltages in green and breakdown voltages in red.

breakdown data occurring once the preceding "conditioning region" is completed. From these sets of data, the VHPM model has been applied to obtain the W_0 and the m parameters of the Weibull distribution, using the least square method. The results for the individual VIs are shown in Table 2, together with the fits (in italic) obtained by merging the data for positive and negative polarity, respectively.

Table 2. W_0 and m values.

Tube	W_0 [$V^3m^{-5/3}$]·10^{17}	m
No. A - positive	1.25	6.3
No. B - positive	1.43	9.4
Merged data - positive	*1.09*	*6.2*
No. C - negative	1.29	7.2
No. D - negative	1.69	8.6
Merged data - negative	*1.37*	*7.2*

Closer values of W_0 and m should be expected (ideally, they should be identical). Nevertheless, considering that the number of tubes tested is not large and the breakdown voltage distributions have not reached a fully "stabilized" behavior, the result can be considered acceptable. Anyhow, a check has been done on the Goodness of Fit (GoF), in order to verify whether the data are actually represented by the Weibull distribution.

The test methodology employed was the Komogorov-Smirnov GoF test [13], suitable for testing the distribution of data samples. For all cases reported in Table 2, the test was passed. The values of W_0 and m resulting from above are the average of the positive and negative values from merged data: W_0=1.23·10^{17} and m=6.7.

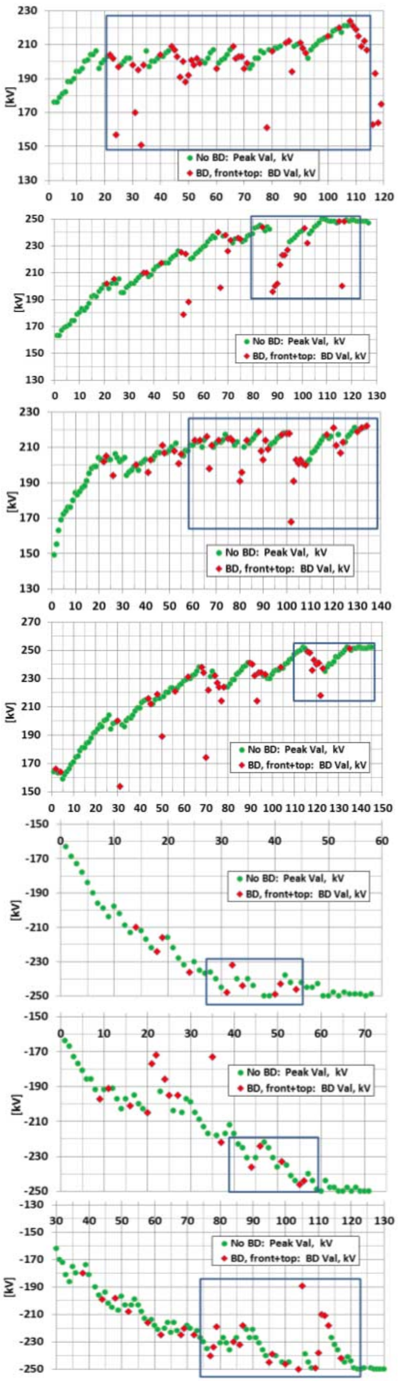

Figure 4. Plot of experimental data for VIs with numbers E, F, G, H (first four diagrams, positive polarity) and VIs with numbers I, J, K (last three diagrams, negative polarity); Gap =15 mm gap; peak voltage in green and breakdown voltages in red.

3 PREDICTION TEST

In order to assess the prediction capability of the VHPM, tests have been then carried out on a set of seven tubes of same VI type with gap length between the contacts increased to 15 mm.

The experimental results are documented in Figure 4. It must be pointed out that the stabilization of the breakdown voltage (i.e. the completion of the conditioning phase) has not been reached due to the limit of the used pulse power supply (V_{max} = 250 kV); this effect is particularly visible for negative polarity. This implies that the distribution of the measured breakdown voltages deviates from the Weibull distribution partially affecting the comparison with the model prediction results. Figure 5 summarizes all analysis results of the present investigation.

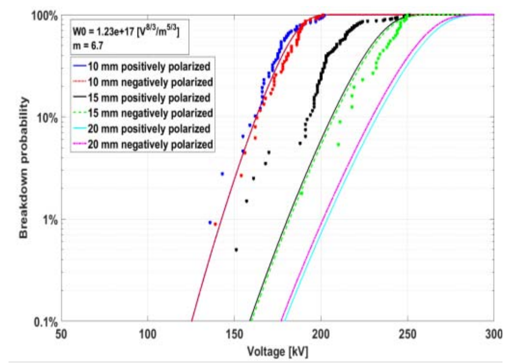

Figure 5. Plots of calculated Weibull distributions (continuous lines) and experimental data (points) for all analyzed cases with positive and negative polarity. Gap 10 mm: blue (pos.) and red-dotted (neg.), gap 15 mm: black (pos.) and green-dashed (neg.), gap 20 mm: light blue (pos.) and magenta-dash-dotted (neg.).

The model predicts for the 15 mm gap case that the 100% probability breakdown is 250 kV, and the distribution of the measured breakdown voltages actually tends to this limit. Nevertheless, such an agreement between measured and computed 100% probability voltage is not sufficient to prove the effectiveness of the VHPM tool: in fact, the model predicts the whole distribution, but the comparison cannot be done for 15 mm gap because the actual voltage breakdown distribution differs significantly from the Weibull one; the measured distribution should be similar to the 10 mm gap case.

It is worth noticing that, increasing the gap, the VHPM is capable to highlight the polarity effect: in fact, the probability distribution curves for negative and positive polarity tend to separate; this occurs because of the dielectric asymmetry of the tube, which determines the polarity effect when the contact gap length is no longer negligible with respect to the distance between the contact system (fixed and movable contact electrodes) and the other metallic shield and wall components of the VI tube. Figure 5 shows - to this purpose - also the 20 mm gap case reflecting the polarity effect in a more marked evidence. No experiments have been performed for this gap length, because the pulse power supply voltage was definitely not sufficient to complete the conditioning sequence.

4 VHPM IMPLEMENTATION IN 3-D

The 3-D VHPM implementation is based on an efficient numerical code (CAFE) for the solution of the electrostatic problem. CAFE combines the standard FEM electric scalar potential formulation, with an original formulation that employs the electric vector potential [8]. Thanks to the complementarity of the two potential formulations, the method is well suited to the adaptive refinement of the mesh based on the two results as a robust error estimator, which is also used to have a reliable control on the accuracy of the solution [14].

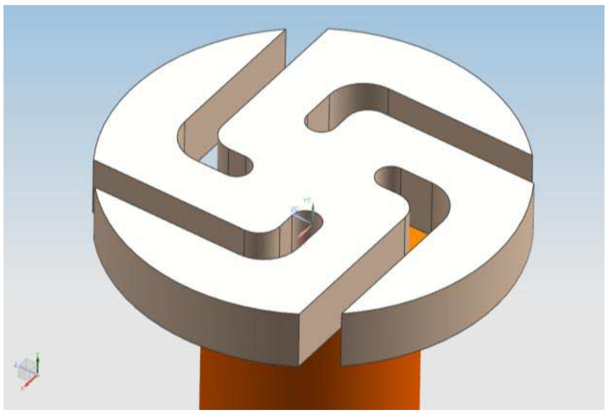

Figure 7. Detail of the spiral-type RMF contact electrode.

The double solution by employing both complementary formulations does not represent an overhead, since the mean of the two solutions is usually much more accurate than the solutions provided by each formulation alone (see Figure 8) and consequently allows a strong reduction in the computational cost of the simulation for a given accuracy.

The 3-D version of the VHPM has been tested by its application to a VI tube with a spiral-type Radial Magnetic Field (RMF) contact system that is characterised by typical purely 3-D features.. In Figure 7 a detail of the RMF contact electrode from the CAD model is shown.

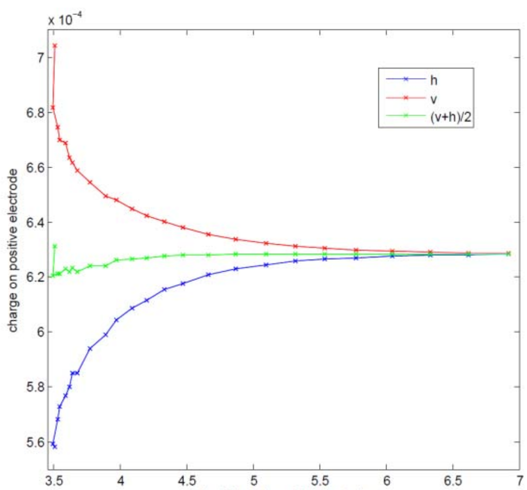

Figure 8. Study of convergence, in terms of electrostatic charge deposited on the positive (moving) electrode.

The model considers the tube in open configuration with a gap distance of 8 mm. In Figure 8 the study of the convergence of the two electrostatic formulations is shown, in terms of the charge on the polarized (positive) electrode as a function of the number of tetrahedral elements. In particular, the figure documents that the mean of the two solutions is much more accurate than the solutions provided by each formulation alone at any level of discretization.

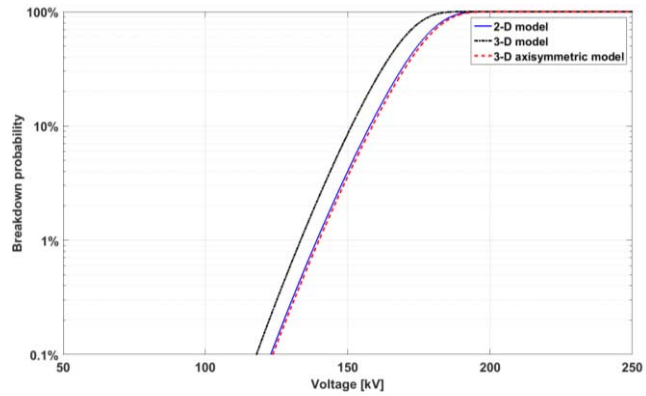

Figure 6. Plot of the Weibull distribution calculated for the RMF tube positively polarized with the parameters obtained from the other tube type data. Results from 2-D (blue), 3-D (black, dashed) and 3-D axixymmetric (red, dash-dotted) models.

In order to test the reliability of the 3-D version of the VHPM method, the same case has been simulated with the actual 3-D model, a 2-D model obtained from a cross section of it and a 3-D axisymmetric model obtained by the rotation of the 2-D model. The results in terms of (probability) Weibull cumulative distributions are compared in Figure 6. The accuracy of the 3-D version is considered proven since the 2-D and the axisymmetric 3-D case almost perfectly overlap, whereas the actual 3-D result shows a lower voltage holding capability as it is expected because of the longer edges with respect to the corresponding axisymmetric geometry.

5 CONCLUSION

An experimental campaign has been carried out at the Siemens VI factory Berlin, aimed at testing the capability of the Voltage Holding Prediction Model – developed at Consorzio RFX - to predict the VI tubes insulation properties under LIV application. The VHPM has given fair but not conclusive results: in fact, even if 100% breakdown probability has been correctly predicted, a full comparison between measured and predicted Weibull probability distribution curve has not been attained, mainly due to the not sufficient number of sampled breakdown voltages acquired after the completion of the conditioning sequence. A preliminary application of the 3-D version of the VHPM method has been carried out on a VI tube type with RMF contact electrodes displaying promising results. This last improvement is particularly important in case of symmetry breaking design features of commercial vacuum interrupter contacts of spiral-type RMF geometry. Further work has then to be done on different areas: first, to improve the statistics of the breakdown voltage, in order to obtain distribution closer to Weibull distribution; second, on the basis of this improvement, to make a sensitivity survey on the exponent of the $W = E_C^{\lambda} \cdot U^{\nu} \cdot E_A^{\gamma}$ triple product in the determination of the Weibull parameters W_0 and m; third, to carry out a precise test of the prediction capability of the VHPM in 3-D geometry.

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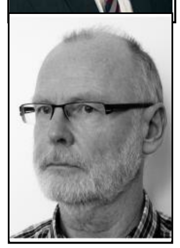
Andreas Lawall (member DPG) was born in Germany in 1971. He received the Dipl.-Phys. from the Technical University of Berlin in 1999. After working as a software engineer in the field of speech processing, he joined Siemens AG in 2003 as a developer and project leader for vacuum interrupters. His current main focus is closing the gap between the basic research and commercial products.



Norbert Wenzel received his M.Ed. degree in physics and mathematics in 1979 from the University of Heidelberg /Germany and his Ph.D. degree in physics in 1985 from the same institution. Since 1985 he has been working for Siemens Corporate Technology as researcher, test laboratory head, project leader, and as radiation protection officer. From 1978 to 1985 he was a research and teaching assistant at the Universities of Heidelberg, Applied Physics Dept., and Stuttgart, Plasma Research Institute, mainly on fusion-oriented plasma physics and plasma diagnostics. In 1982 he held a EURATOM fellowship at the nuclear fusion research center of the Association ENEA in Frascati /Italy. From 1985 to 1992 he applied non-linear Raman spectroscopy to industrial processes, such as low voltage air breakers and gas lasers. And he developed sealed-off carbon dioxide slab lasers excited by radio-waves and microwaves.

Since 1992 he is working in the field of fundamental and applied research of switching arcs at Siemens Corporate Technology. As head of a synthetic test laboratory he was involved in the development of low, medium, and high voltage vacuum interrupters. Since 2006 he has extended his activities to physical modeling and numerical simulation of vacuum arc plasmas taking into account cathode surface phenomena. Currently he holds the position of a Senior Key Expert Research Scientist in the area of Vacuum Switching Technologies