COMMENTS ON THE ATMOSPHERIC CORRECTION FACTORS OF THE NEW IEC 60060-1 (2010) STANDARD

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Abstract: In this paper remarks on the correction procedure for atmospheric conditions of the new edition of the standard IEC 600060-1 Ed. 3, 2010 are made, some on the characteristics of an appropriate correction factor, others on the numerical example of its Appendix E and finally on the proposal for a simple and practical correction factor.
The IEC procedure considers the correction factor as a function of the same voltage to be calculated and requires an iterative method to do it. This is not convenient because obscures the correction procedure itself.
The experimental results for positive lightning impulse show simply that K=δk. For positive switching impulses the results are scarce and show considerable dispersion, average performance in the range between δ=1 and δ=0.7, can be adjusted with a parallel straight lines for different clearances values. This allows obtaining a correction factor simpler, without the drawbacks of the IEC procedure, but requires the knowledge of the standard gap factor.
In the present work a table of correction factor that from the beginning considers the known conditions: type of voltage, configuration and polarity and range of application is proposed; this results in a clear, consist, direct and less dispute procedure.

1 INTRODUCTION

The standard IEC 600060-1 Ed. 3.0, 2010 [1] was recently published and the correction procedure for atmospheric conditions is similar to that of the previous IEC [3], but for the converse procedure considers the atmospheric correction factor as a function of the same voltage to be calculated so an iterative mathematical procedure must be applied, as indicated in the example of the Appendix E of the new standard. The present authors think that this is not convenient because obscures the correction procedure itself and does not reduces the uncertainty of the withstand or critical voltage calculated.

A short and clear revision air density effects on power, lightning impulse and switching impulse strength of external insulation and approaches to systematize the data applying function adjustment is reported in [2]. This reference also discuss the experimental findings of the optical patterns and electrical parameters of lightning and switching impulse discharges of long air gaps at reduced air density and the implication on the atmospheric correction factor of the previous IEC standard [3].

From experimental data of several references [4,5,6,7], the lightning impulse strength is approximately proportional to the relative air density. However, for positive switching impulse more research in needed and in this sense Rizk [2] using a physical approach obtained formulae for the influence of air density on the leader inception voltage streamer and leader length at the final jump for several electrode configurations, and shows that the exponent n is not a unique function of parameter g_0, as the IEC standard assess, which affect the accuracy of the corrected voltage. Papers on atmospheric correction factors usually consider the adjustment of a function to new experimental test results, comparison with previous proposals of corrections or a new approach, or the development of a new semi-empirical model or a theoretical model. Sometimes the connexions with insulation co-ordination or the design of the insulation of electrical equipment are also including.

In this paper some remarks are made on the characteristics of an appropriate correction factor, others on the numerical example of Appendix E of the new IEC standard and finally on the proposals for a simple and practical atmospheric correction factor that from the beginning consider the test conditions know, applicable within the range of the usual atmospheric conditions

2 CORRECTION PROCEDURE OF IEC 60060-1, (2010)

The converse procedure of the new IEC [1] clearly state that to calculate the corrected value of voltage U for given atmospheric conditions from the test voltage U_0 specified at reference standard atmospheric conditions, it may be required an iterative method of calculation. One can express this in mathematical notation as follow:

$$U = U_0 K_t = U_0 K_1 K_2 = U_0 \delta^m k^w \quad (1)$$

where K_t is the total atmospheric correction factor, k_1 is the air density correction factor, k_2 is the humidity correction factor, δ is the relative air density and k the humidity parameter. The exponents m and w are functions of the dimension less parameter g given by,

$$g = U_{50} / (500 L \delta k) \qquad (2)$$

where U_{50} is the unknown disruptive-discharge voltage in kilovolt peak at atmospheric test conditions and L is the minimum discharge air path in meters.

The values of the exponents m(g) and w(g) can be calculated from the functions given in table 1 of the IEC standard [1] or from their relevant graphs; when 0,2<g<1,0,

$$m = g(g - 0.2)/0.8 \qquad (3)$$

and

$$U = U_0 K_t = U_0 (\delta k)^{g(g-0.2)/0.8} \qquad (4)$$

This expression clearly show that U is defined in an implicit form, that is, U is in both sides of the above complicated function not easy to visualize and must be solved with an iterative method. U_{50} can be initially estimated as $1.1U_0$. The solution of the equation (4) within 0,1%, according to [1], may give the impression that the experimental uncertainty is of this order, but this is not true at reduced air density.

In the original paper [6] the evaluation of exponent m was made for various phase to ground configurations, gap clearances, wave shape, and voltage polarity with $g=G_0$, i.e. g calculated at standard atmospheric conditions. From this the functions $m(G_0)$ were obtained for the various ranges of G_0. To calculate U_0 from U obtained in a test at δ, k conditions a rough estimation of G_0 was proposed from the empirical formula $G_0=G(\delta k)^{0.5}$. A refinement for the evaluation of the exponent m was made by Feser and Piginni [18] and served as basis for the revision of IEC standard [3].

The parameter G_0 was also used by Hileman in his very known book [8] in the numerical examples of chapter 1; he calculates $U_{50,0}$ for positive switching impulse from $U_{50,0}=U_0/(1–1,3\sigma)$ and $G_0=U_{50,0}/500L$ and formula (3) to compute m and to calculate U from formula (4). In another example he calculates $U_{50,0}$ from U_{50} at atmospheric conditions δk, but as G_0 is a function of the unknown $U_{50,0}$, he applies an iterative method. The application of Pigini and Hileman procedures differ from the procedure indicated in the past IEC standard [3], in fact they are contrary to that of the present IEC standard [1].

For a.c. voltage, the problem is that no data is available on the effect of high altitude on the breakdown of external long air gaps. Yuhua [15] made test inside an artificial climatic chamber in the range from 54 to 101 kPa with the ratio $h/\delta^{0.78}$ approximately equal to $11g/m^3$ for air gaps until 2,0 m, post insulator and suspension insulator string until1,46 m. He concludes that the influence of relative air density on the parameter g is small and its value may be roughly considered as equal to G_0.

All this remarks on the parameter g and G_0 have given place to much confusions and discussion in the high voltage laboratories at high altitude in México. In fact the initial proposal of the present IEC standard [1] presented some mistakes and confusions and the IEC Mexican committee made some observations and sent to IEC. In this respect a paper [9] was elaborated which extends and discuses the observations.

Rickmann [10] compared different correction methods with values derived by testing and found certain differences in the correction values using the past IEC method [3] between impulse voltages and a.c. voltages. He concluded that these differences can be attributed to less sensitivity of the g-factor and ask for studies of the influence of humidity and air density to improve the corrections in IEC 60060-1.

3 PRACTICAL CONSIDERATIONS

Explicit and consistent definition of K_t.- We think that the implicit definition of K_t in the new IEC standard [1] is not convenient, because obscures the correction procedure itself and does not reduces the uncertainty of the withstand or critical voltage calculated. It is a practical characteristic that the correction factor K be an explicit function of δ and k and other known parameter such as clearance and gap factor F_0 at standard atmospheric conditions, that is, $K(\delta,k,L,F_0)U_0$, but not a function of U or U_0. An explicit definition of K, has the advantage that correction from non standard conditions to standard one and vice-verse, returns to the same value for the same clearance and F_0, that is to say, consistence is guaranteed since K is independent of the value of U or U_0.

Simple and clear K_t.- Other practical characteristic of K_t is that must be simple, that is to say, no many terms or factors with exponents not depending on δ or h, depending only on known parameters of test, and no compound functions. In this way K_t results easy and fast to calculate and avoids dispute during the laboratory test. In one of the first works [4] on the effect of relative air density of long gaps for δ near 0,7 and near 1,0, it was proposed that a linear relationship exists between breakdown voltage and δ. Later the results of Harada [5] in the medium range, for δ=0,82 showed to be consistent with the above proposal since the values interpolated from Phillips [4] were in the average within the 2,3% of Harada´s [5] values.

Some other types of K_t functions have been proposed, for example: for positive lightning impulses [7] K_t=δk, and for positive switching impulses a linear function K(δ) with independent term or a quadratic function of δ [14].

Uncertainty of K_t.- Experimental results for lightning and switching impulses voltages and alternating voltages for long gaps (higher than 2 m) at medium and low values δ and for extreme values of h are scarce and when plotted versus the product δk show dispersion, so only an average behaviour in the range between δk=1 and δk=0,7 can be given. This dispersion allows proposing simple function to fit the data that avoids complications of the model and to have a better idea of the effect of δ and h and other variables considered on the corrected voltage. This function could be connected segments of straight lines that minimize the uncertainty in each section. In any case the uncertainty in the measurement of voltages must be also considered.

Theoretical formulae to calculate U.- Theoretical models allow calculating critical or minimum breakdown voltage at any atmospheric condition applying different formulae for each configuration and type of voltage, so in this sense not correction factor is necessary but, if it were proposed, substitution of the actual or specified voltage to calculate the corrected voltage may be convenient. For switching impulses voltages the theoretical functions are complicated so they are presented in a graphical way as groups of curves according the value of a parameter for each type of configuration [2].

4 PRACTICAL CORRECTION PROPOSALS

The comments given in the above sections suggest that at present there are complications, uncertainties and mistaken in the IEC standard [1] due to the complex behaviour of electrical breakdown, particularly for switching impulses, and also due to the scarce and dispersion of experimental results. In the other hand the physical model is enough complicated to be applied in practical.

In the present work a table of atmospheric correction factors which from the beginning considers the known conditions: type of voltage, configuration, polarity and range of application is proposed; doubts about the type of configuration are solved by using the gap factor F_0. We hope that this proposal results in a clear, consistent, direct and less dispute correction procedure. A preliminary proposal was suggested in previous works [9,17].

The idea of using a table come naturally of the need of organize and analyze the data [4,17] and the procedure has several of the attributes of a good correction factor. In this way we propose table 1, similar to the table of the old version of the IEC 60-1 standard of 1973 [11] for external insulation.

Table 1: Atmospheric correction factors K_t for external phase to earth insulation from δ=1 to δ=0,7.

Wave form	Electrode shape	Pola-rity	Validity range	Correction factor K_t
D.C.	Spherical Diameter=ϕ	+ -	L<0.5ϕ	δ
	Rod-rod Rod-plane	+ -	L<2.5 m	δk
A.C.	Spherical, Diameter=ϕ	N.A.	L<0.5ϕ	δ
	Rod-rod Rod-plane	N.A.	L<1 m	δk
		N.A.	$1+1.25(\delta-1)/(F_0L^{0.6})$ 1m<L<6 m	
Lightning	Spherical, Diameter=ϕ	+ -	L<0.5ϕ	δ
	Any configuration	+	L<10 m	δk
		-	2<L<5m	δk
Switching	Spherical, Diameter=ϕ	+ -	L<0.5ϕ	δ
	Rod-rod Rod-plane Conductor-window and outer phase with V strings	+	L<1 m	δk
		+	$1+1.25(\delta-1)/(F_0L^{0.6})$ 1m<L<6 m	
		-	2m< L<4m*	$(\delta k)^{0.3}$

*Few information available at high altitude. Average value obtained for δ>0,83. See text.

The first four columns of the table show the known test data including the ranges of validity for the clearance, the last column gives the value or formula of the applicable correction factor. For the majority of cases considered in the table the atmospheric correction factor is a linear function of the product δk, where k is considered a linear function of the humidity given by 1+c(h-11) and c is a constant for each type of voltage [5]. A description of the table is given in the following paragraphs.

In base to experimental results and for the more frequent tests of positive lightning impulse, and for alternating voltages and switching impulse voltage with clearance less than 1 m, the correction factor is direct and simply equal to δk.

For spherical electrodes of diameter ϕ, under direct voltages, lightning impulses and switching impulses of both polarities, for distances smaller than the half of the diameter, the correction factor is also directly and simply equal to δk. Except for a.c. the correction factor is based on tests and measurements up to an altitude of 3000 with electrodes of 1.0 m of diameter [13].

In the case of negative lightning impulse one can consider also that in the average, $K_t=\delta k$ for distances from 2m to 5m and δk approximately 0.83, for different configurations with and without insulators [6].

For standard positive switching impulse the results of Harada [5] show clearly the effect of h on U_{50} in the range of $5<h<23$ g/m^3 at two sites, one with average δ=1.0 and the other with δ=0,82, for point-point configuration separated from 1 to 3 m. This data and the following analysis allow to give a consistent correction formula for U_{50} in terms of δ,h and L. For δ=1 the graphs U_{50}-h are parallel straight lines and for δ=0,82 they are almost parallel. These two sets of straight lines are also approximately parallel between them with a slope of 7.95 kV/g/m^3. The position of these lines depends on δ and L, and as the relation of $U_{\delta=0,82}$ /$U_{\delta=1,0}$ can be expressed as δ^n, adjusting an average straight line to the disperse points of the graph n-L, results n=-0,24L+1,24; finally the voltage $U_{50,0}$ can be corrected at any condition δ and h by the formula:

$$U_{50} = \delta^{-0.24L+1.24} U_{50,0} + 7.95(h-11) \qquad (5)$$

If U_{50} is known for given δ, h and L, the value of $U_{50,0}$ can be calculated from the above formula by simple algebra, so consistence and direct converse procedure is confirmed.

For point-plane configuration [12] with a gap spacing of 5 m, the graph U_{50}-h is a straight line for $5<h<23$ g/m^3, and we suppose that was obtained for δ=1 since detailed data was not given, which has a slope of 5.1 kV/g/m^3, lesser than that for point-point configuration. The above type of formula could be valid for other values of δ and L and other configurations, changing the values of the slope and n(L).

For standard positive switching impulse it was proposed in previous works [13,14] that k_1 could be written as a simple function of δ. In this sense, the graphs of U_{50} versus δk of Figure 1, ref. [7] show that the experimental points in the interval of δ from 0.7 to 1.0, and for configurations point-plane and conductor-window with clearances from 3 to 6 m, can be fitted in the average with parallel straight lines for different test distances, with the same positive slope p for each configuration; for this relatively short ranges it can be written as,

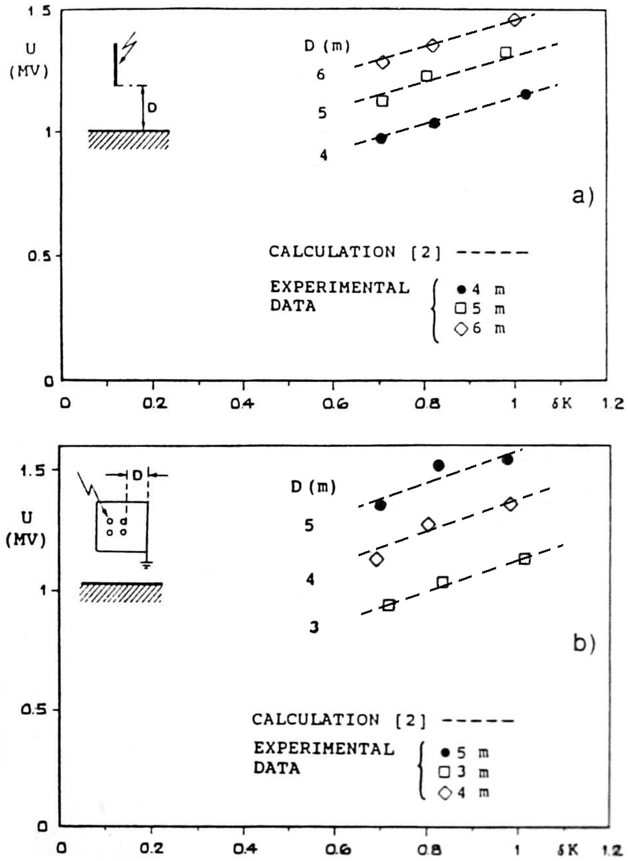

Figure 1: Positive switching impulse experimental results of U_{50} as function of δh for point-plane and conductor-window configuration [7] in the range form δ=1 to δ=0,7.

$$(U_{50} - U_{50,0})/(\delta k - \delta_0) = p = cte. \qquad (6)$$

solving for U_{50} and substituting δ_0=1 results,

$$U_{50} = U_{50,0} + p(\delta k - 1) \qquad (7)$$

and dividing by $U_{50,0}$,

$$U_{50}/U_{50,0} = 1 + p(\delta k - 1)/U_{50,0} = K_t \qquad (8)$$

which obviously satisfies that for δk=1, K_t=1 and $U_{50}=U_{50,0}$. From the graphs of Figure 1, for point-plane configuration $p_{p\text{-}p}$=517 kV and for conductor-window configuration $p_{c\text{-}v}$=649 kV, these slopes are independent of the clearance. For the conductor-window configuration results,

$$U_{50}/U_{50,0} = 1 + 649(\delta k - 1)/U_{50,0} = K_t \qquad (9)$$

As $U_{50,0}$ corresponds to this same configuration and that for positive standard switching impulse it is given by the well known formula of Paris-Cortina in the small range of distances considered,

$$U_{50,0} = 500L^{0.6}; \text{ kV, m} \qquad (10)$$

results

$$K_t = 1 + 1.25(\delta k - 1)/(F_0 L^{0.6}) \qquad (11)$$

the value of F_0 only depends on the clearance and the geometry of the actual configuration and formulae and values can be founded in the literature [16].

It can be noted that in formula (11) K_t does not depend on the value of the test voltage and does not require an iterative calculation, only depends on δ, k, L and F_0. This method of correction is illustrated with the data of the example of appendix E of the IEC 60060-1 (2010) .

Example.- A disconnector with L=2,57 m has a specified a.c. test voltage of 395 kV_{rms} phase-to-ground for a withstand test. Calculate the voltage to be applied in a site with δ=0,7729 (typical value for Mexico city at an altitude of 2240m) and h=4,48 g/m^3.

Assumptions and calculations.- Assuming that our formula (9) be valid for a.c. voltage and assuming that the slope p be the same for the disconnector that for the conductor-window configuration and also assuming that the withstand voltage has the same behaviour that U_{50}; the gap factor for a conductor-lower structure [16] with a height H'=3 m for the lower structure and a total height H=5.57 m is F_0=1,566, by substitution in formula (11) one obtains K_t=0.8743, for which the corrected voltage results 345 kV_{rms}, 12.5 % less than the specified voltage. The reduction according IEC [1] is 9%. The problem is that to verify this difference comparative experimental data is not available for longitudinal insulation under alternating voltages at high altitude.

If new results were available in the future for densities of the air between 0.5 and 0.7, it could be introduced a quadratic correction in δ to fit U_{50} from 0.5 to 1.0 as was proposed in [7,8], similar to the proposal of IEC of 2010 for the humidity correction factor for the case of direct voltage. Two straight line connected segment could also be proposed to fit the data, taking care of the continuity in the common point.

For alternating voltage and for positive switching impulse it is important to clarify that for distance higher than 6 m there are not experimental results to obtain the correction factor K_t. For negative switching impulse, references [6] suggests K_t= $(\delta k)^{0.3}$ for rod-plane configuration for a distance between 2 and 5 m and δ approximately 0,83. However, for other configurations with and without insulators with L=5m, the dispersion of the results is high and it is suggested not correct the voltage.

Finally it is hoped that the table simplifies the selection of the correction factor and avoids discussions, losses of time and save costs in the moment of the test.

5 CONCLUSIONS

In relation to the atmospheric correction procedure of IEC 60060-1 standard (2010) and our proposals, the following conclusions can be given:

1. IEC 60060-1 standard (2010) clarifies details of the correction method of the previous edition, however it is not practical and it still leads to critical and strong discussions during the test with a valuable and expensive time consumption.

2. It is neither simple nor practical to consider that the IEC atmospheric correction factor be an implicit function of the test voltage to be corrected and to apply an iterative procedure to calculate it. which do not improve its real uncertainty.

3. The parameter g=U50/(500Lδk) evaluated at test atmospheric conditions δ, h, is helpful to compare with the kind of pre-discharge and kind of voltage used (at standard conditions.)

4. The use of a table to chose the correction factor, known previously the atmospheric conditions clearance and gap factor; is faster, more practical, simple and reliable.

5. The fact of defining a correction factor which is not a function of the voltage to be calculated avoids using iterative numeric methods and allows verifying the method consistence on a simple and general way.

6. For lightning impulses, the correction factor is simple and directly proportional to δk.

7. For dry positive switching impulse tests, the correction factor is $K=1+1,25(\delta k-1)/(F_0L^{0.6})$, where F_0 is the gap factor of the configuration under test. This formula is also proposed for alternating voltages

8. As the uncertainty of the correction factors is bigger than measurement uncertainty, the use of simple and practical methods are more suitable.

9. For a point-point configuration a correction formula with two terms instead two factors in limited ranges is proposed.

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