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A3-210

CIGRE 2008

SIMULATIONS AND CALCULATIONS AS VERIFICATION TOOLS FOR DESIGN AND PERFORMANCE OF HIGH-VOLTAGE EQUIPMENT

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Cigré WG A3-20

SUMMARY

Recognizing an increasing role of commercial modelling software in the power industry, Study Committee A3 decided to evaluate existing simulation technologies to determine the extent to which they can be used as verification tools to enhance understanding of equipment performance, to extrapolate test results, to provide an alternative to testing, or to replace some of the tests.

WG A3.20 compiled an inventory of electrical, mechanical, thermal, magnetic, and other stresses which "A3-type" components (substation equipment except transformers) are subjected to in service, based on the relevant tests mandated by IEC/ANSI standards. For all investigated applications, WG A3.20 listed expected simulation results and the preferred numerical methods to be used for different specific problems. An assessment has been made to determine to what degree such stresses can be simulated.

The purpose of the assessment is to analyse the accuracy of modelling the behaviour of a device under certain physical constraints as re-produced during the tests. This process is performed in two steps:

1. Stress calculation: the ability of the model to compute certain physical parameters such as temperature, electric and magnetic field, pressure etc.
2. Performance forecast: prediction of capability to withstand the stresses. It has been found to be much more difficult task, because models of physical failure processes like breakdown, burst, re-ignition, melting, rupture or explosion are generally not yet available, let alone software that would implement them. Instead, "design rules" based on practical experience and observations from tests are applied.

Several examples of this assesment are presented in this paper. These include:

- Application of electric field analysis to estimate the dielectric stresses and to predict the withstand voltages of HV equipment:
  A benchmark of dielectric simulation tools has been conducted by the WG. An experimental SF_6 circuit breaker has been manufactured and subjected to high voltage tests specifically for this purpose. Based on the digital CAD files, the electric field was calculated by six major manufacturers. The analysis showed that different software tools predicted almost identical

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dielectric stresses. However, the comparison between predicted and measured withstand voltages (performance forecast), showed with one exception, that the predicted values from the manufacturers were up to 40 % below the measured value.

- Substitution of type tests which are impractical or difficult to implement such as the internal arc withstand test of GIS enclosures:
  Due to the complexity of handling the contaminated SF_6 after tests, and the risk of release of SF_6 to the environment, very little testing is carried out on the equipment, and manufacturers usually rely on calculation.

- Thermal modelling to simulate the behaviour of single components or complete assemblies during a heat-run test:
  Temperature (and temperature rise) is directly specified by the standards and relatively straight forward to simulate by software. From a theoretical aspect, electromagnetic and thermal models are extremely reliable for both solid and fluid parts. Consequently, simulation tools can help to predict the thermal behaviour of equipment. An example showing the accurate calculation of the temperature rise in a 4000 A GIS is presented.

- Experience using simulations to determine design parameters for new equipment that is not covered by the standards:
  When the rating of the equipment exceeds the laboratory’s capacity, the verification of performance relies on simulation results. This is the case for new 1100 kV switchgear designs. Particular examples are seismic analysis and the use of EMTP simulations to establish the TRV peak, RRRV value and DC time constant of the 1100 kV circuit breaker.

It is concluded that simulation is an excellent and instructive tool in the development process, and that good prediction of performance can often be possible in cases where performance is proven by tests on similar designs (interpolation). At the same time, extrapolation of test results and performance prediction of "new" equipment designs seems to be possible only in a limited number of cases.

KEYWORDS

High voltage, Switchgear, Design, Testing, Dielectric analysis, Thermal modelling, Arc burn-through

1. INTRODUCTION

Historically, A3-type power equipment like circuit breakers, switches, instrument transformers, and others have always been thoroughly tested for conformance to standard requirements for their electrical, mechanical, thermal, and environmental operations, as well as their endurance. Over the years, the standards covering those devices have evolved, and new testing requirements to cover more and more different and complex cases have been developed. Power system applications become more complex. On the other hand, the equipment and the technologies employed in the design of this equipment have also evolved significantly. Today, high voltage switching is done primarily in SF_6 and vacuum media, rather than in oil or air, and new solid insulating materials such as epoxies and silicones result in smaller and more compact designs.

Due to these evolving trends, it is more difficult to be able to predict and test a device for all possible cases and for increasing number of applications.

Another important aspect is the economics of testing. Typical testing, such as certification of equipment to standards, is performed and paid for by manufacturers. This cost, depending on the number of units involved, results in higher cost of R&D and consequently of final products. On the other hand testing permits to increase the reliability of the equipment.

The WG A3.20 is examining what can be done in order to supplement and even reduce the amount of tests with the aid of modern simulation and calculation techniques. Many software tools exist to simulate electrical, thermal, mechanical and other stresses. These tools are used extensively today within the manufacturer's internal R&D. A natural step is to extend the acceptance of those tools beyond the R&D environment. Precedence exists, for example, in power transformer standards.

The different levels of prediction power of simulations and calculations as verification tools are [1]:

a) interpolation, i.e. data from the actual tests could be interpolated to a new condition not covered by the tests but between the boundaries of the previously tested cases.
b) extrapolation, i.e. data from the actual tests could be extrapolated to a new condition not covered by the tests but outside the boundaries of the previously tested cases.
c) verification, i.e. since the laboratory testing is also only an approximation of the actual conditions computer simulation can provide an independent confirmation of the validity of the test conditions.
d) test replacement, based on feasibility, availability and cost of testing

Several examples of this evaluation are presented in this paper. These include:

- Application of electric field analysis to estimate the dielectric stresses and to predict the withstand voltages of HV equipment.
- Substitution of type tests which are impractical or difficult to implement such as the internal arc withstand test of GIS enclosures.
- Thermal modelling to simulate the behaviour of single components or complete assemblies during a heat-run test.
- Experience using simulations to determine design parameters for new equipment that is not covered by the standards as in the case of new 1100 kV switchgear.

2. CALCULATIONS OF ELECTRIC FIELD AND DIELECTRIC BENCHMARK

The knowledge about the electric field distribution is of basic importance to evaluate the electric stresses on high voltage equipment. Calculation and simulation of electric fields have been standard development tools for manufacturers of high voltage equipment for many years. Analytical calculations can be used only for simple configurations. In the past, "home made" software programs made for the digital calculation of more complicated problems were used. Today manufacturers use mainly commercial software, which can be coupled with CAD programs. The most commonly used calculation methods are the finite-element-method (FEM) and the boundary-element-method (BEM). The FEM method determines the electric potential in the calculated space by minimization of the field energy [2]. Examples of software packages which use the FEM method are ANSYS®, FLUX®, and Maxwell®. The BEM method does not directly calculate the potential, but sums up the equivalent charges that satisfy the boundary conditions [3]. Examples of software packages, which use the BEM method, are ELECTRO®, COULOMB®. In all cases the results of the calculations are the electric potential and field distribution.

According to the relevant standards, dielectric type tests must be carried out on high voltage equipment to ensure the insulation strength in service. Particularly these are lightning impulse, switching impulse, alternating voltage and their combinations. The dimensioning of the insulation is determined by these voltages. The WG questioned how far it is possible to predict the insulation strength for impulse and alternating voltage from the knowledge of the electric field distribution. A prediction of the withstand voltages based on the electric field distribution delivers inaccurate results at strongly inhomogeneous fields with discharges, e.g. air insulation for outdoor high-voltage equipment. In cases of solid or liquid insulation material, dielectric performance is strongly influenced by material properties and manufacturing processes. However, the withstand voltages can be predicted with a certain precision for weakly inhomogeneous fields in gaseous dielectrics, like SF_6. To check this a benchmark test has been created by the working group. By comparing simulation results from benchmark participants the validity and accuracy of dielectric calculations for a high voltage SF_6 interrupter has been examined. It has been analysed how close the calculations are to the test performance.

Dielectric Benchmark

A model of a simplified interrupting unit of a SF_6 circuit-breaker with insulating nozzle (rated voltage Ur = 170 kV) has been designed and manufactured by two members of the WG [3]. Six companies calculated the electric field distribution for this model independently of each other; four different software packages were used for it. The results were collected and compared by KEMA as an independent testing laboratory. The calculations were carried out for two contact gaps of 30 and 60 mm. The field stress was evaluated at all contacts. All calculations showed the maximum field stress at the arcing contacts. The maximum difference between the companies' results was 3-4 %. The prediction of the lightning-, switching- and alternating withstand voltage was carried out with the internal proprietary dimensioning data of the companies. The predicted withstand values were within a range of -20%.. +20 % of the average value.

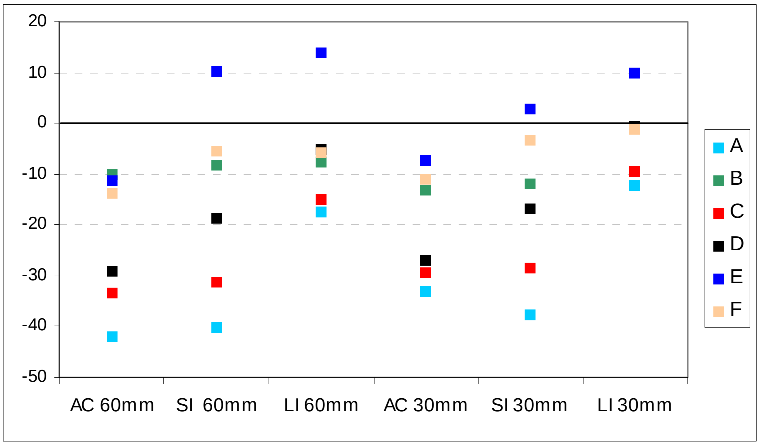


Fig. 1: Deviation (%) from test results of predictions (A-F) of withstand volt. against AC, switching (SI) and lightning impulses for 60 and 30 mm gap

The actual dielectric tests were carried out in the high voltage laboratory of the Technical University of Delft, NL [1]. The withstand voltages were determined for positive and negative lightning and switching impulse voltage and for alternating voltage. The test voltages were in accordance to IEC 60060-1. Total of 21 breakdowns were observed and registered. Most breakdown traces have been found on the arcing contacts and 1 or 2 on the main contacts.

The comparison between the predicted and measured withstand voltages (see Fig. 1) showed, with one exception, that the predicted values from the companies (A-F) were up to 40 % (for lightning impulse voltage 18 %) below the measured value. One prediction was up to 15 % above the measured withstand voltage.

Evaluation

- There were only small differences between the field stresses calculated by the companies independent from the used software. This suggests the adequate performance of the software used by these companies.
- The prediction of the withstand voltages, however, showed greater differences between the companies. Nearly all companies predicted lower values than measured. That means that the internal data of the specific breakdown voltages of SF_6 are different between the companies. These data are based on experience of the manufacturers with their own products, proved by tests.
- The data for different gap lengths (30 and 60 mm) is proportionally consistent. So it seems feasible to perform calculations to interpolate (and not extrapolate) withstand voltages for different gap lengths between 30 and 60 mm.

3. CALCULATION METHODS FOR INTERNAL ARC TESTING

Internal arc testing of metal enclosed switchgear is intended to offer a tested level of protection to personnel in the vicinity of switchgear in the event of an internal arc. Relevant tests are defined in the IEC standard IEC 62271-203 (for GIS), IEC 62271-200, 201 (for metal/insulation enclosed switchgear).

GIS > 52 kV (IEC 62271-203)

Evidence of internal arc withstand of enclosure against bursting and burn-through shall be demonstrated by the manufacturer when required by the user. The IEC standard allows evidence to consist of a test or calculations based on test results performed on a similar arrangement or a combination of both. Test shall be carried out with the normal insulating gas, usually SF_6, at rated gas density. The switchgear is considered adequate if no external effect other than the operation of pressure relief devices occurs within the specified time and if escaping gases are directed so as to minimize the danger to personnel.

Given the complexity to handle contaminated SF_6 after tests, and the risk of release of SF_6 to the environment, very little testing is carried out on the equipment, and manufacturers usually rely on calculation. In such calculations, the chemical processes of SF_6 (and its decomposition products) with the vaporized metallic parts (bus bars, enclosures) has to be included to a sufficiently detailed level. Especially in case of the presence of aluminium, the severe exothermal reaction between Al and dissociated SF_6 (AlF3 formation) leads to significant calculation complexity.

Metal enclosed switchgear ≤ 52 kV (IEC 62271-200, 201)

With the advent of IEC 62271-200 the IAC (Internal Arc Classification) is defined, taking into account various types of accessibility. This depends on effects from internal arc faults, such as overpressures acting on covers, doors, inspection windows etc., as well as the thermal effects of arcs, arc roots, ejected gasses and glowing particles. In contrast to internal arcing in GIS > 52 kV, the relevant IEC standard leaves no possibility to verify internal arc withstand through calculation, even not based on testing on equivalent designs. For this reason, and because of safety concerns, internal arc testing of metal enclosed medium voltage switchgear is very common. Data from KEMA [4] show that success rate of internal arc tests is around 70% in the past couple years. In countries where the user safety requirements became severe, more recently, this success rate is much lower then above. At the same time, many different calculation tools have been produced for the product development stage. These tools range from a collection of empirical relationships, to computational fluid dynamical models based on multi-physics finite element methods.

Various phenomena should be considered:

- dependency of the amount of electrical arc energy that is transferred to the gas on many test- and geometrical parameters;
- complicated chemistry and interactions with insulation/metallic material, especially in SF_6;
- shock waves and turbulent flow processes after pressure relief; role of arc absorbers;
- motion of the arc by the electrodynamic forces acting upon it;
- dependence on the location of initialisation of the fault;

Objective comparison criteria shall be established to enable extrapolations of test results via simulations in metal enclosed switchgear ≤ 52 kV. Criteria "doors shall not open" mean that the stresses exerted on plates, bolts and others can not go above certain materials limits. A comparison criterion to be considered is the comparison between pressure vs time curves and the related calculated stresses in the untested and tested objects. Criteria "not to burn cotton indicators" means that the ejected particles can not arrive to a fixed geometrical point. The comparison criteria are the particle trajectories and speed of gasses vs time in the exit of the pressure relief part.

The WG A3.20 has taken up the issue of internal arc testing for two reasons:

1. The primary driver for this investigation is the wish to ban (for environmental reasons) testing where SF_6 gas is released from the arcing volume into the environment.
   At present, in IEC medium voltage standard 62271-200, Annex A 3.1, a statement is included that allows to replace SF_6 with air at the rated SF_6 filling conditions, and discussions in the maintenance team MT 14 in charge of the revisions of this standard include a proposal to even oblige replacement of SF_6 by air in testing. However, there are many technical publications suggesting that differences do exist between internal arc testing in air and in SF_6. The WG A3.20 will be dedicated to define (with the aid of calculation tools) test conditions under which testing in air is equivalent to testing in SF_6.
2. Given the destructive nature of the test and the costs involved, a study should reveal possibilities to interpolate or even extrapolate from the existing test results with the aid of calculation. At least definition of worst case conditions may be within the range of modern calculation methods.
   Practise has shown that calculations generally can predict pressure rise in compartments relatively accurately. However, the effects of the internal fault arc outside of the enclosure, because of the release of exhaust gases, is more difficult to predict.

4. BENCHMARK TEMPERATURE RISE ANALYSIS

From low to extra high-voltage equipments, the temperature rise of the parts shall not go beyond certain limits dictated by the properties of the insulating and conductive materials. If these limits are exceeded, ageing or even destruction of parts may occur. IEC Technical Report 60943 is a useful reference for the concepts related to this subject.

From a theoretical aspect, electromagnetic and thermal models are fully reliable for both solid and fluid parts. Consequently, simulation tools can help to predict thermal behaviour of equipment and to reduce or partially replace thermal tests.

The main data affecting the results are the current, the materials involved, the contact resistances, the ambient air temperature and the gas volume. The contact resistances, not so easy to define, have to be determined as a function of the contact forces, materials and coatings. Electrical and thermal properties have to be properly defined as a function of temperature. These can be obtained from literature or experimental data.

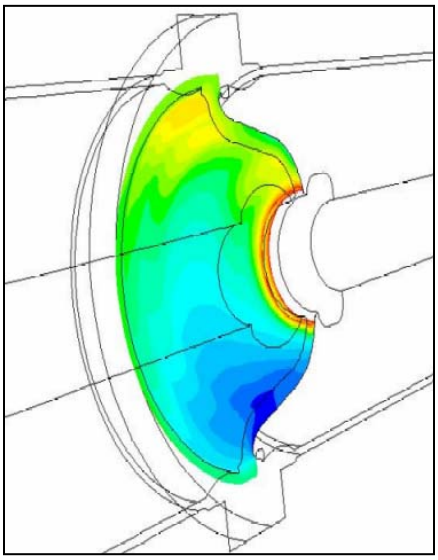


Fig. 2: Example of temperature distribution calculated along a spacer of a 4000A GIS

A full analytical approach can be possible but is limited to very simple configurations or empirical data and formula for both electromagnetic and thermal models. Such approach gives quite good results very rapidly for average temperature values but with no accuracy for hot spots.

2D or 3D numerical approach corresponds to a real geometry simulation without any major approximations. Tools enabling virtual temperature rise tests are available in most of the commercial software. For certain applications, electromagnetism takes into account all the skin or eddy current effects. Thermal calculation considers the heat propagation inside solids and fluids. Appropriate mesh and choice of models have to be analysed since many different fluid models can be applied. Depending on the complexity of the models and the time constants involved, the resolution can be time consuming but still less than real temperature rise tests.

The comparison factors which are useful to correlate test and simulation results are:

a) The temperature at different locations in steady state. These are relatively easy to obtain by direct measurement

b) The evolution of the temperature rise of the hottest point.

The difference between simulated and measured temperature is typically between 1K and 5K for the 4kA GIS application of Fig. 2.

5. INTERPOLATION OF TEST RESULTS FOR NON STANDARD TRV

The verification of a circuit breaker interrupting performance is realized with type tests. Various tests have to be performed as defined in the IEC 62271-100 standard. Depending on the test type the breaker is exposed to different stresses. While dielectric stresses are dominant for capacitive and inductive current switching tests, other stresses such as mechanical, thermal or chemical become important for terminal or short line faults breaking tests.

Models of physical failure processes are generally not available and the prediction power for most of the test duties is limited to interpolations. The WG sees possibilities for interpolation of test results of basic short circuit test.

Basic short circuit test duties are performed at 10, 30, 60 and 100 % of the circuit breaker rated short-circuit breaking current with standardized parameters. The standardized TRV, which is defined for each current level, is said to represent the "more severe switching conditions" and covers most of the cases (90 % for IEC). Although it is generally admitted that TRV with lower rate of rise represent "less severe switching conditions", service experience have shown, in various cases, that this is not a universal rule.

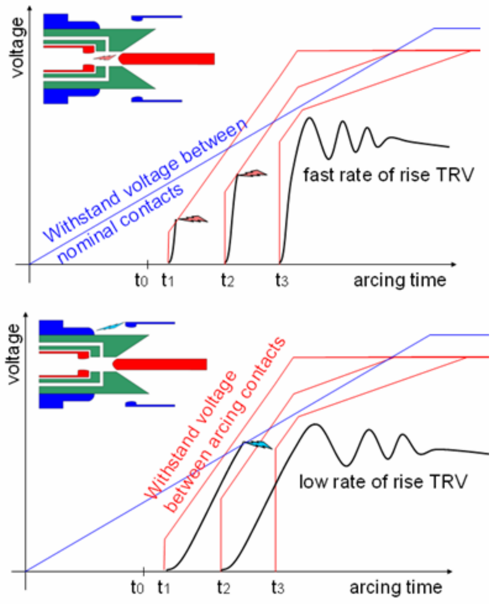


Fig. 3: Example of a circuit breaker that reignites between the nominal contacts only for a low rate of rise TRV

One example is the field experience, where successfully type-tested circuit breakers failed to clear with a low short-circuit current (T10 conditions) with a lower rate of rise TRV than standardized. In that example, this TRV condition made the circuit breaker to attempted to clear with a very short arcing duration (not reached during the original type tests) leading to an unexpected reignition between the main contacts.

The circuit breaker has to be designed to withstand any TRV up to the rated TRV for any current up to the corresponding rated current. Any reignition, which may occur for arcing times shorter than the minimum arcing time, shall take place between the arcing contacts. This is ensured by proper dielectric coordination of the interrupter chamber [6].

An approach for a design check to reveal a design weakness and check the dielectric coordination has been discussed within the WG. The reignition occurs after arc interruption if the TRV exceeds the dielectric strength of the contact gaps. These contact gaps increase with the arcing time.

A design check could be done in three steps. First the electric field has to be simulated for the circuit breaker in a number of gap lengths for each location where electrical breakdown can initiate. The second step is to correlate the electric stress with measured breakdown voltages. In the third step it can be shown that for any contact distance and any TRV the reignition is to take place only between the arcing contacts.

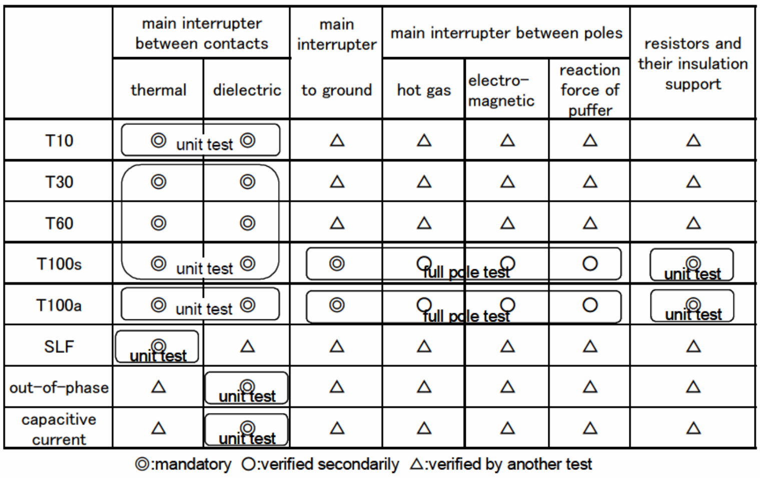
The discussed design check is an example for interpolation of test results by means of simulations. Type testing cannot cover all the network conditions but the above example shows that an E field calculation can be used to check the correctness of the contact coordination along the total arcing window.

6. EXPERIENCE OF SIMULATION FOR 1100KV SWITCHGEAR

In case where the rating of the equipment exceeds the laboratory's capacity, the verification of performance relies on simulation results. One example is the seismic test for an 1100kV GIS.

Simulations are also used to determine design parameters for new equipment that is not covered by the standard. EMTP software was used to establish the TRV peak, RRRV value and DC time constant of 1100kV breakers. The EMTP simulations also indicate the possibility of delayed current zeros and a distortion of current near zero.

Table 1: Interruption Test Set up for 1100kV Breaker Main



	main interrupter between contacts		main interrupter	main interrupter between poles			resistors and their insulation support
	thermal	dielectric	to ground	hot gas	electro-magnetic	reaction force of puffer	
T10	◎ unit test	◎	△	△	△	△	△
T30	◎	◎	△	△	△	△	△
T60	◎	◎	△	△	△	△	△
T100s	◎ unit test	◎	◎	○ full pole test	○	○	◎ unit test
T100a	◎ unit test	◎	◎	○ full pole test	○	○	◎ unit test
SLF	◎ unit test	△	△	△	△	△	△
out-of-phase	△	◎ unit test	△	△	△	△	△
capacitive current	△	◎ unit test	△	△	△	△	△

◎:mandatory ○:verified secondarily △:verified by another test

All making and breaking performances are required to be verified by physical tests. In other words, simulation is not relied on for any making and breaking performances of an 1100kV breaker at present. Whenever possible, a full pole test with set up as close as possible to the actual application is desirable. In fact, stresses imposed on the 1100 kV breaker in Japanese case were verified separately by combining both full pole and unit tests as shown in Table 1, from streamlining and economical viewpoints of the test. In this table, "verified secondarily" (circle symbol) means that they were automatically verified in the same test, and "verified by another test" (triangle symbol) means that they were obviously lower stress than some other test, therefore well accepted to be omitted.

Table 2: Seismic analvsis results of the 1100 kV aas bushinas

Manufacturer	Analysis method	Analysis result		Test result [N/mm^2]	Error [%]
		Specific frequency [Hz]	Bending stress at porcelain shell's root [N/mm^2]		
A	Shell model	4.35	11.3	11.5	1.7
B		4.92	10.4		9.6
C		4.63	11.8		2.6
D	Bar model	4.86	11.1		3.5

When a full pole test with grounded tank is possible, the test will be done this way since it is closest to the field application of the breaker. In this case, the voltage source of the test circuit must be able to generate the full peak of the TRV and maintain its envelope requirements. In case where the single voltage circuit is not able to generate the TRV, another circuit can be used, where partial TRVs are injected from both terminals with tank insulated from the ground.

In some cases, the simulations are used for the whole equipment and verification test is done on one part of the equipment. For example, seismic analysis is done on the whole 1100kV breaker, but only the bushing which is considered as the weakest part of the breaker was tested in the laboratory. The stresses from test and the simulation conducted by 4 independent manufacturers were found to be within 10%, as shown in Table 2.

7. CONCLUSION

In this paper the WG A3.20 examined several possible testing topics that are good candidates for using simulations and calculations, in addition to or as a replacement of laboratory testing.

The results of the benchmark show that dielectric calculations can be used in cases where performance is proven by tests of similar designs (interpolation). Extrapolation and performance prediction of “new” designs seems possible only in a limited number of cases.

For internal arc testing it could be possible to predict the pressure rises in different compartments and enclosures but it could be more difficult to include the effects of burn-through or arcing outside the enclosures. The temperature rise tests seem to be the most straight-forward to be predicted by the simulations. Both the temperature distribution at steady-state and the time evolution of the hot spots seem quite possible. For circuit breaker arc interrupting performance some interpolation is possible between proven test results. One can also use simulations to check the dielectric coordination of the interrupter chamber during the opening process at different contact gaps. This is a valuable approach since the actual testing of these specific conditions is often difficult or impossible in the real laboratory environment. Finally, simulations could be used for equipment that exceeds the laboratory capabilities, for example at 1100 kV rating.

Future work of the WG A3.20 will be:

- to define how simulation can be used for standard
- to define the application area for HV products
- to chose a benchmark between the WG partners using different software with the same physical hypothesis
- to develop guidelines how to analyse and validate results with test measurements
- to develop best practice guidelines.

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