CHAPTER-6

BREAKDOWN PHENOMENA UNDER BIAS VOLTAGES: INFLUENCE OF HUMIDITY, TIME SHIFT AND AC BIAS VOLTAGE

6.1 General

It is known that, if the longitudinal insulation of the circuit breakers and the disconnectors is tested under bias voltages, the exact site situation of the equipment can be simulated at the laboratory and the performance of the equipment when installed in the system can be guaranteed better. Also, it is established that, if the longitudinal insulation is tested under bias voltages, the dielectric withstand capability of the gap increases compared to the equivalent test prescribed by IEC. IEC publications 56/90/ and 129/91/ have specified the impulse voltage and AC bias voltage levels to be applied to the test object while conducting bias test for various system voltages. The method of correction and limits of the voltage distortion on ac wave because of capacitive coupling between two terminals of the test object have been also specified in these standards. However, it is not clearly specified how the atmospheric correction factors should be applied. The utilities and industries have followed the practice of applying correction factors to the impulse voltage and AC Bias Voltage separately according to IEC publication 60. It is not known whether this method of correction is correct. Also, in the case of longitudinal insulation, several aspects of the problems are not yet clearly understood due to the increased number of parameters both geometrical and electrical which affect the open gap performance. The large possible combinations arising from the variations in electrode shape, height of the electrode above the ground, relative amplitude of the impulse and AC Bias voltage, time shift between the two peaks of the voltage waves, makes it difficult to fully account for the gap behaviour under bias voltages.

Up to now, there have not been any published data on the humidity dependance of the bias flashover voltages of the longitudinal insulation. Therefore, experiments were carried out at different naturally occuring humidity for sphere-rod and rod-rod gap electrode configuration under bias voltages.

Two types of electrode shapes were chosen for AC terminal to study the effect of AC corona on bias flashover voltages. Few sets of results were obtained for a range of absolute humidity from 2 to 18 $gm.m^{-3}$. The same tests, on an exactly similar configurations and with the same procedures were repeated at different absolute humidity.

In the following sections the results are presented and analysed. The need for considering a new humidity correction method for switching impulse bias voltage has been suggested. Apart from this the influence of the following parameters was also studied and the results are discussed at depth in this chapter.

a. Influence of AC corona on bias flashover voltages

b. Influence of AC voltage level on bias flashover voltages.

c. Influence of time-to-crest of the impulse wave on bias flashover voltages.

d. Influence of time shift between two waves (Δt)

e. Influence of rain on switching impulse bias flashover voltages

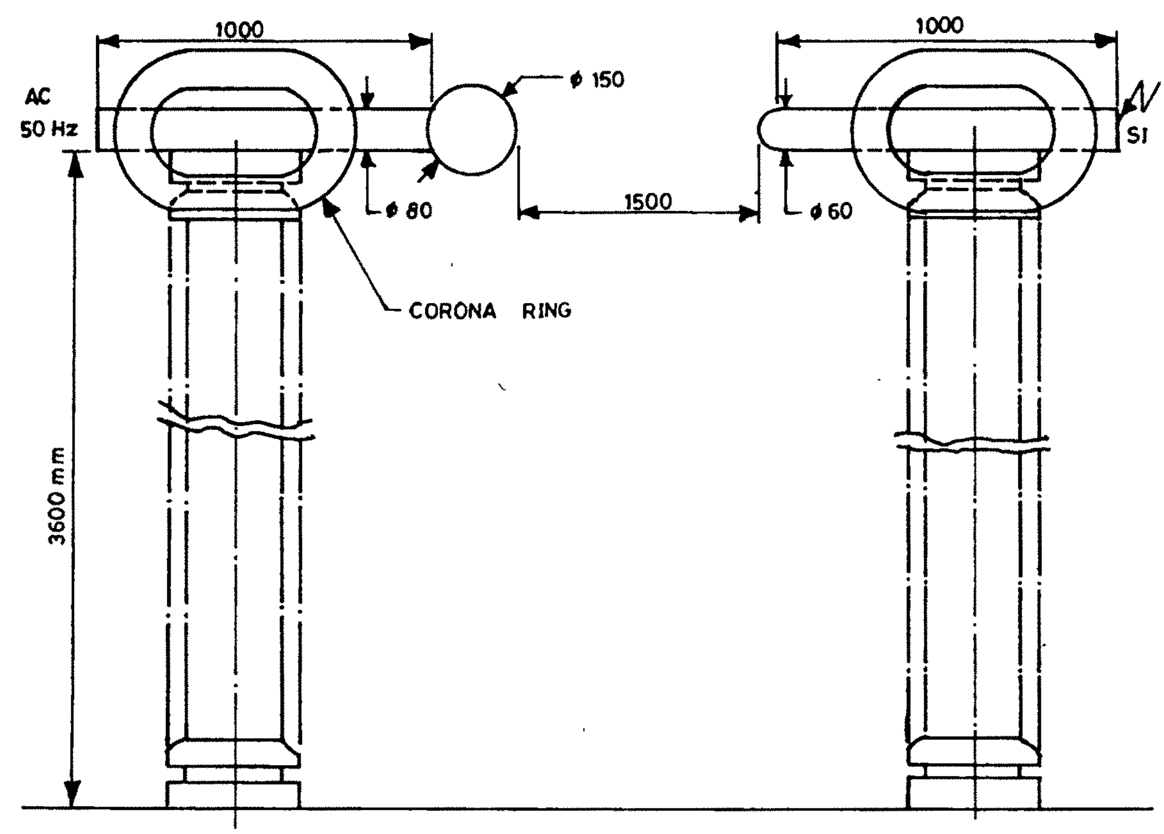
6.2 Humidity correction factor under bias voltages

6.2.1 Test configuration and set-up

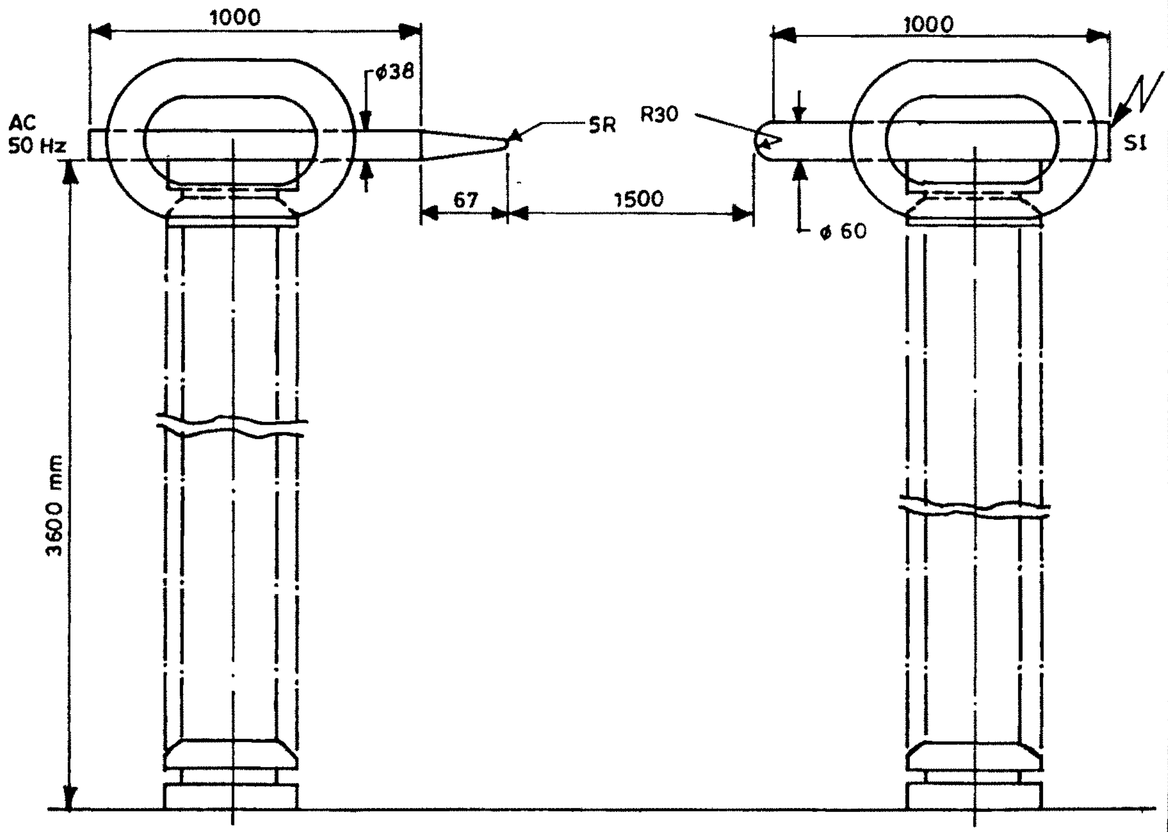
Two test configurations were adopted to study the effect of humidity on the breakdown phenomena under bias voltages. The test configurations are shown in Figure 6.1. The switching impulse voltage was given to a 60mm diamter Aluminium round having a tip radius of 30mm for both types of electrode configurations.

In order to study the influence of AC corona on breakdown strength under bias voltages, two different electrode systems were adopted. For sphere-rod gap electrode configuration, the diameter of the sphere was chosen such that when the required AC bias voltage is applied continuously, it does not give any corona, the diameter of the sphere was 150mm. For rod-rod gap electrode configuration, the shape of the electrode to which ac bias voltage is applied was selected such that it gives continuous corona when AC bias voltage is applied. The tip radius of this electrode was 5mm.

The open gap clearance for both the electrode system was 1500mm. To reduce the complexity of the analysis of the



(A) Sphere - Rod gap configuration



(B) Rod - Rod gap configuration

Figure. 6·1 Sphere - Rod and Rod - Rod gap assembly.

results and because of the test plant limitations, higher gap clearances more than 1500mm were not tested. Also, it was felt that open gap clearance of 1.5 meters is sufficient for this type of study.

The bias test circuit shown in Figure 4.2 was adopted for conducting this study, i.e. the high voltage damping resistor of 8.56 Kilo Ohms was connected between the high voltage testing transformer and the supporting capacitor C_2. The value of the supporting capacitor C_2 was 866.6pF.

It is worthwhile mentioning here that whenever the test was repeated at different humidity, all the equipments and the test gap were located at the same place. Same laboratory clearances were maintained from all the sides.

6.2.2 Test procedure

For each test, two AC 50 Hz Bias voltage levels, 107 kVp and 214 kVp were chosen for each electrode configuration. The required AC Bias voltage was applied to the power frequency electrode continuously and the 50 per cent switching impulse discharge voltage $(U^{+}_{SI})_{50}$ was measured by applying the Up and Down method for at-least 50 impulses, and using a step size of 4 to 6 per cent of the estimated U_{50} voltage. The switching impulse voltage was applied to the opposite electrode at 25 seconds interval. The power frequency voltage was kept constant and only switching impulse voltage was varied to obtain 50 per cent discharge voltage of the gap under bias voltages.

The tests were performed with positive polarity impulses only, which are of particular importance for the external insulation design. Once again, for this study only one wave-shape was used to avoid the introduction of too many variables. The wave shape chosen was a 240 x 2500 μs standard switching impulse as per IEC publication-60/5/.

For two AC bias voltage levels, the test was conducted at more or less the same absolute humidity level. The atmospheric variables, namely the wet and dry bulb temperatures and barometric pressure were measured before each test, and checked at the end of each run. The wet and dry bulb thermometers were located near the test object.

The tests for both the electrode configurations were performed inside the laboratory at various naturally occuring humidity levels. The tests were performed for the range of humidity between 2.0 and 18 $gm.m^{-3}$.

All the tests were conducted in clean and dry conditions during day time. To check the results for consistency, for some range of humidity level, the tests were repeated.

6.2.3 Analysis of test results

As discussed in Chapter-1, IEC specifications have not clearly explained how the correction factors should be applied under bias voltages. The present practice followed by the industries/utilities is to apply correction factors separately to the respective polarity of the impulse and AC voltage as defined by IEC publication-60 and IEEE standard-4. It is not known whether this approach is correct and sufficient.

Thus, one of the aims of this thesis was to study whether the present humidity correction approach is correct. For this purpose 50% discharge voltage for sphere-rod and rod-rod electrode configuration was obtained for a range of humidity between 2 to 18 $gm.m^{-3}$ for two AC bias voltage levels applied to the opposite electrode.

6.2.3.1 Correction factors as per standards

6.2.3.1.1 Air density correction factor

The air density correction factor recommended by the IEC publication-60 and IEEE standard-4 for the positive polarity switching impulse breakdown voltage of symmetrical non-uniform field air gaps consists of dividing the measured voltage by the air density correction factor K_d:

$$K_d = \left(\frac{b}{bo}\right)^m \times \left(\frac{237 + to}{273 + t}\right)^n \qquad \ldots\ldots \quad (6.1)$$

Where

b	=	atmospheric pressure during test (millibar)
bo	=	standard reference atmospheric pressure (1013 milli bar)
t	=	atmospheric temperature (in °C) under test conditions
to	=	standard reference atmospheric temperature (20 °C)
m,n	=	exponents as per curves given by IEC publication-60

The same air density correction factor is also applied to the power frequency AC voltage.

Figure 6.2 shows the uncorrected 50 per cent switching impulse discharge voltages, $(U^{+}_{SI})_{50}$, for sphere-rod and rod-rod gap (under positive switching impulse) as a function of

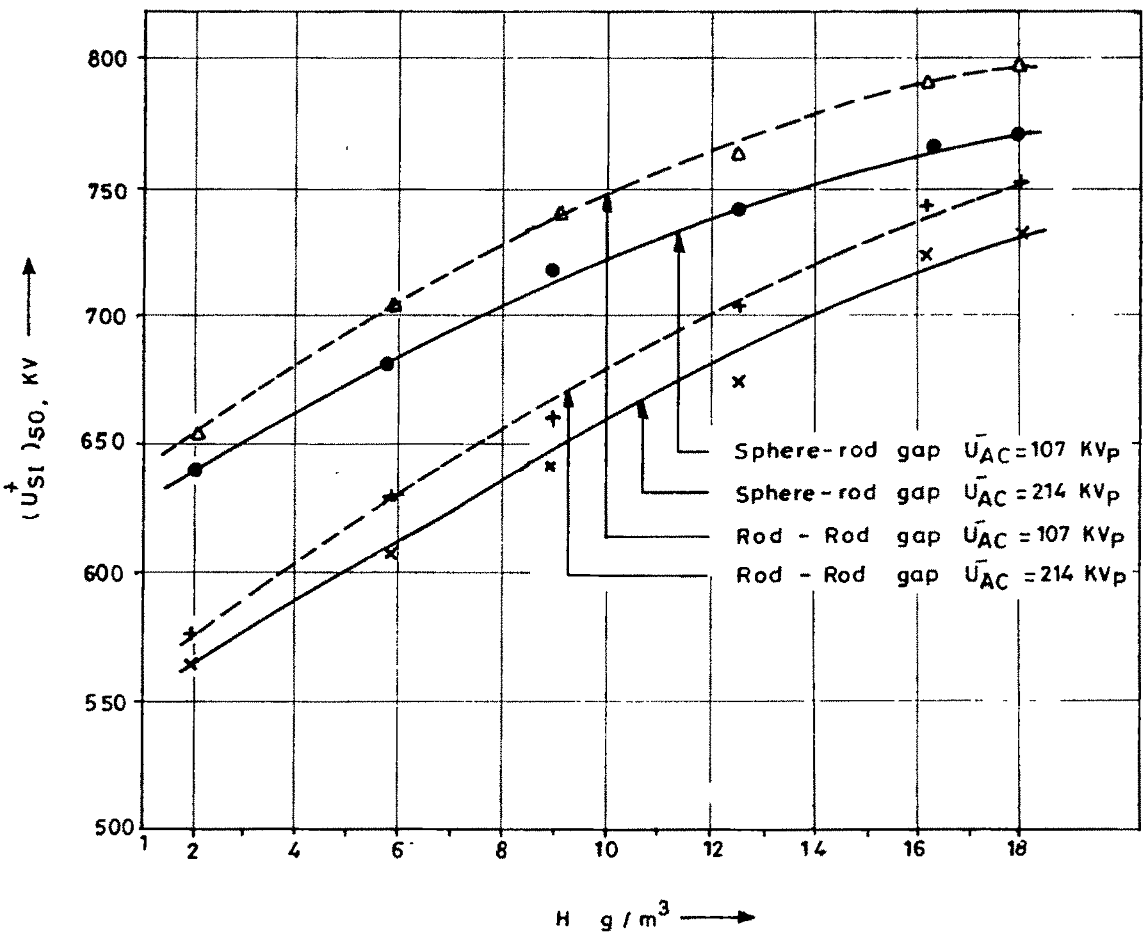


Figure. 6.2 Uncorrected U_{50} voltage as a function of humidity for sphere - rod and rod - rod gap under positive switching impulse.

the absolute humidity. The $(U_{SI}^{+})_{50}$ voltage was obtained for two AC bias voltage levels, 107 kVp and 214 kVp. The $(U_{SI}^{+})_{50}$ voltage increases with the increase in absolute humidity. It may be observed that the difference between $(U_{SI}^{+})_{50}$ voltage for two AC bias voltage level decreases as the absolute humidity increases. Also, for the same electrode gap spacing the rod-rod gap electrodes configuration gives higher breakdown voltages than the sphere-rod gap for the same AC Bias voltage level. It may be concluded that under bias voltages, the AC corona produced at the power frequency terminal enhance the voltage withstand capability of the open gap insulation. When correction for air density are made, the relation shown in Figure 6.3 and 6.4 is obtained. In Figure 6.3, the voltage $(U_{SI}^{+})_{50}$ as a function of absolute humidity is shown and in Figure 6.4 the voltage $(U_{SI}^{+}+U_{AC}^{-})_{50}$ as a function of absolute humidity is shown. As seen from these figures, after air density correction factor is applied the curves are more or less straight lines, while the curves shown in Figure 6.2 are not in straight line.

Thus, it may be concluded that the application of air density correction factor to the raw data results in a linear relationship between the corrected breakdown voltage and the absolute humidity.

6.2.3.1.2 <u>Humidity correction factor</u>

The humidity correction factors recommended by IEC publication-60/5/ and IEEE standard-4/95/ for positive switching impulse breakdown voltage and power frequency volt-

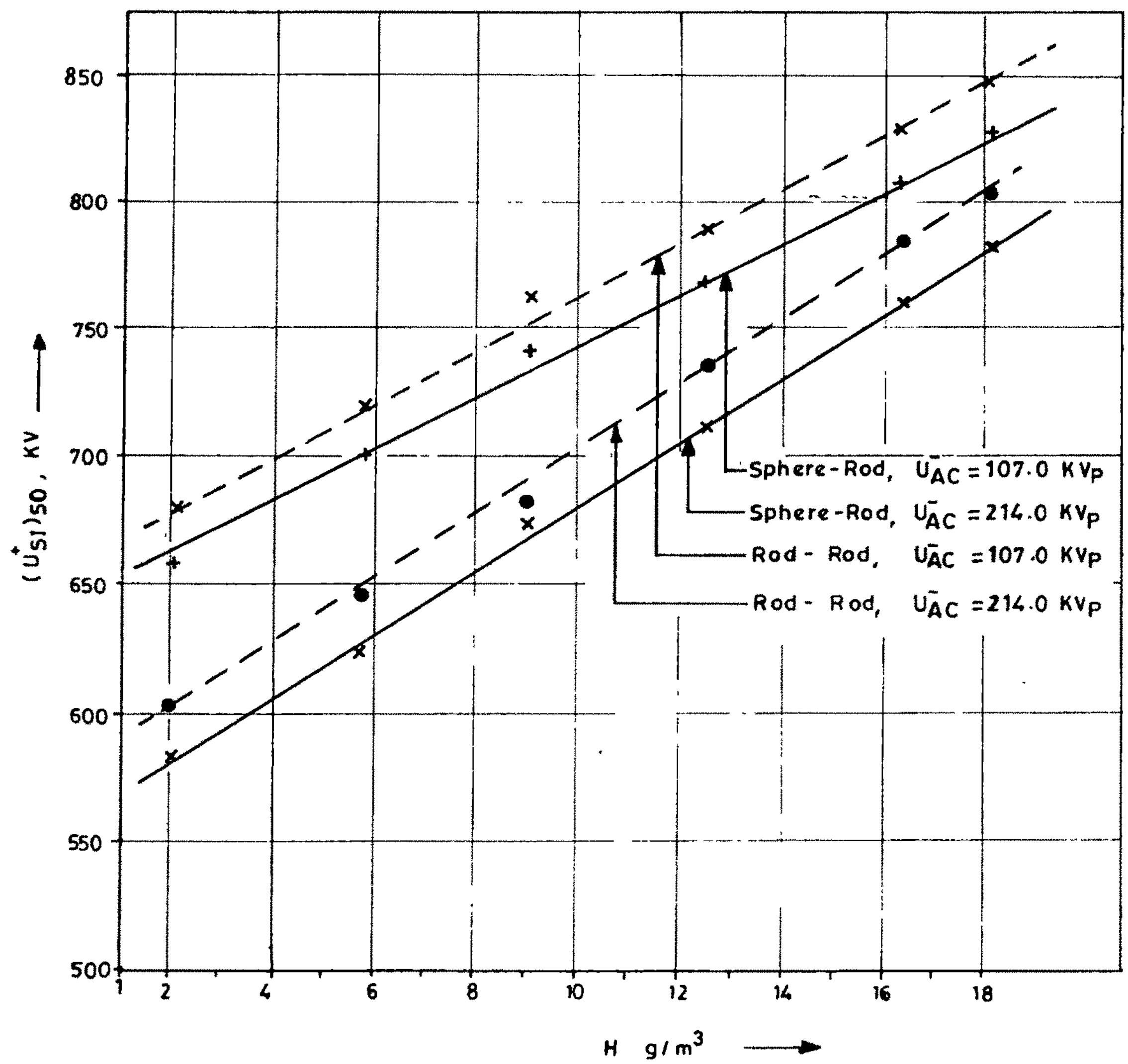


Figure. 6.3 K_d Corrected $(U^+_{SI})_{50}$ voltage as a function of absolute humidity.

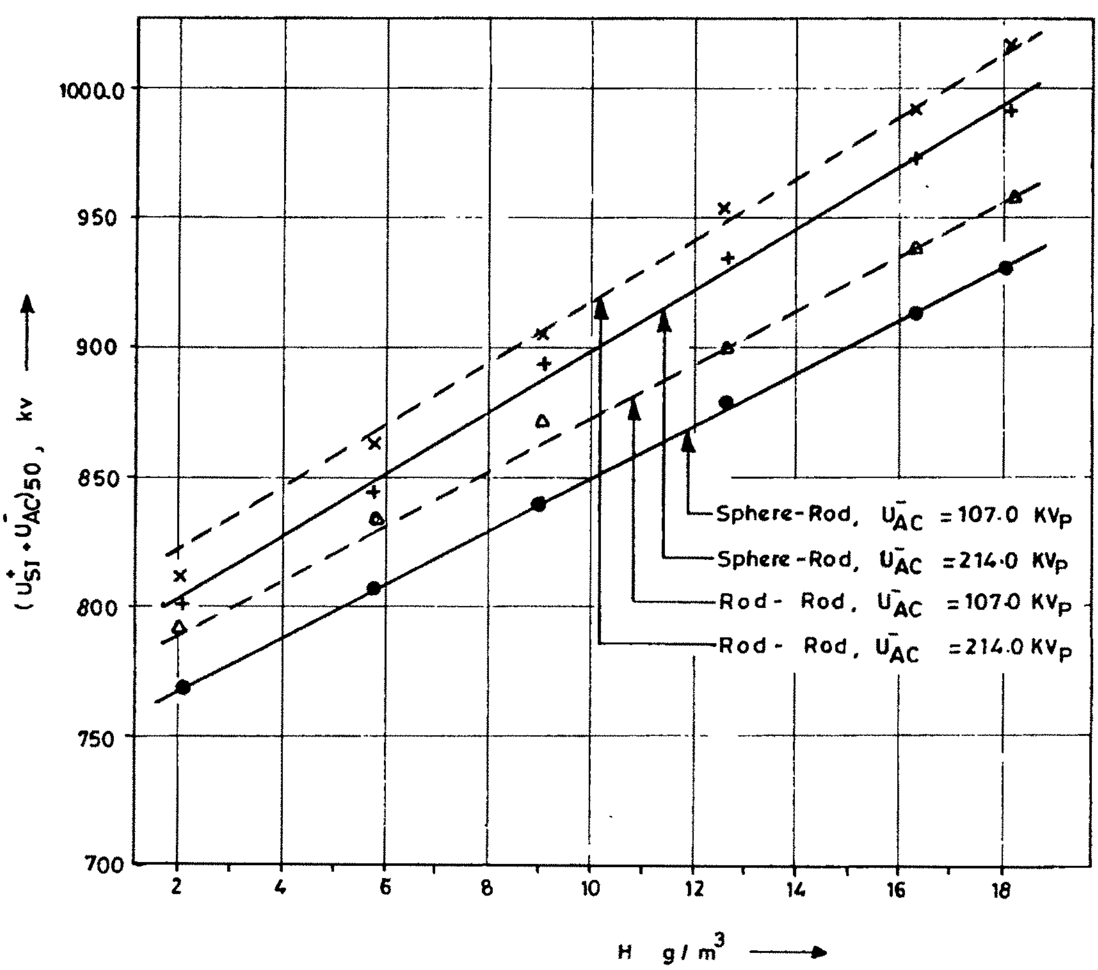


Figure. 6.4 K_d Corrected $(U^{+}_{SI} + U^{-}_{AC})_{50}$ voltage as a function of absolute humidity.

age consists of multiplying the measured breakdown voltage by humidity correction factor K_h given by:

$$K_h = (K)^W \qquad \ldots\ldots\ldots \qquad (6.2)$$

Where,

K =is humidity correction factor as a function of absolute humidity

W =exponent

Both these factors K and W are defined clearly by IEC specifications and IEEE standard-4 for impulse and AC voltages. For switching impulse and AC voltage, this factor was applied separately to the air density corrected critical flashover voltage for both types of gaps. The results of this correction to the $(U^{+}_{SI}+U^{-}_{AC})_{50}$ voltage as a function of absolute humidity (IEC corrected means values for both air density and humidity correction factors as per IEC specification are applied) is shown in Figure 6.5.

Comparing the results shown in Figure 6.4 and 6.5 it is seen that after humidity correction, the slope of the curves have decreased. Also, the difference between $(U^{+}_{SI}+U^{-}_{AC})_{50}$ voltage for two AC Bias Voltage level is more or less same with the increase in absolute humidity, which was not the case when only air density correction factor is considered.

It is seen from the results shown in Figure 6.5, that the $(U^{+}_{SI}+U^{-}_{AC})_{50}$ voltage increases with the increase in humidity even after applying both the correction factors. If the

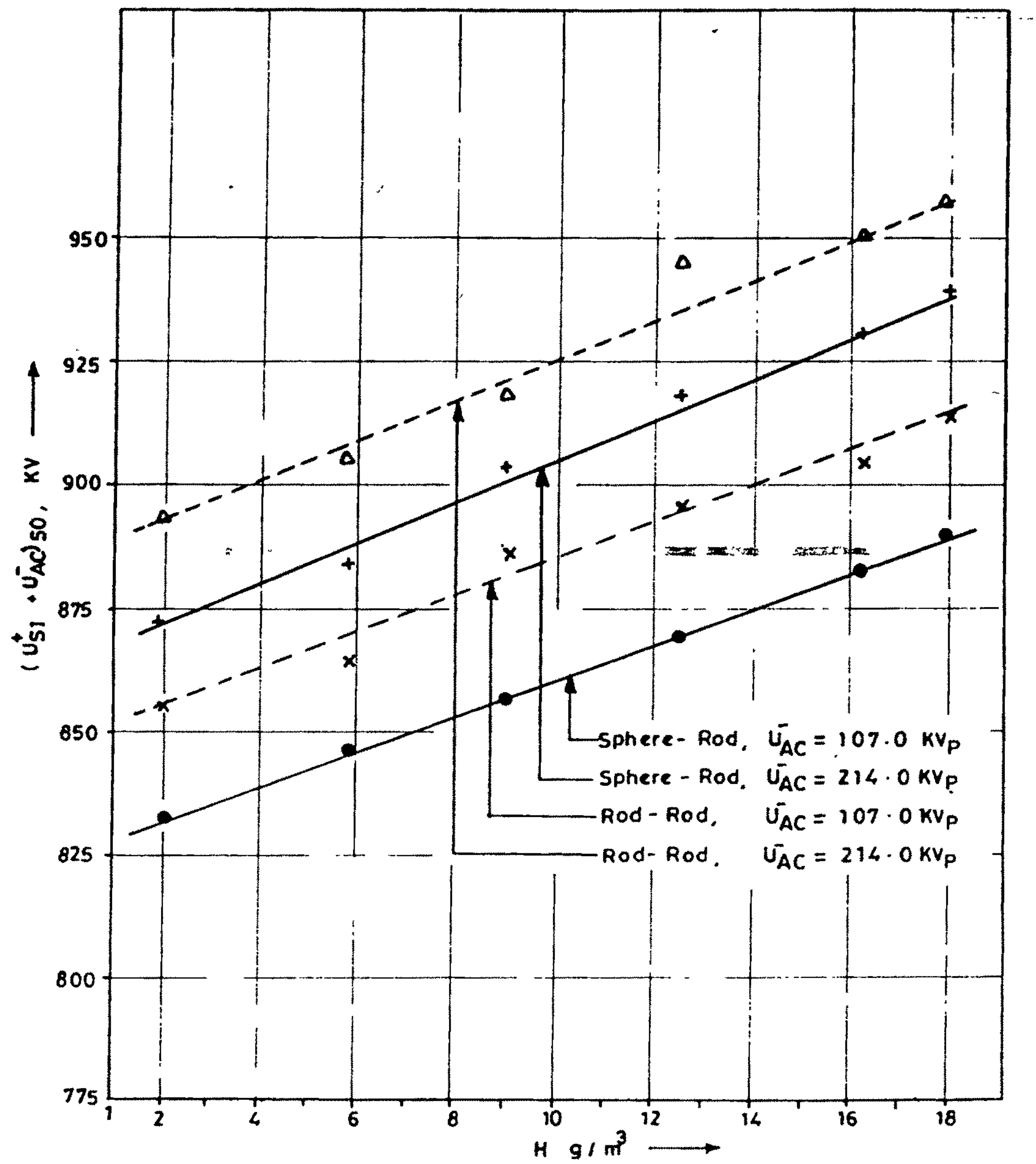


Figure. 6.5 IEC Corrected $(\overset{+}{U}_{SI} + \overset{-}{U}_{AC})_{50}$ voltage as a function of absolute humidity under positive switching impulse voltages.

present correction approach is sufficient/correct then the slope of the curves should have been zero. This is not the case for the results reported in Figure 6.5 and hence it may be concluded that the present correction factors are not sufficient for correcting the bias voltage test results. After correction factors are considered, the curves should have been a straight line with zero slope, i.e. with increase in humidity the breakdown voltage after correction should remain more or less same.

The slope of the curves given in Figure 6.5 is nearly same for both the electrode configurations. From this results, one can evaluate the error in the correction factor with respect to humidity. Figure 6.6 gives the percentage error as a function of absolute humidity. The error is negative for absolute humidity less than 11 $gm.m^{-3}$ and it is positive for absolute humidity ~~for~~ more than 11 $gm.m^{-3}$. (11 $gm.m^{-3}$ is a standard reference absolute humidity). This error is mainly on account of the change in absolute humidity i.e. the error is on account of the incorrect humidity correction factor. The present humidity correction factor is low for the absolute humidity less than 11 $gm.m^{-3}$ and high for the absolute humidity more than 11 $gm.m^{-3}$. As an example the error in the correction factor at 2 $gm.m^{-3}$ humidity is of the order of -3.21 per cent and at 18.0 $gm.m^{-3}$ humidity the error is of the order of 2.8 per cent.

6.2.3.2 Recommended correction approach

Many atmospheric parameters may affect the impulse streng-

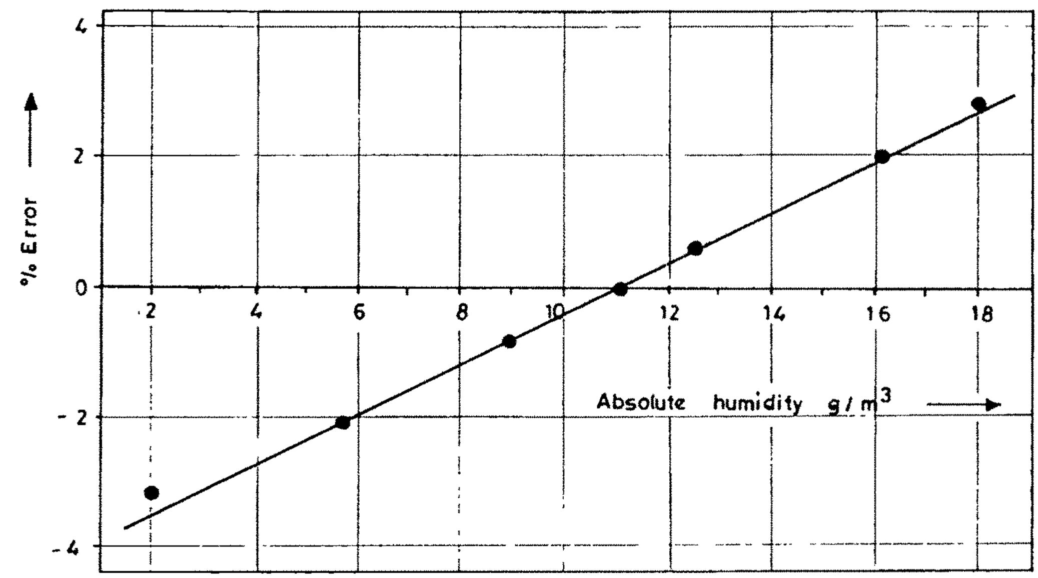


Figure. 6.6 Percentage error as a function of absolute humidity when U_{50} is corrected as per IEC - publication 60.

th of the external insulation, but generally air density and humidity are considered to be dominant.

The one of the aims of this work was to study the effect of humidity under bias voltages. Pigini et al/130/ have proposed a new correction approach for applying the atmospheric correction factors and IEC-WG 42-05/131/ have already considered this and a draft has been circulated for the discussion. This new approach has been discussed in Chapter-2. The humidity correction factor K_h has been defined as follow :

$$K_h = (K)^W \qquad \ldots\ldots\ldots\ldots \qquad (6.3)$$

where,

$$K = 1 + \frac{H-Ho}{100}$$

W = Exponent which may vary with geometry and impulse characteristics

H = absolute humidity in $gm.m^{-3}$

Ho = standard absolute humidity ($11gm.m^{-3}$)

For a given set of results, one can evaluate the exponent W accurately. To obtain an error of 25 per cent on the value of exponent W, the difference h_2-h_1 must not be less than 15 $gm.m^{-3}$ (h_2 and h_1 are the two values of absolute humidity at which the voltage U_{50} is measured for the evaluation of W). This evaluation can be performed on the basis of 50 useful impulses, which leads to a 2 per cent accuracy of sigma equal to 5 per cent.

The results shown in Figure 6.4 were analysed based on the formula (6.3). For both type of electrode configurations the average value of the exponent 'W' is found to be approximately 1.2. Now, if the humidity correction factor is applied to the air density corrected data of Figure 6.4 then a straight line relationship is obtained with zero slope.

Further, IEC publication-60 has given different curves for humidity correction factor as a function of absolute humidity for the switching impulse and AC 50 Hz voltage. Since, these curves are not applicable for bias voltages, a new humidity correction curve is recommended and plotted in Figure 6.7. The data for this curve were obtained from the results of Figure 6.4. It is seen from these results that for humidity less than 11 $gm.m^{-3}$, the recommended humidity correction curve for bias voltages is very close to the curve given by IEC publication-60 for AC 50 Hz voltage. If this curve is adopted for correcting the 50 per cent bias breakdown voltage ($U^{+}_{SI}+U^{-}_{AC}$) then the maximum error in the correction is only 0.8 per cent when absolute humidity is 2 $gm.m^{-3}$. However, for absolute humidity more than 11 $gm.m^{-3}$ if the same characteristics curve is adopted for correcting the bias voltages, than the error in the correction will be more. At 18 $gm.m^{-3}$, the error in the correction will be approximately 1.5 per cent and at 15 $gm.m^{-3}$ the error will be approximately 1.03 per cent.

From this analysis, it may be stated that for the range of absolute humidity between 2 and 15 $gm.m^{-3}$, if the pre-

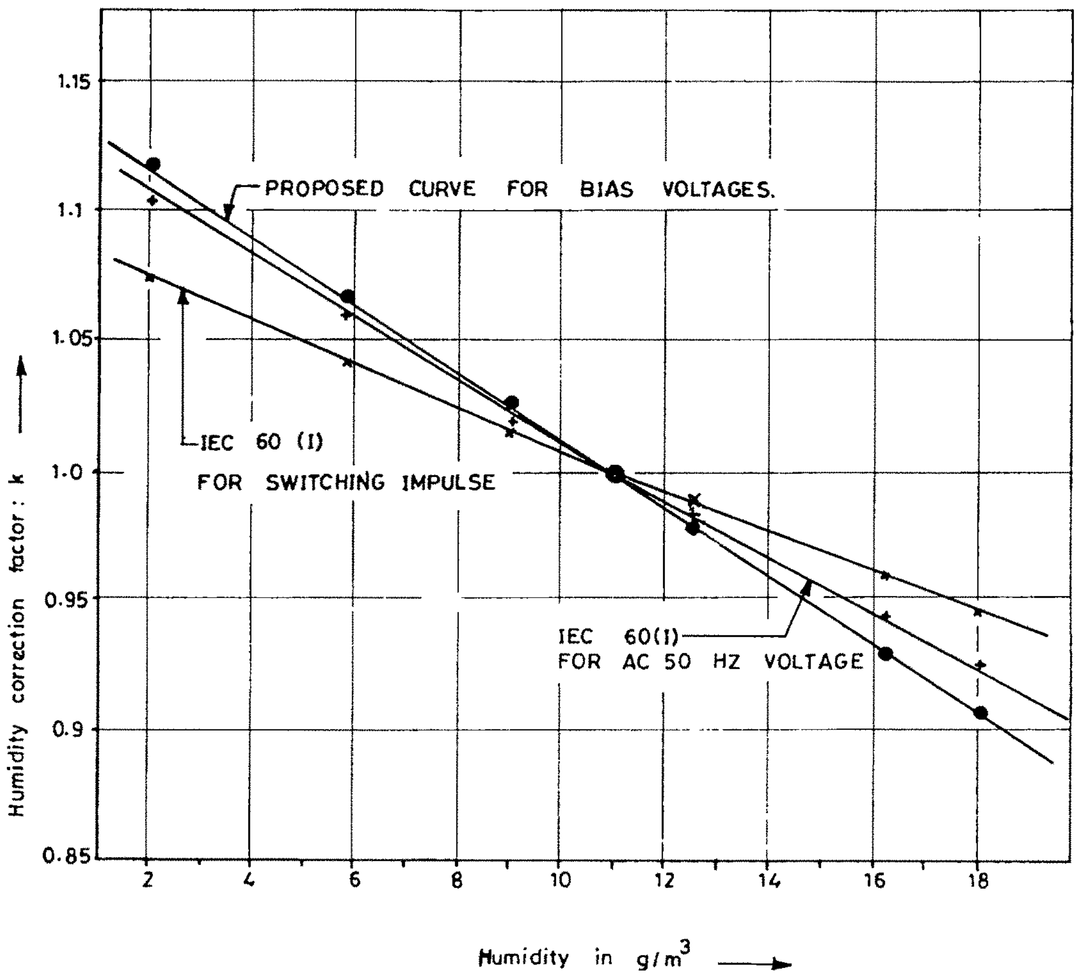


Figure. 6·7 Humidity correction factor k as a function of absolute humidity.

sent IEC publication-60 curve of AC 50 Hz voltage is adopted for correcting the 50 per cent bias flashover voltages, $(U_{SI}^{+}+U_{AC}^{-})_{50}$, then the error will be less than 1.0 per cent.

From this study it may be concluded that if the longitudinal insulation is tested when humidity is very high, say greater than 20 $gm.m^{-3}$, i.e. preferably during summer in tropical countries, then the longitudinal insulation may withstand higher voltages, $U_{SI}^{+}+U_{AC}^{-}$, if corrected as per the present correction approach of IEC publication-60. However, if the same equipment is tested when absolute humidity is very low, say 2 $gm.m^{-3}$, then it may so happen that the equipment which has passed the test when it was tested at higher absolute humidity may not pass the test when the absolute humidity is low.

In order to check whether the humidity correction factor described by IEC publication-60 is sufficient for only positive switching impulse voltages, at more or less the same absolute humidity a set of results with power frequency terminal of the test object earthed were taken and analysed.

Figure 6.8 gives U_{50} switching impulse voltage as a function of absolute humidity. In this figure the U_{50} values for only air density corrected as well as IEC corrected (i.e. corrected for both air density and humidity) are given. As can be seen from this figure, there still exists a relatively large scatter in the fully corrected breakdown voltages for both rod-rod and sphere-rod gap when

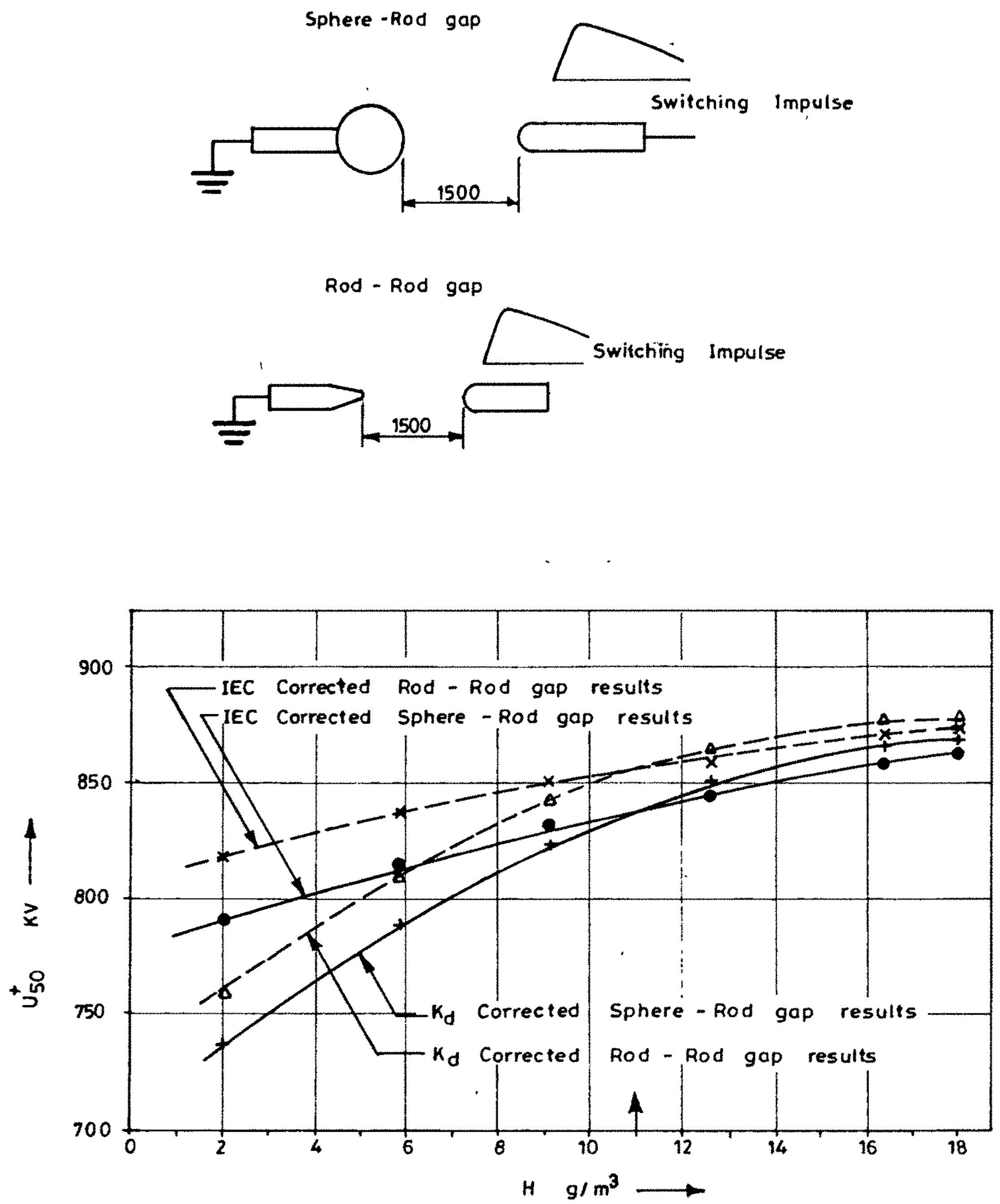


Figure. 6·8 U_{50} Voltage as a function of absolute humidity for sphere - rod and Rod - Rod gap when opposite terminal is grounded.

subjected to positive switching impulses. The error which is negative for the absolute humidity less than 11 gm. m^{-3} is around 4.1 per cent and 5.3 per cent at absolute humidity of 2 gm. m^{-3} for rod-rod and sphere-rod gap respectively. For absolute humidity more than 11 gm. m^{-3} the error is + 1.7 per cent and + 2.30 per cent at absolute humidity of 18 gm. m^{-3} for rod-rod and sphere-rod respectively. This error is large and hence it may be concluded that the present humidity correction approach given by IEC publication-60 for positive switching impulse wave is also not sufficient (for phase-to-ground insulation). Kuffel et.al/128/ have also reported that application of the air density and humidity correction factors recommended by the IEC and IEEE for the positive switching impulse breakdown of non-uniform, symmetrical field air gaps results in corrected critical flashover voltage which exhibit substantial variations (between 8 and 10%) with the absolute humidity.

6.3 Effect of α on bias breakdown voltages

Great many test results have been published by various authors on the influence of ratio α on the voltage withstand capability of the phase-to-phase insulation/32,64,65,69,87/. It has been reported that the 50% discharge voltage, $U^{+} + U^{-}$, increases linearly with the increase in α.

In order to study the influence of AC bias voltage i.e. ratio α on the 50 per cent flashover voltage of the longitudinal insulation, the circuit configuration shown in Figure 6.1 for rod-rod gap was adopted. Figure 6.9 presents the results for the switching impulse bias voltage test. The dependencies of $(U^+_{SI}+U^-_{AC})_{50}$ as a function of α show nonlinearly increasing characteristics. The similar characteristic was obtained by colombo et al/68/ for phase-to-phase tests performed on a 2 meter horizontal rod-rod gap. However, this conclusion is contradictory to the results published by Weck et al/87/. They have shown an approximately linearly increasing characteristics. For the positive switching impulse bias test the α diagram starts at $\alpha = 0$ with the positive 50 per cent switching impulse flashover voltage with power frequency terminal earthed and switching impulse terminal energized. The 50 per cent switching impulse breakdown voltage was obtained for the range of α from 0 to 0.37. As seen from these results, the 50 per cent breakdown voltage $(U^+_{SI}+U^-_{AC})_{50}$ has almost reached to a saturation level for α = 0.28. This voltage is more or less same for α=0.28 and α = 0.37. It may be worthwhile mentioning here that the interesting range of α specified in references/92-94/ for positive switching impulse bias test is from 0.26 to 0.36. The range of α for which the experiments were conducted is within the limits given by the standards. For further values of α the experiments could not be conduced because for U_{AC} greater than 370kV, the corona level at the power frequency terminal was too high. Also, it might not have been possible to take the reading for the obvious reason that 1.5 meter gap may withstand

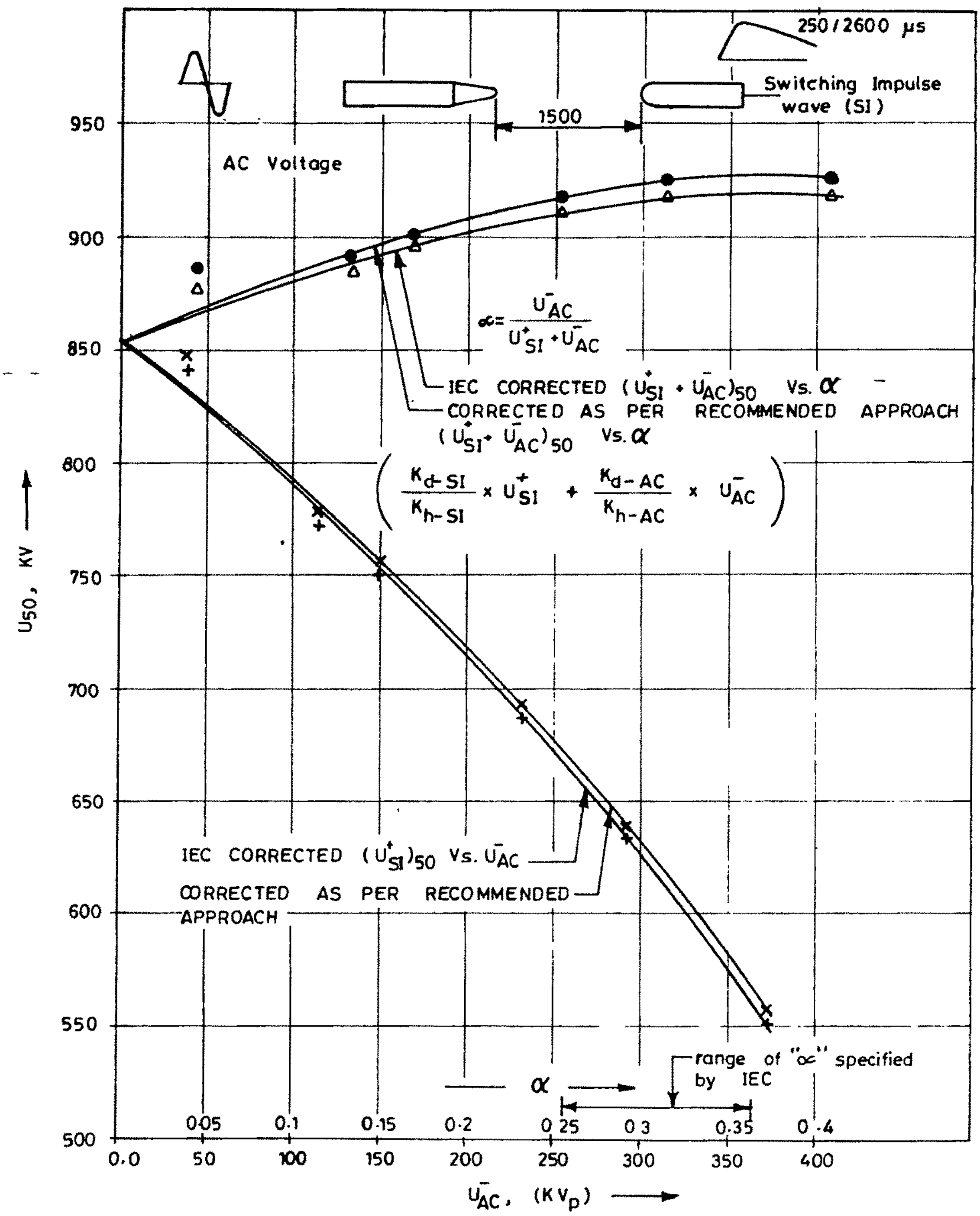


Figure. 6.9 U_{50} voltage as a function of ratio α and U^-_{AC}.

maximum 500 kVp ac 50 Hz voltage, it may even breakdown at this voltage level.

From these results it may be concluded that with the increase in ac power frequency bias voltage, the 50 per cent breakdown voltage $(U^{+}_{SI}+U^{-}_{AC})_{50}$ increases. The maximum voltage withstand capacity of the gap has increased by 9 per cent for the value of $\propto = 0.28$

6.4 Influence of time-to-crest of the impulse wave on bias breakdown voltages

The 50 per cent flashover voltage, when expressed as a function of the time-to-crest, exhibits the famous U-curves which are particularly pronounced for geometries with highly non uniform fields. For a given open gap clearance it gives minimum value of U_{50} obtained at the critical time-to-crest, T_{cr_crit}, and this is very much essential for the design of the insulation co-ordination. Therefore, it is of great importance to examine the influence of time-to-crest of the impulse wave on the flashover voltage of the longitudinal insulation under bias voltages. Till today no such published results are available.

The electrode configuration shown in Figure 6.1 for rod-rod gap was used for this purpose. The open gap clearance was 1500mm.

The experiments were carried out for two ac bias voltage levels as per the procedure described in section 6.2.2. The 50 per cent discharge voltage expressed as a function of time-to-crest for a rod-rod gap is given in Figure 6.10.

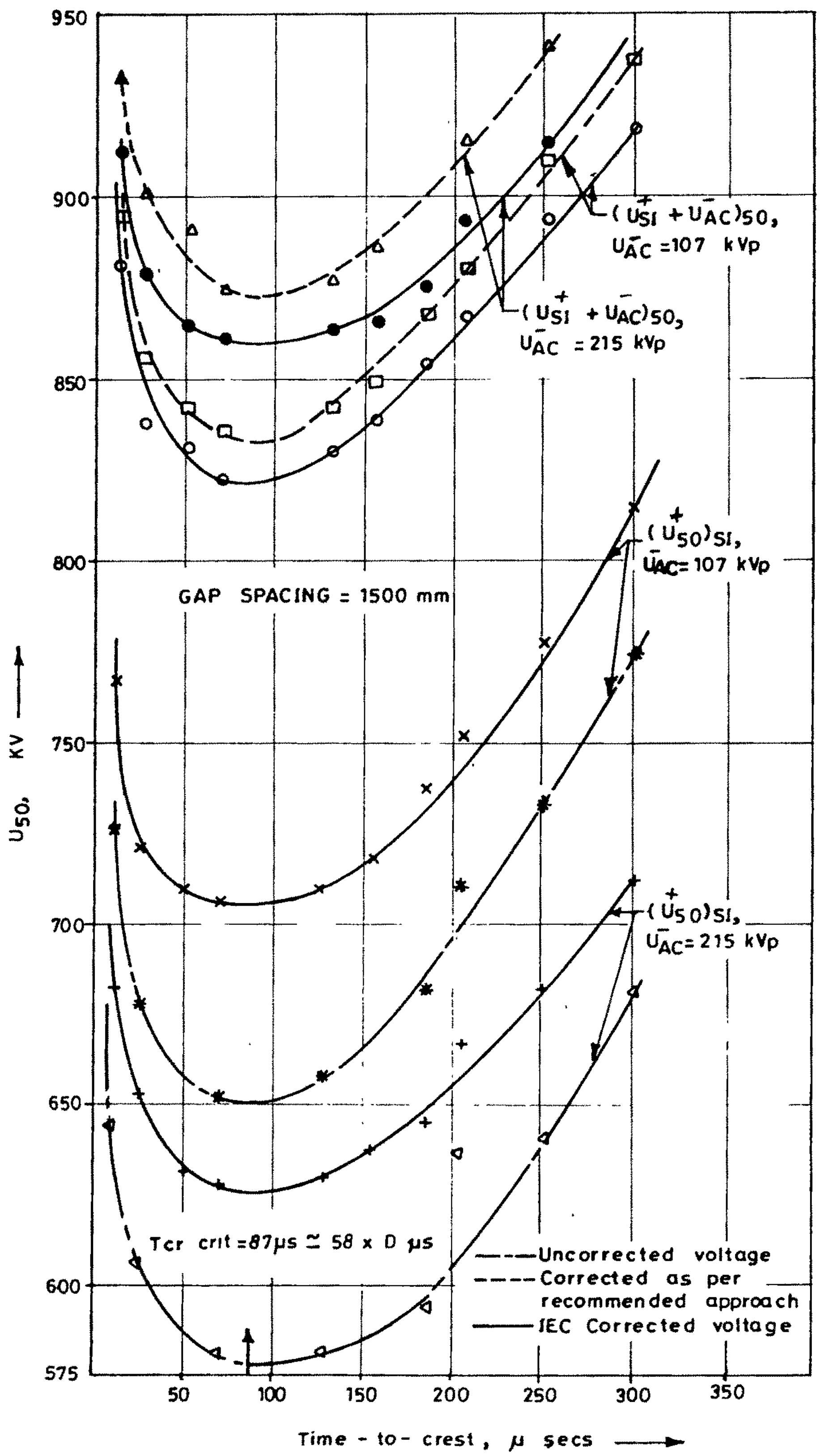


Figure. 6.10 50 percent discharge voltage U_{50} expressed as a function of time - to - crest, Tcr for a Rod - Rod gap.

Few waveshapes used for this study are shown in Figure 6.11. The 50 per cent voltages were corrected according to IEC publication-60 and also as per the recommended correction approach described in this chapter.

The 50 per cent bias flashover voltages, when expressed as a function of the time-to-crest also exhibits the famous U curve relationship. The observed critical time-to-crest for rod-rod gap electrode configuration under bias voltages is about 58 x D μ secs, where D is the gap spacing in meters. The critical time-to-crest is not affected whether the 50 per cent values are corrected as per IEC specifications or as per the recommended correction approach described in this chapter.

The critical time-to-crest for rod-plane gap is usually evaluated to be about 45 x D μs, where D is gap spacing in meters/100/. For phase-to-phase insulation CIGRE working group 33/66/ have reported that the critical time-to-crest are similar to those found for the phase-to-ground insulation, i.e. nearly 45 x D μs only. However Gallet et al/67/ have observed the range of critical time-to-crest from 25 x D to 30 x D μ secs. This is less than the critical time-to-crest for phase-to-ground insulation. These results were once again supported by Cortina et al/116/. However, the critical time-to-crest under bias voltages is found to be more than that for phase-to-ground and phase-to-phase insulation systems. The absolute humidity was approximately 5.5 gm.m^{-3} when this set of results were obtained. It has been reported in the literature/103/ that

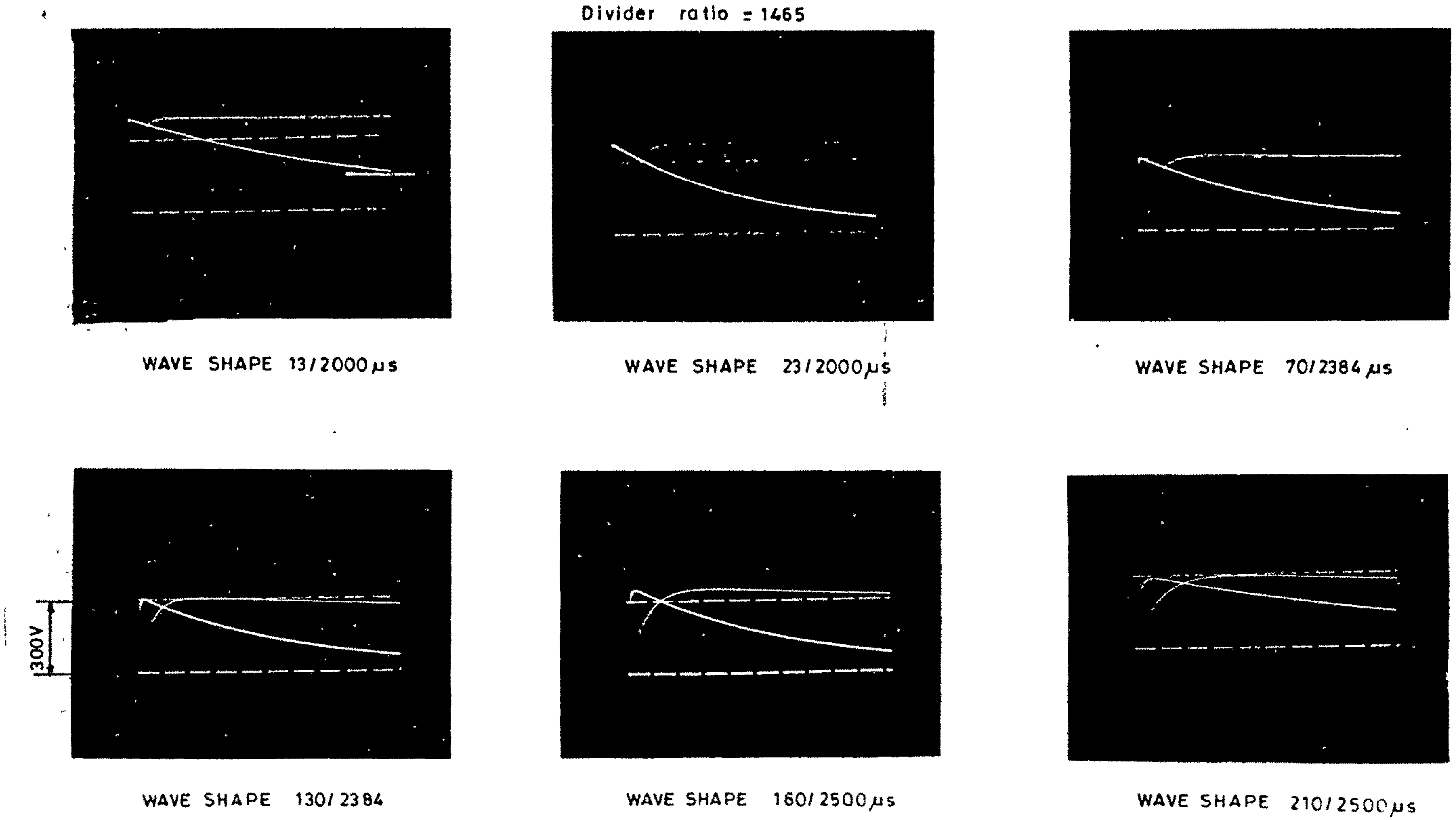


Figure.6.11 Typical oscillographic records of switching impulse waves.

the critical time-to-crest for rod-plane gap depends not only on the gap spacing but also on the absolute humidity, however this effect is pronounced only for gap spacings equal to and larger than 5m. At 1.5m gap spacing the effect of humidity on critical time-to-crest is very small. Since, no published results are available on this subject under bias voltages, it is not known whether under bias voltages also the critical time-to-crest varies with humidity and if so upto what gap spacings.

6.5 Influence of the time shift Δt between the two waves

For phase-to-phase insulation system it has been established that when impulse voltages of opposite polarities are simultaneously applied to each of the electrodes of a given gap, the total breakdown voltage $(U^{+}+U^{-})$ strongly depends on the relative amplitude of the two components/87/, /115/. This is mainly due to the fact that the distribution of the electric field in the gap is affected by the relative weight of the two components and that the processes involved in spark formation in nonuniform field also depends on the direction of the electric field/114,115/.

If the two voltages are not applied simultaneously the problem becomes more complicated. As a matter of fact, predischarges may occur when the first voltage component is applied. This modifies the nature of the gap and consequently its behaviour when the second voltage component is applied.

This phenomena is very important in the case when the negative impulse precedes the positive wave. When the negative impulse is applied first, the predischarges develop in the gap with intensities dependent on the peak value of the negative voltage /115/. In the case of non-synchronous application of impulses, the distribution of the electric field in the gap and consequently its behaviour is defined by:

- the instantaneous value (u^-) of the negative impulse
- the shape and amplitude of the positive impulse
- the time shift Δt during which the charge left in the gap by the former predischarges was allowed to move

In the case of longitudinal insulation system IEC publications 56 and 129 describes that while conducting lightning impulse and switching impulse bias test the peak of the impulse should be synchronised so that it is applied approximately in correspondence to the peak of the opposite polarity of the power frequency voltage. As long as the instanteneous peak value of the AC voltage is adjusted (may be by increasing the AC voltage, if the two peaks do not synchronise) to the required test voltage to be applied during bias test, the test requirements are satisfied. What happens if there is a time shift between the two peaks is to be investigated. Hence experiments were conducted with values of time shift Δt (difference in time to peaks) of a few milliseconds.

6.5.1 Effect of time shift Δt

The experiments were conducted on a sphere-rod gap shown in Figure 6.1a. The time shift between two waves was varied from -5ms to +5ms in steps of 1ms. The power frequency voltage was applied continuously to the test object and only the time shift between the two peaks was varied. The test procedure described in section 6.2 was followed to obtain $(U_{SI})_{50}$ voltage for a given time shift between the two peaks. The definition of the time shift and voltage parameters, and 50 per cent flashover voltage as a function of time shift are given in Figure 6.12. All the voltages were corrected according to IEC publication 60 as well as based on the recommended correction approach. The $(U_{SI})_{50}$ as well as $(U_{SI}^{+} + u^{-}_{AC})_{50}$ voltages as a function of time shift Δt are given in this figure. The instantaneous value of AC voltage u^{-}_{AC} was considered for calculating the total flashover voltage $(U_{SI}^{+} + u_{AC}^{-})_{50}$. It is seen from the curves that when AC voltage was 107kVp, the total flashover voltage, $(U_{SI}^{+} + u_{AC}^{-})_{50}$, varies between +1.4% and -0.6% (of the total flashover voltage $(U_{SI}^{+} + u_{AC}^{-})_{50}$ when time shift is zero). When Δt is equal to +5ms, the flashover voltage $(U_{SI}^{+} + u_{AC}^{-})_{50}$ is higher by 1.4% as compared to the voltage when Δt is equal to zero. The variations of this voltage is almost negligible as compared to the published results on the phase-to-phase insulation testing/66,67/ /114,115/. The reason may be that the intensity of the predischarges which develop in the gap is a function of peak value of the negative voltage, the effect of such predischarges with the variation of time shift may be negligible when AC voltage of 107 kV_p was applied.

However, when the AC voltage magnitude is 214 kV_p, it is

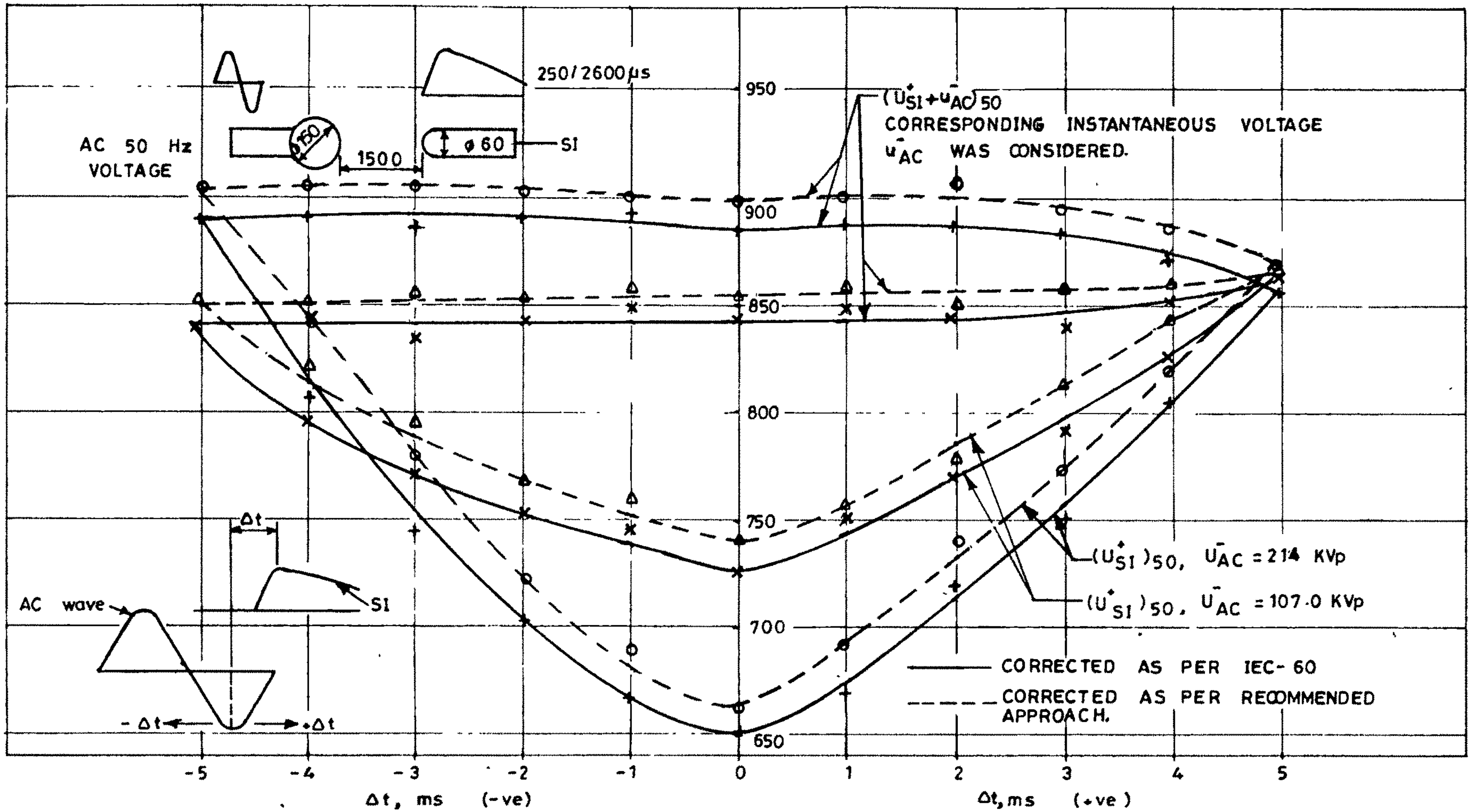


Figure. 6.12 Results of tests on sphere - rod gap with 250 / 2600 μ secs. waves, U_{50} voltage versus Δt for U^{-}_{AC} equal to 170.0 KVp and 214.0 KVp.

seen that the variations in the total 50% flashover voltage is more. The flashover voltage $(U_{SI}^{+} + u_{AC}^{-})_{50}$ is less by approximately 3.5% when Δt is equal to +5ms. This variation is large as compared to the case when AC voltage magnitude was $107kV_p$. When AC voltage was $107kV_p$ and Δt =-5ms, the $(U_{SI}^{+} + u_{AC}^{-})_{50}$ voltage is more or less same as $(U_{SI}^{+})_{50}$ obtained by earthing the power frequency terminal.

Baldo et al/114/ have reported that while testing phase-to-phase insulation system, the occurrence of a negative surge before the positive one leads to a large reduction (to the extend of 20% for particular combinations of negative component amplitude and time shift) of the instantaneous sparkover voltage between phases. Kosztaluk et al/51/ have reported that the gap strength varies to the extend of 28% for particular combinations of negative component amplitude and time shift. This phenomena may be attributed more to the amount of the injected space charge during the negative impulse than its drift. They have also stated that "when a negative charge is present in the gap, whatever the way by which this charge is injected, a decrease in the gap strength has to be expected".

In the case of longitudinal insulation, when the open gap is tested for bias voltages, then the maximum reduction in the gap strength is 3.6% when AC voltage of 214 kV_p is applied. The effect of 50 Hz voltage which is continuously applied to the lower rod is not same as compared to the switching impulse voltage having the same peak value and is applied to the power frequency terminal of the test object instead of AC voltage. The reason may be that in the case of longitudinal insulation testing the power frequency voltage is applied continuously to one terminal of the test object and the switching impulse is applied at approximately 25 secs. interval to the other terminal. In this case during positive half cycle of the AC wave, positive space charge is injected into the gap and during negative half cycle, negative space charge is injected. The positive space charge may neutralise some of the negative space charge in the gap. Because of this reason the effect of negative space charge may not be large in the case of longitudinal insulation testing. In the case of phase-to-phase insulation testing two switching impulses having opposite polarity are applied to the test object at approximately 20 to 30 seconds interval. If the negative impulse is applied first then there will be a negative space charge drift in the gap. Before the effect of this space charge diminishes, positive switching impulse is applied and hence it reduces the dielectric strength of the open gap insulation to larger extend.

6.5.2 Effect of time shift Δt and peak magnitude of voltage $\hat{U}_{AC}$

The results shown in Figure 6.12 were obtained by keeping same magnitude of power frequency voltage $\hat{U}_{AC}$ and only the time shift between the two peaks was varied. In this case instanteneous value of AC voltage $\bar{u}_{AC}$ will change with time shift.

Figure 6.13 shows the results of the breakdown strength of the same gap when peak value of the AC voltage is also varied with time shift. The peak magnitude of AC voltage was varied such that voltage u^{-}_{AC}(equal to 215kV peak) remains same for a given value of time shift Δt. As seen from these results the 50% discharge voltage $(U_{SI}^{+} + u_{AC}^{-})_{50}$ decreases with the positive value of Δt . The voltage $(U_{SI}^{+}+u_{AC}^{-})_{50}$ remains more or less same for negative values of Δt . In other words when the switching impulse voltage is applied after the negative peak of AC voltage, the breakdown strength of the gap decreases. When Δt is equal to +3ms, the reduction in the gap strength is approximately 15.5%.With the increase in time shift, the peak magnitude of AC voltage U^{-}_{AC} is increased to maintain the same value of voltage u^{-}_{AC} when switching impulse voltage is applied. This will increase the intensity of the negative predischarges in the gap and hence leads to decrease in the gap strength. These results are inline with those obtained by Baldo et al/114/ and Kosztaluk et al/51/ while testing phase-to-phase insulation using two switching impulses.

IEC publications-56 and 129 says that the switching impulse shall be synchronised so that it is applied approximately in correspondence to the peak value of the opposite polarity of the power frequency voltage. If the switching impulse voltage is applied before the negative peak of the AC voltage, and the power frequency vol-

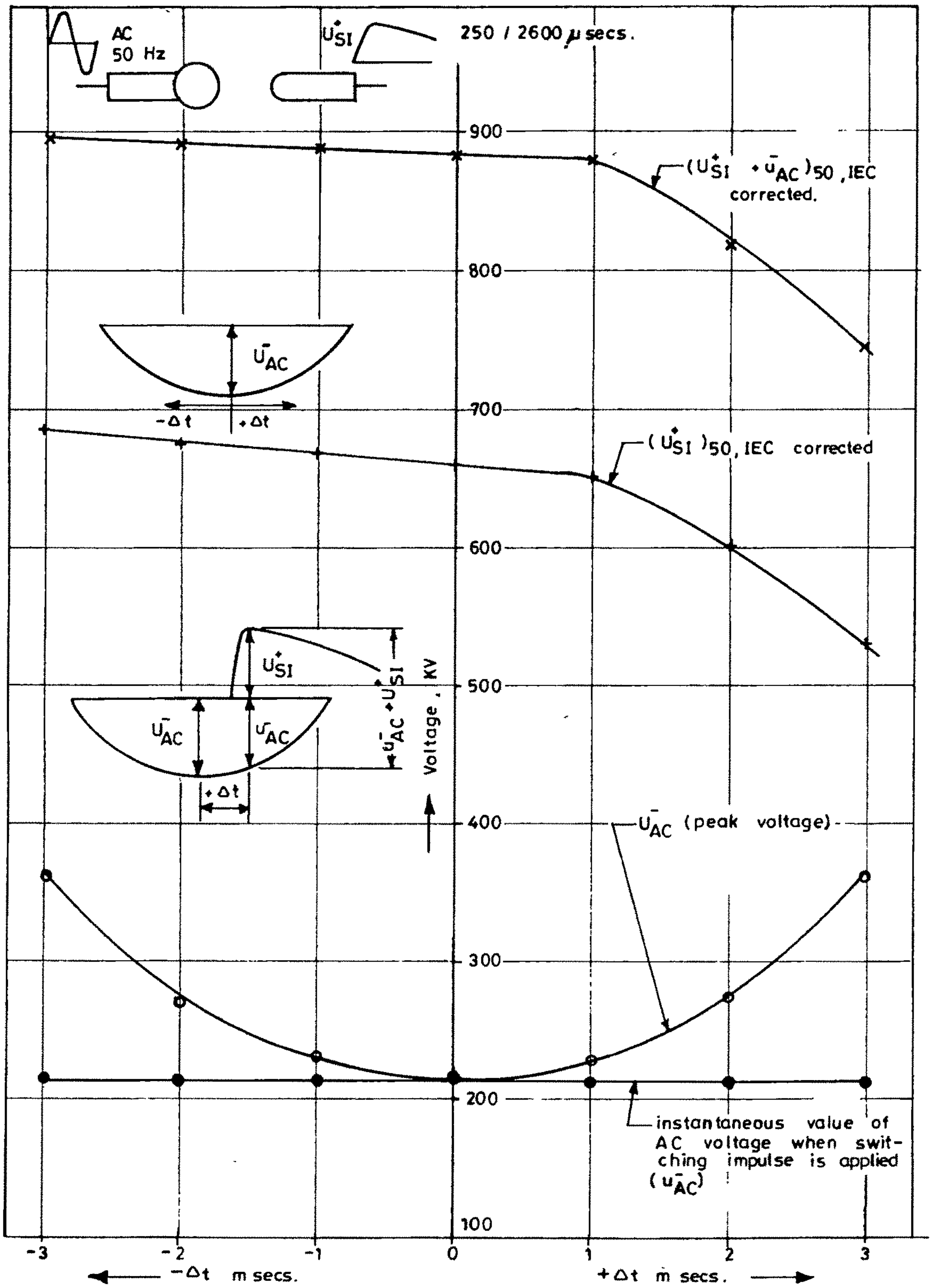


Figure. 6·13 Results of tests on sphere – rod gap with 250 / 2600 μ secs. waves when peak value of AC voltage and time shift is varied.

tage is increased to apply the desired value of the power frequency test voltage, the probability of the test object passing the test remains the same as it would have been when tested by synchronising the switching impulse voltage exactly at the negative peak of the AC voltage. However, if the switching impulse voltage is synchronised after the negative peak of AC voltage, the probability of the test object passing the test reduces. Thus, while conducting withstand voltage test on the longitudinal insulation it is a must that the switching impulse voltage should be synchronised exactly at the negative peak of the AC voltage and the desired value of power frequency test voltage should be adjusted.

6.6 Influence of rain under bias voltages

Few sets of experiments were conducted for both rod-rod gap and sphere-rod gap electrodes configuration by creating artificial rain. The electrode configurations shown in Figure 6.1 were used for obtaining 50% bias flashover voltages.

Throughout the wet test the open gap assembly was sprayed with artificial rain according to the procedure described by IEC publication-60. The rate of precipitation was measured using a collecting vessel having both a horizontal and vertical opening each of 225 cm sq. The collecting vessel was moved slowly over the area being measured for the duration of one minute. The open gap was pre-wetted for a minimum duration of 15 minutes before testing commenced. The measured precipitation rates were as follows:

Vertical component = 1.4 mm/minute

Horizontal component = 1.45 mm/minute

The resistivity of the water was measured using a conductivity bridge having standard cell. The corrected resistivity at 20°C was 108 Ohms-meter. The power frequency voltage was applied continuously to one terminal and the $(U^{+}_{SI})_{50}$ voltage was obtained using Up and Down method by applying 50 useful impulses at 25 seconds interval. The experiments were conducted for two ac bias voltage levels. The results are given in Table-6.1. The raw data were corrected for air density according to IEC publication-60. The humidity correction factor was applied according to IEC publication-60 and as per the recommended correction approach. Humidity correction factor was applied only to dry test results. It is seen from this results, that the air density corrected 50 % bias flashover voltages are more or less same under wet and dry test conditions. However, when the humidity correction factor is applied to the dry flashover voltages, the dry flashover voltages are found to be higher by 8 to 10 per cent as compared to the wet flashover voltages.

From these results, it may be concluded that the difference between the 50 per cent flashover voltages $(U^{+}_{SI} + U^{-}_{AC})_{50}$ under dry and wet conditions is a function of humidity correction factor.

TABLE 6.1

Switching Impulse Bias Wet Test Results

Configuration	Wet/ Dry test	$(U_{SI}^{+})_{50}$ kV	(U_{AC}^{-}) kV_p	Air density corrected voltages $(U_{SI}^{+})_{50}$ kV	Air density corrected voltages U_{AC}^{-} kV_p	Air density corrected voltages $(U_{SI}^{+}+U_{AC}^{-})_{50}$ kV	IEC corrected voltages $(U_{SI}^{+})_{50}$ kV	IEC corrected voltages U_{AC}^{-} kV_p	IEC corrected voltages $U_{IEC}=(U_{SI}^{+}+U_{AC}^{-})_{50}$	Recommended correction approach $U_{TN}=(U_{SI}^{+}+U_{AC}^{-})_{50}$	$\frac{U_{TN}\ wet}{U_{TN}\ dry}$	$\frac{U_{IEC}\ wet}{U_{IEC}\ dry}$
Sphere-Rod	Wet	645.5	107	661.5	110.2	771.40	661.5	109.9	771.4	771.40	0.902	0.926
	Dry	641.6	107	660.4	110.2	770.60	710.8	122.2	833.0	855.2		
	Wet	570.33	215	593.5	220.0	813.5	593.5	220.0	813.5	813.5	0.912	0.93
	Dry	564.8	215	582.7	220.0	802.7	627.7	245.0	872.7	891.8		
Rod-Rod	Wet	661.33	107	684.0	111.36	795.36	684.0	111.36	795.36	795.36	0.92	0.927
	Dry	654.2	107	683.3	111.36	794.66	734.5	123.5	858.0	881.96		
	Wet	575.0	215	602.0	222.73	824.73	602.0	222.73	824.73	824.73	0.901	0.92
	Dry	570.0	215	603.0	222.75	825.75	648.7	247.0	895.7	916.0		

Note: Humidity correction factor was applied to only dry test results.

6.7 Conclusion

1. The air density corrected 50 per cent flashover voltages results in a linear relationship when plotted as a function of absolute humidity.
2. During bias voltage tests the AC corona produced at the power frequency terminal enhance the voltage withstand capability of the open gap insulation system.
3. The present humidity corrections specified by IEC publication-60 are not sufficient for bias voltages. For example the error in the humidity correction factor, when absolute humidity is 2 $gm.m^{-3}$ is of the order of 2.80 per cent. This is too large and cannot be neglected.
4. A new correction approach is recommended for humidity correction factor under bias voltages. The value of exponent "W" for an open gap clearance of 1500 mm is found to be 1.2 for both rod-rod and sphere-rod gap electrode configurations.
5. The humidity correction factor specified by IEC specification-60 for ac 50 Hz voltage may be used for applying humidity correction to $(U^{+}_{SI}+U^{-}_{AC})_{50}$ voltages upto the range of absolute humidity from 2 $gm.m^{-3}$ to 15 $gm.m^{-3}$. The maximum error in the correction will be less than 1.0%
6. The humidity correction factors specified by IEC publication-60 for positive polarity switching impulse voltage is not sufficient (phase-to-ground insulation).

7. The dependencies of $(U_{SI}^{+}+U_{AC}^{-})_{50}$ voltage as a function of α shows nonlinearly increasing characteristics.

8. With the increase in AC bias voltage level, the total 50 per cent discharge voltage increases. The maximum voltage withstand capacity of the gap has increased by 9 per cent. In case of higher open gap clearances, the ac bias voltage level may further enhance the bias voltage withstand capability of the longitudinal insulation system.

9. The 50 per cent bias flashover voltages, when expressed as a function of the time-to-crest, exhibits the famous U-curve relationship.

10. The critical time-to-crest for rod-rod gap under bias voltages is evaluated to be about 58 x D μs , where D is gap spacing in meters.

11. The 50% discharge voltage $(U_{SI}^{+} + u_{AC}^{-})$ decreases by approximately 3.5% when time shift between two peaks is +5 ms. and peak value of voltage U_{AC} is not varied. This reduction in the gap strength is too low as compared to the reduction in the gap strength observed while testing phase-to-phase insulation system. However, the voltage $(U_{SI}^{+} + u_{AC}^{-})_{50}$ decreases by approximately 15.5% when time shift between two peaks is 3 ms and the peak magnitude of voltage U_{AC}^{-} is also varied such that voltage u_{AC}^{-} (=215kV_p) remains same when time shift is varied.

12. Air density corrected 50 per cent bias flashover voltages are same under wet and dry test conditions. When humidity correction is applied to the dry flashover voltages then the dry flashover voltages are higher by 8 to 10 per cent as compared to the wet 50% flashover voltages.