CHAPTER-2

LITERATURE REVIEW

2.1 General

The ever increasing demand of more electricity for industrial and public consumption and the trend of progressive concentration of generating plants at the mouth of the coal mines are major factors in favour of bulk power transmission. The use of Extra High Voltage (EHV) and Ultra High Voltage (UHV) overhead lines is still seem to be the preferable solution.

Air is the least expensive and major outdoor insulation,its importance increases as the rated system voltage goes upwards. Hence, the insulation in air becomes one of the most important parameters for the design of overhead lines and the various equipments required for substations e.g. circuit breakers, isolators etc. While designing such systems, safety margins for dimensioning air clearances have to be considered in order to avoid unexpected flashovers. On the other hand, the dimensions have to be optimised for economical conditions. As a consequence, care has to be taken in evaluating withstand voltages and in clarifying the nature of standard deviation σ.

Various types of overvoltages occur in power systems because of system disturbances. Switching operations in three phase systems result in switching overvoltages to ground on all three phases. Since these overvoltages are not synchronous and have different polarity and shapes, they also cause overvoltage stresses across the longitudinal insulation and between phases, bearing in mind that the overvoltage is the difference of the phase-to-ground components.

The longitudinal insulation is understood to be an insulation which is subjected to the combined stress of the operating voltage on the one side and an overvoltage or an out-of-phase operating voltage on the other. If the two voltage components have opposite polarity at the instant of which the overvoltages to ground reach their peak values, the overvoltage stress across the longitudinal insulation will be much higher than that to the ground. Besides the air insulation in substations between different systems, the insulation across the terminals of open disconnectors and open circuit breakers are typical representative of this class of insulation. IEC Technical committee 17 'Switchgear and control gear'/92,93,94/ has specified to conduct two-terminal tests with both the terminals energized simultaneously apart from the switching impulse tests for rated voltages 300kV and above.

A great many tests have been conducted and results are reported on more realistic configurations with better representation of service stresses for phase-to-ground, phase-to-phase and longitudinal insulation systems considering the effect of various influencing factors, which affect the breakdown parameters and withstand voltages of a system. Further, the flashover voltages are greatly influenced by the air density and humidity variations.

The various published reports/literature on these subjects have been reviewed in brief in this Chapter. This Chapter has been divided into five sections as detailed below:

- Breakdown phenomena under switching impulses,
- Longitudinal insulation: general philosophy,
- Longitudinal insulation testing,
- Air density correction factor, and
- Humidity correction factor.

All the topics mentioned above are described in brief in the following sections.

2.2 <u>Breakdown phenomena under switching impulses</u>

With the advent of transmission voltages higher than 300kV, the switching surges have become an important factor for the design of the insulation. Until about 30 years ago, the informations on the switching impulse dielectric strength of air clearances were limited to few reference configurations, and principally to the rod-plane gap. Subsequently many tests were conducted on more realistic configurations and empirical methods were derived for assessing the required open gap clearances/17,19,20,22,62/.

The breakdown voltages for various electrode configurations were then co-related to a reference value by the concept of the gap factor first by Paris/20/ and later re-examined by Schneider and Weck/107/, and that was extensively and successfully used for the design of typical air insulation for 750kV system configurations/52/.

Also, a large amount of work has been performed to investigate from a physical point of view, the phenomena of the dielectric discharge in large air gaps subjected to impulse voltages mainly of positive polarity, having time-to-crest between few tens and some thousands of micro-seconds/21/, /23-30, 61-63/.

Some of the important factors which affect the breakdown strength of the open gap insulation are briefly discussed in the following sections. Special reference is made to the switching impulses of positive polarity.

2.2.1 Influence of switching impulse waveshape

Switching overvoltages, occuring mainly in networks at closing and reclosing off load lines, have a variety of damped complex waves. Unidirectional waves with positive polarity and fairly long time-to-crest produce the most unfavourable conditions for testing the dielectric air strength.

Many authors conducted laboratory testing by producing unidirectional double exponential wave shapes/13-20/. The test results are represented by U_{50} and σ, mean value and standard deviation of the law of probability of the disruptive voltage. Figure 2.1 gives the 50% discharge voltage U_{50} as a function of time-to-crest and the gap distance/17/. The voltage U_{50} as a function of time-to-crest varies according to a U curve. The minimum of this curve, i.e. the critical sparkover voltage (CSOV) corresponds to a particular value of the time-to-crest called the 'Critical time-to-crest', ($T_{cr-crit}$). The critical time-to-crest increases with gap distances/17,52/.

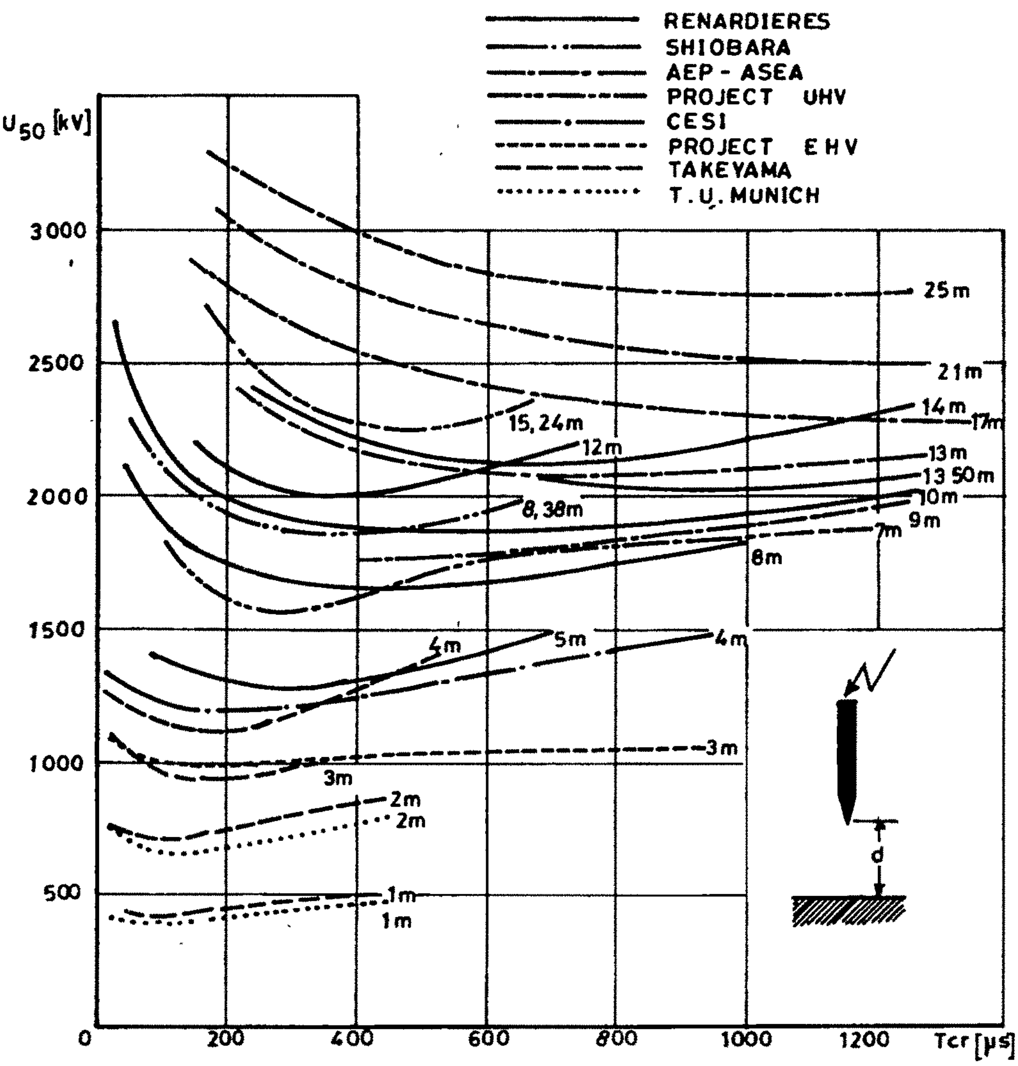


Fig. 2.1 50% disruptive discharge voltage U_{50} expressed as a function of the time to crest, Tcr, for various distances, d, of a point-plane gap. Results coming from various laboratories.(ref.17)

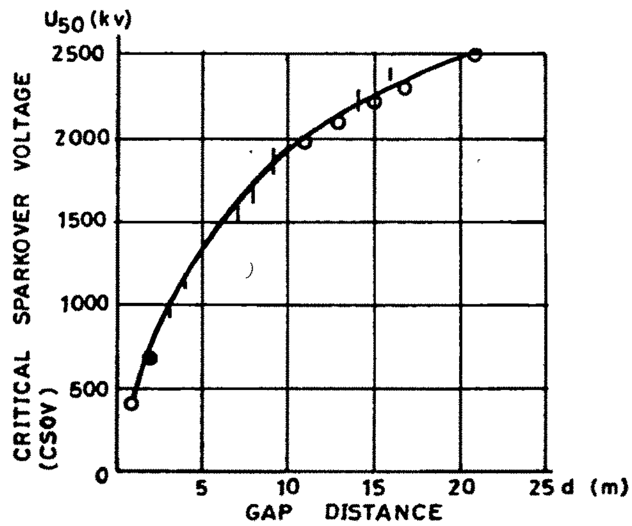


Fig. 2.2 Variation of CSOV versus distance: experimental points and estimated curve.(ref.52)

The analysis of the results obtained by damped oscillatory switching impulses virtually gives the same U_{50} value for each distance but corresponds to a very different $T_{cr-crit}$ /28/. This difference will compel laboratories to define more clearly their wave-shapes, making greater allowances for the part where it affects the breakdown process.

The other electrode configurations show curves $U_{50}=f(T_{cr})$ as having the same characteristics using different numerical values. $T_{cr-crit}$ remains same for a given distance.

The value of σ is more difficult to determine as its estimation needs very long series of impulses during which the U_{50} value presents erratic fluctuations making interpretation of the test results difficult. However, the little information available on this subject seems to show that the standard deviation σ as a function of T_{cr} also presents a U shape characteristics/52/.

2.2.2 Influence of gap clearance

From Figure 2.1, it is seen that the electrode gap clearances increases rapidly with the increase of switching impulse disruptive discharge voltage. Therefore, it is interesting to study how this voltage increases with gap clearance. Figure 2.2 gives the critical sparkover voltage (CSOV) as a function of gap distance'd'/17,52/.

Gallet et al/17/ represented this characteristic by the following formula:

$$U_{50} = \frac{3400}{1+\frac{8}{d}} \quad \ldots\ldots\ldots \quad (2.1)$$

Where U_{50} is 50% critical discharge voltage (kV) and d is open gap clearance in meters. This expression is in good agreement with the experimental results obtained over a range of clearances from 1 to 21 meters. Test results up to 29 meters for time-to-crest lower than the critical values are also available/108/ and are consistent with this expression. A generalization of all wave shapes is possible but the results are less consistent, since the results obtained by different laboratories disagree/19/. Many other researchers have conducted extensive testing at various international laboratory and have suggested new empirical formulae for calculating the switching impulse flashover voltage, which are summarised in reference no. 22.

2.2.3 Influence of electrode configuration

The switching impulse strength of air gaps for a given sparkover distance depends strongly on the geometrical characteristics of the gap electrodes. When the electrode configuration differs from the extreme rod-plane gap, the switching impulse sparkover voltage with positive polarity is higher.

Paris/20/ conducted experiments on rod-plane, rod-rod, conductor-plane, conductor-rod, conductor-structure, conductor-window, conductor-rod, at various gap spacings using 120/4000 µs wave. It was observed that the behaviour of all the tested air gaps at positive polarity, either with or without insulator strings through them, can be characterised both in dry and wet conditions by a similar law for variation of U_{50} as a function of gap spacing.

In other words, the ratio between U_{50} values of different gaps do not vary with gap spacings. Thus, the positive polarity discharge voltage of any gap can be defined by associating the variation law with the spacing of 50% discharge voltage U_{50} of one gap only, which is assumed as the reference gap with a multiplying factor representing the constant ratio between the U_{50} of the gap considered and that of the reference gap.

This multiplying factor is called 'GAP FACTOR'.

2.2.3.1 Gap factor concept/109-113/.

The gap factor for a given configuration is defined as the ratio between the minimum U_{50} value measured for a given electrode configuration and the minimum U_{50} value for a rod-plane gap with equal gap length. The rod-plane electrode configuration is chosen as a reference because it usually gives reproducible results depending on the gap spacing and after applying atmospheric correction factors according to IEC publication-60/5 /. The 50% discharge voltage U_{50} of a rod-plane configuration can be calculated with a good accuracy using equation (2.1). The critical flashover voltage U_{50} of any other electrode configurations subjected to critical time-to-crest switching impulses can be determined by the expression.

$$U_{50} = K\left[\frac{3400}{1+\frac{8}{d}}\right] \qquad \ldots\ldots\ldots\ldots \qquad (2.2)$$

Where d is gap spacing in meters, and K is gap factor corresponding to the electrode configurations, K equal to one, corresponds to the rod-plane configuration. For rod-rod gap configuration K is in the range of 1.3 to 1.4. The most representative air gaps for substation installations are the rod-structure and conductor-structure configurations. It is possible that the height of the structure and the rod may vary from system to system and hence it is usual to express the gap factor as a function of ratio H/(H+h)/46/. Where H is height of the bottom structure from ground level and h is open gap spacing. The ratio of the switching impulse strength of such air gaps to the switching impulse strength of basic rod-plane configuration as a function of ratio H/H+h is shown in Figure 2.3.

While using the calculated value of the discharge voltage, care should be taken such that it is applicable only to similar structures because any modifications in the design may lead to change in the value of the gap factor and hence extrapolation is not valid. With the knowledge of the gap factor the behaviour of the gap under the two other typical stressess i.e. lightning impulses and AC voltage can be also determined. However, the generalization is hardly applicable to switching impulse shapes other than the critical ones. This is probably due to the incomplete representation of the phenomena involved, i.e. the lack of weighing parameters playing an important role/52,110,112/.

2.3 Longitudinal Insulation:General Philosophy:

The insulation between terminals of circuit breakers and disconnectors known as longitudinal insulation is most important for the system reliability. Failure of longitudinal insulation is considered a major failure of the eq-

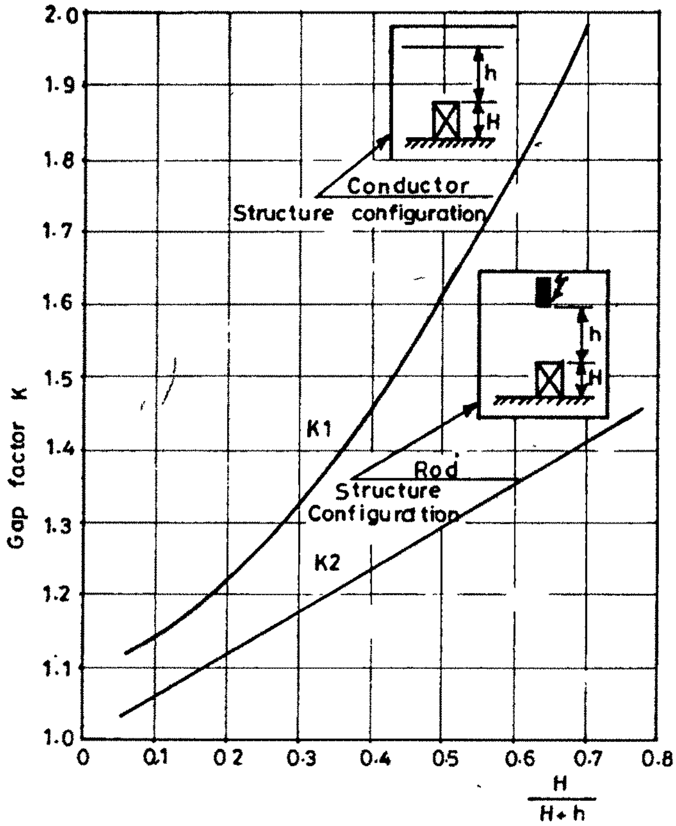


Fig. 2-3 Effect of ground clearance on flashover voltage (ref. 46)

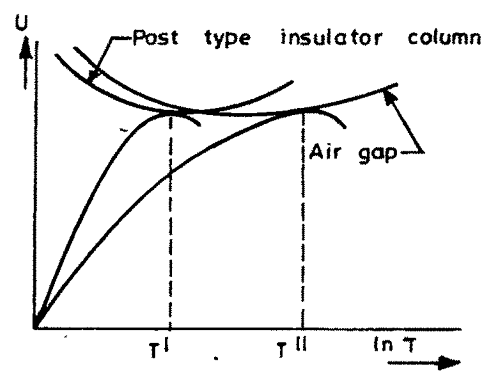


Fig. 2.4 Switching surge sparkover characteristics as a function of the impulse front time (ref. 118)

uipment/154/. A disconnector in the open position provides a visible separation between the segments of the electrical network which it interconnects when closed. The requirements regarding the insulation of a disconnector are thus defined according to the following two functions/88/.

- A working function by which it is required to isolate two parts of a network, each of these parts generally being energised and operating at the same frequency or at slightly different frequencies.
- A security function by which it is required to isolate an energised part of the systems from another part and the latter is grounded for maintenance work.

The circuit breaker is generally required to satisfy a single function, generally identical to the working function of the disconnector.

Some of the standards/117/ recommend that the insulation across the open disconnector should be higher than the insulation to ground by some arbitrary margin usually expressed in percent of the insulation level to ground, such as 12.5% higher than the insulation to ground. At first glance this recommendation may look appealing because of its simplicity, but a closer analysis indicates that it is not accurate and leads to ambiguous interpretations (discussed in section 2.3.1)/118/. Moreover, the insulation level of the open gap selected in accordance with the above rules may even result in an unnecessarily large gap. Historically, the gap clearance was not a major concern in the design of disconnectors for rated voltages upto 245kV because an increase of the gap by another length of a meter or so was not a big problem. However, in the range of rated voltages greater than 300kV, disconnectors become more susceptible to mechanical failures as the gap size increases.

In the following sections the aspects of self-co-ordination between the insulation of a disconnector to ground and across the gap, and of the voltage stresses which appear in service across the longitudinal insulation of circuit breaker and disconnector are described. The requirements for the longitudinal insulation and a basis of tests intended to verify its ability to withstand the relevant stresses are also described.

2.3.1 Self co-ordination of two gaps

The basic philosophy of insulation co-ordination is to take appropriate measures so that the flashovers which cannot be prevented should preferably occur where the least damage will result. Based on this concept, the idea of self co-ordination was developed and designers used to keep open gap clearance of a disconnector little more than the ground clearance to prevent flashovers across the open gap. However, this approach has several shortcomings.

The two parallel insulation paths, namely the open gap and the insulation to ground, will respond differently to variations of parameters such as magnitude, polarity and shape of the applied voltage. Figure 2.4 gives an example of the dependence of the dielectric strength on the front time of the applied impulse voltage. The minimum strength of the open gap insulation will not necessarily coincide with the minimum dielectric strength of the insulation to ground. Depending on the distances involved, the time shift between the two minimum values may be such that for an impulse with front time T', self co-ordination is successfully demonstrated whereas for an impulse with front time T" it is not (T' and T" are defined in Figure 2.4.).

Secondly even if the influence of the shape or polarity of the applied voltage or the assymmetry of the gap configuration is neglected, the fact that only flashovers to ground have occured at a certain voltage is by no means a valid proof of self co-ordination for voltage magnitudes below or above tested level. This is so, because of the complex flashover performance of the parallel gaps when simultaneously exposed to a voltage stress/77/.

While conducting dielectric tests on a disconnector intended for 550kV system it was observed that even if the distance across the open disconnector was 1.5 times greater than that to ground, flashovers across the gap could not be avoided if the voltage magnitude is sufficiently high/118/. If one takes into account all the parameters that could affect the result of such tests, (like voltage polarity, impulse shape, gap configurations, dry and wet conditions,, etc.), the picture will only become more confusing. Therefore, an alternative approach for the selection of the gap insulation had been proposed/118/ and the same is discussed below:

The logical alternative to the concept of self-co-ordination is to select the insulation of a disconnector based on a comparison between the various voltage stresses expected to occur under service conditions and the ability of the insulation to withstand the stresses. The margin by which the dielectric strength should exceed the stress may be either arbitrary or calculated so that a specific value of the risk of failure is achieved/119/.

The obvious pre-requisites for this method are:

- a thorough analysis of voltage stresses which occur in a system
- an accurate determination of the dielectric strength of the equipments.

2.3.2 Voltage stresses

The technical committee 28 of IEC have defined the following stresses in publication 71 (5th edition), 1972.

- Power frequency voltage under normal conditions.
- Temporary overvoltages at or near to 50 Hz
- Switching overvoltages.
- Lightning overvoltages.

These are important both for deciding the ground insulation and open gap insulation requirements. The longitudinal stresses in the security function are the same as those appearing on one terminal.

The combination of these stresses appearing on each terminal are important as far as the working function of the longitudinal insulation is concerned. Under operating conditions, the voltage applied to one terminal will be the power frequency voltage and on the opposite terminal, it may be one of the types of overvoltage mentioned above. On account of this situation the open apparatus is subjected to overvoltages depending upon the phase-shift between peaks of two voltages.

The voltage stress on a disconnector will depend on its intended application as well as on the operating practice of the particular user. For example, a H.V. circuit breaker will usually have one disconnector at each of its terminals. These two disconnectors will be open at the same time. Obviously the stress across these two gaps connected in series is considerably lower than the stress occuring on an open disconnector isolating an overhead transmission line.

Furthermore, the voltage stress likely to appear across the disconnector gap is not identical to that occuring on the insulation to ground, although this may be the case when one of the disconnector terminals is grounded. In all other cases, the stress across the open disconnector will be the result of stresses appearing at each of its terminals.

Qualitative analysis of overvoltages appearing on a system has been carried by many researchers/4,7,9,11/ and the same have been also verified experimentally/1,6,10/. As a result, the magnitude of overvoltages and the frequency of their occurrence is known. Hence, it remains to define the tests necessary to determine the dielectric strength of the insulation system. For longitudinal insulation the tests for the insulation to ground are not different from those for other high voltage apparatus and hence in the following sections only the tests required for the longitudinal insulation is discussed in detail.

2.3.3 Withstand Voltage and tests

According to IEC publication 71, each type of voltage stress must be represented by a test and a withstand test. As far as insulation between phase and earth is concerned, the IEC publication 71 leaves it to the relevant Technical Committee to fix the withstand voltages for the power frequency tests intended to represent the power frequency stresses arising under normal operating conditions as well as stresses due to temporary overvoltages.

IEC publication 71 has specified the rated withstand voltages for switching impulses and lightning impulses intended to represent the corresponding stresses in the system. It has been also mentioned to eliminate those tests which would be rendered superfluous by other more severe tests, as for example, if wet switching impulse test is to be conducted, then dry switching impulse test may not be conducted.

2.3.3.1 Switching overvoltages:

The choice of the insulation level between terminals of a circuit breaker and disconnector depends on the accepted risk of flashover. This probability of flashover may be decided based on the probability of flashover to earth of the circuit breaker or of the substation.

Assuming as a first approach that the total stress is expressed by the sum of the peak value of the switching overvoltage on one terminal and of the peak value of the power frequency voltage of opposite polarity on the other terminal, the ratios between withstand voltage of the terminal-to-terminal insulation and the withstand voltage of the phase-to-earth insulation can be derived with the help of IEC publication 71. For 420kV and 765kV systems this ratios would be 1.21 and 1.3 for closing overvoltages, and 1.37 and 1.5 for reclosing overvoltages respectively/88/. Also, the longitudinal insulation withstand level depends upon the ratio between the closing overvoltages and the reclosing overvoltages.

It may be concluded from these ratios that, lower the level of the phase-to-earth insulation, the higher is the ratio between the two withstand voltages. The trend to reduce the insulation levels leads to 'long circuit breakers'. This means circuit breakers in which the phase-to-earth insulation is reduced more than the longitudinal insulation.

For longitudinal insulation the withstand voltage results from the combination of a switching overvoltage and a power frequency voltage (namely known as Bias voltage test, recently IEC has defined this as a 'combined voltage test' instead of 'Bias voltage test'). It is certainly not admissible to consider that the sum of two such components corresponds to a 'pure switching overvoltage'. Consequently, any attempt to replace this combination by a pure switching impulse, for example by replacing the 'bias' with an appropriate increase in the amplitude of the switching impulse voltage (known as equivalent test) necessitates to increase the earth insulation to avoid flashovers to earth. This modifies the electrode field configuration and hence exact site conditions are not simulated in the laboratory while conducting the withstand voltage test. Thus any tentative view to replace this combination must be based on the tests conducted on sufficiently representative apparatus: in the case of air insulation, the 'conversion factor' depends upon the electrode shapes and for other types of insulation, it depends upon many parameters.

2.3.4 Bias voltage test

In the bias voltage test one terminal of the test object is energised at the rated voltage while the other terminal is impulsed with either a switching impulse or lightning impulse of opposite polarity. This test has been introduced several years ago/88/.

The bias voltage test is a simple proof of the adequacy of the gap to withstand the combined voltage stresses likely to occur in service. Also, it demonstrates that the insulation across the open pole is capable of withstanding a voltage stress exceeding the applied switching or lightning impulse level by at least the value corresponding to the power frequency voltage applied to the other terminal.

Tests have been conducted by few researchers with such combinations having various proportions of 'bias voltage' together with a 'switching impulse'/75,87,121,122/. It has been established that the total withstand voltage $(U^{+}_{SI}+U^{-}_{AC})$ of the open gap insulation increases with the increase in bias voltage level. The lowest withstand voltage correspond with a pure switching impulse, that is $\alpha = 0.0$ where $\alpha = U^{-}_{AC} / (U^{-}_{AC} + U^{+}_{SI})$, and U^{-}_{AC} is peak value of ac voltage and U^{+}_{SI} is switcning impulse voltage.

If there is no correlation between the instantaneous value of tne power frequency voltage applied at tne bus-bar end and the amplitude of tne switching overvoltages appearing at tne line end, the probability of simultaneous occurrence of a switching overvoltage and a power frequency voltage of opposite polarity of greater amplitude than $K' \cdot \sqrt{2}/\sqrt{3} \times U$ is given in Table2.1 (U is rated system voltage).

TABLE 2.1

Probability of simultaneous occurrence of two peaks

Sr. No.	K'	Probability of occurrence
1	1.0	0.0
2	0.9	0.15
3	0.7	0.25
4	0.5	0.33

From this, it is clear that the value of K' should be fairly high. Even when K' = 0.9, the probability of simultaneous occurrence is still 15%. It should be attempted to consider this problem in a more general manner, investigating the scatter affecting the breakdown voltage and the law of the distribution of the values of the overvoltages.

In bias voltage test, the magnitude of the switching impulse voltage to be applied is less than the rated switching impulse withstand voltage to earth, because the simultaneous application of the rated switching impulse withstand voltage and the peak of the power frequency voltage would correspond to an overvoltage whose probability of being exceeded would be much less than the standard 2%. Therefore, some reduced value is applied, but what really of interest is to relate this test value to the actual dielectric strength of the disconnector.

In conclusion, it can be said that for the majority of cases:

- the withstand voltage between terminals for switching impulses should depend upon the value of the closing overvoltages.
- the test voltages should be a combination of the following stresses:

a. On one terminal a power frequency voltage equal to

$$U \cdot \sqrt{2} / \sqrt{3}$$, and

b. On the other terminal a switching impulse, the amplitude of which should be determined from a statistical study of the closing overvoltages taking into account a suitable safety factor.

2.4 Longitudinal insulation testing

Switchgears are differentiated in respect of dielectric testing from other H.V. apparatus through the existence of a longitudinal insulation, besides the phase-to-earth and phase-to-phase insulation. The insulation between two terminals of a pole is denoted as longitudinal insulation. It is subjected to a voltage stress of difference of the voltages at the two terminals. If these voltages are of different polarity then the voltage stress on the longitudinal insulation is higher than that of the phase-to-earth insulation. If one disregards the very improbable case of simultaneous occurrence of overvoltage waves of opposite polarity at the terminals of the pole then the maximum stress on the longitudinal insulation is different from that of the phase-to-earth insulation by the peak value of the phase-to-earth operating voltage. The relative difference between the longitudinal and the phase-to-earth voltage stress is especially large in hv switchgear, where the ratio between the insulation level and operating voltage is small.

There are two principal possibilities to test the longitudinal insulation of a switchgears with higher voltage stress than the phase-to-earth insulation, which are described in Chapter-1, section 1.4. Bachofen/121/ conducted dielectric tests using both these procedures. It was concluded that for the switchgears of EHV class, it is an important considerations that the test objects need not be isolated (i.e. ground insulation should not be raised) for testing of the longitudinal insulation, i.e. the one terminal test procedure should be avoided. Markussen et al/88/ have also recommended that the longitudinal insulation system should be tested using bias test procedure. Various researchers have conducted extensive research work on the dielectric strength of phase-to-phase insulation using two impulse waves/9,64-70/. It has been concluded that the conclusions reached for the phase-to-phase insulation are also applicable to the longitudinal insulation. Weck et al/87/ conducted experiments on phase-to-phase and longitudinal insulation and have proved that the behaviour of the insulation is same for both type of insulation systems.

The longitudinal insulation should be normally tested with an impulse wave on one terminal and a power frequency AC wave on the other terminal. However, the power frequency voltage may be replaced by a switching impulse voltage/87/. In such case two impulse generators would be required to conduct bias voltage test. This procedure solves many other problems which are discussed in Chapter-3.

Some of the published results on rod-rod gap (disconnector type open gap) and capacitive controlled rod-rod gap (circuit breaker type open gap) obtained for lightning impulse and switching impulse bias voltages are discussed in the following sections.

2.4.1 Bias voltage test on rod-rod gap insulation

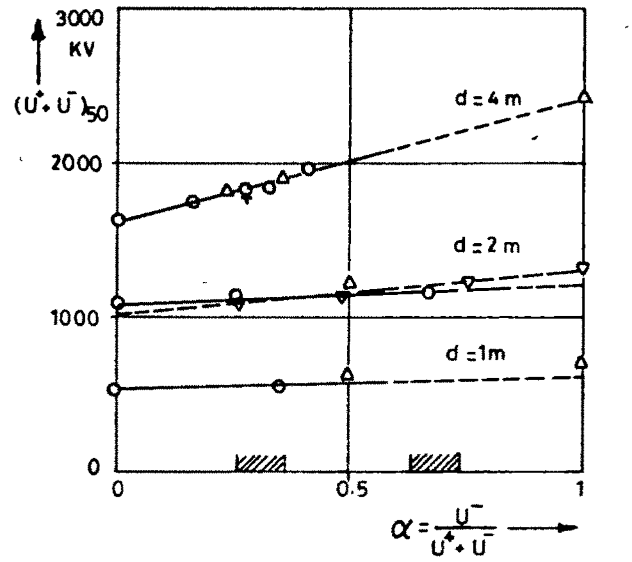
2.4.1.1 Switching impulse bias test

Weck et al/87/ conducted the bias voltage test on a disconnector by simulating the open gap using horizontal rod-rod gap configuration. The results for the switching impulse bias test are shown in Figure 2.5. The test set up of the rod-rod gap as the simulation of a disconnector type isolating gap is shown in Figure 2.7a. The results of bias voltage test obtained by them using two switching impulses (SI-SI) are also given for comparison. The dependencies of $(U^{+} + U^{-})_{50}$ as a function of α show an approximately increasing characteristics. For $\alpha = 1$, the value is only presumed, since the gap will breakdown in the positive AC half-cycle.

Similarity exists in the results for the switching impulse bias voltage test with SI-SI test results. For a 4m gap, the 50% breakdown voltages are equal, whereas for the lower distances the bias test results in slightly lower values. The differences are about 6% for the 1m gap and about 2% for the 2m gap. The decreasing tendency may be caused by a decreasing influence of the AC-corona. However, this influence is practically zero for the 4m gap, which was proved by a comparative tests with and without AC corona. The total breakdown voltage always increases with α even for very non-symmetrical gap configurations/66/.

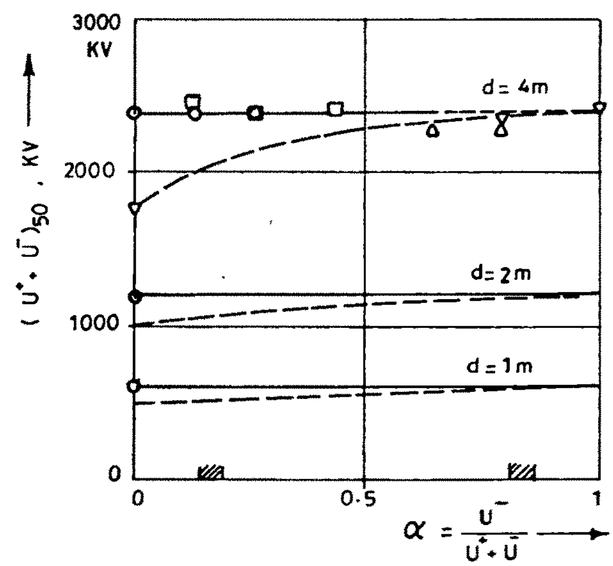
The positive impulse bias test results in lower breakdown voltages than the negative one, therefore negative switching impulse bias test is less severe compared to the positive switching impulse bias test.

Udo/75/ obtained such sparkover characteristic for rod-rod gap when a switching impulse voltage and a 50 Hz voltage is



o: positive SI-AC,
▽: negative SI-AC,
///: test range
+ : positive SI-AC, without AC corona
Δ : SI - SI

Figure. 2·5 Switching impulse bias test results of horizontal rod - rod gaps. 50 percent flash-over voltage $(U^+ + U^-)_{50}$ as a function of α (ref. 87)



——o——: positive LI - AC
---▽--- : negative LI - AC
////// : test range
□ : positive LI - SI
Δ : negative LI - SI

The α - diagrams for d = 1 and = 2 m are estimated.

Figure. 2·6 Lightning impulse bias test results for horizontal rod - rod gaps. 50 percent flash-over voltage $(U^+ + U^-)_{50}$ as a function of α. (ref. 87).

applied to each electrode separately. It was observed that the positive switching impulse bias flashover voltage $(U_{SI}^{+} + U_{AC}^{-})_{50}$ is some what higher than the ordinary positive switching impulse flashover voltage $(U_{SI}^{+})_{50}$. On the otherhand, the negative switching impulse bias flashover voltage $(U_{SI}^{-} + U_{AC}^{+})_{50}$ is found to be extremely lower than the ordinary negative switching impulse flashover voltage $(U_{SI}^{-})_{50}$. This data is indispensible for the design of the clearances between the electrodes of a disconnect switch.

Bachofen /121/ conducted dielectric tests on 420kV and 525kV system voltage swivel type isolators using one terminal test and bias voltage test procedures. It is reported that when the longitudinal insulation is tested under bias voltages, the voltage withstand capability of the gap under positive switching impulse bias voltages increases by 12% and 17% for 420kV and 525kV swivel isolator respectively.

Boehne and Carrara/122/ also conducted experiments on a rod-rod gap (gap spacing 1.65m and 3.8 m) to study the influence of bias voltages on total flashover voltage. The test performed showed that the existence of a bias voltage on the electrode opposite to that subjected to the switching surge causes a reduction in the permissible overvoltage to ground that the gap may withstand. The reduction, however, is smaller than the crest value of the bias voltage. It was observed that only 70% of the peak value of the bias voltage need be added to the peak value of the switching impulse to be withstood in order to determine the 'equivalent' switching impulse voltage with no bias, that the gap must withstand.

2.4.1.2 Lightning impulse bias test

Lightning impulse bias voltage test on rod-rod gap configuration was conducted by Weck et al/87/ on the 4m gap.The results are shown in Figure 2.6. The results obtained with lightning impulse voltage on one terminal and switching impulse voltage on the other terminal (instead of AC voltage) are also given for comparison. The differences in the results of the two test procedures are negligibly small in the specified α range of 0.14 to 0.19 for the positive lightning impulse bias test. It is seen from the results, that, for the positive lightning impulse bias voltage test, the total 50% discharge voltage is nearly independent of and equal to the sum of the two voltage components. This means that the bias test produces the same stress in the gap as the one-terminal test with the sum of the two voltage components applied to one terminal the opposite being earthed (i.e. $\alpha = 0.0$). The same conclusion was also drawn by Bachofen/126/ when he conducted lightning impulse bias voltage tests on 420kV swivel type isolator. For the negative lightning impulse bias test the 50% discharge voltage slightly increases with α. The bias test is, therefore, slightly more severe than the one terminal test with the sum of the two voltage components (α=1).The reason is that for the latter, the AC part, which is responsible for a leader formation has been removed.

2.4.2 Bias voltage test on capacitive controlled gap insulation

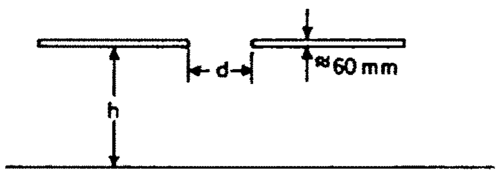
More parameters need to be considered in the case of bias voltage testing of the longitudinal insulation of the circuit breaker than the isolating gap of a disconnector. Here, the internal insulation of the control capacitors is tested in parallel with the external insulation across the breaker units. The open gap of the resistance chambers also comes in parallel with the main gap of the breaker. Secondly, as regards the external insulation two flashover paths are involved, if two or more breaker units are connected in series. One flashover path is given by a direct flashover between the terminals, the other by a subsequent flashover of the breaker units. Both the gaps differ in their dielectric flashover strength at the various test procedures.

The voltage distribution across the units connected in series was studied using computer simulation/87/ and it was observed that the overstress of the unit at the high voltage terminal increases with the number of units connected in series. For example of an 8 unit circuit breaker, having a ratio of control capacitance to stray capacitance of about 100, the overstress of the first unit is of about 17% for a one terminal test ($\alpha = 0.0$). It is of about 11% for a lightning impulse bias test ($\alpha = 0.2$), and of about 9% for a switching impulse bias test ($\alpha = 0.3$). Although the degrees of overstress are not very large, their decrease with α should be taken into account when substituting a two terminal test by a one terminal test with the sum of the two voltage components/87/. The one terminal test always represents the higher voltage stress for the breaker unit at the high voltage terminal.

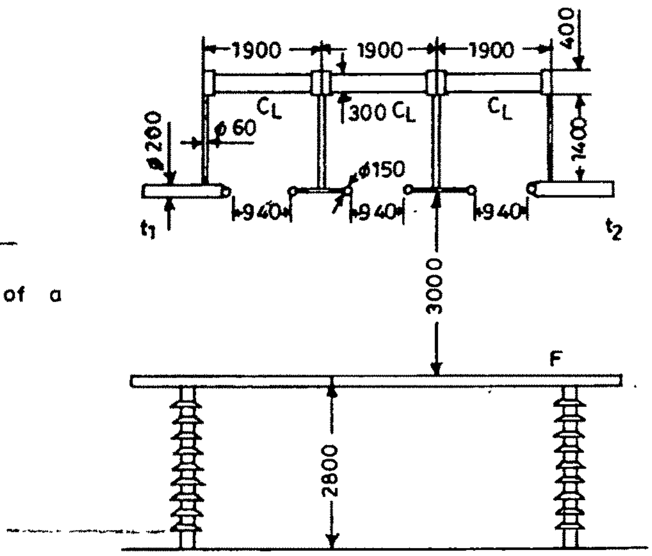
2.4.2.1 Switching impulse bias test/87/

The test set-up of the capacitive controlled gap as the simulation of an open circuit breaker is shown in Figure 2.7b. The test results are shown in Figure 2.8 for the metal base grounded as well as ungrounded. The results of switching impulse-switching impulse (SI-SI) test (i.e. switching impulse voltage is applied to both the electrodes having opposite polarity i.e. U_{SI}^{+} and U_{SI}^{-}) are also given for comparison. For $\alpha < 0.5$ both the test procedures result in practically the same 50% discharge voltages. With the increase of α, the U_{50} increases as for the case of single air gap. For $\alpha > 0.7$ non-gaussion distributions have been obtained, which indicate the complexity of the discharge phenomena of multiple gaps. However, from the testing point of view the range of $\alpha > 0.5$, is of lower interest because the measured 50% discharge voltages are considerably higher than for $\alpha < 0.5$, i.e. the positive switching impulse bias test is more severe than the negative one. The difference in the results reported for the grounded and the ungrounded base is because of the higher flashover probability to ground for the arrangement with grounded base, for $\alpha = 0$ nearly all flashovers occur from the high voltage terminal to ground.

Figure 2.9 shows the comparison of the positive switching impulse test results of the controlled gap as a simulation of circuit breaker and actual circuit breakers. All values indicated are relative numbers with the 50% discharge voltage at $\alpha = 0$ as the basis. The results for the actual breakers show a considerable dispersion, which may, howe-

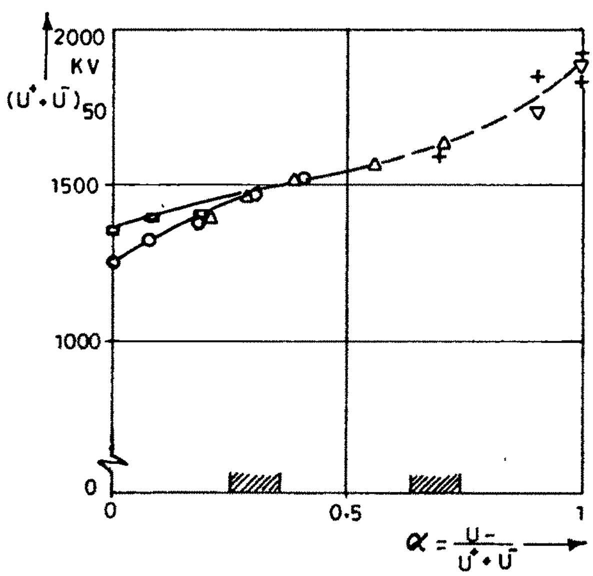


a) rod-rod gap as the simulation of a disconnector isolating gap.
d: gap distance
h: height above ground
$\frac{h}{d} \geq 2.5$



b) capacitive controlled gap as the simulation of an open circuit-breaker.
t_1, t_2 : terminals
F : metal base frame (8x 0.3 x 0.15 m)
C_L: control capacitance (1050 pF ± 1%)
dimentions in mm.

Figure. 2.7 Investigated longitudinal gap configurations, (ref. 87)



o : positive SI-AC, metal base grounded
+ : negative SI-AC, metal base grounded
/// : test range
□ : positive SI-AC, metal base ungrounded
▽ : negative SI-AC, metal base ungrounded
Δ : SI-SI, metal base grounded

Figure. 2.8 Switching impulse bias test results for the circuit breaker simulation. 50 percent flashover voltage $(U^+ + U^-)_{50}$ as a function of α. (ref. 87)

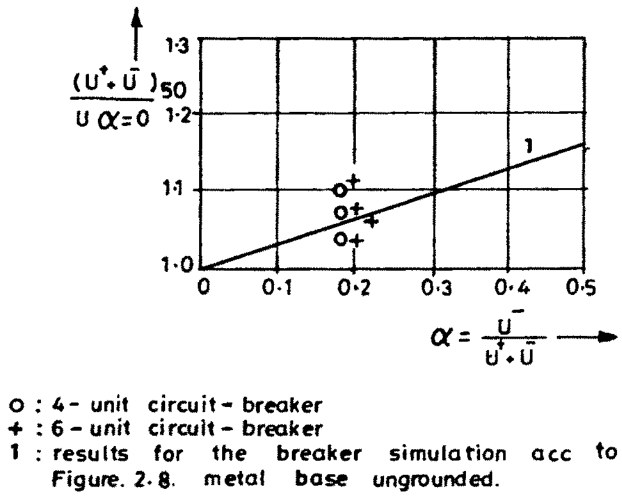


Figure. 2·9 Positive switching impulse bias test, comparison between circuit - breaker simulation and actual circuit - breaker test results. Related 50 percent flashover voltage $(U^+ + U^-)_{50} / U\ \alpha = 0$ as a function of α. (ref. 87)

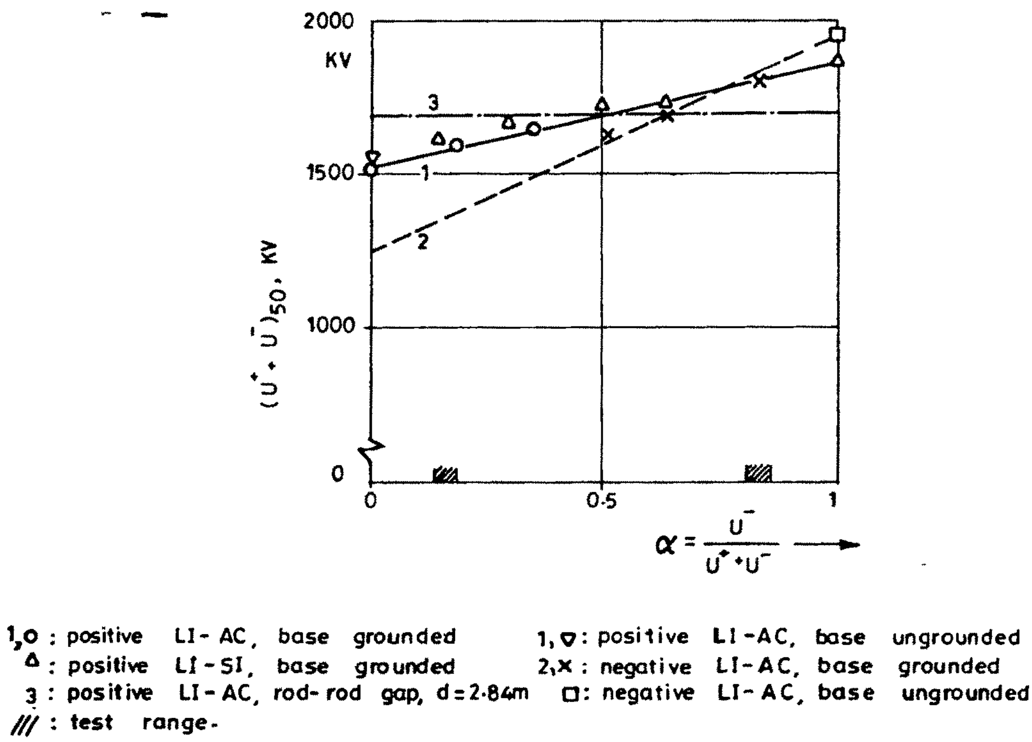


Figure. 2·10 Lightning impulse bias test, controlled breaker simulation. 50 percent flashover voltage $(U^+ + U^-)_{50}$ as a function of α. (ref.87) ver, be simply caused by statistical inaccuracies in the determination of U_{50}. In average, the circuit breaker results are in good agreement with those of the breaker simulation for the ungrounded base.

2.4.2.2 Lightning impulse bias test/87/

The lightning impulse bias test results obtained by Weck et al/87/ for a gap simulating a circuit breaker are shown in Figure 2.10. The results of lightning impulse-switching impulse (LI-SI) bias test are also given for comparison. The 50% discharge voltages obtained with both the procedures show a difference of about 3%.

It is seen from Figure 2.10 that the positive lightning impulse 50% discharge voltage increases with α. This is in contradiction with the results for the single rod-rod gap presented in Figure 2.6. For a rod-rod gap with the same open gap distance as a simulated circuit breaker gap, the total 50% discharge voltage is practically independent from α, (curve 3 of Figure 2.10). The single air gap behaves symmetrically, i.e. the positive and the negative 50% lightning impulse discharge voltages are nearly equal. The capacitive controlled gap behaves non-symmetrically as a rod-plane gap. The positive and the negative 50% lightning impulse flashover voltages of the capacitive controlled gap are practically the same as the relevant rod-plane values. The explanation of this gap behaviour can be partly found in the presence of the capacitance feeding energy into the stremer channel.

For all bias voltage tests the positive polarity of the impulse voltage is more severe than the negative polarity. In all bias voltage tests the power frequency voltage can be substituted by a switching impulse voltage which may be of advantage especially for the switching impulse bias test. It seems the lightning impulse bias test governs the requirement of the open gap clearances for circuit breakers.

2.5 Air density correction factor

The dielectric strength of air decreases at high altitudes where air is less dense. The extent of this lowering is much affected by the electrode configuration, the gap spacing and the waveshape of the applied voltage. Uncertainties about the influence of the above factors may therefore have important economic consequencies in the design of transmission lines and substation.

A few studies have been conducted on the influence of air density on the impulse strength of large air gaps for different electrodes configurations/98,125,126/ and some correction factors have been suggested/5/. The correction philosophy of the standards is based on in depth analysis of a large quantity of experimental results. Neverthless, the matter cannot be considered as sufficiently rationalised. As an example, in the standards/5,95/ a subdivision between non-uniform configurations with 'essentially symmetrical voltage distribution', and with 'pronounced asymmetrical distribution' is made and it is difficult to decide to which category the actual line and sub-station configurations belong.

In order to get comprehensive information on the influence of air density as a function of gap geometry, impulse shape and voltage polarity, systematic tests were performed at altitudes ranging from 0 to 1800 m/129,130/. The same tests, on very similar configurations and with the same procedures, were carried out in three laboratories, the results are reported in the literature/130,134,135/. It was observed that the air density influences both the minimum value of the U curves and their shapes, thus contributing to deter-rmine the critical time-to-crest of the impulses/135/. A decrease of air density causes a decrease of the critical time-to-crest. Also, the time to breakdown and standard deviation, σ, decreases with increasing air density /135/.

Kucera and Fiklik/99/ conducted experiments on rod-plane and rod-rod gap, using switching impulses of 200/3200 μs and 450/4300μs wave. It was observed that the correction factors specified by IEC publication-60 for gap spacing greater than 1.5m are too high. For 3m gap spacing the difference is about 3%. The results published by them were further analysed by Kachler et al/127/ and it was investigated that the influence of both humidity and relative air density is similar to a change in dimension of the test object, the change being the same in percentage for any kind of object and stress.

Kuffel et al/128/ carried out extensive work on rod-rod gap. Although, IEC publication 60 and IEEE Standard-4 do not give specific recommendations for correcting the data measured under negative switching impulses, it was confirmed that the air density has a very significant influence on the breakdown value. The application of this correction factor to the data obtained with the negative polarity rod gap results in a linear relationship between the corrected breakdown voltage and the absolute humidity.

Aihara et al/100/ conducted experiments on rod-plane gaps using switching impulses. It was observed that the variation of flashover voltage with relative air density depends only on the gap spacing irrespective of the waveform, polarity and electrode configuration.

2.5.1 New correction approach

Pigini et al/130/ have slightly modified the present correction factors specified by IEC publication 60 for atmospheric correction.

A relation of the following type is assumed between the 50% discharge voltage U_{50}, relative air density δ and absolute humidity H evaluated in the prevailing atmospheric conditions, and the corresponding parameter U_{50_o} evaluated in the standard atmospheric conditions.

$$U_{50} = U_{50_o} (\delta)^n . (K)^W \quad ..... \quad (2.3)$$

$$\text{with } K = 1 + \frac{H-H_O}{100} \quad ..... \quad (2.4)$$

where n, w = exponents which vary with the geometry and impulse characteristics

H_o = Standard reference humidity, 11 $gm.m^{-3}$.

The above expressions are slightly different from those given by IEC publication-60. Here, both the correction factors are acting as a multiplying factor /131/. In principle, the determination of the density influence from experimental results would imply the correction of the data for the influence of humidity.

Assuming that n and w are very similar/5,130/, the following expression may be assumed:

$$U_{50} = U_{50_o} \ (\delta \cdot k)^n \qquad \ldots\ldots \qquad (2.5)$$

The exponent n can be determined by applying formula (2.5) to the sets of results obtained at different atmospheric parameters.

Joint research work was conducted by ENEL, CESI, ESCOM and CFE to study the influence of air density on the impulse strength of external insulation/130,134,135/. The tests were performed on various electrode cofigurations with positive and negative polarity impulses, whose shapes were varied from the standard lightning to long switching impulses.

Three sets of results were obtained at three different sites and exponent n was derived by applying formula 2.5. Eventhough the determination of exponent n is affected by a large statistical uncertainty, the following qualitative remarks were made for standard impulses/130/.

a) For lightning impulse n is close to 1, with some tendency to lower values for the negative polarity and small gaps.

b) For positive switching impulses n is in the range 0 to 0.7, with a tendency to decrease with increasing gap clearance.

c) For negative switching impulses n is strongly dependent on the configuration, ranging from 0.2 to 1.2

The above trends are in line with the present IEC Standards for lightning impulse. However, when switching impulse is considered, the IEC correction factors seem to be too large for positive polarity, and completely inadequate for negative polarity. In a more general way, the data obtained indicated a very complex dependence of air density influence on impulse shape, polarity and gap geometry. Based on basic discharge processes involved they have proposed a new correction approach which is described in reference no. 132.

2.6 Humidity Correction Factors:

Flashover voltages of external insulation such as air gaps, suspension insulator strings, bushings, capacitors and so on vary with the change of atmospheric humidity.

For this reason, this effect must be taken into consideration for the design of various external insulation systems. While standard correction factors are available for positive polarity switching impulses, no such corrections are given by the IEC or IEEE for the negative switching impulse breakdown of non-uniform symmetrical field gaps "owing to uncertainty of the available experimental data". Also, no mention is made of the likely effect of the electrode shape or of conditioning of the electrodes. The correction factors given by standards are based on the data obtained from nearly standard lightning and switching impulses, therefore, it is not clear whether application is possible for various other impulses including wave fronts of very long duration, as for example 1000 μs.

Busch/103/has studied the effect of humidity on the flashover characteristics of air gaps with spacing of 5 m or more and has reported that for rod-plane gaps of 5 m or more in spacing, the critical time-to-crest and the time-to-flashover changed significantly according to the absolute humidity.

Aihara et al/100/ have investigated the influence of atmospheric humidity on rod-rod and rod-plane gaps with various wavefronts of positive and negative polarities at CRIEPI. It was observed that the ratio between two flashover voltages under standard atmospheric conditions of which the **gap spacing** , size of the electrode and the duration of impulse are all in a constant relation, is determined by each gap spacing irrespective of the electrode configuration, waveform and polarity. Further, the humidity correction of flashover voltage when air density is constant differs with the waveform, polarity, gap spacing and electrode configuration. The humidity correction factor and the humidity co-efficients(K) assume U-shaped curves when shown as a function of wavefront. However, if the ratio of time-to-crest to the gap spacing is constant, the humidity correction factor has only one value, whereas humidity co-efficient becomes smaller as the gap spacing is increased. Based on these investigations, they have proposed a new humidity correction factor for UHV class equipments which is described in reference no. 100.

Many reports of test results concerning the effect of atmospheric humidity on impulse flashover voltages for short and long air gaps have been published for phase-to-ground insulation. However, no published results are available concerning the humidity correction factors for bias voltages.

A brief summary of the published results on humidity correction factor for phase-to-ground insulation is given in the following sections.

2.6.1 Influence of humidity on rod-rod-gap

Allibone and Dring/97/ conducted experiments on rod-rod gap which were made of 1.25 cm square cross-sectional steel-bar, cut square. To determine the breakdown voltage, twenty impulses of the same voltage were applied below the expected breakdown value at intervals of 15 to 20 secs. Figure 2.11 gives the results of breakdown voltage at several humidities from 4 to 18.6 $gm.m^{-3}$ for impulses of short wavefront, i.e., 1/50 μs. From these curves humidity correction factors can be determined with fair precision. Figure 2.11b gives the breakdown voltage as a function of gap spacing for three humidities for positive polarity and one curve for negative polarity (as the correction factor on negative polarity is small, only one curve is shown in this figure). The standard deviation σ ranges

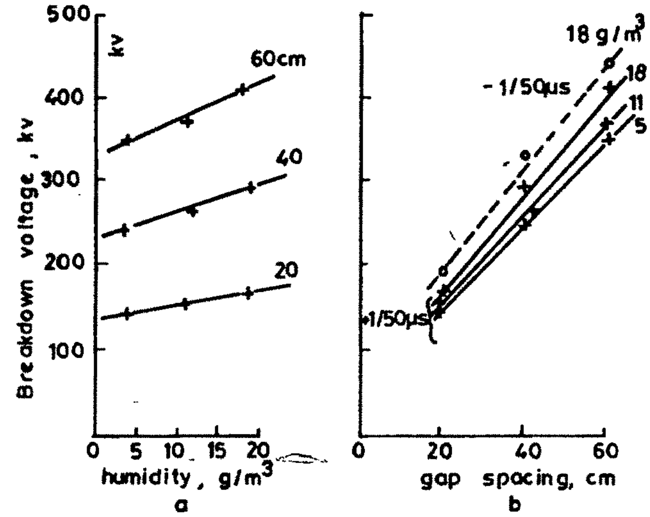


Fig. 2·11 Effect of humidity on breakdown voltage for different gap spacings. (ref. 97)

a. Breakdown voltages (corrected to s.t.p.) of rod rod gaps under ± 1/50 μs waves at various humidities ———— positive - - - - - - - negative.

b. Curves for +1/50μs waves derived from fig. 2·11 a and −1/50 μs waves derived from the results obtained.

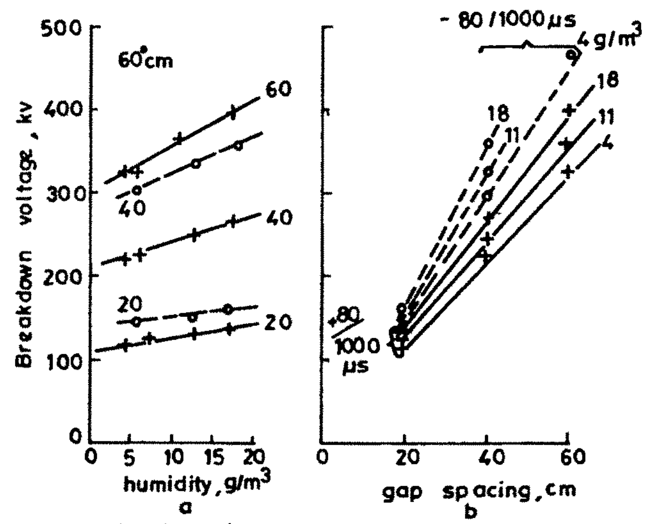


Fig. 2·12 Effect of humidity on breakdown voltage for different gap spacings. (ref. 97)

a. Breakdown voltages (corrected to s.t.p.) of rod rod gaps under ± 80 / 1000μs waves at various humidities

———— positive

- - - - - - - negative

b. Curves derived from fig. 2·12 a

from 1% to 4%.

Figure 2.12a gives the switching impulse (80/1000 μs) 50% discharge voltage for positive and negative polarities. The breakdown voltages were corrected to standard temperature and pressure. The breakdown voltage increases with the increase in humidity. The breakdown voltage curves derived from Figure 2.12a for three selected humidities are given in Figure 2.12b. The scatter for all tests was small, ranging from 1% to 4%. It was concluded that the humidity correction factor does not change much with the gap spacing. The breakdown voltage under positive polarity is more affected by humidity than the breakdown under negative polarity, and switching surge breakdown is more affected by humidity than the lightning impulse breakdown. These results were in good agreement with those of others for lightning impulses of positive polarity/98,99/.

Kuffel et al/128/ conducted extensive research work on 1 m rod-rod and sphere-sphere gap (the sphere diameter was 12.5cm). The tests were performed outdoors at various naturally occuring humidity conditions. It was found that the breakdown voltage, when corrected for air density using the factor recommended by IEC for positive polarity switching impulses changes by approximately 1.7% per 1 $gm.m^{-3}$ increase in absolute humidity for the rod gap under switching impulses of both polarities and for the sphere gap under positive switching impulses. It was also observed that in general the spread between statistical withstand and statistical flashover voltages increases with the increase in humidity. This is due to the general trend towards increased values of sigma at higher humidities/128/.

2.6.2 Influence of humidity on rod-plane gap

Allibone and Dring/97,104/ conducted experiments upto 80cm rod-plane gap spacing using lightning and switching impulse waves by creating different humidities artificially. The correction factor did not appear to depend much on the gap length over the voltage range of 130kV to 500kV. Standard deviation of the scatter of results fall with increased spacing to about 2% and are not dependent on humidity for the range of 4 to 18.6 $gm.m^{-3}$.

Hahn et al/101/ conducted experiments on a 50 cm rod-plane gap. It was observed that with increase in humidity the U_{50} increases approximately by 1.04% $/gm.m^{-3}$(results were obtained with an impulse waveshapes of 45/2500 μs. and 520/3000 μs). The standard deviation σ also increases, changing from about 3% to more than 5%. U_{50} and time to break down T_B were not influenced by the shape of the h.v. electrode (hemisphere or cone).

Busse and Feser/136/ also conducted experiments on a rod-plane gap. The rod was made of 4cm diameter tube which ended in a cone, 30° radius 0.5 mm. The earthed plane was made of aluminium sheet (2 x 2 m^2) and the open gap spacing was 1 meter. In the case of lightning impulse voltage a correction factor of 1.02% $/gm.m^{-3}$ was evaluated upto a absolute humidity of 30 $gm.m^{-3}$. At higher humidity the predischarge at the lightning impulse voltage becomes a leader predischarge and hence the correction gets lowered. It was also concluded that the effect of humidity on U_{50} of a positive rod-plane gap is dependent upon the different discharge phenomenas.

The 50% flashover voltage when expressed as a function of the time-to-crest, exhibits the famous U-curves (refer Figure 2.1) which are particularly more pronounced for geometries with very divergent fields. The minimum value of U_{50} obtained at the critical time to crest is essential for the design of insulation and therefore it is of great importance to examine the influence of humidity on the U-curves and especially on the values of U_{50} minimum and $T_{cr-crit}$. Busch/103/examined this effect on rod-plane gap and the following observations were made.

- the U-curves are significantly modified by humidity,
- with an increase of humidity, the minimum of the curve shifts towards shorter values of time to crest and the minimum flashover voltage decreases.
- for a given spacing the influence of humidity is more pronounced for long time-to-crest.
- the critical time-to-crest is a function of humidity and gap spacing.