Safety clearance between high voltage test systems and parts of air-insulated substations in operation

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Abstract

In the context of high voltage testing on-site within operating air insulated substations (AIS), the question of safe distances between high voltage test systems and live switchgear parts is an important safety issue. Until now no official guidelines or published state of the art exists. That question of safe distance arises particularly in testing of GIS, hybrid switchgear, AIS and high-voltage cable with air terminations.

The risk of sparkover in general between the test system and a switchgear part under operating voltage is assessed. Generally, the occurrence of transient overvoltage cannot be excluded both in the tested system, as well as in the operating system. Considering the worst case, transient differential voltages in the range of 2 MV may occur during tests even at nominal voltage of 400 kV in AIS. Depending on the physical model, safety clearances between 8 and 11 metres in 420 kV AIS must be result in this worst case.

A simple method for determining a safe distance based on basic principles of insulation coordination relevant to the question of maximum sparkover distance is presented. In order to cover all cases, the proposed method includes certain safety margins; in this form, it has already been applied by the authors in the past. Hence, the proposed method seems to provide the required safe distances and may be seen as a starting point for discussions to formulate a harmonized and commonly accepted state of the art.

1 Introduction

With the increase of cable connections, from GIS and hybrid switchgear to the highest voltage levels, the number of tests during commissioning is also increasing. As test equipment, series resonance systems are used, which are often erected in air-insulated outdoor switchgear. In many cases, only the tested plant components can be taken out of operation. This raises the question of the required distances (i.e. *safety distances*) to be respected between the test equipment and the system parts under operating voltage (see Figure 1) guarantying a safe operation.

The necessity of decommissioning an adjacent switching bay represents a significant disadvantage for the operator and possibly also for the supplier of the tested equipment. This leads to conflicts of interest, which is why a clear regulation of the required safety distance is indispensable.

During AC withstand tests utilizing air-insulated high-voltage resonance test systems, it must be considered that the mains frequency of the power grid and the frequency of the test voltage differ from each other. As a result, instants with phase opposition between the grid voltage and the test voltage occur periodically, with considerable potential difference amplitudes as a consequence.

Furthermore, the occurrence of transient overvoltage cannot be excluded on the test-voltages due to operation of test system (e.g. due to insulation break-down in the tested component) as well as on the grid-voltage, such as due to switching actions in the HV grid. Considering the worst case, these transient overvoltages must be added to the peak values of the AC voltages in phase opposition.

Under this assumption, total transient differential voltages in the range of 2 MV may occur during tests of equipment with a rated voltage U_r of 420 kV.

Depending on the rise time of the transient, for such high voltages the mechanism of leader sparkover may have to be assumed, with propagation field strength in air, particularly in positive channel discharges, falling to very low values down to 0.1...1.5 kV/cm.

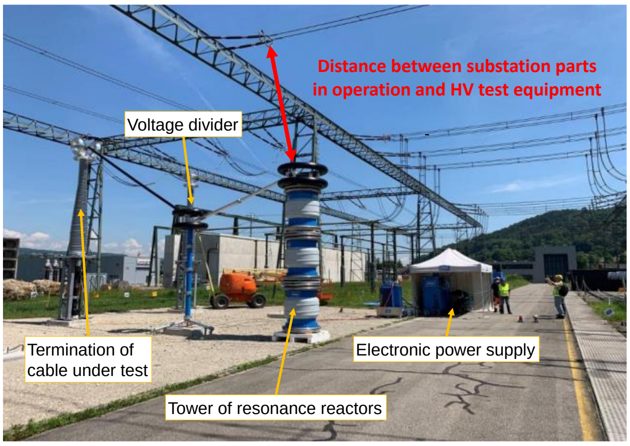

Figure 1 Typical situation during a 400-kV-cable resonance test in the substation in operation

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2 Consequences of a disruptive discharge between test equipment and life substation parts

In order to assess the risk, the first question to be asked is what consequences are to be expected from a sparkover between the test equipment and switchgear parts under operating voltage.

A sparkover leads to a transient in the range of microseconds, which is damped by the impedances of the sources and the arc. This transient is to be considered an overvoltage. After the transient event is decayed, the grid voltage is forced upon the test voltage system as long as the arc exists.

As the applied test voltage is normally higher than the grid voltage and as the test installation with the resonance reactors has a relatively high impedance, a low current arc is present which even may extinguish by itself. In this case the sparkover may remain without further consequences.

However, if the transient involved with the sparkover leads to a failure of the insulation of the test equipment or if the arc – especially if its current is too large to be extinguished – vagabonds to an earthed structure, the current rises to the short circuit value of the corresponding switchgear and thus a serious danger to persons results.

The inestimable consequences of a sparkover are an important reason for preventing it.

3 Proposed rule to determine the required safety distance

A simple universal rule is proposed below for determining a safety clearance:

Due to the possible occurrence of unforeseen transient overvoltages of varying origin and unknown shape during the high voltage test, a switching impulse overvoltage with critical rise time is taken as the base for determining the safety distance.

To determine the minimum acceptable distance in air to live system parts, the following simple concept is introduced.

The concept is based on a total safety-relevant differential total voltage ΔU. It has already been applied by the authors in the past. In order to cover all cases, the proposal includes certain safety margins.

3.1 Peak voltage for switchgear in service $\hat{U}_A$

The initial point is the maximum permissible operating voltage U_r of the outdoor switchgear. Considering the phase voltage in three-phase systems, U_r is divided by a factor of $\sqrt{3}$; in two-phase (railway) systems U_r is divided by a factor of 2. For consideration of the peak value, U_r is multiplied by $\sqrt{2}$.

Hence, the following applies for three-phase systems:

$$\hat{U}_{\mathrm{A}} = \sqrt{2/3 \cdot U_{\mathrm{r}}} \quad .$$

3.2 Test system peak voltage $\hat{U}_{ds}$

Maximum peak voltage for alternating voltage tests: $\hat{U}_{\mathrm{P}} = \sqrt{2} \cdot U_{\mathrm{ds}}$. For impulse voltage, the peak value of the transient is designated $\hat{U}_{\mathrm{ds}}$.

3.3 Safety-relevant differential crest voltage ΔU

Here the higher of the two peak voltages is counted double for consideration of the overvoltages (on the test or network voltage side): $\Delta U = \hat{U}_{\mathrm{A}} + \hat{U}_{\mathrm{ds}} + max(\hat{U}_{\mathrm{A}}, \hat{U}_{\mathrm{ds}})$. For impulse voltage tests, the peak value of the network voltage $\hat{U}_{\mathrm{A}}$ is doubled.

3.4 Determining the corresponding safety distance

The required safety distance d is then calculated with the following equation:

$$d\ [\mathrm{m}] = 8\ m \cdot \frac{\Delta U\ [\mathrm{kV}]}{3400\ \mathrm{kV} - \Delta U\ [kV]} + D_s\ [\mathrm{m}] \qquad (1)$$

This correlation can be used for all test safety relevant differential crest voltage of $\Delta U = (0 \dots 2000)$ kV and gives the shortest necessary direct distance between parts under voltage of the test system and the switchgear. It is derived from a familiar empirical formula for the 50% leader breakdown voltage for positive switching voltage with critical rise time ([1-3], see also measurement curve in [4][1]). The additional added distance D_s is a safety margin which takes into account the following uncertainties:

- Atmospheric influences
- Statistical scatter of sparkover voltage
- Movements of HV conductors and high voltage test connections
- Measurement uncertainties in the geometry

The authors use a D_s of 1.5 m in their internal on-site testing practice following the safety surcharge in [5], which is a conservative value. In the absence of the above uncertainties smaller values or even the complete omission of the extra safety margin are conceivable as is shown in section 4.

[1] Original relation $U_{d,SI50RP} = \frac{3.4}{1+\frac{8\ m}{d}}$ MV for the critical time to crest with lowest breakdown voltage

3.5 Example

Test of a HV device of U_r=420 kV (short duration withstand test 515 kV_{eff} according to IEC 62271-203, table 107) with an outdoor series resonance system near a 420 kV outdoor switchgear part under operating voltage.

i) Peak voltage for switchgear in service:

$$\widehat{U}_A = \sqrt{2/3} \cdot U_\mathrm{r} = 0.816 \; \cdot \; 420\,\mathrm{kV} \; = \; 343\,\mathrm{kV}$$

ii) Test system peak voltage $\widehat{U}_{ds}$:

$$\widehat{U}_\mathrm{ds} = \sqrt{2} \cdot U_\mathrm{ds} = \; 1.414 \; \cdot \; 515\,\mathrm{kV} \; = \; 728\,\mathrm{kV}$$

iii) Safety-relevant differential crest voltage ΔU

$$\begin{aligned}\Delta U = \widehat{U}_\mathrm{A} + \widehat{U}_\mathrm{ds} + \max\left(\widehat{U}_\mathrm{A}\;,\;\widehat{U}_\mathrm{ds}\right) \\ = \; 343\,\mathrm{kV} \; + \; 728\,\mathrm{kV} \; + \; 728\,\mathrm{kV} \\ = \; 1{,}799\,\mathrm{kV}\end{aligned}$$

iv) Determining the corresponding distance:

$$d\;[m] = 8\;m \cdot \frac{\Delta U[\mathrm{kV}]}{3'400\;\mathrm{kV} - \Delta U\;[\mathrm{kV}]} + 1.5\;\mathrm{m} = \; 10.5\;\mathrm{m}$$

4 Possible model refinement based on knowledge from insulation co-ordination

In this section an approach to determine the safety distance is provided, following concepts of insulation co-ordination [6]. To this end the influence of the various forms of stresses are analysed. The possibility of taking them into account when determining the safety distance is discussed. From this, conclusions can also be drawn regarding safety clearances necessary in connection with impulse voltage testing.

4.1 Overvoltages to be considered

4.1.1 Overvoltage in the test-setup

In case of a failure within the test-set or the test-object, an oscillatory transient is expected, which may surmount the test-voltage amplitude $\sqrt{2}\,U_\mathrm{ds}$. It is a worst-case approximate, when assuming an overvoltage of $2 \cdot \sqrt{2}\,U_\mathrm{ds}$, which may result, when those transient voltages propagate along the test object and are reflected at its ends.

As such transients are considered to be fast (i.e. in the MHz-range), the resulting overvoltage would be a fast-front overvoltage. As a worst-case that overvoltage is now expected to happen at the instant of the opposed voltage-peak of the system still being in operation (unlike the logic adopted across open switching devices and insulating distances, where only 70% of the continuous voltage peak is taken for fast-fronts due to statistical reasons [7]), resulting in

$$\Delta U_\mathrm{FT} = \sqrt{\frac{2}{3}} \cdot U_r + 2\sqrt{2} \cdot U_\mathrm{ds} \quad .$$

Example:

For $U_\mathrm{r} = 420$ kV with values from [7]

$$\Delta U_\mathrm{FT} = \sqrt{\frac{2}{3}} \cdot 420\,\mathrm{kV} + 2\sqrt{2} \cdot 515\,\mathrm{kV} = 1800\,\mathrm{kV}$$

As the test voltage is larger than the rated voltage U_r this provides the same result as for $\widehat{U}_S$ in section 3.5.

4.1.2 Overvoltage in the system still being in operation

The overvoltages to be expected in the operating switchgear is not known a priori. However, they may be estimated in the sense of a worst case based on the rated withstand voltages.

According to the idea of the insulation coordination [6], the required rated withstand voltages are determined such that they are considerable larger than those to be expected in the foreseen operation. For example, the expected co-ordination withstand voltages are multiplied by safety factors to derive the required withstand voltages and the latter are than rounded to the next larger set of standard rated withstand voltages.

Hence, it must be considered a worst-case, when deriving minimum clearances on the basis of the standard rated withstand voltages, by which we get as a representative of:

- A slow front overvoltage in the system still being in operation, the rated switching impulse withstand voltage U_s or, in range I of [6], the rated short-duration power-frequency withstand voltage U_d; the latter is disregarded in the following
- A fast front overvoltage in the system still being in service, the rated lightning impulse withstand voltage U_p

As a worst-case between that overvoltage is now expected to happen at instant of the opposed voltage-peak of the test-set (unlike the logic adopted across open switching devices and insulating distances, where only 70% of the continuous voltage peak is taken for fast fronts due to statistical reasons [7] mentioned before), results in

$$\Delta U_\mathrm{LI} = U_p + \sqrt{2} \cdot U_\mathrm{ds} \quad ,$$

$$\Delta U_\mathrm{SI} = U_d + \sqrt{2} \cdot U_\mathrm{ds} \quad .$$

Example (continuation for $U_r = 420$ kV):

$\Delta U_\mathrm{LI} = 1425\,\mathrm{kV} + \sqrt{2} \cdot 515\,\mathrm{kV} = 2153\,\mathrm{kV}$
$\Delta U_\mathrm{SI} = 1050\,\mathrm{kV} + \sqrt{2} \cdot 515\,\mathrm{kV} = 1778\,\mathrm{kV}$

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4.2 Maximal potential difference

Taking the maximum of the two fast-front overvoltages resulting from the last two sections results in

$$\Delta U_{\mathrm{LI\,max}} = \max\left(\Delta U_{\mathrm{FT}}, \Delta U_{\mathrm{LI}}\right)$$

and the following maximal potential differences

- Slow front ΔU_{SI}
- Fast front $\Delta U_{\mathrm{LI\,max}}$

Example (continuation for $U_r = 420$ kV):
$\Delta U_{\mathrm{LI\,max}} = \max(\Delta U_{\mathrm{FT}}, \Delta U_{\mathrm{LI}}) = 2153$ kV

4.3 Normative phase-to-earth and phase-to-phase clearances in AIS

According to the insulation coordination [6], air-insulated installations (such as substations or transmission systems), which typically cannot be tested as a whole, are considered to be sufficiently insulated, when using the clearances provided in Appendix A of [6], up to altitudes of 1000 m. Above of this altitude, corrections have to be adopted. Nota bene, this would not only impact required clearances for testing but also for the whole substation design, which would be subjected to altitude corrections as well. It is suggested to use such altitude corrections in case of need (i.e. in case of altitudes higher than 1000 m), but specific discussion is omitted here.

In this said Appendix A, Table A.1 provides air clearances for rated lightning impulse withstand voltages, while Table A.2 and A.3 provide air clearances for rated switching impulse withstand voltages for phase-to-earth (A.2) and phase-to-phase (A.3).

For the maximum potential ΔU_{SI} and $\Delta U_{\mathrm{LI\,max}}$ are now to be rounded up to the next standard value provide in the corresponding tables and the corresponding maximum clearance for this voltage is to be noted.

Example (continuation for $U_r = 420$ kV):

- Next larger value for $\Delta U_{\mathrm{LI\,max}} = 2153$ kV in A.1 [6] is 2250 kV with required clearance of 4500 mm (rod-structure)
- Next larger value for ΔU_{SI} in
  - A.2 [6] is 1800 kV with required clearance of 8300 mm (rod-structure)
  - A.3 [6] is 2210 kV with required clearance of 7400 mm (rod-conductor)

Hence, the resulting distance is 8.3 m, being the maximum of the three values. Irrespective the various worst-case approximations taken in its derivation, this value is still somewhat smaller than the 10.5 m resulting from the simple rule (section 3).

However, in [6] Appendix A it is pointed out that these distances are intended for the purpose of insulation coordination and not to define safety distances.

5 Required breakdown distance calculation according insulation coordination standards

The insulation coordination standard [8] also contains formulas to calculate "[…] air gap breakdown strength from experimental data" in its Appendix F for *informative* purpose. The most relevant ones are discussed in the following and compared with the formula determining the withstand distance (1) used in the simple rule proposed in section 3 in this paper.

5.1 Standard switching impulse voltages

To determine the 50% breakdown voltage $U_{50\mathrm{RP}}$ in [kV] in rod-plane gaps with clearance d in [m] under standard switching impulse at sea-level, usage of

$$U_{50\mathrm{RP}} = 500\, d^{0.6} \qquad (2)$$

is promoted in [8]. As rod-plane is the most critical geometry (i.e. featuring the smallest breakdown voltages, see Table F.1 of [8]), no further geometries are discussed here. Hence, above formula is to be considered a worst-case.

5.2 Standard lightning impulse voltages

For standard lightning impulse, usage of

$$U_{50\mathrm{RP}} = 530\, d \qquad (3)$$

for 50% breakdown voltage in [kV] for a rod-plane gaps with clearance d in [m] at sea-level is suggested in [8].

5.3 Comparison of the formulas

Resulting clearances in dependence of the voltage calculated by the various formula are summarized in Figure 2. As technical electrode-arrangements deviate from the worst-case given by rod-plane, the considering the distance calculated by equation (1) to be a safe withstand voltage for technical arrangements seems fair.

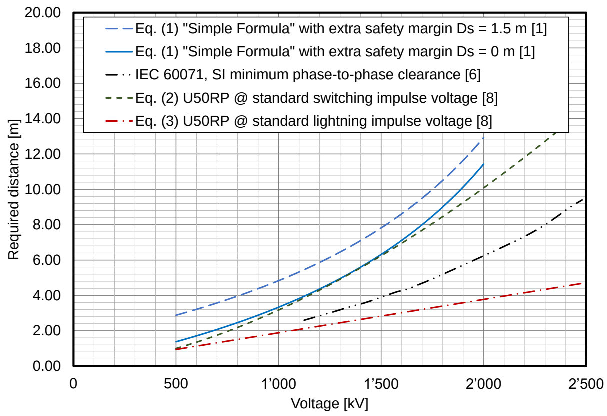

Figure 2 Resulting clearances in dependence of the voltage calculated by the various formula from [1] and IEC [6], [8]. It should be noted that the formulas from IEC are meant for 50% breakdown voltages in rod-plane gaps at sea levels.

6 Conclusion

During high-voltage tests in outdoor switchgear systems, the high differential voltages due to recurring phase opposition and transient overvoltages can cause sparkover developing according the leader mechanism, which may bridge large air distances. Therefore, large safety distances are required, which easily reach 10 m with the presented worst-case approximations for rated voltage $U_\mathrm{r} = 420$ kV.

Taking into account the worst-case assumptions described, the authors have been using relationship (1) for several years to determine the safety margin, which also largely corresponds to relationship (2).

Maintaining such distances may make it necessary to disconnect adjacent substation parts during HV tests.

To facilitate the associated decisions, uniform guideline values for the minimal necessary safety distances are desirable.

The present proposal for a simple rule to determine such safety distances can be understood as a starting point for a discussion in corresponding committees and the community of test engineer charged with on-site testing. This discussion shall help in formulating a harmonized state of the art, providing practical rules which do not take compromises regarding health and safety.

7 Literature

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