CHAPTER - 3

DEVELOPMENT OF BIAS VOLTAGE TEST FACILITY

3.1 General

Among the various dielectric type tests which are performed on high voltage switchgears namely circuit breakers and disconnectors, the test to ensure the ability of the longitudinal insulation to withstand higher voltages is more important than the phase-to-ground voltage withstand capability. These two withstand levels should be co-ordinated so that when phase-to-ground overvoltage occurs, the phase-to-ground insulation should flashover and not the longitudinal insulation.

IEC publications-56 /90/and 129/91/ allow to conduct either equivalent test (i.e. the sum of the two voltages is applied to one terminal, the opposite being grounded) or bias voltage test on the longitudinal insulation.The equivalent test is performed by over-insulating the base in order to prevent flashover to earth. The disadvantage of this method is that over insulation changes the field configuration across the open gap, and consequently, the breakdown strength of the open gap under these circumstances may be different from that under normal service conditions. Another method (described by ANSI standard C-37.07.4-1972) specifies the application of three switching impulses of either polarity having a crest value equal to or greater than the rated switching impulse withstand voltage. Any external flashover to ground from the energised terminal of the circuit breaker will be considered as a withstand on the open circuit breaker. One flashover across the breaker, either external or internal is allowed within the first three tests provided there is no reoccurrence in the test series.

In case of bias voltage test, the AC power frequency voltage is applied to one terminal and impulse voltage is applied to the other terminal, the peak of the impulse being synchronised with the AC voltage peak having a polarity opposite to that of the applied impulse. This technique results in a higher than normal overvoltage developing across the longitudinal insulation. For conducting bias voltage test it is not necessary to raise the ground insulation and hence, the exact site conditions can be created at the laboratory and the performance of the equipment can be guaranteed better.

For conducting bias voltage test, many additional equipments are required to meet the requirements of standards and for the protection of the testing transformer in case flashover occurs across the test object open gap. All these aspects have been described in detail in the following sections. The use of additional equipments and their location in the bias test circuit for the effective protection of the testing transformer against chopped waves was studied at depth and the results are discussed. To meet certain important requirements of the standards, the method of calculation of the required value of the supporting capacitance to be connected to the AC terminal has been also discussed.

Preliminary test procedure has been suggested to check the proper functioning of the various auxiliary equipments required while conducting bias voltage test.

3.2 Requirement of equipments' standards for conducting bias voltage withstand test

For conducting bias voltage test on longitudinal insulation it is necessary to subject one terminal to an impulse voltage and other terminal is energised at power frequency voltage. The triggering of the impulse voltage generator is adjusted so that it delivers the impulse voltage at the peak of the AC voltage with opposite polarity.

According to IEC Publications-56(4) and 129, the power frequency voltage should have a value of $U/\sqrt{3}$kV rms when switching impulse voltage is applied and a value of 0.7 $U/\sqrt{3}$ kV r.m.s. when lightning impulse voltage is applied, where U is the rated system voltage. The reason for the difference between the two power frequency voltages is due to the fact that in service, switching impulse can have such a long durations that it is very likely that the instants of voltage peaks on both sides of an open gap will occur simultaneously. Lightning impulses, on the otherhand, have durations which are relatively short compared to the power frequency waveform and consequently, the statistical probability of a lightning impulse occuring at the instant of AC voltage peak is low. For this reason an AC test voltage of $0.7U/\sqrt{3}$kV r.m.s. is chosen for the lightning impulse bias test /88/.

The bias test, like other dielectric tests on the longitudinal insulation, is performed by applying the test voltages to each side of the equipment in turn. However, if the design of the equipment is such that it is symmetrical from either end (as is usually the case for circuit breakers, but not necessarily for the disconnect switches) than the number of tests can be halved.

These standards also discuss about the compensation of the voltage drop on the power frequency wave, also known as transferred impulse voltage on AC terminal because of the capacitive coupling. This aspect is further discussed in detail in section 3.6.

3.2.1 Additional equipments required for conducting bias voltage test

The complete bias voltage test circuit is shown in figure 4.2. As compared to the equivalent test the following additional equipments are required for conducting the bias voltage test on circuit breakers and disconnectors:

a) Point on wave selector

b) Double beam impulse CRO

c) Voltage grading capacitors for cascaded test transformer

d) Supporting capacitor on the AC terminal

e) Protective device across the transformer terminals

f) Voltage divider for the measurement of AC voltage and voltage drop

g) High voltage damping resistor

3.3 Method of protection against the recovery overvoltages:

Extra High Voltage cascaded testing transformer represent an expensive investment which must be protected against stresses that could endanger it. During flashover tests with AC Voltages, both the transformer insulation and the test object may be subjected to excessively high overvoltages. If the test system is unfavourably constructed or incorrectly manipulated, dangerous conditions for the system can occur when impulse voltages or transient overvoltages with negative polarity are present /139-143/.

If the transformer insulation is not designed to withstand such stresses without endangering the life of the same, then it is a must to incorporate some protective measures. A high withstand capability against voltage transients in the order of microseconds, e.g. in the case of applied impulse voltages or rapid voltage collapse due to flashover or discharge of the test object, can usually be achieved by constructive measures and additional external protective devices.

3.3.1 Protective measures

Train and Giao Trinh /140/ have described such methods of protection against the recovery overvoltages. A number of protective methods have been developed to prevent overvoltages from occuring. The techniques used tend to achieve any one of the following objectives:

- Equalization of the flashover voltages at both polarities at voltages slightly higher than the test voltage.
- Limitation of the short circuit energy to the test transformer.

- Diversion of the energy from the transformer following a flashover.

While conducting bias voltage test on longitudinal insulation, it was planned to use sphere gap across the terminals of the test transformer and a high voltage damping resistor in series with the HV terminal. A discussion on first two techniques is presented in the following. The explanation for the third technique is presented elsewhere /140/.

3.3.2 Protective device across the terminals of the test transformer

During bias voltage test, the first case to consider with respect to the protection of the test transformer is the generation of an overvoltage on the AC terminal of the object under test when flashover occurs across the longitudinal insulation. When such flashover occurs, ideally, if the charge in capacitances connected across the AC test transformer (C_l) is equal to the charge in capacitor connected across the impulse generator (C_f) at the instant of flashover, then the voltage will drop to zero on each terminal of the test object. That is, if the following condition is fulfilled /139/.

$$U_{AC}\ C_l = U_{SI}\ C_f \qquad \ldots\ldots\ldots\ldots \qquad (3.1)$$

where U_{AC} = AC voltage

U_{SI} = Switching impulse voltage

Usually, it is impossible to meet this criterion because of some other requirements of the standards (refer eq.3.4). Whenever flashover occurs, therefore, the voltage on the AC terminal will drop to some value which is greater or even less than zero. This is not important if the arc sustains. Because under such conditions the transformer will be almost short-circuited and the normal overcurrent protection system will cause the supply circuit breaker to trip and thereby deenergise the transformer. In such an event no overvoltages will appear on the transformer terminal.

However, if the premature arc extinction should occur across the open gap, there is a strong possibility that a transient recovery voltages may appear on the transformer terminal. This overvoltages may be sufficiently high to damage the internal insulation of the transformer /144-147/. As described earlier, if the recovery overvoltages occur during the negative half cycle, then they are more dangerous for the transformer. This possibility of occuring overvoltages on negative half cycle is a function of circuit inductance and capacitance. This topic is further discussed at depth in section 3.5.

Thus, in order to prevent this possibility it is preferable to connect a protective device across the HV terminal-to-ground of the testing transformer. Following three types of protective devices have been in vouge at various international laboratories.

a) Lightning arrester

b) Rod-Rod gap

c) Sphere gap

The lightning arrester has been used by HOCHASPANNUNGE FABRIK, oberentfelden /121/. Any problem faced during the bias voltage test is not reported in the literature. This is a costly means for the protection of the testing transformer. This would require two separate lightning arresters for conducting lightning impulse bias test and switching impulse bias test, as the voltages to be applied to the test object differs and hence the protective level. Also, the lightning arresters which are available in the market for the 400kV system, cannot be used directly for this application because of different protective levels. Hence, if one plans to use lightning arrester for the protection of the HV transformer, the cost will be very high because of special design.

Rod-Rod gap was used by CESI laboratory. The difficulty with this device is that the time to sparkover is longer and also because of non-uniform field, the U_{50} value for positive polarity wave and negative polarity wave will not be same. It may happen that in case of negative polarity this device may not provide effective protection to the transformer. The advantage of this device is that it is economical and the erratic flashover of the protective gap will not take place. The protective gap may flashover only when the test object has flashedover.

Brown Boveri & Cie and IREQ used sphere-gap. Sphere gap have almost the same flashover voltage on both polarities. By adjusting the gap setting to flashover at a voltage slightly higher than the test voltage, the protection can be obtained for any voltage level and test circuit parameters.

The likely problems with the sphere gap is that it may so happen that the sphere gap will flashover eventhough the test object does not flashover. This spurious flashovers are because of dust, flies etc. Also, their dimensions and cost increases with the increase in protection level. However, while conducting bias test if such flashover occurs, one can know easily by using photographs of the impulse wave and customer can be convinced about the spurious flashover of the sphere gap.

Looking at the advantages and disadvantages of the various protective devices from the point of view of the effective protection to the test transformer and the disturbances/interruption caused during the test by the operation of the various protective devices, it would be better to adopt a lightning arrester for the protection of the testing transformer instead of other two devices. If the lightning arrester is used then, when flashover occurs, the lightning arrester will operate because of higher voltage and as soon as the impulse voltage disappears (within few micro-seconds) the lightning arrester will recover and the short circuit from the transformer will be removed before the other protective devices of the testing transformer operates. Because of this, there will be no interruption and/or halt to the testing.

In case of sphere gap and rod-rod gap, once the flashover has occured across the protective gap, the arc may not get extinguished (it depends on the gap spacing) and this may lead to the tripping of the power supply circuit breaker and hence interruptions while conducting the test.

3.3.3 High voltage damping resistor:

During the bias voltage test care must be taken to protect the test transformer in the event of a flashover across the longitudinal insulation. The sudden voltage collapse on the terminal of the power frequency transformer may be dangerous to the internal insulation of the transformer since effectively a chopped wave would be applied to the transformer insulation.

In order to reduce the severity of the chopped wave on the testing transformer terminal, a series damping resistor 'R' is normally connected between the transformer terminal and the terminal of the test object. The resistor prolongs the discharge of the transformer capacitance until the power frequency current from the supply can build up to a sufficiently high level to maintain the arc in a conducting state /141/. This technique is relatively inexpensive and also protects the transformer against the chop produced by the flashover at the test object. The value of the resistance 'R' is chosen such that the time constant formed by this resistance and the self capacitance of the transformer plus any external capacitor connected across the terminal of the transformer should be of the order of 100 microseconds. This will, therefore, reduce the severity of the chopped wave on the transformer windings. However, such protective resistance should not have a value of over 10 k Ohms, together with a maximum voltage drop of 3% /148/. Also, the protective resistance may have to dissipate several tens or even hundreds of kilowatts if the supporting capacitor is large.

For the protection of the High Voltage Testing Transformer shown in Figure 4.2, a high voltage damping resistor was designed/manufactured. The specifications of the resistor are given below:

a.	Voltage rating	:	400kV rms
b.	Resistance	:	8.56 K Ohms
c.	Continuous current rating	:	0.9 Amperes
d.	Wire used	:	Ni-Cr 80/20 Silk covered

Figure 3.1 gives the picture of the high voltage damping resistor. The resistor is supported on a porcelain insulator.

3.3.3.1 Location of high voltage damping resistor in the bias voltage test circuit

In order to reduce the severity of the chopped voltage on the transformer winding, a high voltage damping resistor is connected in series between the terminal of the transformer and the terminal of the test object. As discussed earlier, if the time constant formed by the HV damping resistor and the self capacitance plus any additional load capacitor connected between the damping resistor and the transformer terminal is of the order of 100 microseconds, then the severity of the chopped voltage on the transformer can be reduced.

The value of damping resistor should not be high, otherwise it has to dissipate large amount of losses and also the dimensions of the resistor might become too large. Also, if

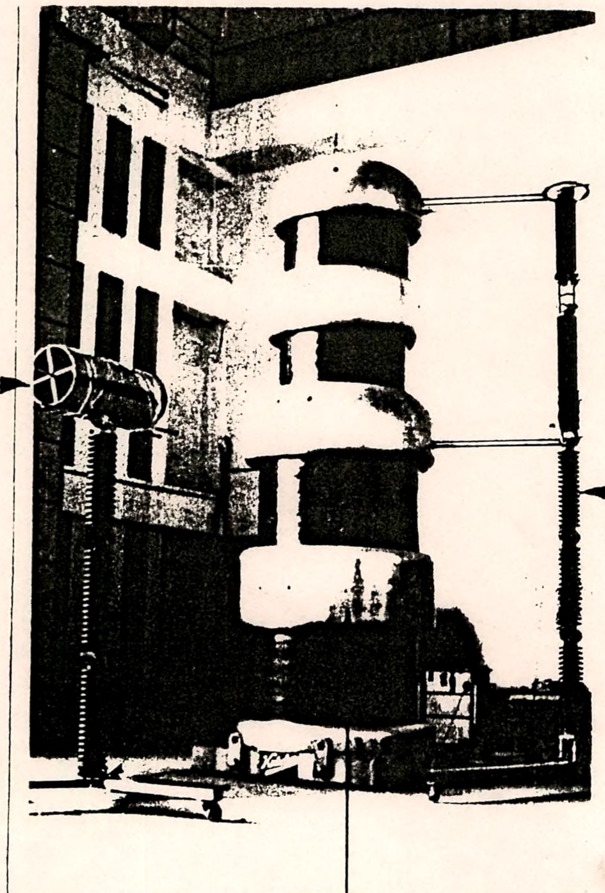


Figure 3.1 : Photograph of damping resistor and grading capacitor

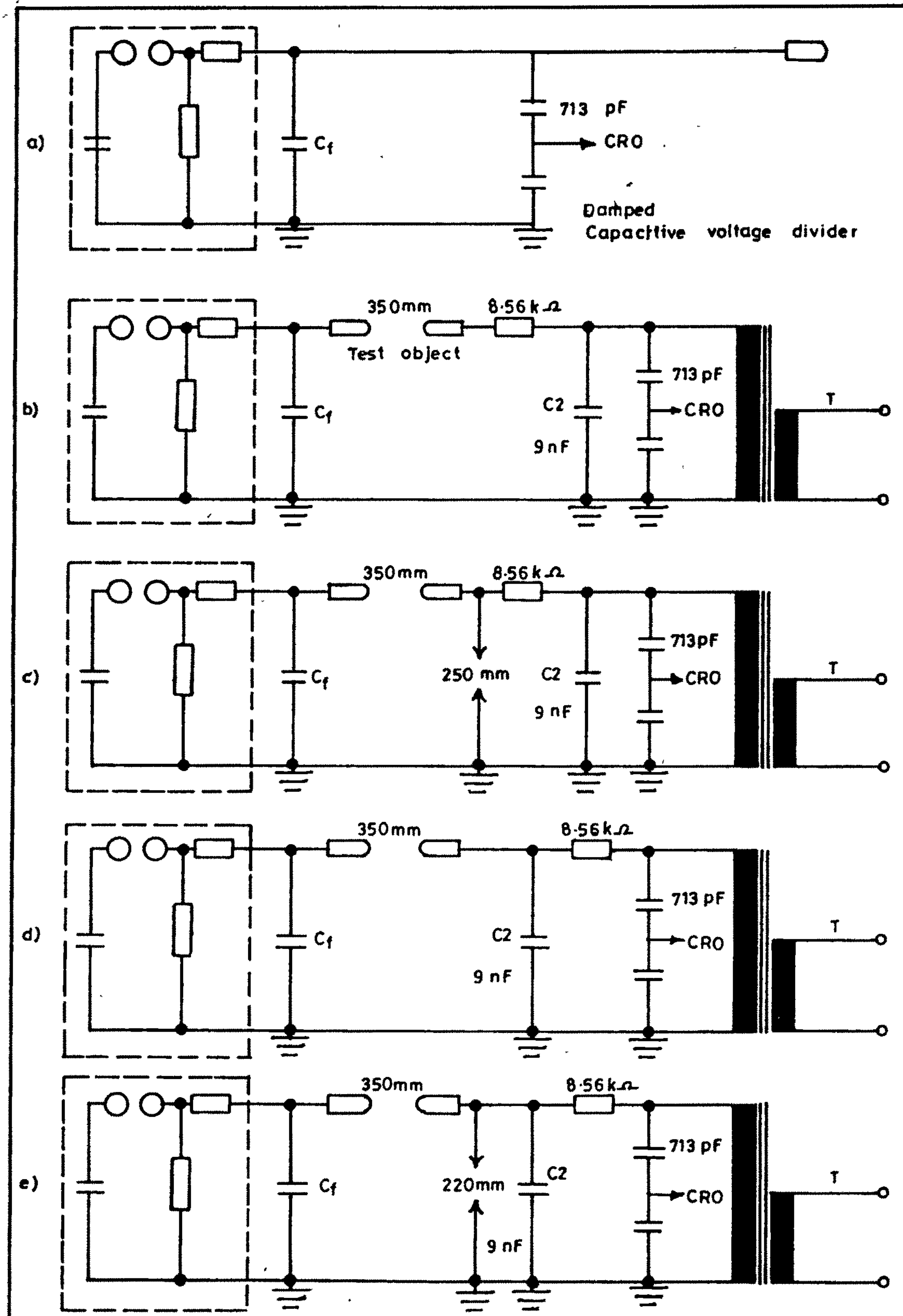
the value of the damping resistance is too large, then, during short circuit across the transformer terminal, the current will be limited and the same may not be sufficient for the over-current relay to actuate and cut off the power supply of the testing transformer. Under such situations the transformer will remain dead short circuited for longer time till the operator trips the supply circuit breaker manually. VDE standard-0433/148/ has specified to use damping resistance in the range of 10 K Ohms. This value of damping resistance may not be adequate to achieve higher circuit time constant. The other alternative left is to connect large value of supporting capacitance directly across the testing transformer, i.e. the damping resistor should be connected between the supporting capacitor and the power frequency terminal of the test object. This circuit arrangement will give higher value of the circuit time constant. Higher value of the capacitor may be chosen to reduce the severity of the chopped voltage, if transformer has adequate current capacity. One of the international laboratories had connected the damping resistor in this fashion and tested UHV class circuit breaker for switching impulse bias test. From the protection point of view of the testing transformer this is the best location of the damping resistor during bias voltage test. Also, if the damping resistor is connected after the supporting capacitor (refer Figure 4.1), then the required current rating of the resistor will reduce and hence the size of the resistor.

Experiments were carried out on a small open gap(350mm) to study the effect of location of the damping resistor in the bias voltage test circuit. The various circuit configurations used for this study are shown in Figure 3.2, and the results are reported in Table 3.1. It is seen from these results that, if the damping resistor is connected between the test object terminal and the supporting capacitance then the front time of the wave which appears across

TABLE : 3.1

Sr. No.	Wave	Voltage kV	Measured waveshape /us	Remarks
1	LI	399	1.29/59	Input voltage applied to the opposite terminal. Circuit connection as per Figure 3.3a
	SI	350	225/2200	
2	LI	198	75/225	Circuit connection as per Figure 3.3b
	SI	250	425/3420	
3	LI	70	25/225	Circuit connection as per Figure 3.3c
	SI	100	-	
4	LI	188	37/150	Circuit connection as per Figure 3.3d
	SI	259	350/2200	
5	LI	35	10/225	Circuit connection as per Figure 3.3e
	SI	74	270/3000	

the transformer terminal increases and the magnitude of the voltage decreases, thus the severity of the chopped wave reduces. It may be noted from these results that when parallel protective gap is used, the magnitude of voltage which appears across the transformer terminals reduces substantially, however the increase in wave front time is nominal. When parallel protective gap is not used than the increase in wavefront time is substantial,



T = Test Transformer
C_f = Loading capacitor
1200 pF for Lightning impulses
7200 pF for Switching impulses
IG = Impulse voltage generator

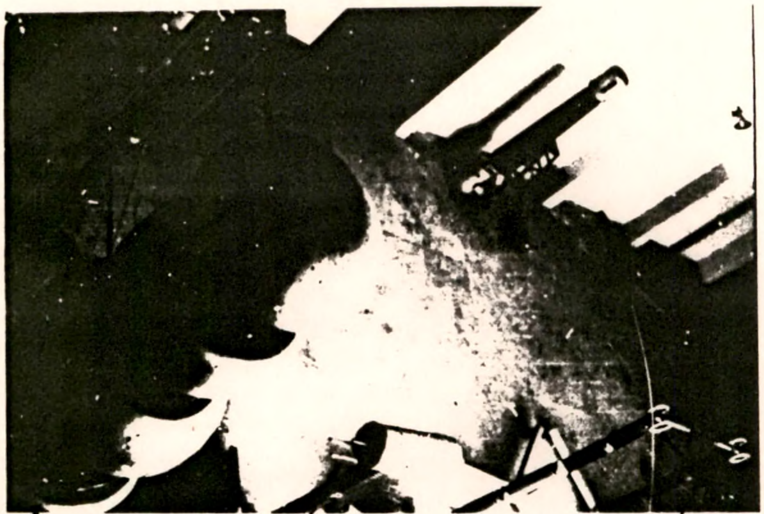
Figure. 3.2 Various circuit configurations used to study the severity of the chopped wave on transformer insulation.

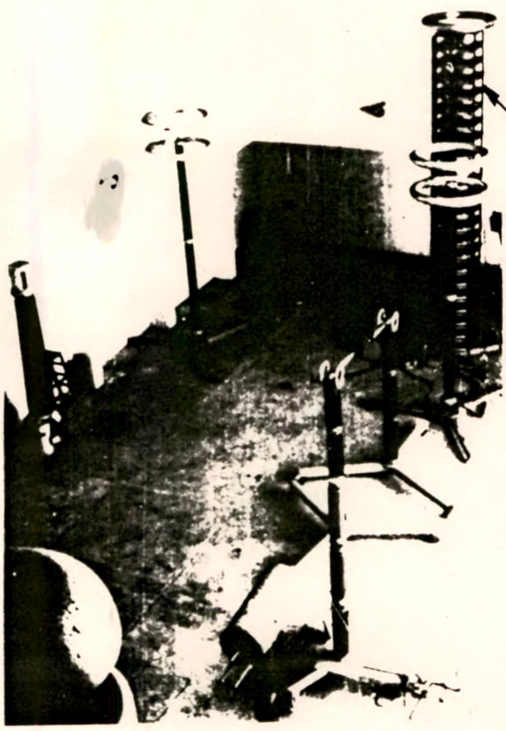
however the reduction in voltage magnitude is nominal.

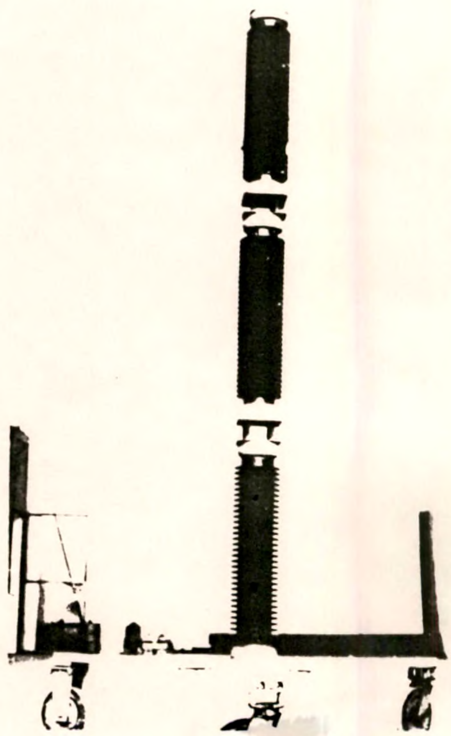
Experiments were also carried out on a rod-rod gap with gap spacing 1.5 meters. Figure 3.3 shows the aerial view of the bias test set-up. Some of the typical oscillograms recorded for switching impulse and lightning impulse waves at different points are shown in Figure 3.4 and 3.5 respectively for α equal to zero ($\alpha = U^-_{AC}/U^+_{impulse}+U^-_{AC}$, where U^-_{AC} is peak value of AC 50 Hz voltage and $U^+_{impulse}$ is impulse voltage. If $U^-_{AC} = 0$, $\alpha = 0.0$). The conclusions drawn for small gaps confirms for the larger gap also.

Figure 3.6 shows the typical oscillographic records of voltage on AC terminal when flashover occurs across the test object during switching impulse bias test. AC voltage (214 kV_p) was applied continuously to terminal 'A' of Figure 4.1. The voltage waves were recorded at the terminal of the test object when supporting capacitor is connected at test object terminal (Figure 3.6a) and also at the terminal of the HV testing transformer when supporting capacitor is connected at transformer terminal (Figure 3.6b). Because of the damping effect of the series damping resistor the oscillations/disturbances on AC voltage have reduced when the voltage is recorded at the transformer terminal. Figure 3.7 shows the typical oscillographic records of switching impulse voltage when flashover occurs across the test object. This voltage was recorded at terminal D of Figure 4.1.

From this analysis it may be concluded that the damping

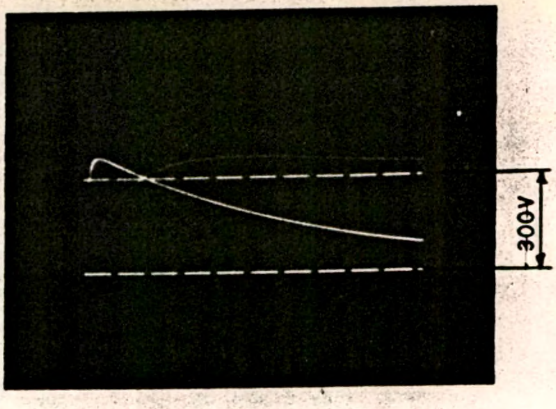




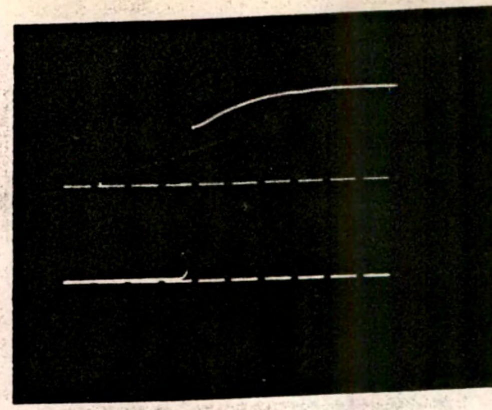


Divider for measurement of AC voltage and transferred impulse voltage.

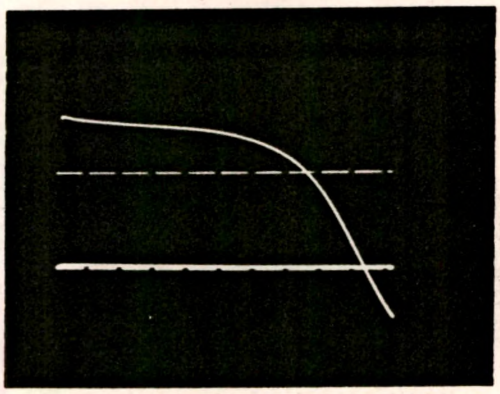
Figure. 3.3 Aerial view of Bias test set-up



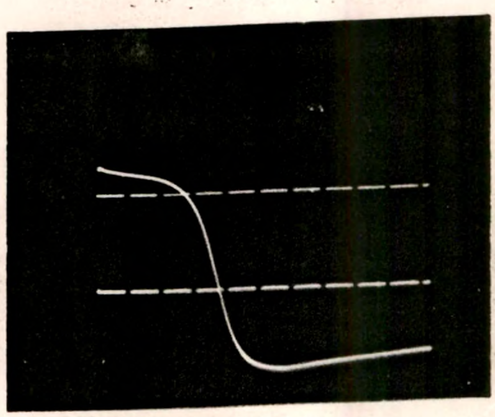
(A) SI Voltage applied to the impulse terminal. (divider ratio = 1465 x 1.59)
Time base: 50 μs/div. for front
500 μs/div. for tail



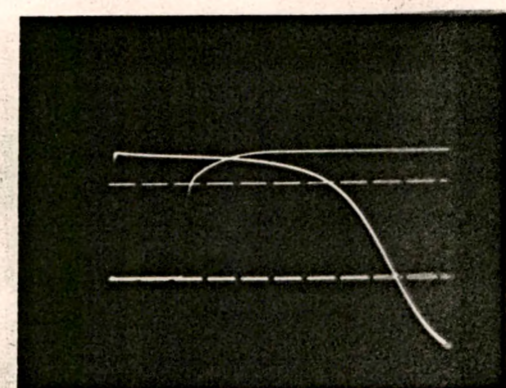
(B) SI Voltage measured at the power frequency terminal of the rod-rod gap. (Divider ratio = 1465)
Time base: 25 μs/div.



(C) Same as (B), but
time base: 1 m sec/div.

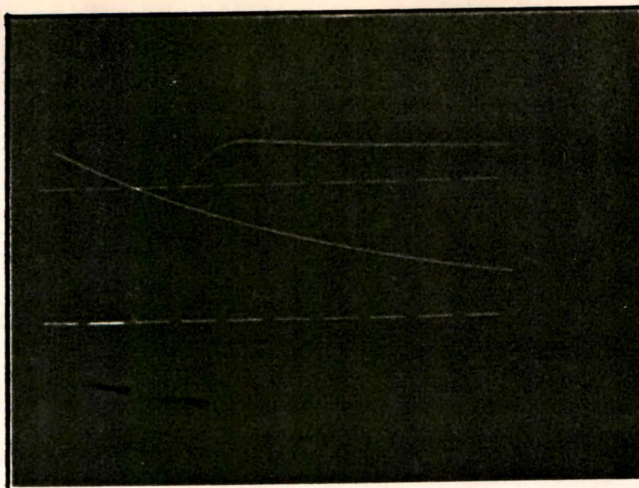


(D) Same as (B), but
time base: 2.5 m sec/div.

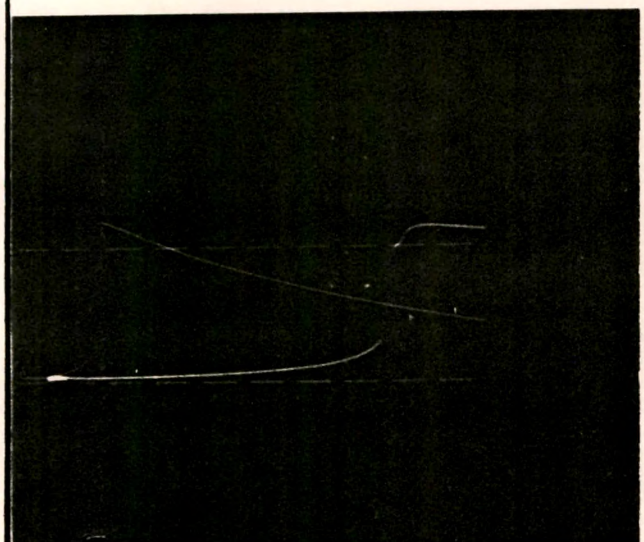


(E) SI Voltage measured across the power frequency testing transformer. (divider ratio = 1465)
Time base 50 μs/div. for front and
1 m sec/div. for tail.

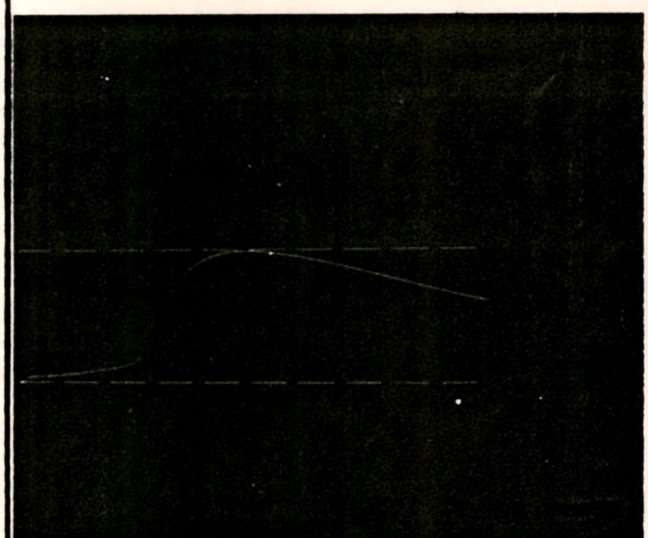
Figure 3.4 Typical oscillographic records of switching impulse waves at different points of the Bias test circuit for rod-rod gap



(A) Applied lightning impulse wave shape
kV = 737.0
Time base = 500 ns/div. for front and 10 μs/div. for tail.

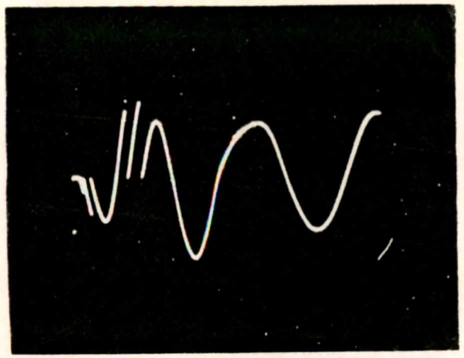


(B) Lightning impulse voltage wave shape at power frequency terminal of rod-rod gap.
kV = 547.0
Time base = 2.5 μs/div for front and 10 μs/div. for tail.

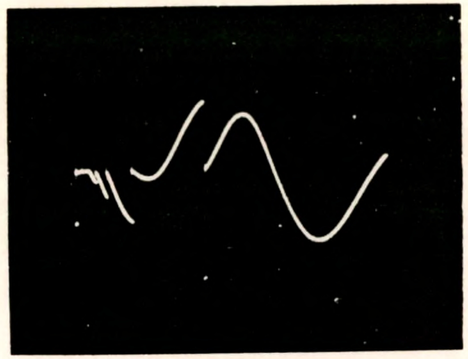


(C) Lightning impulse voltage wave shape at the terminal of the test transformer
kV = 350.0
Time base = 10 μs

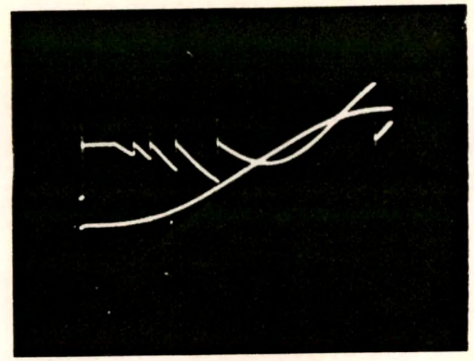
Fig 3.5 Typical oscillographic records of lightning impulse voltage wave at different points of the Bias test circuit



TIME BASE = 5 ms

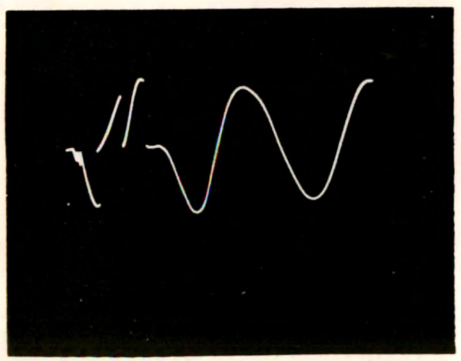


TIME BASE = 2.5 ms

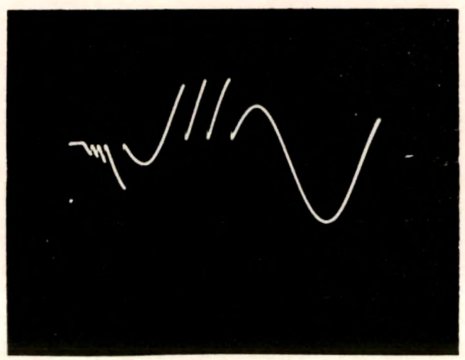


TIME BASE = 1.0 ms

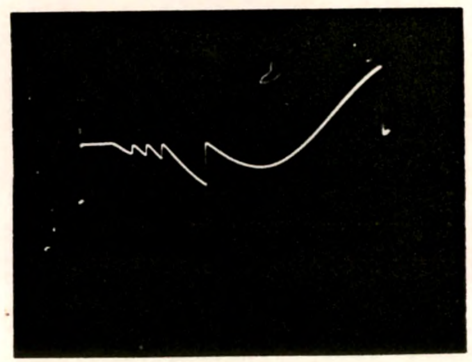
a) AC voltage recorded when supporting capacitor is connected at point A (Figure 4.1)



TIME BASE = 5 ms



TIME BASE = 2.5 ms

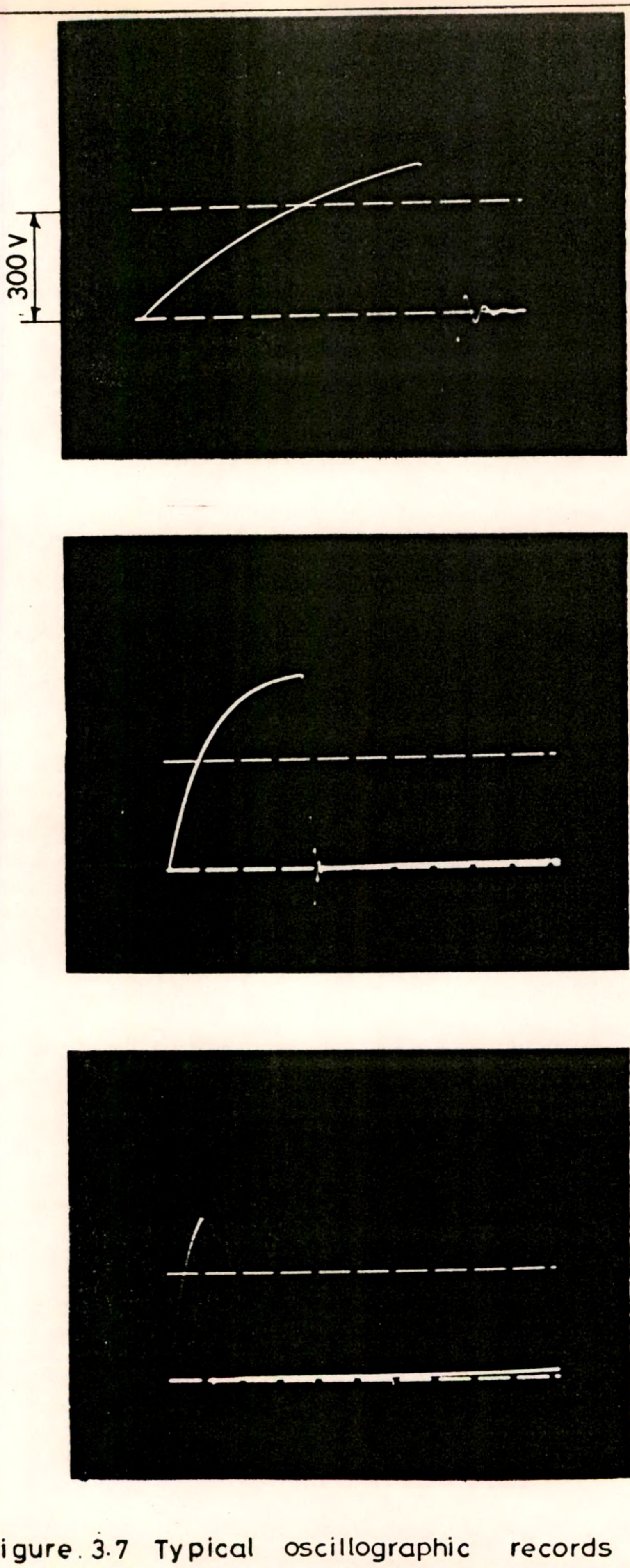


TIME BASE = 1.0 ms

b) AC voltage recorded when supporting capacitor is connected at point B (Figure 4.1)

Figure.3.6 Typical oscillographic records of AC voltage when flashover occurs across the open gap.

Divider ratio = 1465



Time Base 10 µs/div.

Time Base 50 µs/div.

Time Base 100 µs/div.

Figure. 3.7 Typical oscillographic records of SI; for open gap flashover.

resistor should be connected between the terminals of the test object and the supporting capacitor to reduce the severity of the chopped wave on the transformer insulation.

3.4 Impulse voltage distribution in a cascade circuit

In cascaded transformer, commonly used for HV testing, the problem arises of a non linear distribution of voltage across the various stages. The distribution of impulse voltages across the individual stages of a cascade circuit is dependent on the relationship of the inherent capacitances (especially of the windings) and the stray capacitance between the top and intermediate electrode to ground as well as to the high voltage terminal. Normally, the inherent capacitances are higher so that the stray capacitances can be virtually neglected. The withstand capability against impulse voltages of a single-column cascade of insulated cylinder transformers need only be reduced slightly from the withstand capability of one transformer times the number of stages/144/.

In the case of extended cascade circuits with two parallel connected base transformer, the doubling of the inherent capacitance of the lower stage, while still neglecting the stray capacitances, causes a non-linear impulse voltage distribution between upper and intermediate stages.

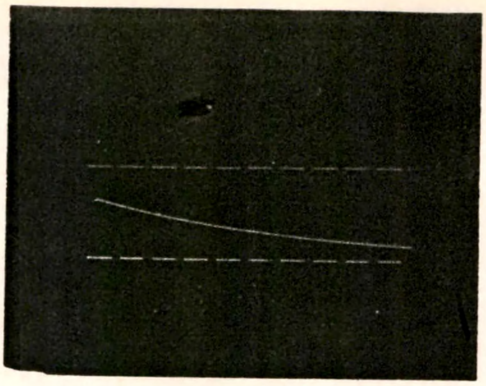
In the case of flashover across the test object, the rapid voltage collapse does not endanger the test transformer to such a high degree since the resulting impulse voltage distribution substracts itself with relatively low amplitude from the linear AC voltage distribution.

3.4.1 Measurement of the self capacitance of the transformer

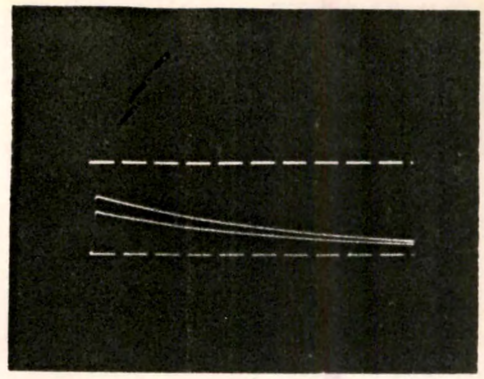
During bias voltage test if the open gap insulation flashover, the large part of the impulse voltage appears across the transformer terminals. To check the impulse voltage distribution of 750kV, 750kVA cascaded HV testing transformer the self capacitance of the two cascaded units, separately and combined was measured using the procedure described in Appendix-1. The cascaded 750kV unit consists of one no. 500kV unit and one no. 250kV unit. The measured value of the self capacitance of the 500kV unit is 438.0 pF and that of the 250kV unit is 280 pF. The voltage share of the 250kV unit is 61% when an impulse voltage having a waveshape of 1.2/50 micro-seconds is applied to the transformer terminal. The actual impulse voltage share of this unit should have been 33.33%. The typical oscillographic records of applied impulse voltage Ua and the voltage drop across the transformer terminal U_b is shown in Figure 3.8.

3.4.2 Effect of front time on voltage distribution

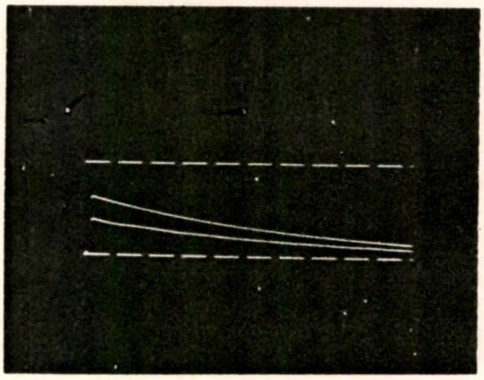
In order to measure the self capacitance of the cascaded unit accurately, it is better to measure the same at fast rising pulses so that the inductance of the transformer does not come into picture. The impulse voltage distribution at fast rising pulses will be highly non-linear and the non-linearity will go on decreasing as the front time of the wave increases. At power frequency voltage, the



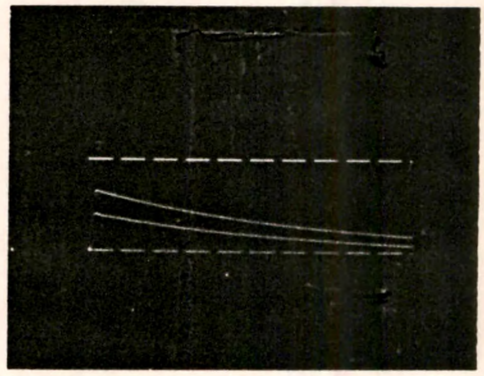
(A) Impulse wave shape used for the measurement of self capacitance (1.3 / 54 μs)



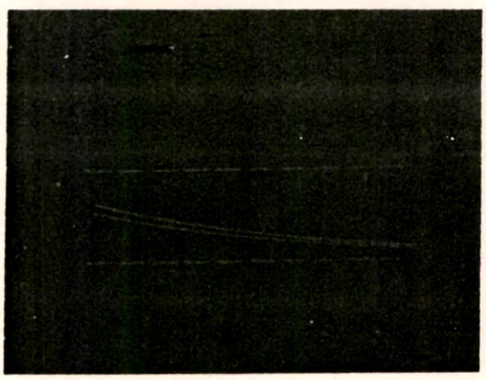
(B) Measurement of self capacitance of 750 kV cascaded unit. U_a = 68.7 kV, U_b = 44.3 kV, C = 600 pF



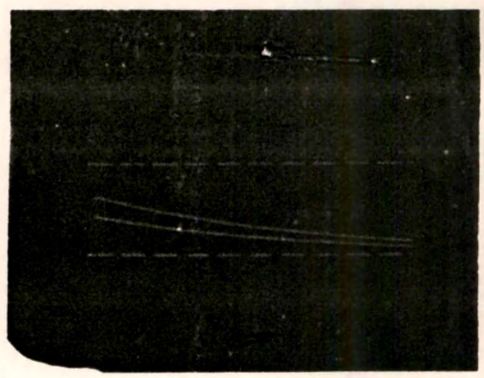
(C) Measurement of self capacitance of 500 kV unit separately U_a = 68.4 kV, U_b = 36 kV, C = 600 pF.



(D) Measurement of self capacitance of 250 kV unit separately U_a = 68.7 kV, U_b = 42.0 kV, C = 600 pF



(F) Measurment of self capacitance of 750 kV cascaded unit with grading capacitance of 600 pF connected across 250 kV unit U_a = 69.0 kV, U_b = 53.2 kV, C = 1500 pF



(G) Measurment of self capacitance of 250 kV unit with grading capacitor of 500 pF connected across it U_a = 68.8 kV, U_b = 41.6 kV, C = 1500 pF

Figure 3·8 Typical oscillographic records of applied impulse voltage U_A (Top wave) and voltage drop across the transformer terminal, U_B (Bottom wave) voltage distribution will be quite uniform and linear.

In the bias test circuit generally one HV damping resistor is connected in series with the transformer terminal to reduce the severity of the chopped wave. Because of the series resistance and self/stray capacitance to earth the front time of the wave will change, and hence the voltage distribution will be better with this arrangement.

Experiments were conducted to check the voltage distribution across the cascaded units by applying impulse voltage waves of varying front time. Figure 3.9 shows the voltage distribution across the 500kV unit as a function of time-to-crest of the impulse wave. It is seen from the results, that the voltage share of 500kV unit will be 66.66% (theoretical value calculated based on its rating) when the time-to-crest of the impulse wave is of the order of 2.1 ms.

3.4.3 Voltage grading capacitor

As discussed earlier, the voltage share of 250kV unit of the 750kV cascaded transformer is 61% instead of 33.33% when lightning impulse wave is applied to the HV terminal. A linearisation of the impulse distribution can be obtained with the aid of voltage grading capacitors when high demands are to be placed on the impulse voltage withstand capabilities of the cascaded transformer. Thus, in order to make the voltage distribution uniform, it was necessary to connect external voltage grading capacitor across the 250kV unit. Theoretical calculations were made and it was found that to achieve uniform voltage distribution across the two units, it was necessary to connect approximately 600pF capacitor across the 250kV unit. The grading

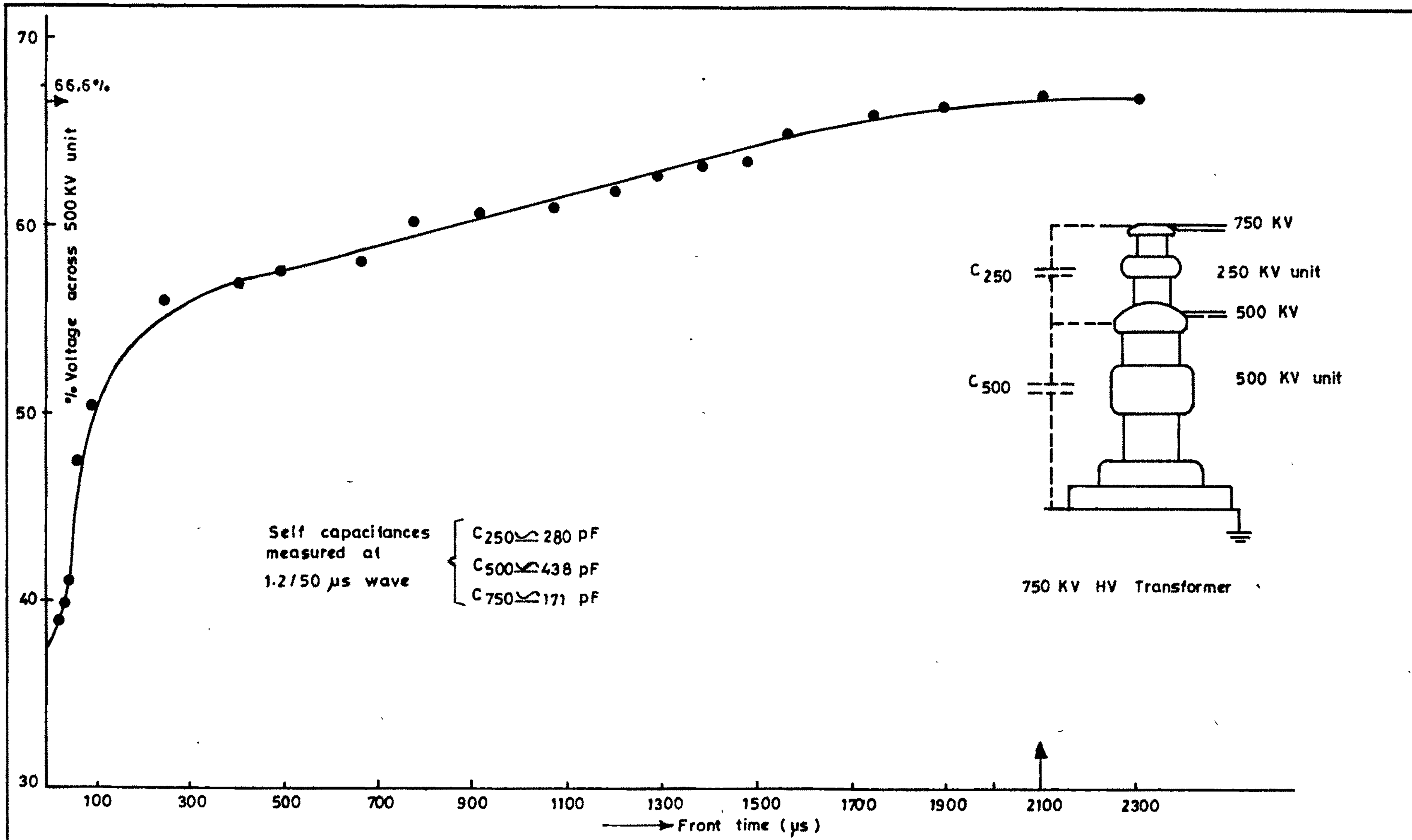


Figure.3.9 Voltage distribution across 500 KV unit as a function of front time of the impulse wave.

capacitor was designed/fabricated and connected across the 250kV unit. The grading capacitor and its connection across the 250kV unit is shown in Figure 3.1. The grading capacitor is supported on a porcelain support insulators. After connecting the grading capacitor, the lightning impulse voltage share of the 500kV unit has increased from 39% to 67%. The self capacitance of 250kV unit was again measured after connecting the voltage grading capacitor. The oscillographic record of applied impulse voltage U_a and the voltage drop across the transformer voltage U_b, is shown in Figure 3.8G.

3.5 Low and high frequency oscillations

It is well known that asymmetric air gaps exhibits a large polarity effect with respect to their flashover voltage. For a rod-plane gap, which represents a considerably asymmetric configuration, the ratio of the negative to positive discharge voltage is approximately 2:1. Generally, the flashover across the gaps occur in the vicinity of the crest of the AC voltage and the current from the power source is virtually zero. If the first flashover of a gap is at the positive crest of the AC voltage, virtually only the current from the capacitances connected to HV terminal are available for ionization and increasing the conductivity of the discharge path. Normally, the flashover will be extinguished after the rapid discharge of these capacitances. If the transformer possesses a low short circuit voltage or stray reactance, a recovery voltage can rapidly appear in the under-critically damped resonant circuit comprising inductance (L) of the transformer and the total capacitance (C) at the high voltage terminal of the transformer/144/. This occurs in a race with the dielectric recovery of the gap after the first discharge and leads to a new discharge which will occur, latest, after reaching approximately a full flashover voltage. This will once again feed energy into the discharge path. With transformers having a high short circuit reactance, this increase in the voltage will be slower and the recovery of the discharge path will take place faster than the increase of the voltage stress due to the recovery voltage. The time lag between the individual voltage discharges will be so great that the energy will be virtually dissipated in the meantime. No summation of the partial energy occurs and thus no heating of the discharge path.

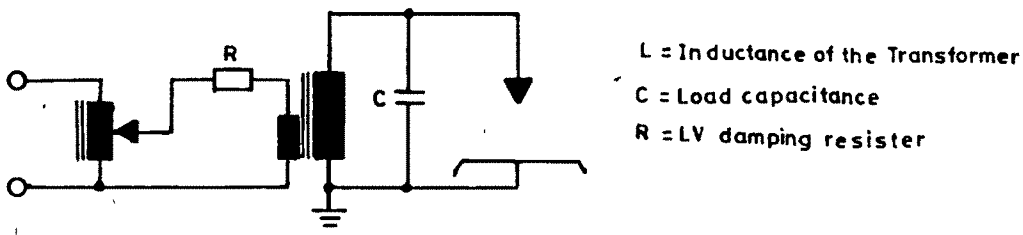
Figure 3.10 shows this condition at the comparatively low transient frequency fe, which is given by /144/.

$$f_e = \frac{1}{2\pi\sqrt{L.C}} \qquad \text{.............(3.2)}$$

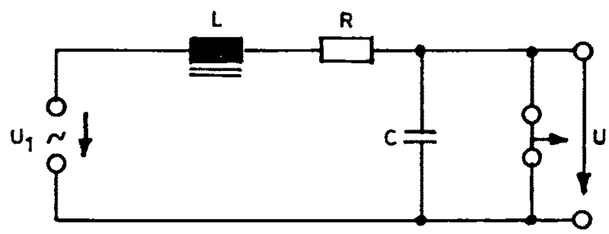
Where L = total inductance of the system

C = total capacitance in parallel to the transformer

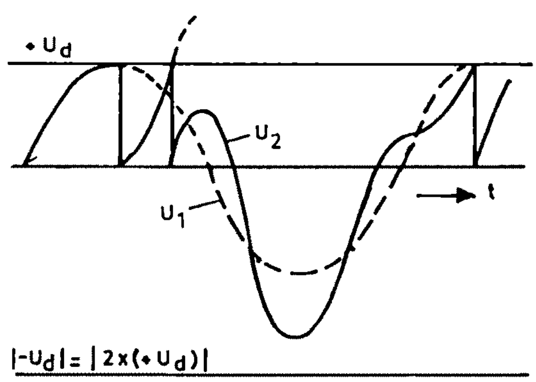
This frequency coincides to approximately 1.5 to 2 times the power line frequency. As seen from the figure 3.10, negative overvoltages of virtually twice the peak value of the normal secondary voltage can occur at this frequency ratio according to the previous time of discharge. This was also experimentally verified by Train /145/ and Parnell /142/. The negative overvoltages will not nece-



(a) Test circuit



(b) Equivalent circuit diagram



(c) wave form

Figure 3.10 Waveform of the transient voltage U_2 on extinction of flashover (ref. 144).
$\pm U_d$ = Breakdown voltage of the spark gap, with polarity effect.

ssarily produce an air flashover (because of polarity effect) but they could damage the paper and oil insulation of the transformer or the supporting capacitance. Due to high negative flashover voltage of the gap and the missing heating of the discharge path during the positive half cycle, an assymetrical gap with polarity effect will not be able to protect the transformer under all conditions.

The tendency to extinction of the arc on assymetric gaps can be reduced if the inherent resonant frequency is increased. For a given testing transformer, the lower is the short circuit impedance, the greater is the current that will flow through the flashover path after the circuit capacitances have been discharged in order to increase the conductivity of the flashover path. Also, lower the short circuit impedance, higher is the inherent resonant frequency. A high resonant frequency allows a rapid sequence of ionizing discharges during the positive half cycle which maintains a sufficient conductivity of the flashover path until the negative half cycle. Thus, where small load capacitances are encountered the frequency of the recovery is high and the polarity of the overvoltage will be the same as that of half cycle in which flshover has occured. Where this is the case further flashovers occur and the overvoltage is unlikely to reach its maximum possible value. However, the critical conditions exist for the cascaded transformers with a relatively high short circuit voltage and large capacitive load because of low resonant frequency.

The supporting capacitance required to limit the voltage drop on AC terminal while conducting bias voltage test on circuit breakers is large (a few nano farads) and for disconnector type open gaps small value of supporting capacitor is sufficient (approximately 1000pF). Thus, for a given value of short circuit impedance of the testing transformer the transient frequency, fe, will be low when bias test is conducted on circuit breakers and the transient frequency, fe, will be high when bias test is conducted on disconnector type open gaps. It should, therefore be examined under which circumstances and conditions these overvoltages actually appear, when they obtain dangerous values and what protective measures can be taken to reduce their magnitude.

3.6. Control of voltage distortion on AC wave

The basic circuit for the bias voltage test with one terminal energised at power frequency voltage and the other terminal subjected to an impulse voltage is shown in Figure 4.2. During bias voltage test, the AC voltage is adjusted to a required phase-to-ground voltage of the system, and the impulse voltage generator is set to deliver impulses having a magnitude equal to the test voltage level of the test object. The triggering of the impulse voltage generator is synchronised to coincide with the peak of the AC waveform and the polarity of the impulse is opposite to that of the AC waveform at the instant of triggering. The voltage appearing across the longitudinal insulation has therefore a nominal value equal to the sum of the impulse voltage plus the peak of the power frequency voltage.

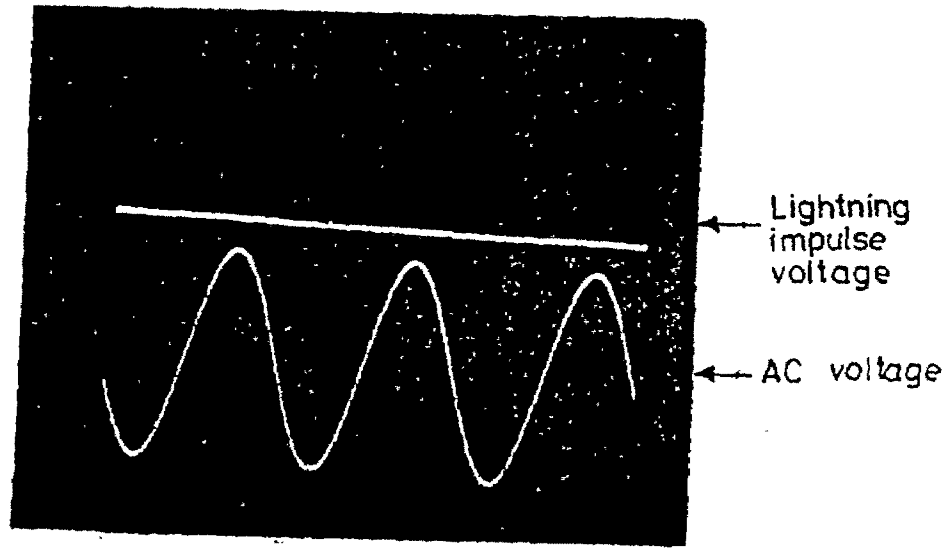
In practice, the peak voltage across the test object is less than the sum of the two voltages due to the fact that the capacitance across the open gap insulation forms a potential divider with the capacitance to ground on the AC terminal of the test object. Consequently when the impulse voltage is applied to one terminal, the impulse voltage appearing on the power frequency terminal will result in voltage distortion on the AC wave. The voltage distortion on AC wave can be seen on the oscillograms snown in Figure 3.11 recorded while conducting lightning and switching impulse bias test. The amount of distortion can be calculated by analysing the equivalent circuit of the complete bias test set up.

The equivalent circuit of bias test set up is shown in Figure 3.12. The coupling capacitance C_1 represents the sum of all the capacitances involved on the power frequency terminal of the test object. The power frequency voltage is distorted by an induced voltage or transferred impulse voltage, which is given by:

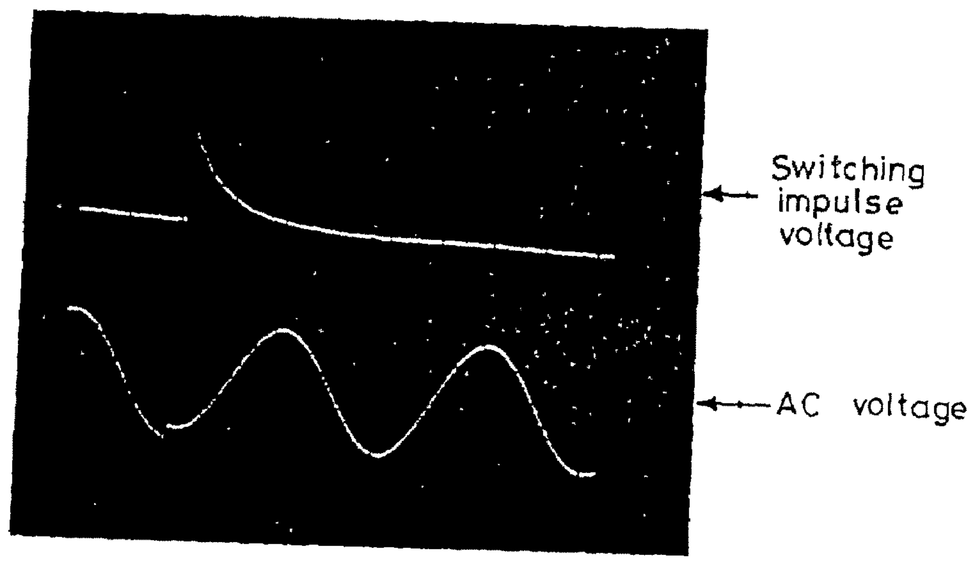
$$\Delta U_{AC} = U_{SI} \frac{C_b}{C_1 + C_b} \qquad \text{...........(3.3)}$$

Where ΔU_{AC} = is the distortion of the power frequency voltage

U_{SI} = applied switching impulse voltage

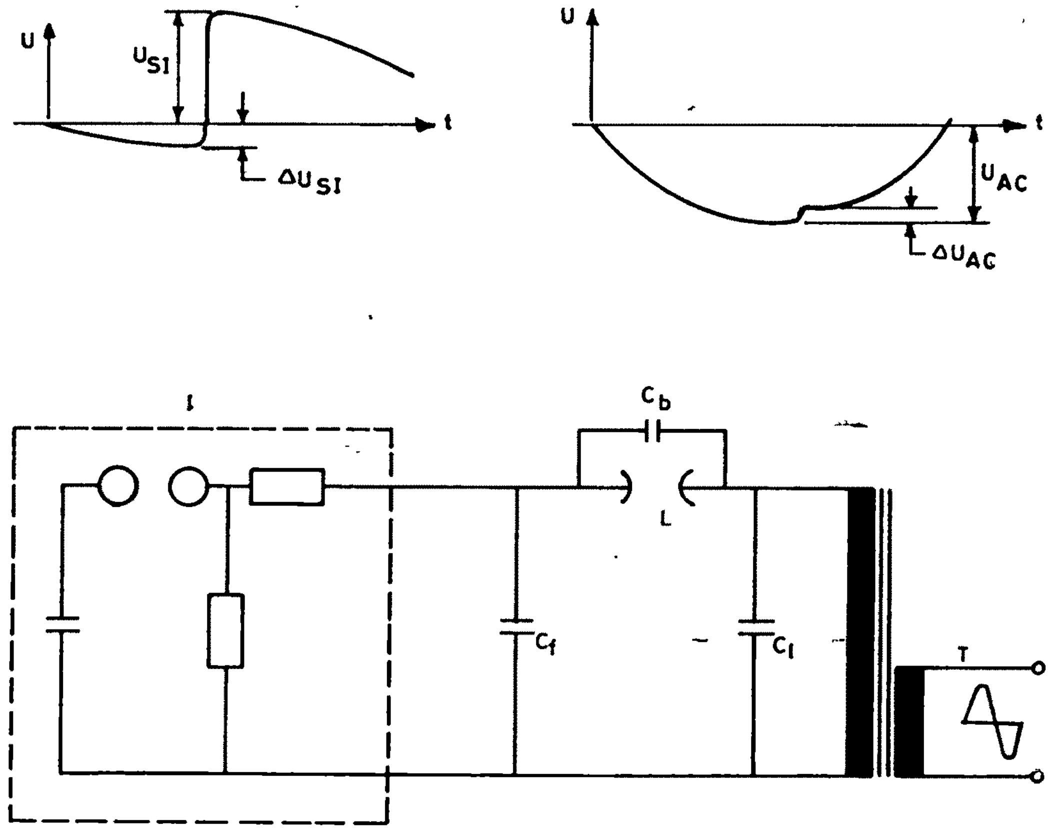


(A) Lightning Impulse bias test.

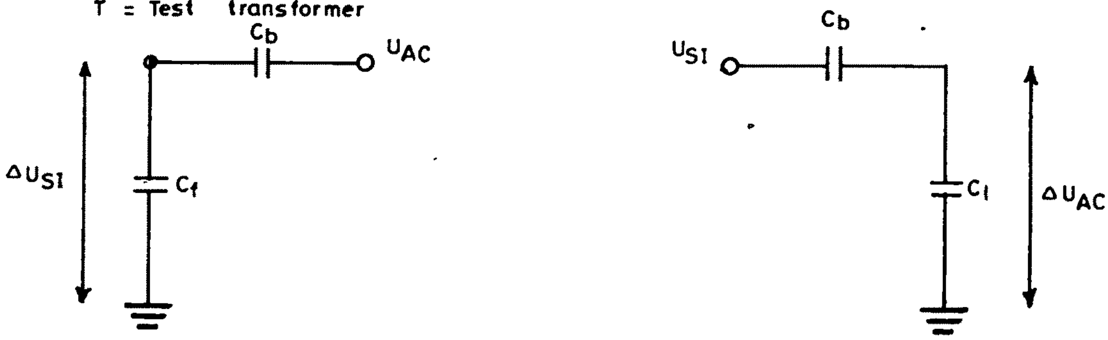


(B) Switching Impulse bias test.

Figure.3.11 Typical oscillographic records of impulse and AC wave taken for the measurment of voltage distortion



C_f = front capacitance
C_b = Test object capacitance
C_l = Total load capacitance on AC terminal
L = Longitudinal insulation
I = Impulse generator
T = Test transformer



Equivalent circuit for calculating ΔU_{SI}

Equivalent circuit for calculating ΔU_{AC}

Figure. 3.12 Equivalent circuit of bias test set-up.

C_1 = total load capacitance at the power frequency terminal of the test object. This capacitance includes the self-capacitance of the transformer, the capacitance of the divider and any additional capacitance which is connected to the circuit in order to limit the voltage depression.

C_b = test object capacitance

$$C_1 + C_b = C_b \times \frac{U_{SI}}{\Delta U_{AC}}$$

$$C_1 = C_b \left[\frac{U_{SI}}{\Delta U_{AC}} - 1 \right]$$

If $\Delta U_{AC} = d \times \hat{U}_{AC}$

where d is permissible percentage voltage distortion on AC wave and

$\hat{U}_{AC}$ = peak value of AC voltage

then

$$C_1 = C_b \left[\frac{U_{SI}}{\frac{d}{100} \times \hat{U}_{AC}} - 1 \right]$$

$$C_1 = C_b \frac{U_{SI}}{\frac{d}{100} \times \hat{U}_{AC}} \quad ; \quad U_{SI} \gg \frac{d}{100} \times \hat{U}_{AC}$$

For $d \leq 6\%$ $\hat{U}_{AC}$ (6% specified by BC Hydro)

$$C_1 \geq C_b \frac{U_{SI}}{0.06 \hat{U}_{AC}} \qquad \text{.............................(3.4)}$$

It is seen from formula (3.3) that the amount of voltage distortion can be reduced by increasing the capacitance to ground on the AC terminal.

Because of the capacitive coupling, the impulse voltage is superimposed to a pre-existing ac voltage, which is given by

$$\Delta U_{SI} = \frac{C_b}{C_b + C_f} \times \hat{U}_{AC} \quad \ldots\ldots\ldots\ldots\ldots \quad (3.5)$$

where C_f is the total capacitive load connected to the impulse voltage terminal of the test object.

Based on IEC publications-56(4) and 129, the maximum permitted distortion of the power frequency voltage is ΔU_{AC} $U_{AC} = 16.7$ per cent for the switching impulse bias test and $\Delta U_{AC} = 30$ per cent for lightning impulse bias test.

Taking into account the rated withstand voltage to be applied during the bias test, the required ratio C_1/C_b should be not less than 13 for $U_m = 300$ kV.

For capacitive controlled gap circuit breakers, the grading capacitance is relatively high as compared to the open gap capacitance of a disconnector. Depending on the design of the circuit breaker under test, if the grading capacitance is high then the necessary supporting capacitance on the AC terminal may result in overloading of the test transformer.

For uncontrolled switchgears, e.g. disconnectors, the series capacitance across the open gap is so small as compared to the capacitance to ground on the AC terminal that the deformation is insignificant. The support capacitance C_1 required for controlling the voltage distortion will be in the range of only 1000pF.

During the bias voltage test, the bias voltage should never be increased to such a level that it causes the formation of corona, since this may affect the breakdown strength of the open gap/139/ .

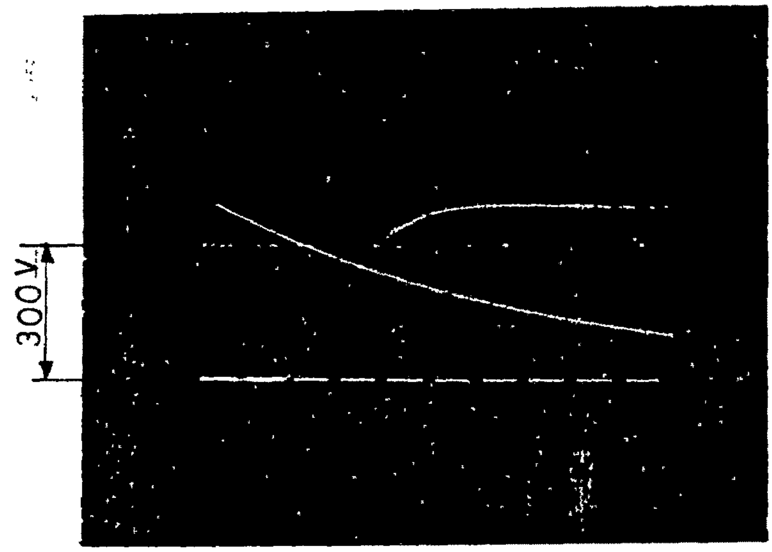
3.7 Measurement of voltage drop on AC terminal

While conducting bias voltage test on the longitudinal insulation, two voltage dividers are required, one for the measurement of impulse voltage and another for the measurement of AC power frequency voltage. It is well known fact that for the accurate measurement of impulse voltages, it is a must to use a damped capacitive voltage divider. For the measurement of power frequency voltage and the voltage drop on AC terminal, it was planned to use capacitive voltage transformer (CVT), which also serves as a required supporting capacitive load on the power frequency terminal.

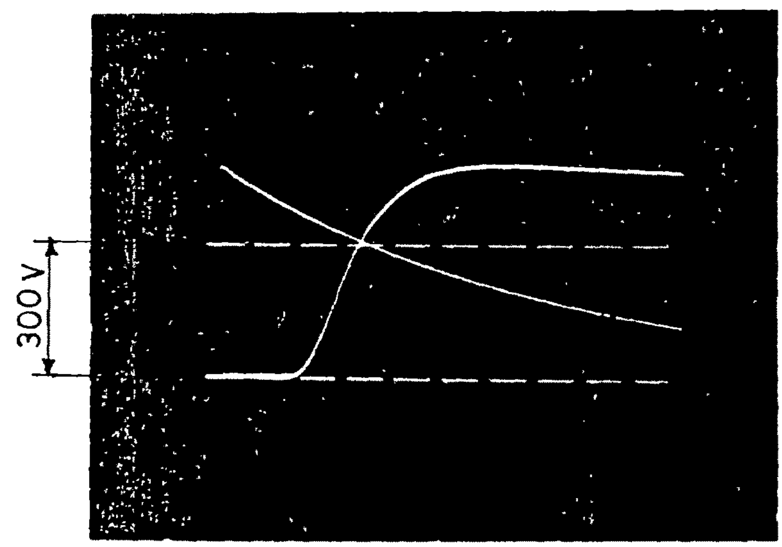
After arranging the complete bias test set up as per circuit layout shown in Figure 4.2, an attempt was made to measure the voltage drop on AC terminal (because of the transferred impulse voltage) by using CVT. Lot of mismatch in the calculated and measured voltage was observed. When impulse voltage is applied, the complete AC waveform was getting distorted and hence it was difficult to measure the voltage drop. These oscillations were on account of the electromagnetic unit of CVT.

To get rid of the oscillations, the electromagnetic unit of the CVT was disconnected and a small capacitive secondary unit was connected to the other terminal of the primary capacitance. This way a pure capacitive voltage divider was formed for the measurement of voltage drop. The measured value of the voltage drop was comparable with the theoretical value. However, the error in the measurement was still considerably high. Very little oscillations were observed on the AC wave when the voltage drop was measured using a capacitive voltage divider. To further reduce the oscillations on AC wave, an attempt was made to measure the voltage drop on AC terminal by using a damped capacitive voltage divider. For this purpose a new damped capacitive voltage divider was designed/fabricated, and the response of this divider was checked with the available damped capacitive voltage divider in the laboratory(this was supplied by M/s HAEFELY and used for impulse voltage measurement). The wave shape of the lightning impulse wave recorded using HAEFELY divider and new damped capacitive voltage divider are shown in Figure 3.13. There is hardly any difference seen in these two oscillograms. The voltage drop on AC terminal measured using the new divider was highly accurate. Theoretical and measured value of the voltage drop were exactly the same.

Thus, one of the important requirement for conducting bias voltage test on the longitudinal insulation is also to have a damped capacitive voltage divider for the mea-



(A) Wave shape recorded using Haefly divider
kV = 580, Time base = 500 ns/div. for front and 10 μs/div. for tail.



(B) Waveshape recorded using new divider
kV = 580 kV Time base = 500 ns/div. for front and 10 μs/div. for tail.

Figure 3.13 Typical oscillographic records of lightning impulse voltage wave using Haefely make damped capacitive voltage divider and New divider.

surement of AC voltage and voltage drop on AC terminal. As per the requirement of the equipments' standards it is necessary to compensate for this voltage drop on AC terminal by increasing the AC voltage. If the voltage drop is measured using capacitive voltage divider than it gives higher value of the voltage and hence more compensation will be done. This may lead to overstressing of the test object insulation. This should be avoided by accurate measurement of the voltage drop on AC terminal.

3.8 Automatic triggering of impulse voltage generator

It is essential to have a controlled triggering capability for the impulse voltage generator with point on wave control for conducting bias voltage test on the longitudinal insulation. The point on wave control circuit was developed and fabricated, and was connected at the appropriate place in the control module of the impulse voltage generator. The AC power frequency voltage to the point on wave circuit was given through an AC line filter. The circuit has a facility to synchronise the waves in the range from 0 to 360 degree. The syncnronisation of the impulse voltage peak with the AC power frequency voltage peak was done using a storage oscilloscope.

3.9 Preliminary test procedure

Although not specified by any equipments' standards, it is generally considered a good practice to perform some preliminary tests at reduced voltage level to check that the test equipments are functioning correctly and also to check that the various equipments used for conducting the bias voltage test do meet the standards and systems requirement. The following procedures are recommended before commencing for final test at 100% BIL.

3.9.1 Check on control and measuring circuit

It is advisable to test the various equipments individually before the final test is started. Individual test voltages are applied independently to each side of the test object in turn, the other side being earthed. The voltage levels are usually increased from approximately 50% to the full test voltage levels. This procedure verifies that, the impulse voltage generator generates the required test voltage and the power frequency test transformer is able to give the required test voltage when the supporting capacitance is connected. Also, it verifies that the control and measuring circuits are operating correctly.

3.9.2 Checks on point on wave selector circuit

A bias voltage test is performed at approximately 50% of the full test voltage. This procedure provides a check that the point on wave selector circuit is working correctly and the two peaks get synchronised accurately. This procedure is also necessary to evaluate accurately the percentage deformation occuring on the power frequency waveform. It should be noted that both the power frequency and the impulse voltage should be reduced by the same percentage in order to produce the correct deformation of the AC power frequency voltage.

It is also necessary to check the functioning of the point on wave selector circuit by creating flashover across the gap. This will ensure that even under transient conditions the circuit operates without any problem. The flashover across the gap may be created by reducing the open gap clearance of the test object.

3.9.3 Check on protection circuit

It has been mentioned earlier that it is desirable to use a lightning arrester for the protection of high voltage testing transformer in case flashover occurs across the open gap of the longitudinal insulation. However because of non-availability and economic reasons we used sphere gap for this purpose. The gap setting of the sphere gap should be such that, when open gap flashover, the sphere gap should flashover and protect the transformer. The sphere gap setting should be approximately 10 to 15% more than that required for a given AC test voltage. For any given test voltage, the required gap setting can be obtained from IEC publication 52. The functioning of the same should be checked by increasing AC voltage.

It is also necessary to verify that when flashover occurs across the sphere gap, the overcurrent relay actuates and gives a tripping command to the power supply circuit breaker of the test transformer.

3.9.4 Calibration of impulse waveshape

The bias test circuit should be arranged as per Figure 4.2.

While calibrating the impulse wave shape, the power frequency voltage may be kept zero. Apply approximately 50% of the test voltage to the test object and calibrate the impulse waveshape as per IEC publication-60.

3.9.5 Measurement of the transferred impulse voltage

After calibration of the impulse wave is completed at about 50% of the test voltage, without disturbing the various settings on the control module of the generator, apply the same impulse voltage to the test object and measure the transferred impulse voltage on the AC terminal. The same may be verified theoretically and compared with the measured value. The measured transferred impulse voltage should be within the permissible limits specified by the equipments' standards.

3.10 Conclusion

The bias voltage test can be conducted on the longitudinal insulation of the HV power equipments and the performance of the equipments can be guaranteed better as compared to the equivalent impulse test. While conducting the bias voltage test some care has to be devoted for the protection of the high voltage testing transformer. Such protection can be conveniently provided by:

- connecting a high voltage damping resistor.
- connecting a sphere gap in parallel with the supporting capacitor on the power frequency terminal.

- connecting a voltage grading capacitor to equalize the impulse voltage distribution across the cascaded transformer.

Dangerous overvoltages are generated when the resonant frequency of the circuit is in the range of twice the power line frequency. If the frequency of the recovery transient is high, overvoltages is unlikely to reach its maximum possible value.

Because of the capacitive coupling between the two terminals of the test object, some waveform distortion will be produced on AC voltage. This deformation can be controlled by increasing the supporting capacitance on the power frequency terminal.

It may not be possible to reduce the deformation within the permissible limits given by the specifications by connecting large value of supporting capacitance. In such a case the required test voltage across the open gap should be achieved by increasing the level of the bias voltage. The bias voltage must not be increased to such a high level that it produces corona.

It is a must to use a damped capacitive voltage divider for the accurate measurement of the voltage distortion on the AC wave. The capacitive voltage divider gives erroneous results.

If the damping resistor is connected between the terminals of the test object and the supporting capacitance, best protection can be achieved for the testing transformer against the chopped waves.

Controlled triggering of the impulse voltage generator is essential for the satisfactory performance of the bias test circuit.