DIELECTRIC STRESS: DESIGN AND VALIDATION OF MV SWITCHGEAR

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ABSTRACT

Medium voltage switchgear is a key component within electrical power distribution networks. It is designed and tested for safe and reliable operation under various operating conditions. Medium voltage air-insulated switchgear (AIS) and gas-insulated switchgear (GIS) have to be validated according to the requirements of international standards like IEC 62271-1 and IEEE C37.100.1 for instance. The dielectric design is optimized with an extensive use of simulation and experimental test validations required by standards, customers specifications or defined by the manufacturers of switchgear for their own quality criteria. That ensures insulation reliability in various applications and operating environments.

The first part of this paper concerns dielectric stresses of switchgear during its operational life under real network conditions. The second part of this paper concerns dielectric design and validation of MV AIS switchgear depending of environmental conditions (humidity, salt, dust…) and in particular the impact on insulation ageing and potential degradation. Insulation techniques (GIS and AIS) and testing procedures are discussed. The degradation of the external insulation of AIS is demonstrated and can be mitigated by the choice of a higher value of the dielectric BIL or power frequency withstand (example for 12 kV rating: 95 kV BIL instead of 75 kV BIL or 42 kV instead of 28 kV 50 Hz). On the other hand, no additional margin on the dielectric withstand is necessary for protected insulation (GIS).

INTRODUCTION

Medium voltage switchgear is a key component within electrical power distribution networks. It is designed for safe and reliable operation under various operating conditions. In order to minimize power losses due to current flow, power distribution is made at reasonable levels of service voltage, a voltage always lower than the rated voltage. The dielectric performance of medium voltage switchgear must be part of the insulation coordination in the network. It needs to withstand not only the service voltage, but also short-duration or impulse overvoltages that can stress the switchgear's insulation.

Generally, medium voltage air-insulated switchgear (MV AIS), gas-insulated switchgear (MV GIS) and (shielded) solid insulation switchgear (MV (S)SIS) have to be validated according to the requirements of international standards. To facilitate the reading of this paper, SIS are considered as AIS and SSIS as GIS.

A distinction is made between dielectric design and validation of MV AIS switchgear, depending of environmental conditions (humidity, salt, dust…) and in particular their impact on insulation ageing and potential degradation, and GIS where electrical field is not sensitive to environmental conditions. When environmental conditions are severe or not well known, it is better to choose GIS or to require the highest insulation level defined in the standards for the rated voltage considered, if the chosen technology is AIS.

SPECIFICATION

An insulation coordination study on the network identifies the external constraints that could exist on the network, and considers what other means of protection may be used. Then the specifications of the required equipment can be defined.

The dielectric tests are specified in IEC and IEEE:

- For switchgear, these are the main standards to consider when choosing a product with the correct rated voltage to suit the network application: IEC 62271-1[1], IEEE Std C37.100.1 [3], IEEE Std C37.20.2 [4] and IEEE Std C37.20.3 [5]. These standards propose several insulations levels for each rated voltage.
- For insulation coordination, the main standards to be referenced are IEC 60071-1 [6], IEC 60071-2 [7], IEEE C62.82.1 [9].

The rated voltage (U_r) is the maximum rms system voltage for which the equipment is designed to be used. When choosing a rated voltage, it should be greater than or equal to the highest system voltage (U_s).

In both IEEE C37.100.1 [3] and IEC 62271-1 [1] there are two series of values for switchgear rated voltage, and although these series are named differently, the voltages within the two series are the same in both standards. These series are shown in Table 1.

standard	series	preferred rated voltage (kV)
IEEE C37.100.1	Series A	4,76 – 8.25 – 15 – 15.5 – 25.8 – 27 – 38 –
IEC 62271 - 1	Series II	48.3 – 72.5 – 123 – 145 – 170 – 245
IEEE C37.100.1	Series B	3.6 – 7.2 – 12 – 17.5 – 24 – 36 – 52 –
IEC 62271 - 1	Series I	72.5 – 100 –123 – 145 – 170 – 245

Table 1: rated *v*oltages from IEC & IEEE standards

For the purpose of discussing insulation coordination in this document, the baseline (1 p.u.) will be defined as:

$$\mathbf{1p.u.} = \frac{\boldsymbol{U_r \times \sqrt{2}}}{\boldsymbol{\sqrt{3}}}$$

OVERVOLTAGES

An overvoltage is any voltage on a system that exceeds the peak value of the highest phase to earth system voltage (12.25 kV for 15 kV maximum service voltage of an electrical equipment) or that exceeds the peak value of the highest phase to phase voltage (21.21 kV, for 15 kV maximum service voltage).
Generally, as defined in IEC 60071-1 [6], there are two ranges of overvoltages: low frequency and transient.
- Low frequency overvoltages can be classified as continuous or temporary overvoltages. These are an increase in the power frequency network voltage usually caused by a change in load or a phase to ground fault that induces an increase of the voltage of the heathy phases up to the phase to phase voltage.
- Switching overvoltages are slow front transient voltages that occur during network switching operations. The magnitude of a switching overvoltage is usually higher than for power frequency overvoltages, but the duration is quite short. For MV applications, the switching overvoltages are covered by the power frequency dielectric tests. There is no explicit link between switching overvoltage and the transient recovery voltage (TRV), as defined in IEC 60271-100 [2]. The magnitude of the transient recovery voltage phase to ground is roughly around 2-3 p.u. and the TRVs duration is usually tens to hundreds of microseconds.
- Lightning fast front overvoltages are caused by lightning strokes either directly on the power network or on equipment adjacent to the power network. Lightning overvoltages give the fastest application of the transient voltage in the range of 1-20 microseconds to the peak, but the peak is usually only present for a few microseconds before the wave decays. The peak value associated with lightning strokes is the highest of all the different forms of overvoltage.

These overvoltages depend on the configuration of the electrical network. The probability that a switchgear undergoes a lightning fast front overvoltage is not zero in overhead network; but it is zero in underground network.
If we now consider the routine and type test levels in terms of a comparison to the rated voltage, then we can see that the most severe test is the lightning impulse test at 95kV for equipment with a U_s = 15kV. In p.u terms when compared to the phase to earth value for rated voltage this represents an overvoltage of 7.75 p.u.

For power frequency (PF) tests we consider that the IEC test voltage level of 38kV is more severe than the IEEE test voltage level of 36kV. For the PF test voltage, we should consider the peak value of the test voltage, which for a 38kV would be 53.7kV or 4.38 p.u.
Both the IEC and IEEE standards specify that the PF test is performed for 60s at either 50 Hz or 60 Hz.

The switchgear manufacturers use the standards as a guide for design and to validate the products' performance.
After having done an insulation coordination study on the network, identifying the external constraints, users select the equipment based on their knowledge of what the highest network voltage will be for their application, and choose a slightly higher rated voltage. They shall also consider choosing the associated insulation level to properly cover the expected voltage stresses on the network. When a user chooses the switchgear, he is then aware that the switchgear has been validated in accordance with IEEE or IEC specifications. In this case, the basic requirements of the dielectric type tests are withstood.

When direct lightning stroke occurs on a distribution network, the voltage created is much larger than the lightning impulse withstand voltage and without protection the network will certainly fail.
However, if properly selected Zinc Oxide surge arresters are installed on the interface between the overhead line and the substation, the maximum voltage that should be observed within the switchgear should be less than 5.5 p.u., which is less than the lightning impulse withstand voltage. The purpose of the surge arrester is to avoid damage or instantaneous failure of the insulation system of a network caused by overvoltage conditions.

Whatever the technology (AIS or GIS), whatever the environment external to the apparatus, the switchgear complies with the same standards. On the overhead-network where the risks of lightning exist, a surge arrestor protects the switchgear in short-circuiting it. Provided that the surge arrestor is properly selected, properly installed, and that the stroke is within the considered range of discharge current, the residual voltage is always inferior to the BIL standard's values of the rated voltage.

DIELECTRIC DESIGN AND VALIDATION

The insulation techniques present in switchgear are listed in the following table 2:

Insulation technique	*Design concerns*	*Self restoring insulation*	*Aging with external environment*
Air insulation in direct line	*Field optimisation, clearance distance*	*Yes*	*Yes*
Gas insulation in direct line	*Field optimisation, clearance distance*	*Yes*	*No*
Barrier insulation	*Positioning of barriers, by-pass distance*	*Possible degradation depending on the discharge energy*	*Yes (condensation, pollution deposit)*
Surface insulation	*Creepage, triple junctions (1), anti-tracking properties of material*	*Possible degradation depending on the discharge energy*	*Yes (condensation, pollution deposit)*
Volume insulation	*Partial discharges, industrial process, material selection*	*No*	*No*

(1): defined by the presence of a conductor, solid insulating material and a gas at the same position

Table 2: Sensibility to ageing with external environment as a function of the insulation technique

MV switchgear must withstand both its rated voltage during its entire life in various operating conditions and transient short duration overvoltages that can stress the apparatus's insulation.

The dielectric validation test procedure has to consider both aspects. Validation takes into account type tests in accordance with standards and aspects which are not taken into account by standards (ageing for instance).
Numerous test methods are available to check the insulation performance:

- Lightning impulse tests
- Power frequency tests
- Partial discharge tests (with inception / extinction voltage)
- Insulation resistance measurements
- Long term aging tests

The dielectric tests can be classified as standardized tests and complementary dielectric tests.

<u>Standardized tests:</u>

<u>Type tests:</u> their aim is to prove the ratings and characteristics of switchgear, thus validating the design. They are performed on a limited number of units of the product, and possibly damage the test object.

<u>Routine tests:</u> they are for the purpose of revealing possible faults in material or construction of switchgear. They are most often performed in the manufacturer's work on each piece of apparatus produced. Alternatively, by agreement, they can be also performed at a customer's site.

Two test voltage shapes are considered for medium voltage switchgear as covering the whole range of overvoltage classes: the short-duration power frequency and the standard lightning impulse. Whatever the technology (AIS or GIS), whatever the configuration of the network, whatever the environmental conditions, the tests are the same.

Complementary dielectric tests are performed by the manufacturer, after the design phase of the switchgear, or in the case of production sampling. These tests are based on the know-how of the manufacturers and cannot be introduced in the standards due to the diversity of situations and parameters.
Some of these tests are specific to AIS due to its sensitivity to environmental conditions.

ENVIRONMENTAL IMPACT ON THE LIFE DURATION OF AIS

Specific tests intend to check the aging behavior of the electrical insulation (both material and design) with various external stresses encountered during the real life of the equipment, such as temperature variations, high humidity, pollution, and mechanical stress (static load (creep) vibration, etc.).
AIS, in opposition to GIS, is sensitive to the external environmental conditions, during its entire life. It can undergo condensation, atmospheric pressure drop chemical pollution; soluble and non-soluble deposits on the insulator surface.
All these environmental stresses strongly impact the dielectric performance of the equipment, with the following possible development:
- Corona partial discharges are initiated near triple jonctions
- Hydrophobic properties of the insulator material are progressively lost
- Leakage current, and dry bands activity (which occur when the surface of the insulator is not fully covered by "conductive" water inducing degradation by Corona effect) amplify the phenomenon along all the insulator surface
- Finally, dielectric tracking and carbonization yields to an insulation failure of the switchgear

Numerous studies, as [10], deal with progressive loss of AC dielectric performance of the insulators. However, loss of electric strength during transient voltage surge, as lightning impulse, is also induced.
- By direct modification of the field repartition in air near the insulator due to the high permittivity (> 50) of water droplets, amplified by the presence of polluted conductive area. A simple moisture absorption by the solid insulating material can also decrease its dielectric strength, by permittivity increase.
- By coupling the voltage impulse to a pre-existing AC stress (i.e. the network voltage). In this case, the preexistence of ionized area around the aged insulator (corona, dry bands, etc…) amplifies the lowering of the electrical strength of the insulator submitted to the lightning impulse

To confirm this, the electrical strength loss during voltage surges was measured during tests performed on standard MV 24 kV epoxy insulators, at different stages of pollution

and induced degradation due to the external environment:
- Dry and undamaged insulators
- Insulators with simulated condensation on the surface
- Insulator submitted to different stages of dielectric ageing stress.

The accelerated protocol used to reproduce ageing is described in [11]. All ageing phases are reproduced: from early ageing, then late ageing, to tracking phenomena, as described in [12]. It has a demonstrated higher severity than the ageing protocol defined by IEC 62271-304 [13] which does not reproduce the full ageing process. The switchgear is energized at its rated voltage during 3000h and is submitted to a succession of 2h humid and 2h dry cycles. It is estimated that a 3000h duration represents 25 years of realistic ageing stress in MV secondary switchgear, used in severe indoor condition. 500h ageing duration correspond to a light ageing degree: surface properties of the insulator (as hydrophobia) just start to evolve.

Visible aging effects on the insulators, are shown on Figure 2.

Figure 2: Picture of insulators after respectively 0, 500 and 3000 hours ageing test at rated voltage, combining dry and wet cycles (internal Schneider-Electric protocol)

The electric strength of the insulators was measured at different steps of the ageing process (4 insulators tested for each ageing step, for statistics), submitted to standardized positive lightning impulses, using an up-and-down method (30 impulses, 3kV gap). The insulators were all equipped with their field deflector, as in the real product, to protect the triple junction from an excessive electrical field. The effect of condensation (dashed bars results in Figure 3) was simulated by an additional deionized water spray applied on the surface on the insulators just before the dielectric test. The results are presented in Figure 3.

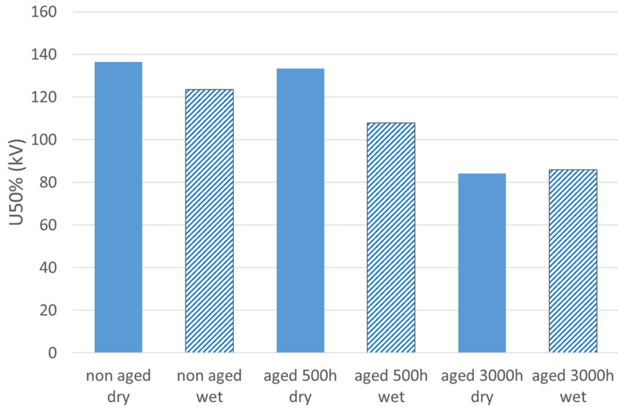

Figure 3: Electric strength of new and aged AIS insulators, submitted to positive lightning impulse test

Non-aged, and 500h aged insulators, tested in dry condition show a similar performance: no surface conductivity is induced by the ageing protocol after 500h. However, the presence of water on the surface induces a decrease of the electric strength (~ 10% loss for non-aged insulators) , probably droplets are creating dielectric singularities on the epoxy surface. This effect is amplified after 500h ageing protocol (~20% loss), probably due to the of hydrophobic properties loss on the epoxy surface, near triple point. After 3000h ageing duration, all insulators, both dry, or wet, show a drastic decrease of their electric strength (~40% loss): the superficial pollution or erosion on the insulator induces permanent conductive area.

In conclusion, despite long and severe tests (performed with mastered environmental conditions), there is a risk that the tests do not cover the actual stresses in service. Then, if the environmental conditions are severe or not well known for AIS or SIS, it can be interesting to choose a higher value than the common value specified by the standard. For instance, for 12 kV switchgear: rating 95 kV BIL instead of 75 kV BIL or 38 kV instead of 28 kV PF).

ENVIRONMENTAL IMPACT ON THE LIFE DURATION OF GIS

GIS are less sensitive to environmental conditions. Corrosion tests [8] (salted fog, humidity tests, exposure to SO_2) are performed according to standards to validate the corrosion withstand of a metallic tank or the adhesion of painting on an epoxy tank for SSIS.
For GIS, electrical field is only inside the tank which play the role of shield. There is no electrical field outside the tank and then the environmental conditions do not play any role for electrical insulation.
Consequently, there is no need to perform additional tests of aging under electrical field and environmental conditions contrary to AIS.

CONCLUSION

The rated voltage of switchgear is generally chosen from values given in the IEEE and IEC standards.
It has been observed that all switching-related transients are of lower amplitude than the lightning impulse withstand voltage for the equipment (theoretically up to 7.75 p.u. of the peak highest system voltage). When lightning occurs on a distribution network, the voltage created is much larger than the lightning impulse withstand voltage and without protection the network would certainly fail. However, if Zinc Oxide surge arresters are applied at the interface between the overhead lines and the substation, then the maximum voltage that should be observed within the switchgear should be less than 5.5 p.u., which is less than the lightning impulse withstand voltage

Only two mandatory dielectric tests are required for switchgear to comply with the standards.
- Lightning impulse withstand testing is dedicated to checking that the design of the switchgear conforms to its ratings. Results need to be understood in the light of the statistical behavior of air breakdown. Due to the possible damage they may create, they are used only as type tests.
- Power frequency testing is performed both as a type and routine test. Because of the longer voltage application duration, it allows detection of issues in the solid insulation parts within the switchgear, as well as incorrect assembly of dielectric barriers.

Tests, not required by the standards, are also performed as complementary tests:
- Partial discharge testing, with a high sensitivity, allows detection of issues in single solid insulation components, and can be used as an efficient routine test to check the molding quality. However, the PD signal of a complete assembled switchgear may be confusing, as the relevant PD signal in solid insulation components can be masked by the Corona presence in air.
- Long term aging tests with humidity, pollution, temperature and mechanical cycles are useful to anticipate the long term withstand of the switchgear in real operation.

If the aging of the internal insulating parts inside a switchgear is well mastered since long time, it is not always the case for the part of the switchgear in contact with ambient environmental conditions (humidity, salt, dust…) and some risks remain. Manufacturers of AIS switchgear are not able to predict for sure the life duration of an insulation part whose degradation of the insulating properties depends on the severity of the ambient environmental conditions which are not well known.
GIS has the advantage to have a “protected” insulation while AIS has its external insulation exposed to external environmental conditions.

In conclusion, when environmental conditions are severe or not well known, it is better to choose GIS. If AIS technology is selected, it is recommended to select the highest insulation level defined in the standards for the rated voltage considered. For example, for 12 kV rating, choosing 95 kV BIL instead of 75 kV BIL or choosing 38 kV PF instead of 28 kV PF at 50 Hz). This increase of the required electric withstand obliges the manufacturers to design consequently by increasing the distance to reduce the electric field. This enables to mitigate the risks of a degradation of the insulation.
On the other hand, GIS insulation is not sensitive to environmental conditions and then does not need additional margin on the dielectric withstand

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