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Altitude corrections for external insulation design: IEC standards and engineering applications

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SUMMARY

The dielectric strength of external insulation is influenced by several parameters, among those the effect of the combination of atmospheric conditions such as humidity, pressure, temperature. The general understanding of the dielectric strength of air is that it decreases with reduction of air density. These effects need to be taken into account when external insulation is designed and tested.

Unfortunately, up to now, the complex process behind the effect of the atmosphere under different conditions like waveform, electric field conditions, among others it is still not fully understood. Therefore, to perform atmospheric corrections, different empirical or semi-empirical approaches are recommended in the international standards, e.g. IEC 60060-1, IEC 60071-2, IEC 62271, etc. However, the existing correction methods could lead to large differences in the applied correction factors. Moreover, simplified and generalized solutions may cause uncertainties especially when different recommendations are given in various standards without enough clarifications.

This paper is dedicated to study the altitude corrections recommended by international standards IEC including informative methods. It highlights the advantages and disadvantages of the different methods and distinguish its applicability depending on its purpose in engineering such as insulation coordination, equipment design and/or high voltage testing.

It is concluded that the altitude recommendation provided in the main body of IEC 60071-2 is suitable for insulation coordination, station design and it is the most adequate method for high altitude applications. Other altitude correction approaches available in the standards require a clear knowledge of the dielectric strength of the equipment, which it can lead to confusion and wrong application. On the other hand, the testing corrections provided by IEC 60060 can be very useful when the breakdown voltage of the arrangement is well known, however, for equipment where the insulation is not recoverable and breakdown voltages are not possible to obtain, the correction could lead to increased error and wrong correction.

KEYWORDS

Altitude correction, discharge mechanism, direct voltage, alternative voltage, switching impulse, mean electric field.

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1. INTRODUCTION

The influence of atmospheric conditions on the dielectric strength of external air insulation is a complicated phenomenon that has not been fully understood. Laboratory tests have demonstrated that the dielectric strength of air decreases with the reduction of air density, however, such reduction depends on the voltage stress, geometry, electric field conditions, i.e., it is very much related with the discharge mechanism.

Usually, the conditions at site, where equipment is installed are different than the standard reference conditions. Also, the equipment site location might have conditions different from the normal service design conditions, e.g., maximum ambient temperature and altitude not exceeding 1000 m.o.sl.. For the sake of achieving proper design and testing of high voltage apparatus, atmospheric correction procedures are recommended in the international standards to translate site or laboratory conditions to standard atmosphere conditions [1]–[3]. Those corrections are performed to temperature, humidity and atmospheric pressure.

The recommended methods to perform atmospheric corrections are based on semi-empirical approximations of experimental data of tests performed to different electrode arrangements type rod-plane, rod-rod and post insulator; together with a semi-empirical relation of the breakdown voltage at standard atmospheric conditions and the mean electric field gradient for positive streamer propagation [4]. Nevertheless, different approaches are given in different standards, making the application of the standard confuse and, in some cases, not really proper.

This publication focusses on altitude corrections for external insulation based on the effect of air density. The influence of air density on the dielectric strength of air depends on the voltage shape, polarity and the geometry of the configuration. For practical engineering applications, it is important to identify which methods are most accurate to apply for insulation coordination purposes, breakdown voltage tests, withstand voltage tests, among others. The aim of this paper is to revisit the different air density corrections available in the standards, and identify its application depending on the purpose, voltage stress and configuration. Recommendations are given for engineering applications.

2. ATMOSPHERIC CORRECTION FOR AIR INSULATION.

The dielectric strength of air is influenced by the air density (temperature and pressure) and humidity. The influence of temperature and pressure can be taken into account simultaneously, as an initial approximation, by the relative air density δ [4]:

$$\delta = \left(\frac{p_1}{p_0}\right) \times \left(\frac{273+t_0}{273+t}\right) \quad (1)$$

where p_0 and t_0 (in degree C) are the pressure and temperature at the standard reference conditions respectively, p_1 and t_1 are the corresponding pressure and temperature at other air conditions.

The atmospheric conditions are converted in mainly two parameters, relative air density, and absolute humidity. Air humidity and air density may vary in the same location. At outdoor conditions, it might be assumed that the effects of ambient temperature and humidity tend to cancel each other [5]. A large variation in air density are encountered when locations at different altitudes are considered.

3. INFLUENCE OF AIR DENSITY

The fundamental process of a discharge is divided in different stages: corona discharge, streamer formation and propagation, leader formation and leader-streamer propagation and final jump [6]. Experimental investigations indicates that the main discharge mechanism influenced by air density is the streamer formation and propagation [4]. Consequently, for gaps where the dominant process is streamer, i.e., gaps shorter than 2 m, the influence of air density is more significant than for longer air gaps where the discharge process is a combination of leader-corona propagation.

Based on above considerations, the change of the dielectric strength of air gaps with air density could be evaluated as δ^n, where the coefficient m is function of a dimensionless parameter called g. The parameter g is a rough estimation of the similarity of the discharge with the mean electric field required for propagation of a positive streamer and mean electric field of the arrangement, equations (2) and (3) of IEC 60060 [3]. The value of g is the ratio of the mean electric field, E, at the breakdown voltage of a given gap, and the average electric field of positive streamer propagation E_s, at same atmosphere.

$g = \frac{U_{50}}{500 \cdot L \cdot \delta \cdot k}$ (2) and $g = \frac{E}{E_s}$ (3),

where U_{50} corresponds to the fifty percent breakdown probability voltage of the arrangement, L to the path of the discharge, k a dimensionless parameter function of type of test voltage and function of absolute humidity and relative air density δ. According to[7], the range $1<g<2$ corresponds to all cases where the main discharge mechanism is streamer discharge, and the range $0<g<1$ corresponds to breakdown of joint phenomena leader and streamer. Therefore, the curve is reliable for streamer discharge cases.

4. RECOMMENDATIONS PROVIDED BY IEC STANDARDS

4.1 IEC 60060-1[3]

The scope of this standard is the different dielectric tests of electrical equipment. In this standard, the correction factor is defined as:

$K_t = \delta^m \cdot k^w$ (4)

For atmospheric correction, the standard relies in the relation between $m=f(g)$. This relation has an acceptable accuracy for cases where $1 \leq g \leq 1.1$. Moreover, in this standard the curve of g is constructed based on the relation $\delta \cdot k=1$ [8], limiting the accuracy for cases $0.9 \leq \delta \cdot k \leq 1.1$. Such limitation may only be fulfilled when correction is made between test results obtained near sea level. For high altitude correction, the application of the relation $m=f(g)$ of this standard would lead to an increased error.

The standard recommends using the 50% breakdown voltage and the minimum discharge path to evaluate g. When U_{50} is not available, U_{50} can be assumed to be 1.1 times of the voltage level of the withstand test. However, such assumption can only be justified when the voltage level of the withstand test is related to the value of U_{50} and the minimum discharge path in such a way that it reflects the discharge characteristics of the test object. In real applications, in some cases, the relation between the withstand voltage and U_{50} is not 1.1 times the withstand voltage. In certain scenarios, the discharge path may not be determined by the voltage level of this test but by other constrains, such as creepage or installation requirement. Therefore, in such a cases error will be introduced in the determination of $E = U_{50}/L$ and thereafter in the determination of g and m.

For the purpose of insulation coordination, the characteristics of the equipment to install, the length of gaps and other details of the future installation are unknown, therefore the determination of the U_{50} and the length of related minimum discharge path are often not available. In such a case, $E=U_{50}/L$ cannot be correctly estimated as recommended by this standard.

4.2 IEC 60071-2[1]

This standard provides the altitude correction, as a simplify pressure dependent correction, according to equations (5) and (6). Equation (5) for equipment design at standard reference conditions, meanwhile

Equation (6) described in Annex H of the latest version of the standard can be applied for equipment that has been designed for normal service conditions i.e. for normal operation up to 1000 m. Equation (6) harmonizes the work of IEC 62271-1[2] with the insulation coordination standard IEC60071-2 [1].

$k_a = e^{m \cdot \frac{H}{8150}}$ (5) or $k_a = e^{m \cdot \frac{H-1000}{8150}}$ (6)

where H is the altitude in meters and m is a coefficient given in function of the withstand coordination voltage. Different values of m are recommended for different types of voltage and insulation. For lightning impulse LI and alternative current AC voltage, m=1 is recommended. For switching impulse SI, the value of m is obtained through a group of curves differentiated depending on the type of insulation i.e. for phase to phase, phase to ground, and longitudinal insulation and rod-plane reference gap. Equation (5) according to the standard, it is applicable for altitudes up to 2000 m and equation (6) according to [2] is applicable for altitudes up to 4000 m.

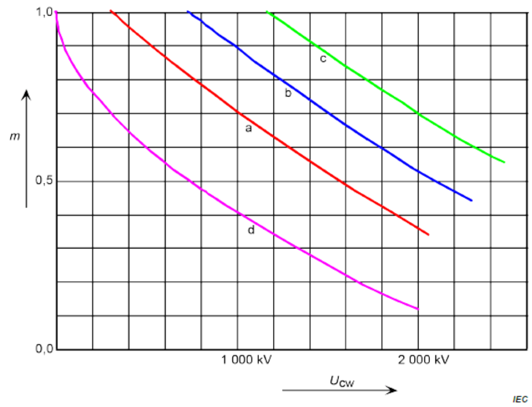

Figure 1. Exponent *m* for standard switching impulse voltage for coordination of switching impulse withstand voltage applicable for: (a) phase to earth insulation, (b) longitudinal insulation, (c) phase to phase insulation, (d) rod-plane gap (reference gap). Taken from [1]

This is a simplified and conservative approach avoiding the difficulties of the need to obtain the breakdown voltage of the arrangement, especially when during insulation coordination process the equipment design has not been clearly defined and its dimensions and characteristics are still unknown. Therefore, this standard is more suitable for insulation coordination and type test voltage application.

4.2.1 Annex H IEC 60071-2 alternative *m* curves for switching impulse overvoltages.

In latest edition of IEC 60071-2 informative Annex H, an attempt to explain the origin of *m* component is presented. The provided clarification is based on the combination of knowing the breakdown voltage of the arrangement, the *g* factor specified in [3] and the corresponding gap factor of the arrangement. A comparison figure between the *m* factor of the body of the standard and for different gap factors is given as valid for altitudes up to 4000 m. The typical values of the gap factor k_{gap} are indicated and compared with insulation phase to earth (k_{gap} = 1.3), phase to phase (k_{gap} = 1.8), longitudinal (k_{gap} = 1.6), rod – plane (k_{gap} = 1.0), see figure 2.

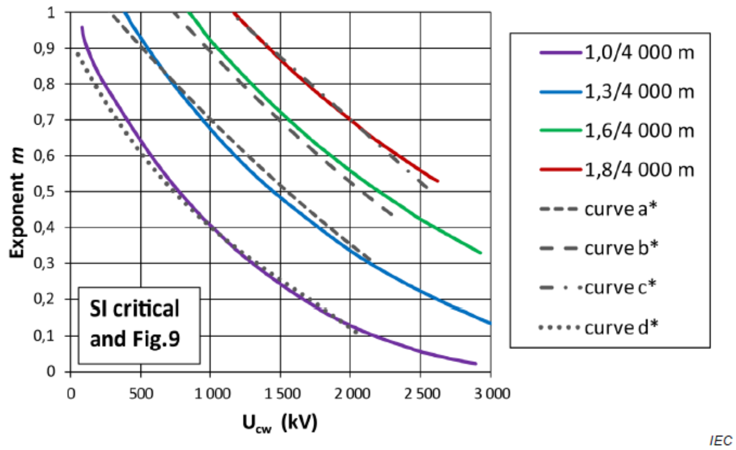

Figure 2. Exponent *m* for standard switching impulse voltage for selected gap factors and altitudes and comparison with exponent *m* provided in the body of the standard. Taken from [1]

In the same Annex of the standard, the reader is warned with hints such as the curves are flatter compared with the standard correction, and that the approach can be used for low altitude, however, it presents a failure of ±3% for high altitudes. Moreover, the standard recommends to investigate the validity of the new curves.

For insulation coordination purposes usually the geometry of equipment, its characteristics, the interconnections in the station, among other details are unknown. In order to get to know the gap factor of a geometry arrangement, it is required well-known detail of the arrangement and be able to perform breakdown test of the corresponding equipment/arrangement. Moreover, for equipment with non-self-restoring insulation such a type of breakdown tests is almost impossible to achieve.

Besides, the gap factor of an arrangement variates with its geometrical characteristics and therefore when the design is preliminary and details are unknown, it is advisable to select conservative gap factors in order to do preliminary design of the station or the corresponding insulation to coordinate. The gap factors provided in the Figure 2 are considered as not conservative as they are very high compared with the range available in the same standard IEC60071-2 [1]. For phase to earth arrangements, the geometry could correspond to geometries type conductor-lower structure, with recommended gap factor according to [1] of 1.15 to 1.35, where a conservative value is a value close to 1.15 instead of 1.3 as the one selected for Figure 2. For a phase to phase arrangements a conservative gap factor is 1.4 instead of 1.8, which according to [1] corresponds to an arrangement with asymmetrical geometries, and phase difference $\alpha = 0.33$. For longitudinal insulation, the gap factor can vary between 1.03 to 1.66, being 1.6 a very high value. Therefore, figure 2 could change accordingly with the selected gap factor and geometry of the arrangement in an uncertain way, introducing more constrains and unknowns to the insulation coordination process.

In conclusion, the applicability of this new approach is very limited and can introduce large error in the insulation coordination design process. It requires to be further investigated and validated before it is applicable in a real design.

4.3 IEC 62271-1

The standard targets high voltage switchgear and control gear. In the standard [2], the normal service conditions including altitude not exceeding 1000 meters are specified. The altitude correction is recommendable for up to 4000 m with the formula (6). Instead of the curves, constant values for *m* are provided for different type of voltages. For alternating current AC, lightning impulses LI and phase to phase switching impulses SI, the *m* factor is equal to 1. For longitudinal insulation switching impulses SI, the *m* factor is 0.9 and for phase to earth switching impulses SI, the factor is 0.75.

Theoretically, for the design and test of external insulation, atmospheric corrections should be applied between the specific site conditions, laboratory test conditions and the standard reference conditions. However, for most equipment, there are normal service conditions specified in the relevant IEC standards. For economic reasons and industrial practice, equipment is designed to withstand the required withstand voltage within the range of normal service conditions. This means that for equipment used at a location with altitude not exceeding 1000 meters; no altitude correction will be necessary. This industrial practice has been supported by vast operational experience and adopted by many IEC standards. This is especially true for the cases when deterministic method is used for insulation coordination, e.g. for HVDC systems [9], where the effect of the air density for $H \leq 1000$ meters, has already been included in the margins commonly adopted for insulation coordination design. Therefore, altitude correction for HVDC practice shall be done based on equation (6).
In order to align the different standards and include equipment already designed for normal service conditions, equation (6) was introduced in the latest version of IEC 60071-2[1] into the Annex H.

5. DISCUSSION

Different standards have different ways to interpret the altitude correction. The mainly difference between standards is on how to interpret the *m* factor and the consideration of normal service conditions in the insulation coordination procedure or not.

For HVDC applications, it is clear that due to the deterministic procedure followed in the insulation coordination, normal service conditions are already considered [9]. For alternating current AC applications where standardized voltages are used, normal service conditions are also already considered in the equipment and clearance design according to [1]. Therefore, for insulation coordination purposes in such applications the proper altitude correction to use is the one provided in IEC 60071-2 equation (6), which it is aligned with IEC 62271-1[2]. For other applications at standard atmospheric conditions, equation (5) shall be followed.

Regarding the *m* factor, there are different recommendations in the standards, depending on the voltage stresses, e.g. fast impulse, slow front impulse, alternating current AC, etc. For stresses type lightning LI, the recommendation from [1], [2] is to use, a *m* factor equal to 1. Meanwhile, for [3] the *m* factor will variate with *g* factor, which it is function of another non-dimensional factor called *k*. As exposed above the *g* factor is an approach relation that distinguish between the different discharge mechanisms. A *g* factor equal to 1, corresponds to a positive lightning impulse applied to a rod-plane arrangement, i.e., a fast-transient discharge, where the main discharge mechanism is the streamer inception and propagation process and the dielectric strength is proportional to the air density [4]. Consequently, for stresses type LI, it is appropriate to consider the *m* factor as equal to one, as recommended by IEC 60071-2 [1] and IEC 62271-1[2].

For AC voltages, the discharge mechanism is similar to the discharge process observed for slow front impulse voltages - SI, i.e., like positive and negative switching impulse. The formation of streamer discharge and the electric field required for the propagation of a positive discharge is 500kV/m, same as it is considered for slow front impulses where the mechanism of streamer-leader propagation occurs [10], [11]. Therefore, the *m* coefficient can be variable as it is recommended for switching impulse, i.e., for air gaps larger than 2 m where discharge mechanism is known as joint phenomena leader – streamer, the *m* coefficient shall be lower than 1 and for uniform configurations where the leading breakdown mechanism is streamer discharge, e.g., gaps shorter than 2 m, the *m* coefficient shall be equal to 1. The standards [1], [2] recommend to use *m* coefficient equal to 1, which it can be considered a conservative approach.

For continuous voltage DC, the breakdown mechanism for non-uniform electric field arrangements consists of impulses similar to streamer discharges. Observations for both positive and negative polarity in different gap arrangements have shown that the mean breakdown field is closed to 500 kV/m, which it is typical the propagation electric field for positive streamer discharge [8]. However, same investigation recommends that taking into account the possible influence of the duration of voltage application, values of about 400 kV/m maybe retained as a conservative value for air clearance design. Therefore, based on the limited information available up today, for non-uniform gaps of lengths shorter than 2 m, *m* shall be equal to 1; for gap lengths longer than 2 m, the *m* factor taken from switching impulse could be followed.

For switching impulse SI, different *m* factors curves are available in the standards that can be used depending on the application, for insulation coordination purposes and the determination of withstand voltage testing, where equipment characteristics, fifty percent breakdown voltage U_{50}, location of equipment, bus-bars, etc. are unknown the most appropriate approach is to follow the recommendation of Figure 1 taken from IEC 60071-2 [1].

For breakdown tests of pure air gaps and insulators gaps under switching impulses, where the fifty breakdown voltage U_{50} is possible to know, the approach of IEC 60060 [3] is the most accurate. However, for large air density variations, as those connected to large variations of altitudes, it is not recommended the application of the *m* factor provided by IEC 60060 [3], as the method is not sufficiently accurate when adopted to extrapolate air density influence for positive switching impulses in a large density range [4]. Therefore, for high altitude applications, it is more precise to apply the correction method recommended in IEC 60071-2 [1], as it is recommended by other standards [2].

6. CONCLUSIONS

Altitude correction methods recommended by IEC standards and its applicability are revisited. It is highlighted the need to clearly identify the purpose of the correction such as insulation coordination, withstand test or breakdown test as well as the atmospheric correction in context, e.g., normal service conditions of equipment, standard reference conditions, specific site conditions or laboratory test conditions in order to select the appropriate correction method to apply.

Recommendations on the applicability of the different standards are given for the different type of electrical stresses and configuration arrangement. The major difference between standards is given in the non-dimensional factor *m*, which depends of the discharge mechanism characteristics. For insulation coordination purposes, it is identified that the most convenient approach is to use the recommendations provided in the main body of the IEC 60071-2. For breakdown test of air gaps at altitude not larger than 2000 m, the approach of IEC 60060 is the most accurate. For high altitudes up to 4000 m, insulation coordination, withstand test and breakdown test, the altitude correction recommended by IEC 60071-2 which it is aligned with IEC 62271-1 is the most appropriate to follow.

More research is required from the point of view of the physics of the discharge in order to have a more complete air density correction approach for engineering application. Such research may include the relation of different voltage stresses, configuration arrangement, and electric field conditions among others.

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