CHAPTER : 5

EFFECT OF DAMPING RESISTOR ON CRITICAL FLASHOVER VOLTAGE U_{50} AND VOLTAGE DISTORTION ON AC WAVE

5.1 General

The method of measurement of voltage distribution across the test object is discussed in detail in Chapter Number-4. The transferred impulse voltage on AC terminal of the test object was measured at points A and B using damped capacitive voltage divider as well as resistive voltage divider. As discussed in Chapter-4, in the case of capacitive controlled rod-rod gap, some difficulties were faced in the measurement of lightning impulse transferred voltage U_A. Hence, it was felt necessary to adopt a method of indirect calculation of voltage U_A. The magnitude of voltage U_A should be derived without connecting any divider, because, once an element is connected between terminal A and earth, the circuit configuration and response of the circuit to fast rising pulse changes and hence on account of self and stray capacitance of the divider the measured value of voltage U_A may not be accurate. Thus it was a must to verify the accuracy of the measured voltage U_A. It is more important to verify this for the case of capacitive controlled rod-rod gap because large difference exists between voltage U_A and U_B. Because of this large difference the actual voltage stress across the longitudinal insulation will be less. In the case of rod-rod gap the difference between voltages U_A and U_B is very small. Hence, if the damping resistor is connected between the terminals of the test object and the supporting capacitance C_2, then the voltage stress across the open gap is not affected much in the case of rod-rod gap.

The indirect method adopted for estimating voltage U_A is to derive critical flashover voltage U_{50}, with and without damping resistor R for α equal to zero ($\alpha = U_{AC}^{-}/U_I^{+}+U_{AC}^{-}$ where U_I^{+} is impulse voltage and U_{AC}^{-} is peak value of AC voltage, if U_{AC}^{-} is equal to zero, α is zero). To derive U_{50} of a given test object it is not necessary to connect any divider at point A and hence the stray capacitance to earth does not play any role in deriving U_{50} voltages. The most popular Up and Down method was used to derive U_{50} voltage of the test object. This method is described in this section.

The measurement of critical flashover voltage and standard deviation sigma was done for capacitive controlled rod-rod gap and rod-rod gap electrode configuration. The results are analysed and discussed at depth in the following sections. Comparison of measured and calculated transferred impulse voltages is also discussed.

If the damping resistor is connected between the terminals of the test object and the supporting capacitance C_2, it introduces an error in the measurement of transferred impulse voltage (voltage U_B) on AC terminal and hence this leads to an error in the compensation of the voltage drop on AC terminal. Also the voltage distribution across the test object is affected. These two phenomena leads to an error in deriving actual U_{50} voltage of the test object. The method of calculation of total reduction of voltage stress across the test object because of such type of circuit connections is discussed.

Finally, if it is a must to connect a damping resistor betwenn the terminals of the supporting capacitor and the High Voltage testing transformer, the question that arises is, how to protect the high voltage testing transformer? The time constant of the circuit can be increased either by increasing the value of the damping resistor or by connecting an additional capacitor across the terminals of the testing transformer. The effect of additional capacitor (C_3) on the voltage distribution across the test object was also studied and the results are discussed in this chapter.

5.2 Up and Down method/149/

The Up and Down method is more and more frequently used in dielectric testing because of its simplicity and accuracy for U_{50}. In IEC publication 60, only the estimate of U_{50} is discussed. But there also exist estimates of sigma, and of the variances of U_{50} and sigma/151,152,153/.

It is widely known that in comparison with the interpolation method, the Up and Down method enables to estimate U_{50} with smaller number of voltage applications when the estimation of reliability is assumed to be the same/149/.

Various laboratories have used different methods like interpolation method, Up and Down method, extended Up and Down method and sequential Up and Down method. Digital computer simulation technique was used to clarify the relation between testing method and estimation of reliability. It was clearly shown both theoretically and experimentally that when the number of test voltage application is finite, the estimate of σ obtained by the interpolation method is greater than the true value and that obtained by the Up and Down method is smaller/149,152/.

Having chosen a voltage step called d (also known as ΔU) this method consists of applying a series of test voltages. The result of application of any impulse determines the voltage for the next one; if it is a breakdown, the next impulse voltage is applied at one step lower, and if it is a withstand, one step higher. Figure 5.1 explains the modality of this method. The first significant voltage level is selected as being the first one giving a result different from the preceeding series. Only this one and the following ones are taken under consideration in the calculations. These so called "significant tests" should be made at voltage U_k, k being the index of the voltage levels, the first one corresponding to k=0 is U_o. The estimation proposed by Dixon and Mood/150/consists in forming n_k^o and n_k^1 (the total number of withstands and breakdowns at each voltage level U_k), calculating,

$N_o = \sum_k n_k^o$ and

$N_1 = \sum_k n_k^1$ and then working with only the

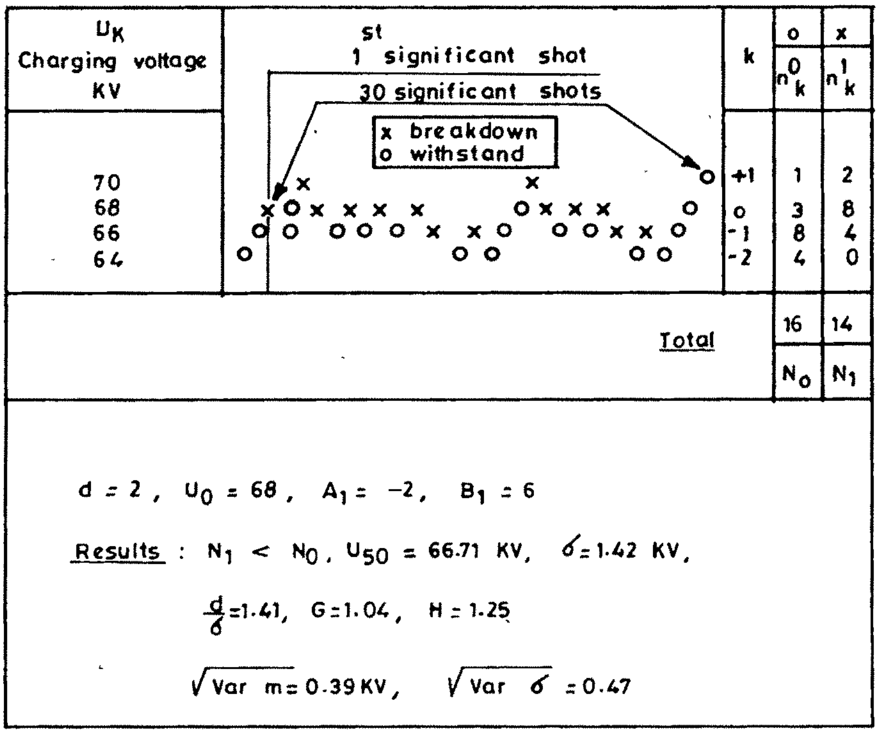


Figure. 5·1 Typical example of 30 shots applied according to the modalities of the "Up and Down" method (ref. 149).

n_k^o or n_k^1 values giving the smaller of N_o and N_1.

The estimates of U_{50}, sigma and their standard errors are given by the formulas: ("$\wedge$" read as "estimate of"):

If $N_1 \leq N_o$,

$$\hat{U}_{50} = U_o + d \times \left[\frac{A_1}{N_1} - \frac{1}{2} \right] \qquad \text{..........} \qquad (5.1)$$

$$\hat{\sigma} = 1.620 \times d \left[\frac{N_1 \times B_1 - A_1^2}{N_1^2} + 0.029 \right] \qquad \text{........} \qquad (5.2)$$

with

$$A_1 = \sum_K k \, n_k^1$$

$$B_1 = \sum_K k^2 \, n_k^1$$

$$\sqrt{Var\ (U_{50})} = G \times \hat{\sigma} / \sqrt{N_1} \qquad \text{........} \qquad (5.3)$$

$$\sqrt{Var\ (\sigma)} = H \times \hat{\sigma} / \sqrt{N_1} \qquad \text{........} \qquad (5.4)$$

If $N_0 < N_1$,

$$\hat{U}_{50} = U_o + d \times \left[\frac{A_o}{N_o} + \frac{1}{2} \right] \qquad \text{........} \qquad (5.5)$$

$$\hat{\sigma} = 1.620 \times d \left[\frac{N_o \times B_o - A_o^2}{N_o^2} + 0.029 \right] \qquad \text{.......} \qquad (5.6)$$

with $A_o = \sum_k k \, n_k^o$

$B_o = \sum_K K^2 n_k^o$

$$\sqrt{Var\ (U_{50})} = G \times \hat{\sigma} / \sqrt{N_o} \qquad \text{.......} \qquad (5.7)$$

$$\sqrt{Var\ (\hat{\sigma})} = H \times \hat{\sigma} / \sqrt{N_o} \qquad \text{.......} \qquad (5.8)$$

G and H can be derived from Figure 5.2

In practice, with some tens of significant impulses, the

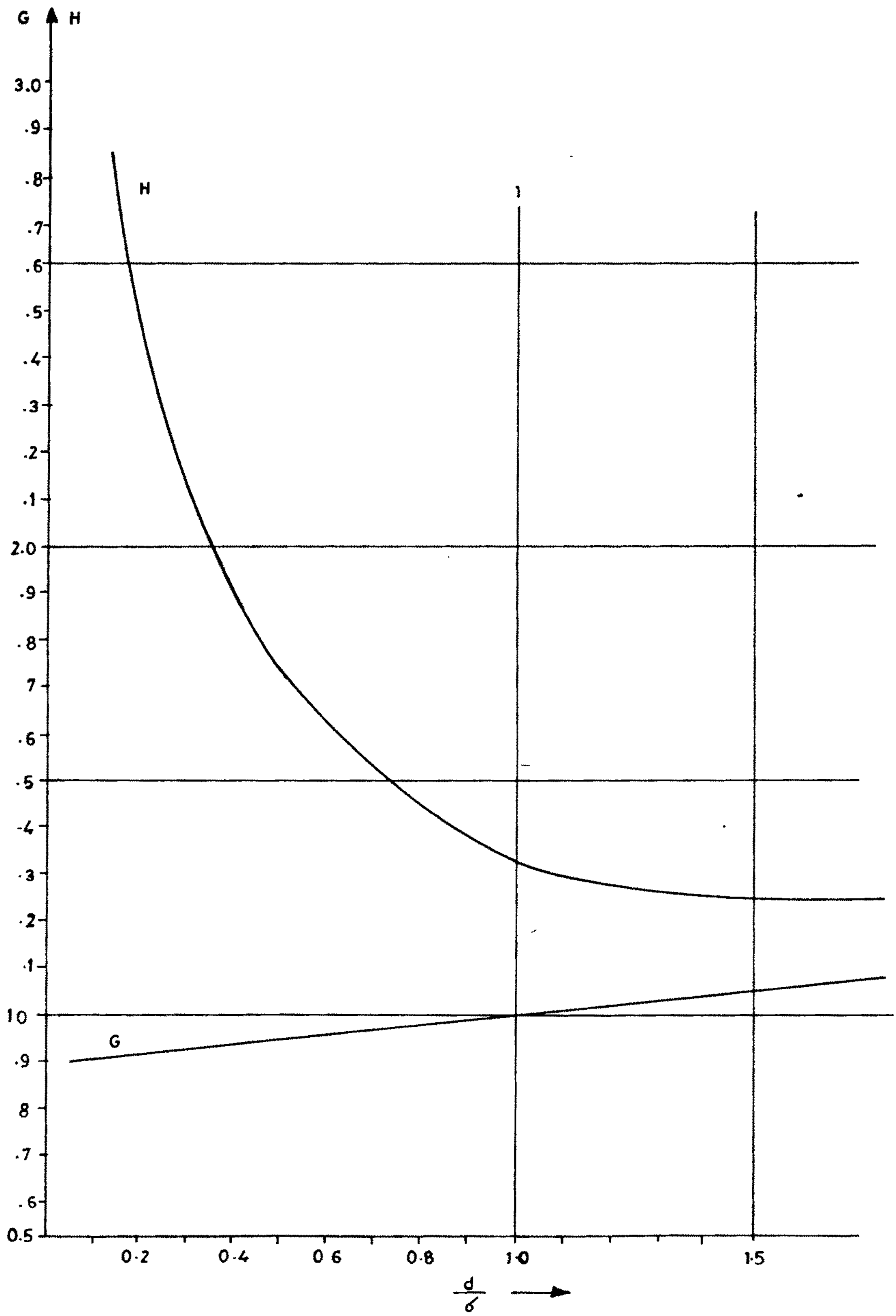


Figure. 5.2 Variation of variance coefficients G and H for the "Up and Down" method (ref. 149).

formulas are only correct if

$$\frac{N_1 \cdot B_1 - A_1^2}{N_1^2} \quad \text{OR} \quad \frac{N_o \cdot B_o - A_o^2}{N_o^2} > 0.3$$

$$\text{And } 0.5 < \frac{d}{\hat{\sigma}} < 1.7 \qquad \text{..........(5.9)}$$

As it can be seen from figure 5.2 it is desirable that the voltage step 'd' should be roughly equal to $\hat{\sigma}$.

These limits are respected if after ten or more significant impulses, the number of U_k values used is 3,4 or 5. Otherwise $d/\hat{\sigma}$ is probably out of the limits specified and must be modified/149/.

5.3 Measurement of critical flashover voltage and sigma

As discussed in the earlier section the aim of this study was to estimate the transferred impulse voltage U_A accurately, and to study the effect of damping resistor and supporting capacitance C_2 on the critical flashover voltage U_{50} of the rod-rod gap and capacitive controlled rod-rod gap. The circuit connection shown in figure 4.1 were used for the measurement of voltage U_{50}. The applied impulse voltage to terminal D of Figure 4.1 was measured using damped capacitive voltage divider (Z). The gap spacing used for this study was not of much importance as the aim was only to study the effect of various elements which are required while conducting bias voltage test for the protection of the high voltage testing transformer from transsient overvoltages on U_{50} and standard deviation sigma.

It has been reported in the literature/151,152/ that in the case of Up and Down method 95% confidence limit of U_{50} can be easily obtained when number of applied impulses are more than or equal to 30. Hence, to get required accuracy of the results for each combination of damping resistance and supporting capacitance fifty impulses at 25 seconds intervals were applied to the test object to derive U_{50} values. The voltage step d (also known as ΔU) for lightning impulses was taken from 2 to 3% of the approximately estimated value of U_{50} and for switching impulses the voltage step was taken from 4 to 6% of the approximately estimated value of U_{50}.

The laboratory conditions and layout of the various equipments shown in Figure 4.1 were maintained more or less same to obtain a set of sufficient results. The atmospheric parameters were recorded at 10 minutes interval. Average value of the atmospheric parameters were taken for applying correction factors k_d and K_h according to IEC publication-60. The measured 50% discharge voltages U_{50} reported in the following sections are corrected to those applicable for standard reference atmosphere by dividing by K_d/K_h. The standard reference atmosphere is:

Temperature	t_o	=	20°C
Pressure	b_o	=	1013 mbar
Humidity	H_o	=	11g water per m^3.

5.3.1 Capacitive controlled rod-rod gap

The layout of the capacitive controlled rod-rod gap is shown in Figure 4.9a. The Up and Down method was used to derive U_{50} and sigma, which is already discussed in detail in section 5.2.

5.3.1.1 Lightning impulse voltage

The complete bias test circuit was arranged according to Figure 4.1. Lightning impulses having a waveshape of 1.38/56 microseconds were applied to the impulse terminal D of Figure 4.1. The power frequency voltage was not applied, i.e. α is equal to 0.0. Fifty impulses were applied to the test object at 25 seconds interval to derive U_{50}.

Figure 5.3 gives voltage U_{50} as a function of damping resistance R for various values of supporting capacitance C_2, the test object capacitance C_1 was 600pF. Figure 5.4 gives the same results when test object capacitance C_1 is 1200pF (only one electrode gap shown in Figure 4.9a was used for C_1= 1200pF, the open gap spacing of rod-rod gap was 550mm). For both the cases U_{50} increases with the increase in the value of damping resistance and it decreases with the increase in the value of supporting capacitance C_2. To highlight this phenomena more effectively, percentage increase in U_{50} with respect to damping resistance is calculated, the results are given in Figure 5.5 for the test object capacitance equal to 600pF. The percentage increase of U_{50} in case of lightning impulse (LI) voltage is as high as 23% when a damping resistance of 8.56Kilo Ohms is connected between the terminals of the test object and the supporting capacitance (for C_2 equal to 19800pF). Since the curves are nonlinear, it is difficult to say what happ-

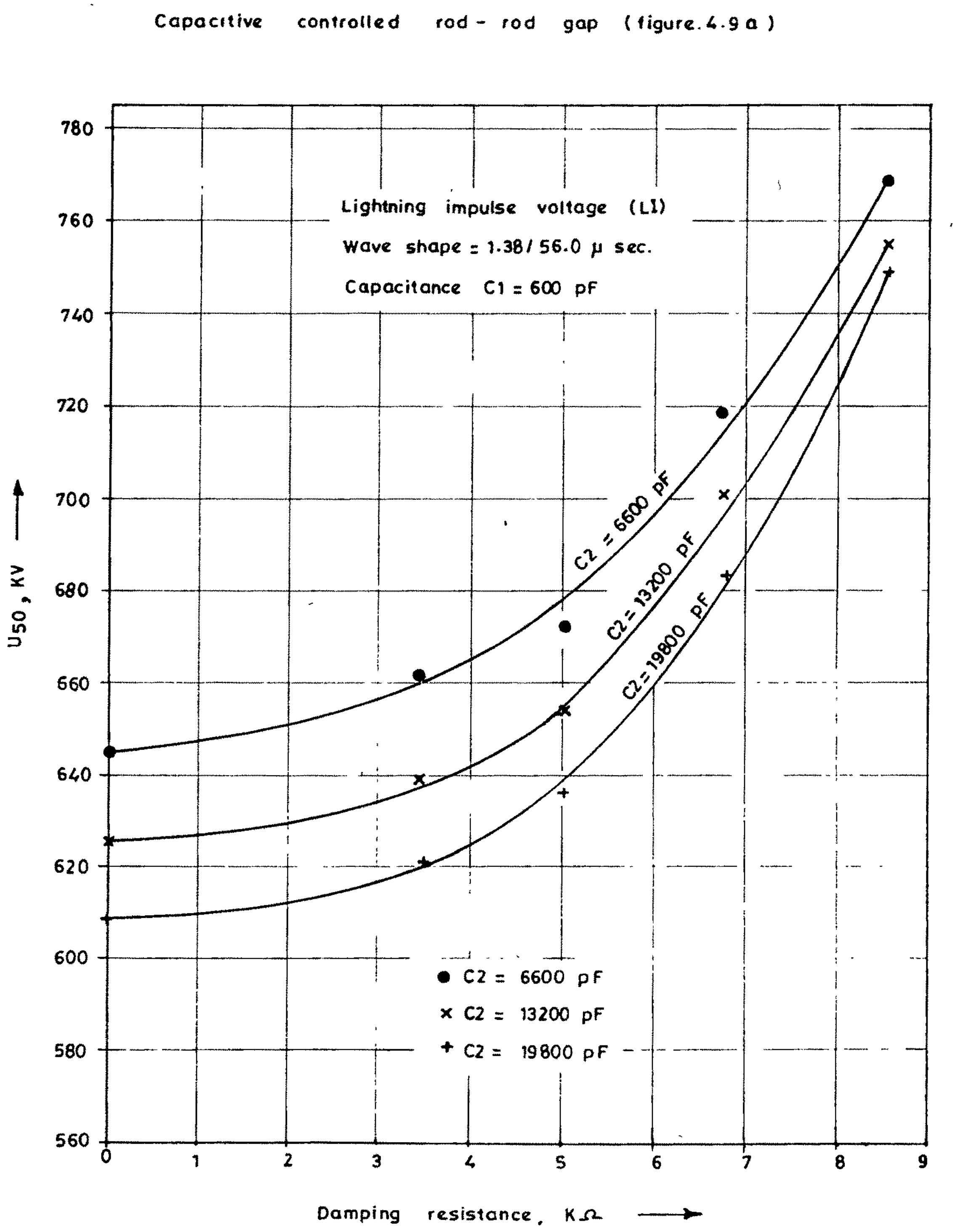


Figure. 5.3 U_{50} (LI) as a function of damping resistance, C_1 = 600 pF.

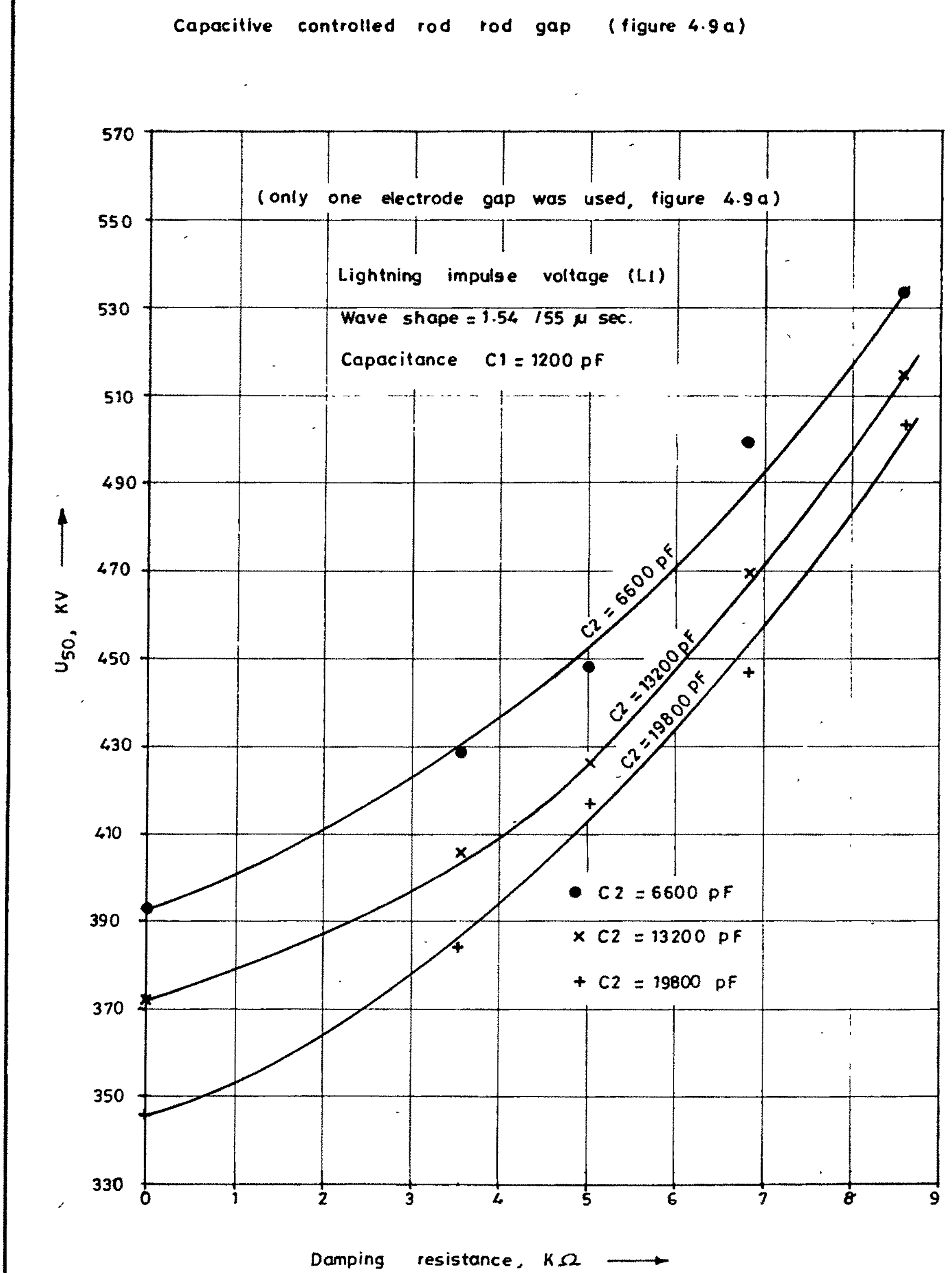


Figure. 5.4 U_{50} (LI) as a function of damping resistance, $C_1 = 1200$ pF.

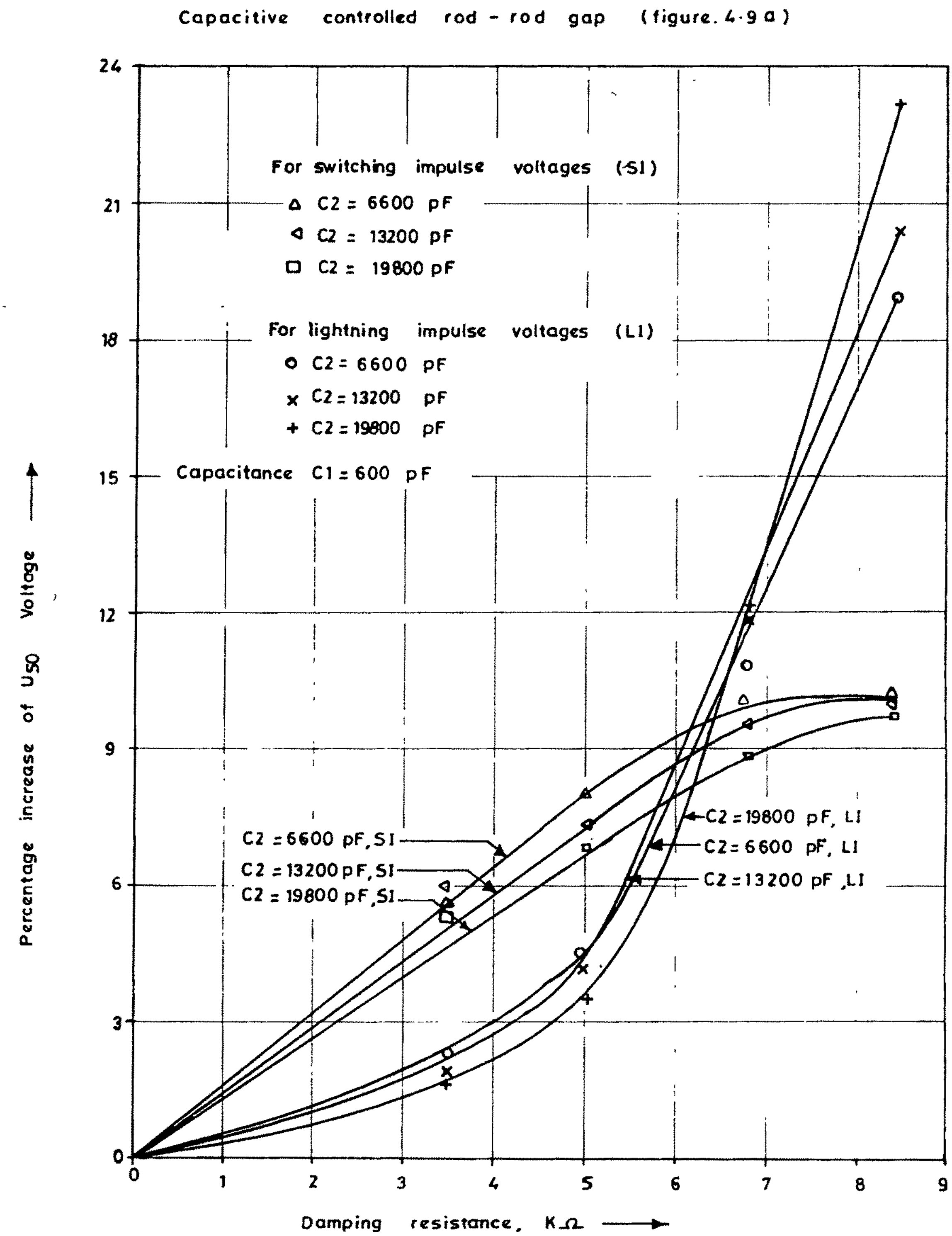


Figure. 5·5 Percentage increase of U_{50} voltage (LI and SI) as a function of damping resistance, C_1 =600 pF ens when the value of damping resistance R is large. Ofcourse one can get an idea about the error introduced in deriving the actual critical flashover voltage or withstand voltage of the test object by not connecting the supporting capacitance C_2 directly at the terminal of the test object.

5.3.1.2 Switching impulse voltage

The same capacitive controlled rod-rod gap shown in Figure 4.9a was used to derive U_{50} for various values of damping resistance and supporting capacitance C_2. Switching impulse wave shape was 250/2750 microseconds. Fifty impulses were applied for each case at 25 seconds interval. The atmospheric parameters were recorded at 10 minutes intervals.

Figure 5.6 gives U_{50} as a function of damping resistance for various values of supporting capacitance C_2 for test object capacitance equal to 600pF. The increase in U_{50} is nonlinear with the increase in damping resistance R. The curves obtained for three different values of supporting capacitance C_2 are parabolic and parallel to each other. Figure 5.7 gives the same results for test object capacitance equal to 1200pF. The switching impulse voltage wave shape for C_1=1200pF was 259/2700 microseconds. The percentage increase of U_{50} with increase in damping resistance is shown in Figure 5.5 for C_1= 600pF. The percentage increase in U_{50} for three values of supporting capacitances 6600pF, 13,200pF and 19,800pF is nearly same for a given value of damping resistance. The increase in U_{50} is appro-

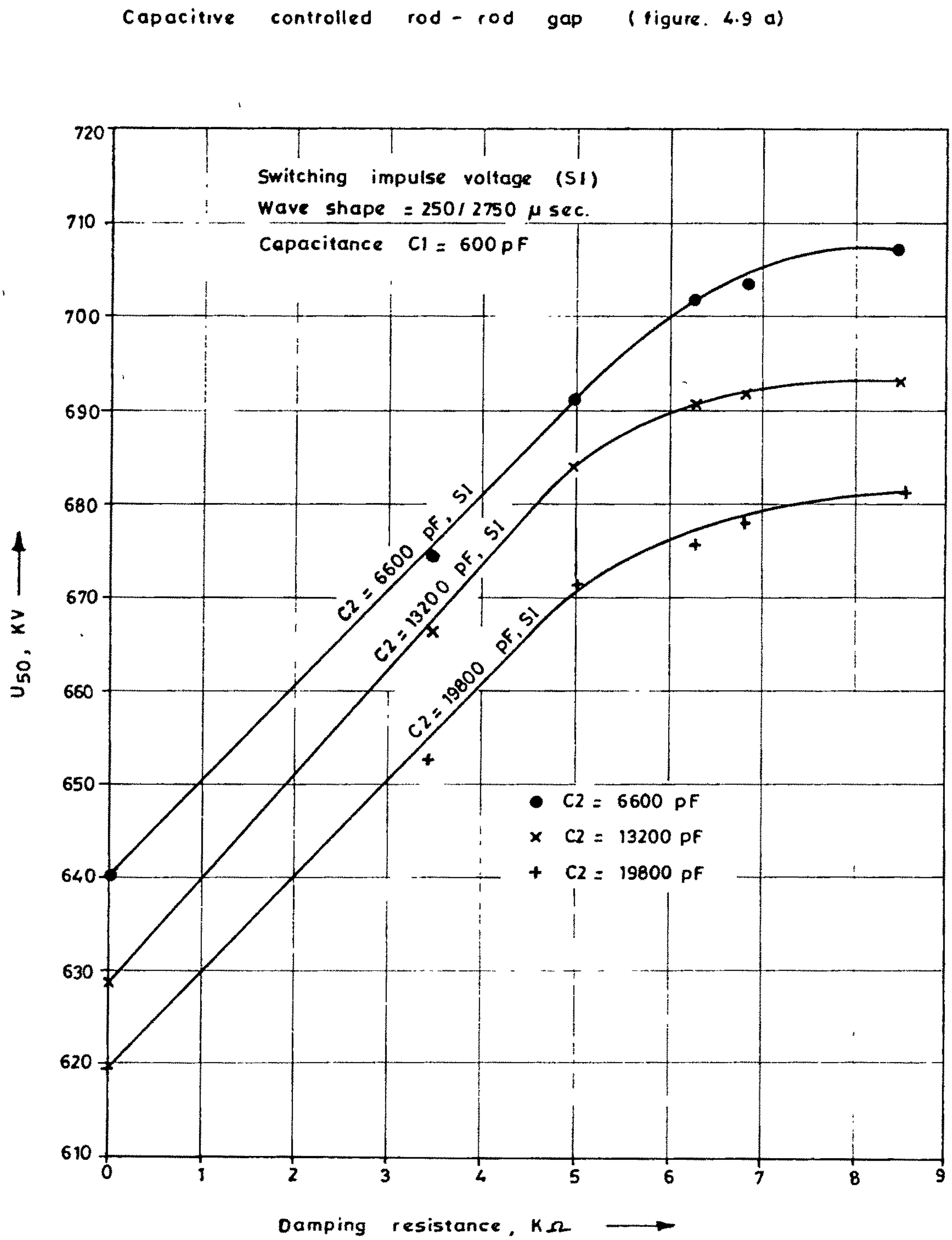


Figure. 5.6 U_{50}(SI) as a function of damping resistance, $C_1 = 600$ pF.

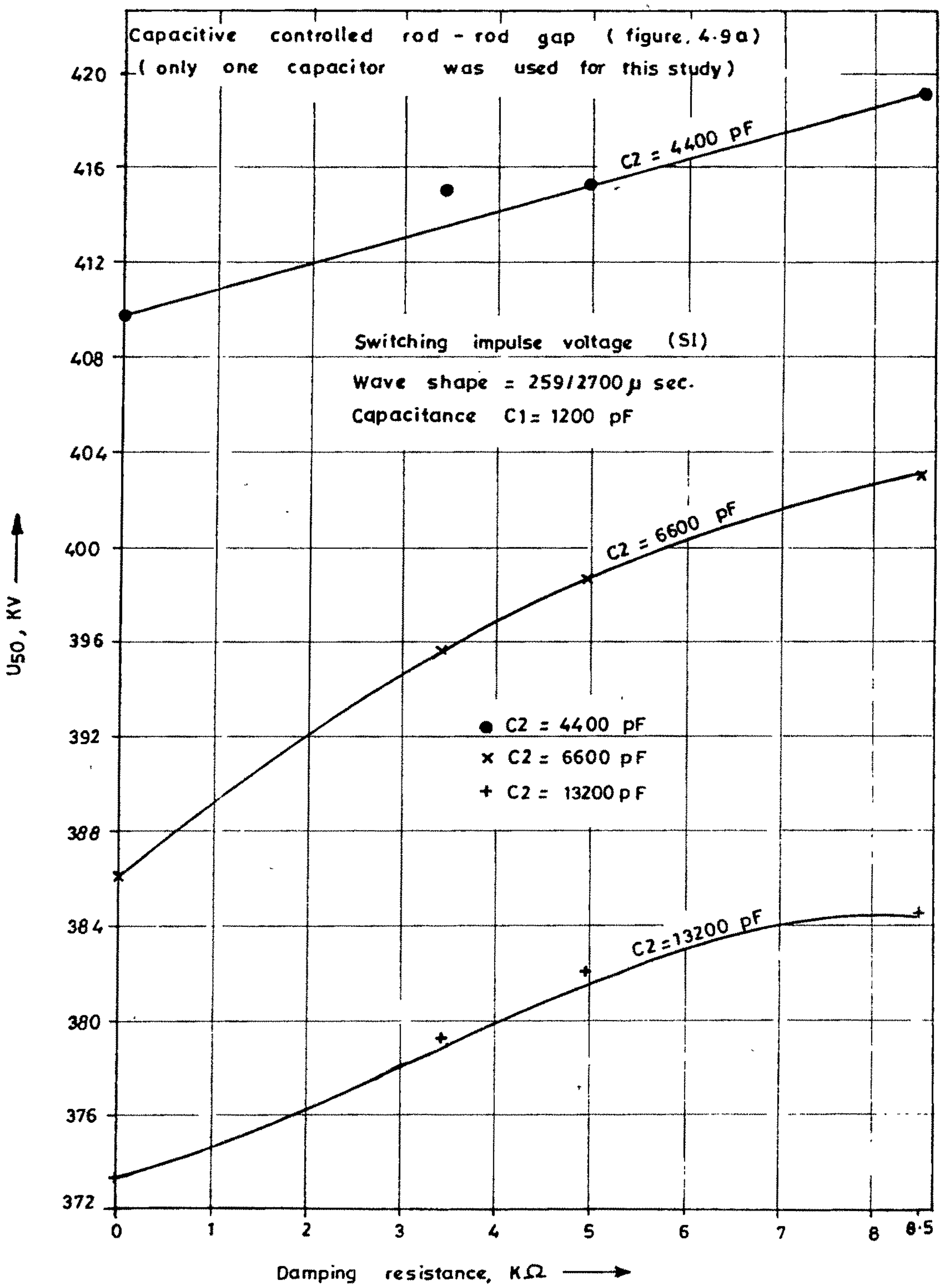


Figure. 5.7 U_{50}(SI) as a function of damping resistance, C_1= 1200 pF.

ximately 10% when damping resistance of 8.56 Kilo Ohms is connected between the terminals of the test object and the supporting capacitance C_2. This is approximately 2.3 times less compared to the case when lightning impulse voltage is applied. As seen from Figure 5.5, the percentage increase in U_{50} for damping resistance greater than 7 Kilo Ohms is very small. Almost a saturation has reached for damping resistance R equal to 7.0 Kilo Ohms, i.e. further increase in damping resistance does not lead to increase in U_{50}. However, it might be necessary to verify the characteristics of the curves for damping resistance greater than 8.56 Kilo Ohms. Since maximum available value of high voltage damping resistance was only 8.56 Kilo Ohms, further tests could not be conducted.

5.3.2 Rod-rod gap

5.3.2.1 Lightning impulse voltage

The electrode arrangement shown in Figure 4.9b was used to derive U_{50} of rod-rod gap having an open gap spacing of 770mm. The wave shape of the lightning impulse voltage was 1.08/47.0 microseconds. Fifty impulses were applied to the electrode system at 25 seconds interval to obtain U_{50} for each test set up conditions. The voltage step was equal to 3% of the estimated U_{50} voltage. Figure 5.8 gives U_{50} voltage as a function of damping resistance for various values of supporting capacitance. The curves are more or less linear, i.e. the value of U_{50} increases linearly with the increase in damping resistance. Many times it was also

Rod - Rod gap Configuration (figure. 4·9b)

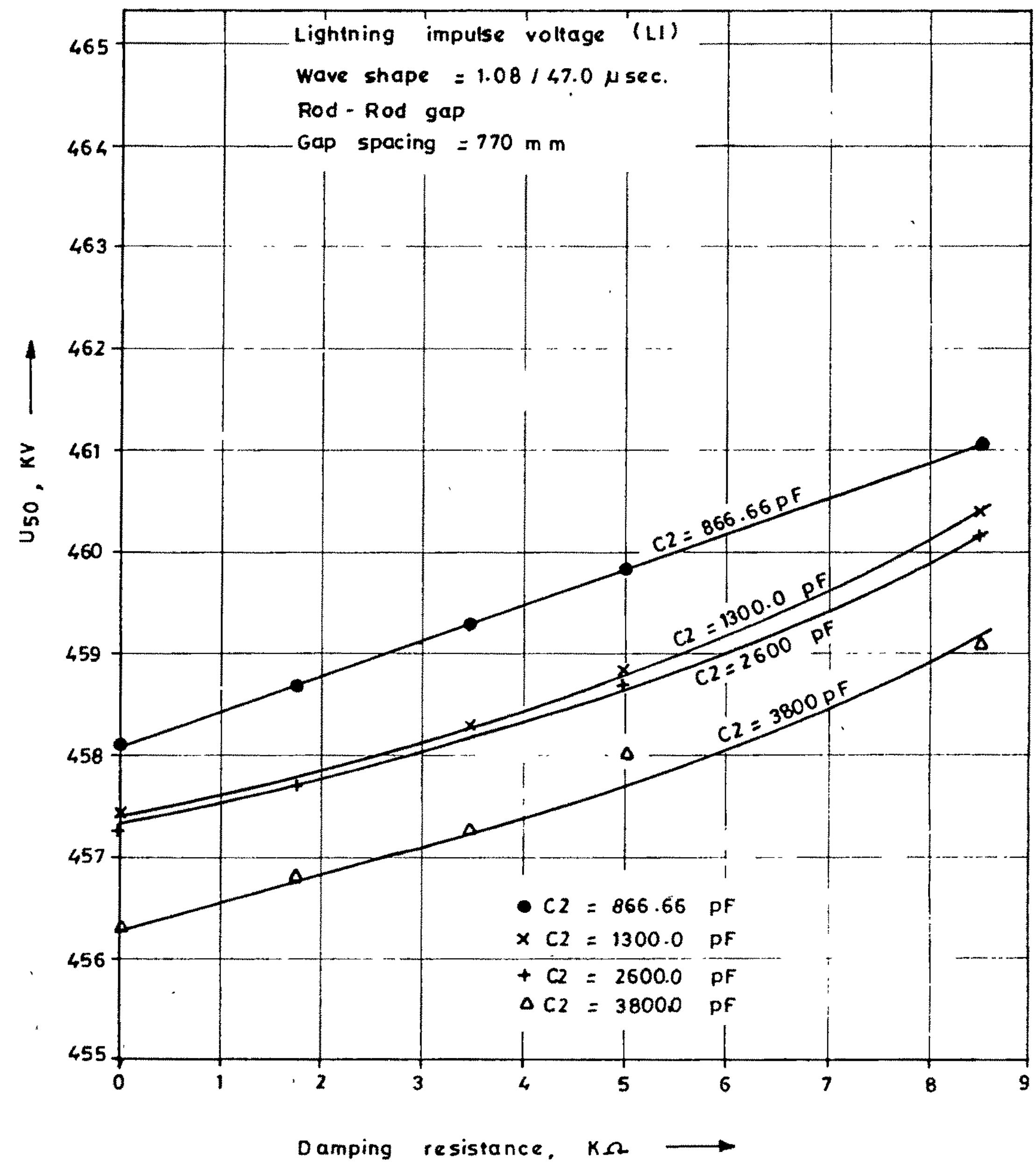


Figure. 5·8 U_{50} (LI) as a function of damping resistance, rod- rod gap.

observed that U_{50} for higher value of damping resistance is lower than that obtained for lower value of damping resistance (the difference was within ±1.5 to $\pm$ 3.0kV), theoretically this is not correct and hence many times the test had to be repeated even three to four times to get the correct value of U_{50} i.e. the value of U_{50} should be higher for higher value of damping resistance or it should be atleast equal but not less. This difference may be because of the statistical variation of U_{50}. It is worthwhile mentioning here that, when the test was conducted for various values of supporting capacitance C_2 and damping resistance R, the atmospheric parameters were not same because of change in day and time. Hence, this phenomena may be also attributed to the variations in the correction factors K_d and K_h given by IEC publication-60.

Figure 5.9 gives the percentage increase of U_{50} as a function of damping resistance. The percentage increase in U_{50} is maximum 0.7 per cent when damping resistance of 8.56 kilo ohms is connected between the terminals of the test object and the supporting capacitance. This is negligible compared to the case of capacitive controlled rod-rod gap. Hence, it may be concluded that in the case of disconnector type open gaps, (which represents rod-rod gap) the placement of a damping resistance in the bias test circuit is not important. It may be connected between the terminals of the disconnector and the supporting capacitance C_2, so that the severity of the chopped wave is not dangerous for the winding insulation of High Voltage power frequency

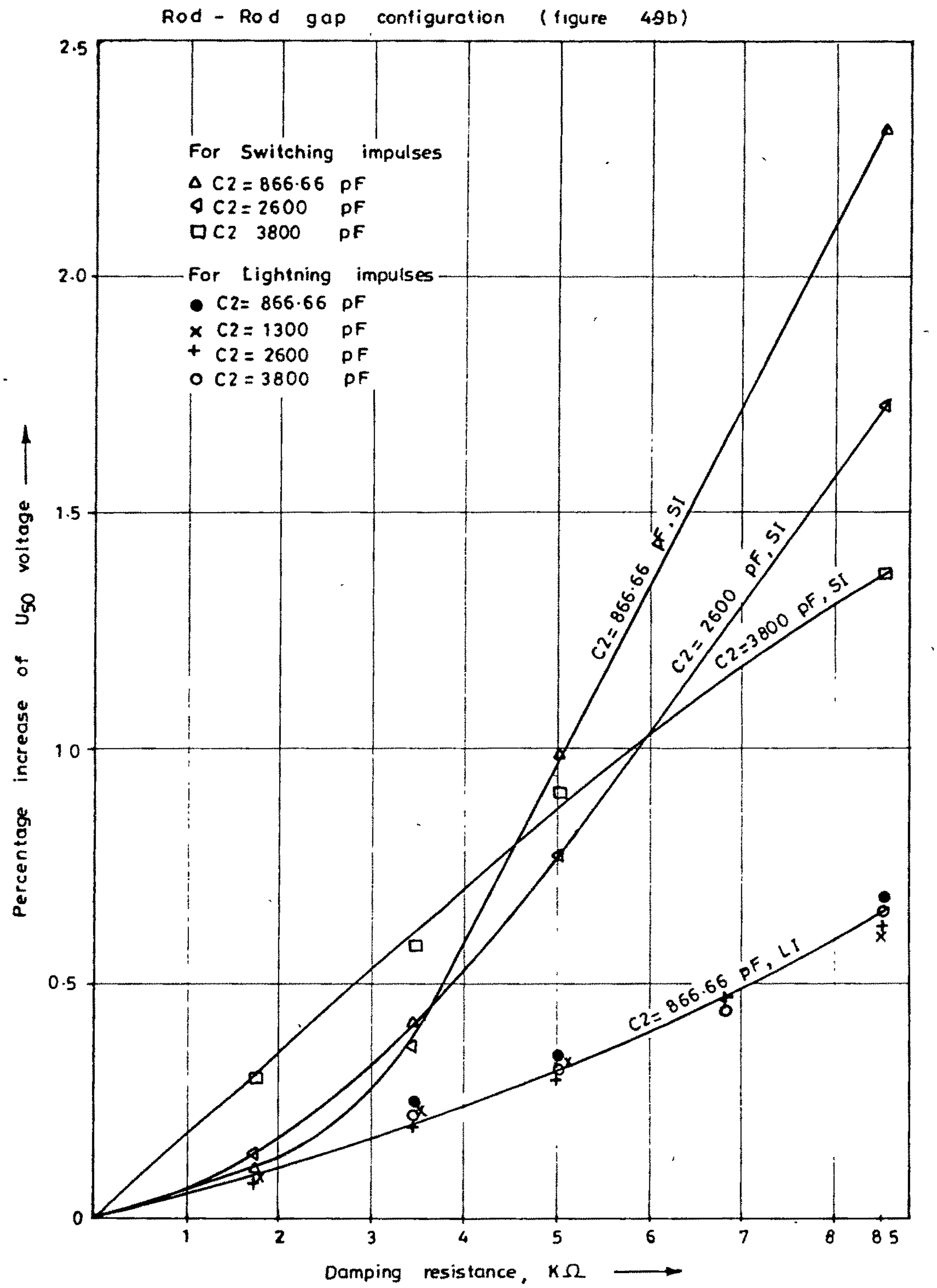


Figure. 5·9 Percentage increase of U_{50} voltage (LI and SI) for rod-rod gap as a function of damping resistance.

test transformer.

5.3.2.2 Switching impulse voltage

The same electrode configuration, shown in Figure 4.9b, was used to derive U_{50} of rod-rod gap but having an open gap spacing of 500mm. The open gap had to be reduced from 770mm to 500mm because of flashovers occuring from live electrode to earth while deriving 50% discharge voltage U_{50}. It was decided to reduce the open gap clearance instead of increasing the height of the horizontal rod-rod gap electrode configuration to prevent flashovers to earth. The switching impulse voltage waveshape was 238/2655 microseconds. Fifty impulses were applied at 25 seconds interval to the impulse terminal D of Figure 4.1 at voltage step ΔU equal to sigma (i.e. 6% in case of switching impulses). Figure 5.10 gives U_{50} voltage as a function of damping resistance for various values of supporting capacitance. The difficulty which was encountered in the measurement of U_{50} voltage in case of lightning impulse voltage was also noticed in the case of switching impulses and hence the test had to be repeated for certain values of damping resistance and capacitance C_2. The percentage increase of U_{50} voltage is given in Figure 5.9. The percentage increase in U_{50} is between 1.3 and 2.3 per cent when damping resistance of 8.56 kilo Ohms is connected between the test object terminal and the supporting capacitance C_2 ranging from 866.66pF to 3800pF. The conclusion drawn in case of lightning impulse voltage is also valid for switching impulses, and hence in this case also one can connect the damping resistor between the test object ter-

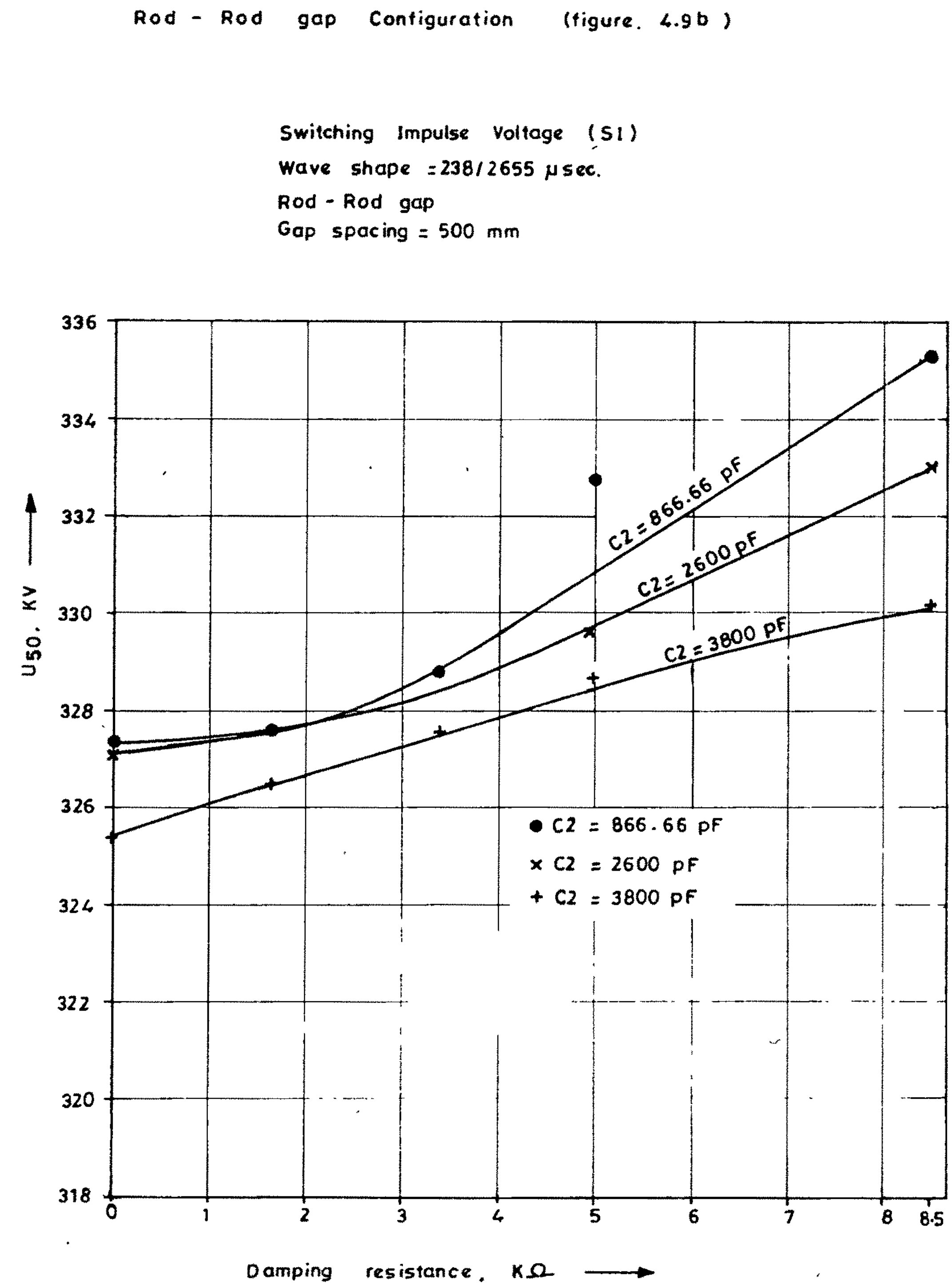


Figure. 5.10 U_{50} (SI) as a function of damping resistance, rod – rod gap.

minal and the supporting capacitance C_2.

5.4 Comparison of measured and calculated U_{50}

For both the electrode systems, before obtaining U_{50} with supporting capacitor C_2 and/or damping resistance, first U_{50} of only rod-rod gap and capacitive controlled rod-rod gap configuration was obtained by earthing point A (refer Figure 4.1). This gives U_{50} of only the test object gap. In other words, this is the test circuit layout used while conducting the equivalent bias voltage test on the test object, i.e. a sum of two voltage components specified by the relevant standards is applied to one terminal the opposite being earthed. U_{50} voltage was obtained this way and then this value was compared with the U_{50} voltage of the same test object when connected as per circuit given in Figure 4.2, i.e. Bias Test circuit.

5.4.1 Capacitive controlled rod-rod gap

The U_{50} for lightning and switching impulse voltages for capacitive controlled rod-rod gap was obtained by earthing point A (refer Figure 4.1), and also when supporting capacitance C_2 is connected in the circuit (U_{50}*). When supporting capacitor C_2 is connected in the circuit, the part of the voltage U_{50}* appears across the power frequency terminal of the test object and earth. This voltage, U_B, can be calculated using the following formula (damping resistance R = 0.0 Ohms, in this case voltage U_A is same as voltage U_B):

$$U_B = \frac{C_1}{C_1+C_2} \times U_{50}^* \quad .... \quad (5.10)$$

where C_1= test object capacitance in pF, C_2 = supporting capacitance in pF and U_{50}^* is the 50% discharge voltage of the test object when supporting capacitor C_2 is connected. Now U_{50} of only test object (i.e. when terminal 'A' is earthed and α= 0.0) is known, and it should remain more or less same. When supporting capacitor C_2 is connected (without any damping resistor, i.e. in this case the damping resistor may be connected between the supporting capacitance and the terminal of the high voltage testing transformer), the percentage of voltage which will appear at the terminal A or B can be calculated. Based on this U_{50}^* can be derived theoretically as follows:

$$U_{50}^* = \frac{U_{50} \text{ of only gap}}{1 - \frac{C_1}{C_1+C_2}} \quad .... \quad (5.11)$$

$\frac{C_1}{C_1+C_2}$ gives the per unit voltage U_B when an impulse voltage is applied to the impulse terminal D of Figure 4.1. By using this philosophy U_{50}^* voltage was derived theoretically and results are compared. Figure 5.11 gives the calculated U_{50}^* and measured U_{50}^* voltage for lightning and switching impulse voltages (the test object capacitance C_1 was 600pF). It is seen from this figure that the measured value of U_{50}^* is approximately 4.5 per cent more compared to the calculated U_{50}^* for both lightning impulse and switching impulse voltages. Figure 5.12 gives the measured and calculated

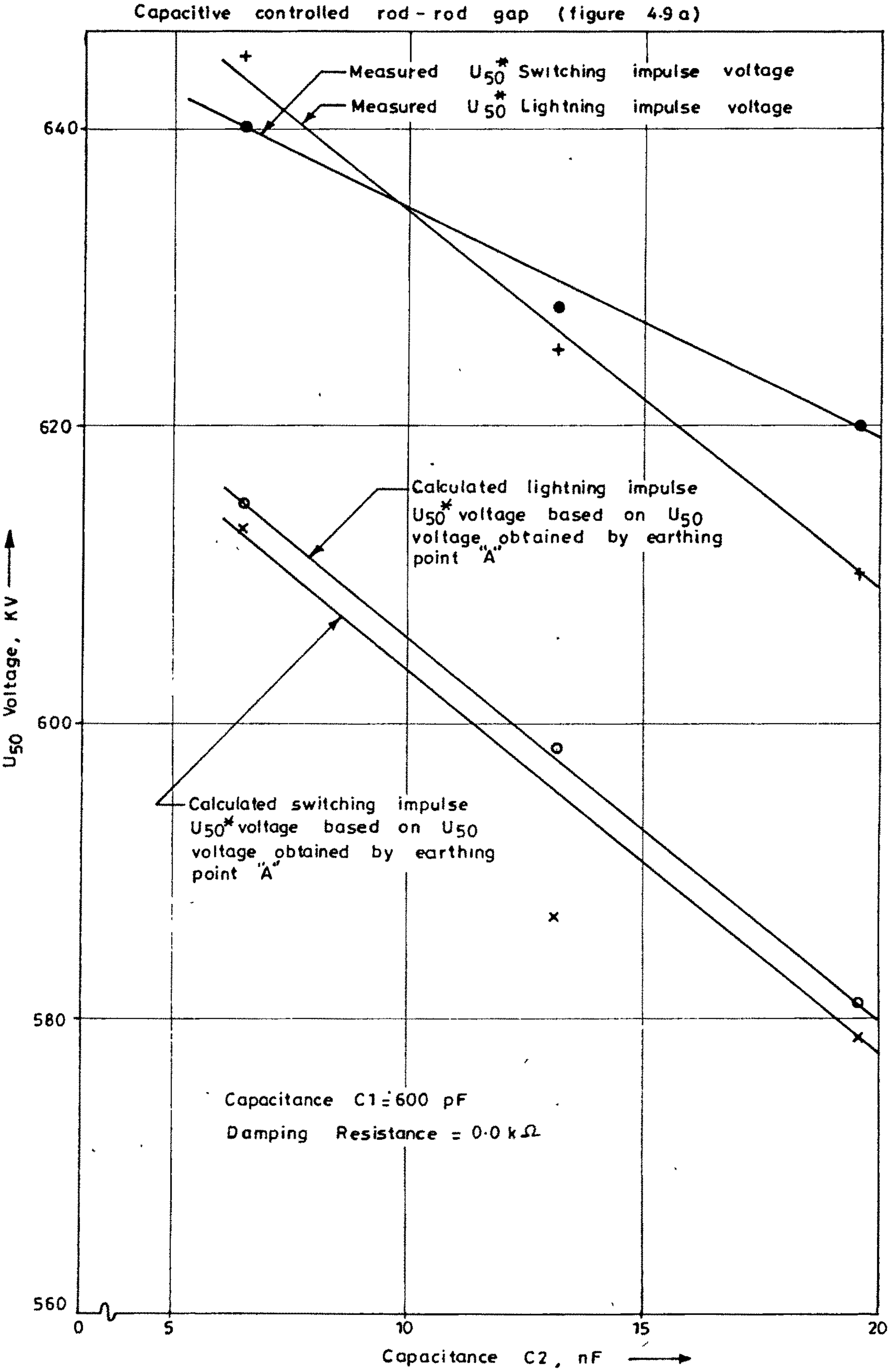


Figure. 5.11 Calculated and measured U_{50} voltage for a capacitive conrolled gap, C_1=600 pF.

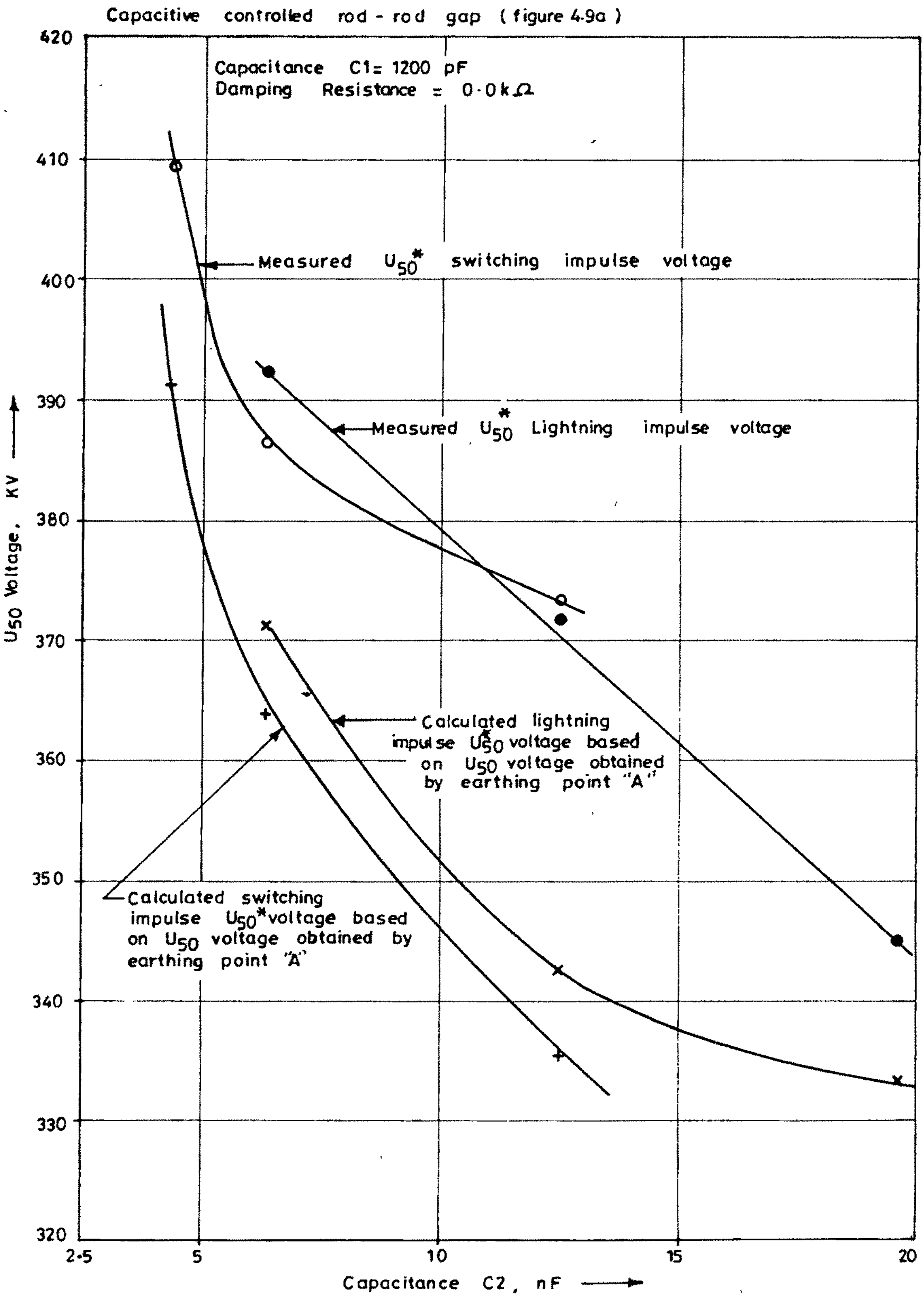


Figure. 5.12 Calculated and measured U_{50} voltage for capacitive controlled gap, $C_1 = 1200$ pF.

U_{50}* voltages when test object capacitance is 1200pF. In this case also the measured values are higher by approximately 4.5 per cent.This difference may be explained as follows:

When terminal 'A' is earthed to obtain U_{50} of only test object gap, then one terminal of the test object is live and other is at earth potential.However, when supporting capacitor C_2 is connected, the other terminal of the test object is earthed through the supporting capacitor C_2. In this case the other terminal of the test object is not directly at earth potential and hence the electrode field configuration is not same compared to the earlier case. This effect may be also because of the stray capacitance. It may be stated that the measured values of U_{50} are accurate.

5.4.2 Rod-rod gap

Figure 5.13 gives the measured and calculated values of U_{50} for various values of supporting capacitance C_2 for rod-rod gap for both lightning and switching impulse voltages. The value of U_{50}* voltage for various values of supporting capacitance C_2 was calculated using formula (5.11). The capacitance between two rods was of the order of 11.5pF. For lightning impulse voltages the measured values of U_{50}* are approximately 3.8 per cent higher and for switching impulse voltage the measured values of U_{50}* are approximately 6.5 per cent higher. The percentage difference between measured and calculated U_{50}* remains approximately same irrespective of the value of the supporting capacitance C_2 for both lightning and switching impulse voltages.

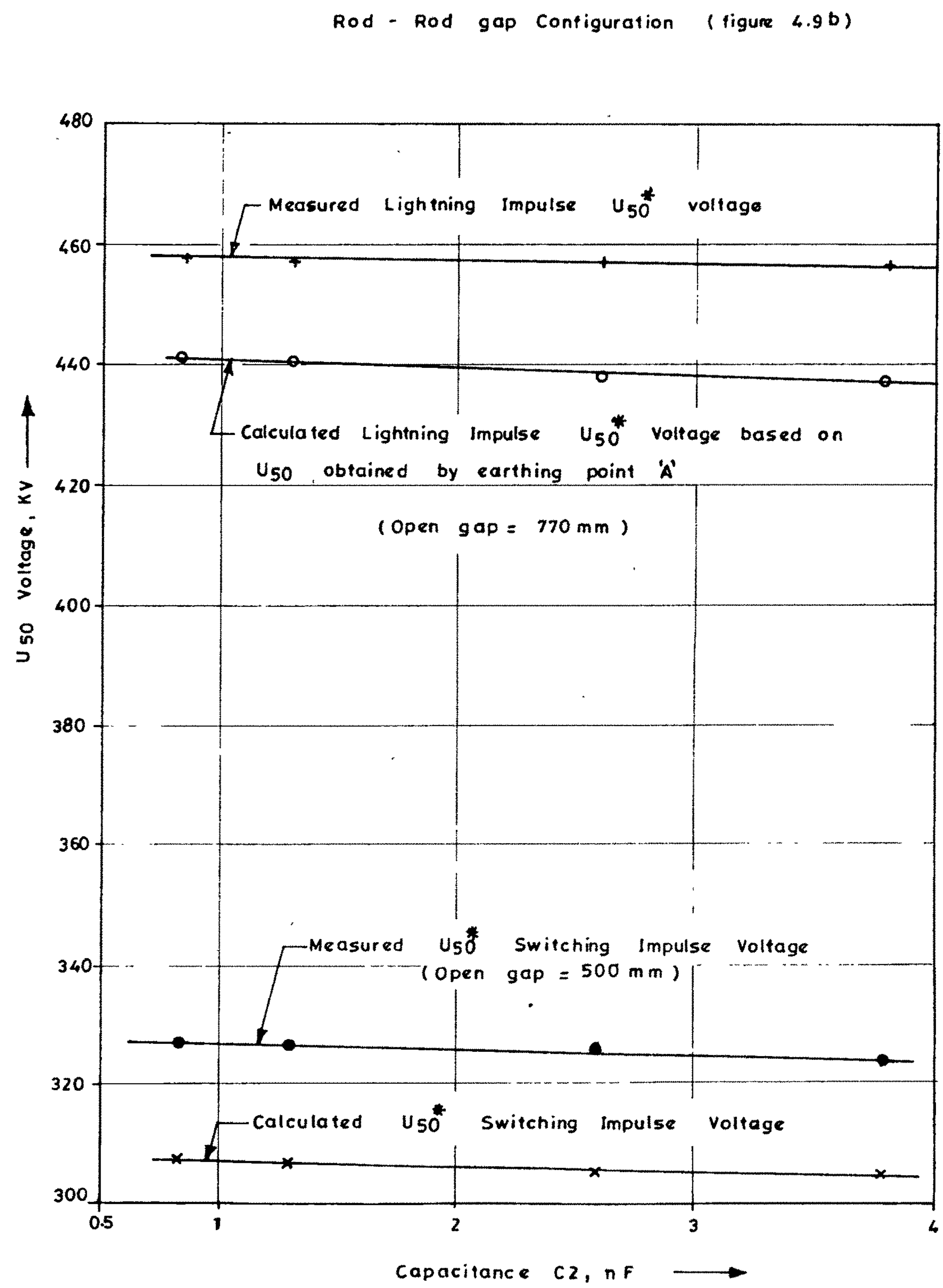


Figure. 5.13 Calculated and measured U_{50} Voltage for horizontal Rod - Rod gap.

5.5 Comparison of measured and calculated transferred impulse voltage U_A

In Chapter-4, the method of measurement of transferred impulse voltages U_A and U_B have been discussed in detail. To verify the accuracy of the measured voltage U_A, indirect approach was adopted for both types of electrode configurations shown in Figure 4.9. The accuracy of the measured value is compared with the calculated value in the following sections.

5.5.1 Capacitive controlled rod-rod gap

5.5.1.1 Lightning impulse voltage:

Figure 5.14 gives the percentage of measured lightning impulse transferred voltage U_A as a function of damping resistance obtained for various values of the supporting capacitance C_2 for capacitive controlled rod-rod gap. This voltage was measured using damped capacitive voltage divider as well as resistive voltage divider for both lightning and switching impulse voltages. The magnitude of voltage U_A does not decrease with the increase in supporting capacitance C_2 (for a given value of damping resistance R) theoretically this is not correct, the voltage U_A should have decreased with the increase in supporting capacitance C_2. However, because of the measurement difficulty the voltage U_A remained the same on account of the divider capacitance and/or stray capacitance to earth.

On account of the above mentioned difficulty in the meas-

Capacitive controlled rod - rod gap (figure - 4.9a)

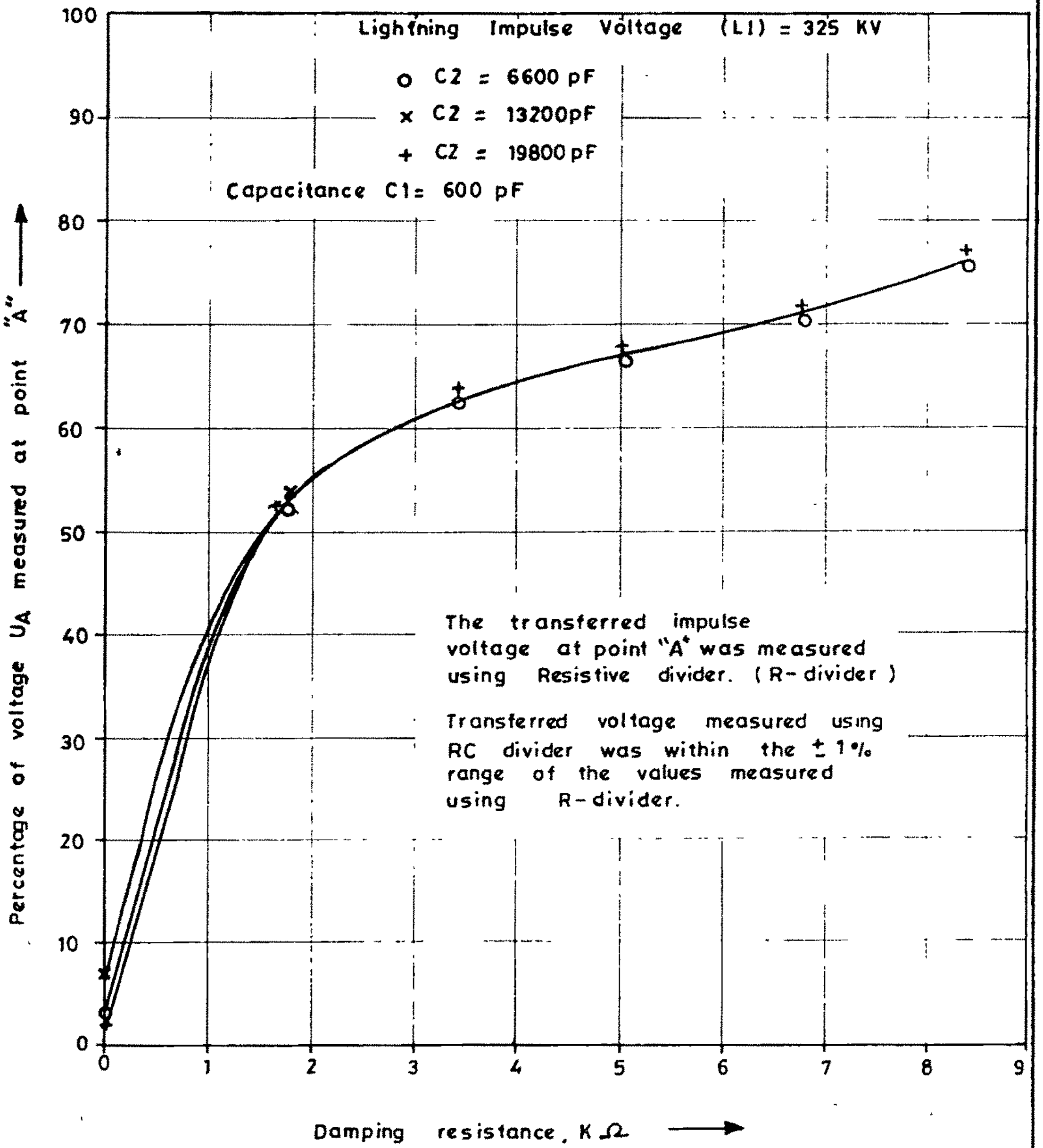


Figure. 5.14 Variation of transferred voltage U_A (LI) as a function of damping resistance, $C_1 = 600$ pF.

urement of the transferred impulse voltage U_A, indirectly the voltage U_A was calculated based on U_{50} voltage obtained for various combinations of supporting capacitance C_2 and the damping resistance. For damping resistance equal to zero Ohms, the percentage of the transferred impulse voltage at point A or B can be calculated as follows:

$$\text{Percentage of transferred impulse voltage } U_B = \frac{C_1}{C_1+C_2+C_{cvd}} \times 100\% \qquad \text{.........(5.12)}$$

Where C_1 = Test object capacitance in pF

C_2 = Supporting capacitance in pF

C_{cvd} = Divider Capacitance in pF

For a given value of supporting capacitance C_2 (R=0.0 Ohms) the U_{50} value of the test object is known. It is observed that when damping resistance is connected between the test object terminal and the supporting capacitance C_2, the U_{50} increases. Theoretically this increase in U_{50} with resistance is on account of the different voltage distribution across the test object capacitance C_1, and the series combination of damping resistance and the supporting capacitance. Hence the difference in U_{50} with and without damping resistance plus the transferred impulse voltage given by equation (5.12) should be the voltage of point A, i.e. voltage U_A when damping resistance is connected between the terminals of the test object and the supporting capacitance.

Figure 5.15 gives the percentage of lightning impulse transferred voltage U_A calculated based on U_{50} voltages for

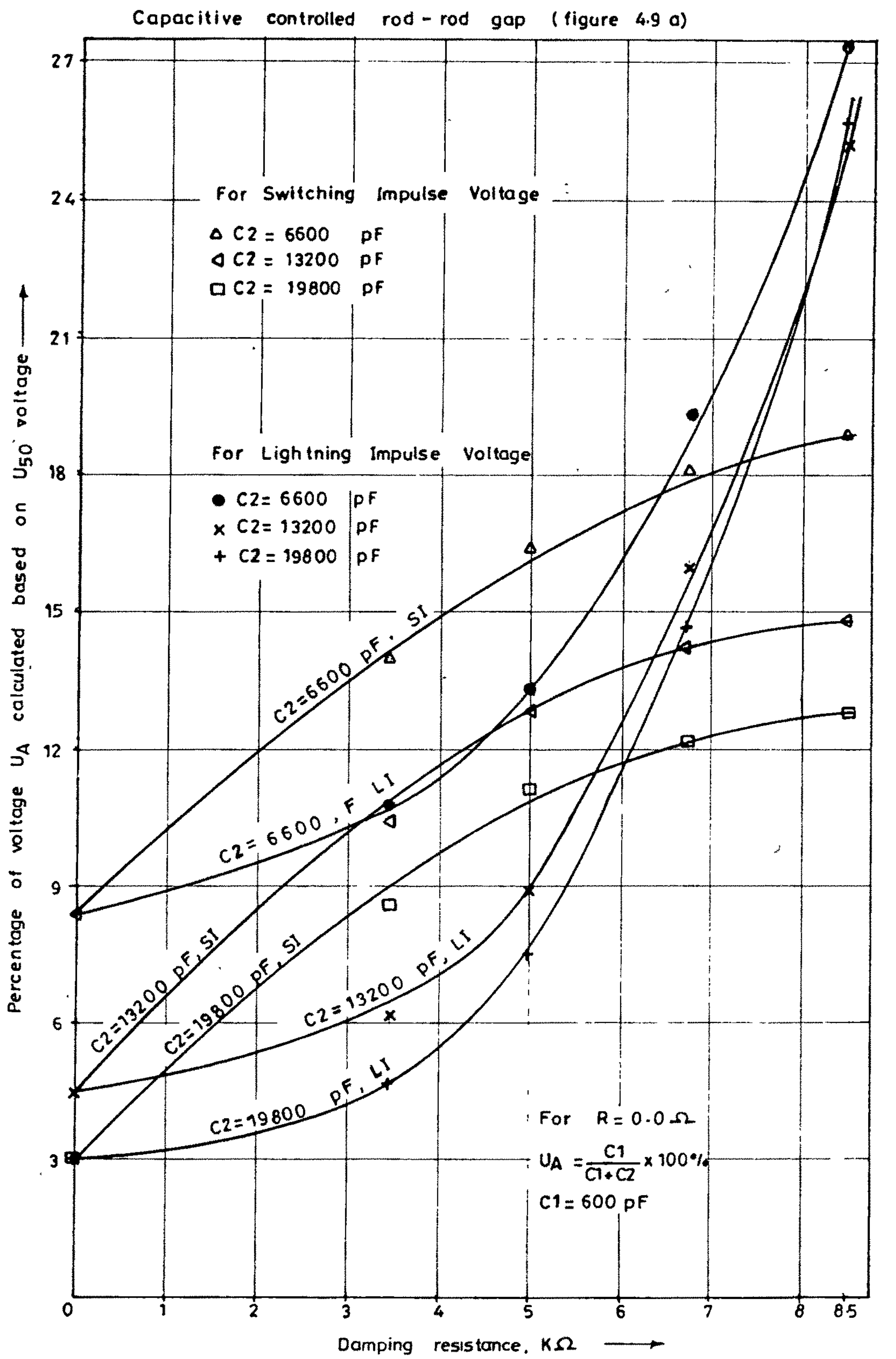


Figure. 5.15 Variaition of transferred voltage U_A calculated based on U_{50} as a function of damping resistance, $C_1 = 600$ pF

various values of damping resistance and supporting capacitance. The calculated voltage U_A increases with the increase in damping resistance and decreases with the increase in supporting capacitance. The percentage increase of lightning impulse transferred voltage at point A is of the order of 19.0 to 22.6% when damping resistance of 8.56Kilo Ohms is connected. The percentage rate of increase of voltage at point A is much high with the increase in damping resistance. It may be concluded that for lightning impulse bias testing, it is incorrect to connect the damping resistor between the terminals of the circuit breaker and the supporting capacitance C_2.

5.5.1.2 Switching impulse voltage

Figure 5.16 gives the percentage of switching impulse transferred voltage U_A measured at point 'A' using damped capacitive voltage divider as a function of damping resistance R for various values of C_2. The results obtained are little better than the case of lightning impulse voltage. In figure 5.15 the calculated percentage of switching impulse transferred voltage U_A for various values of damping resistance R and capacitance C_2 is also given.

It is seen from the results reported in Figure 5.15 and 5.16 that for supporting capacitance of 6600pF, the calculated and measured values of voltage U_A compare very well. However, with the increase in supporting capacitance C_2 the difference in the measured and calculated values of voltage U_A increases with the increase in damping resist-

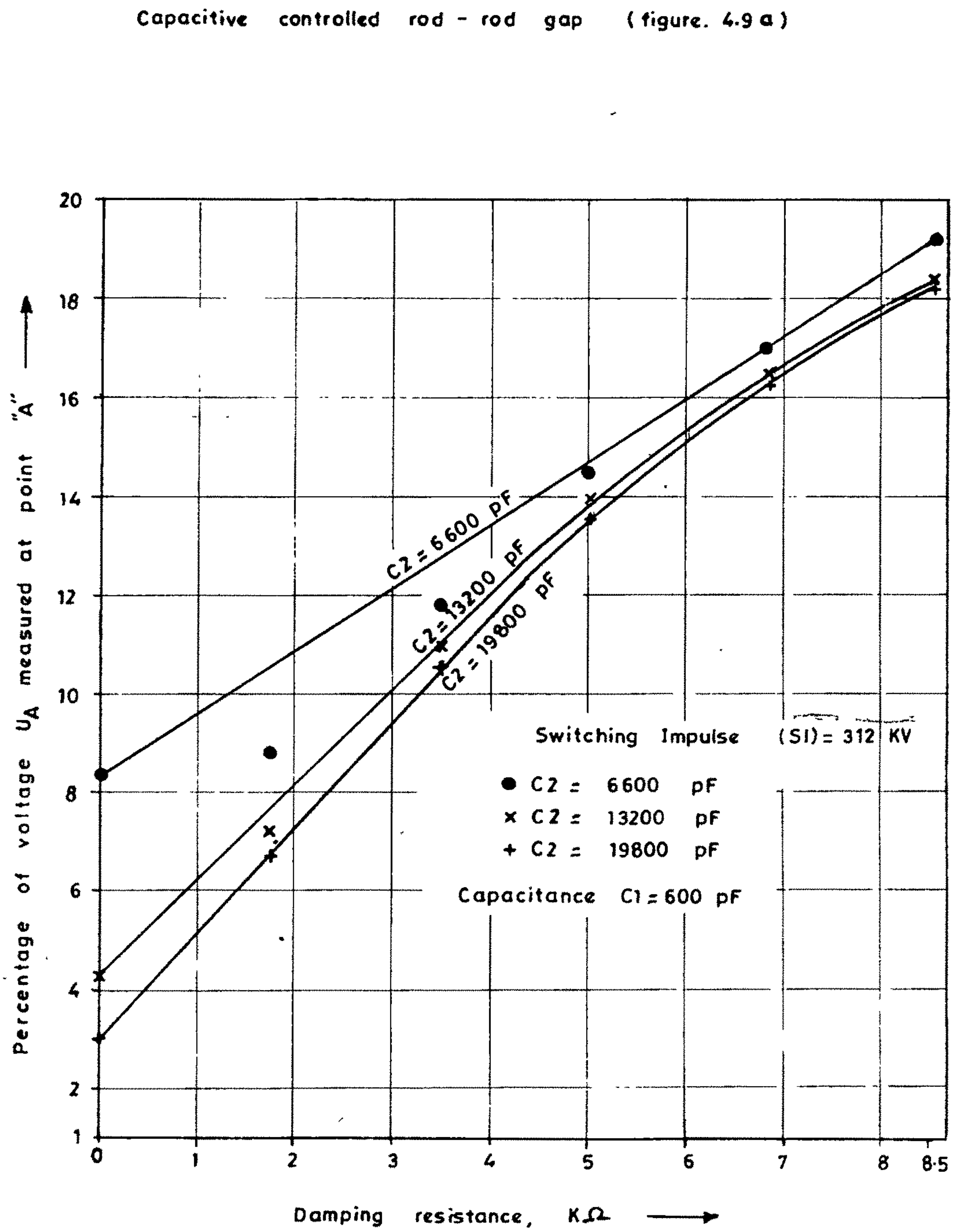


Figure. 5.16 Variation of transferred voltage U_A (SI) as a function of damping resistance, C_1 = 600 pF.

ance. The measured value of switching impulse transferred voltage U_A when damping resistance of 8.56 Kilo Ohms is connected is approximately 0.7, 3.6 and 5.4% higher compared to calculated value when supporting capacitance is equal to 6600 pF, 13200 pF and 19800 pF respectively.

As discussed earlier, when divider is connected at terminal A to measure voltage U_A, the circuit configuration is changing and also while measuring lightning impulse transferred voltage U_A(refer figure 5.14) un-usual relationship between measured voltage U_A with damping resistance is observed. For measuring U_{50} values no element was connected in the circuit at terminal A. Hence, the difference between the measured and calculated voltage U_A is on account of the error in the measurement of voltage U_A. This measuring error is much lower as compared to the measuring error observed in the measurement of lightning impulse transferred voltage U_A.

5.5.2 Rod-rod gap

5.5.2.1 Lightning impulse voltage

Figure 5.17 gives a set of curves of the percentage of lightning impulse transferred voltage U_A as a function of damping resistance for various values of supporting capacitance. With the increase in damping resistance R, the voltage U_A is increasing and it decreases with the increase in supporting capacitance. The curves for various values of supporting capacitance C_2 are parallel to each other, but the percentage increase in voltage U_A is not linear with the increase in damping resistance. Figure 5.18 gives

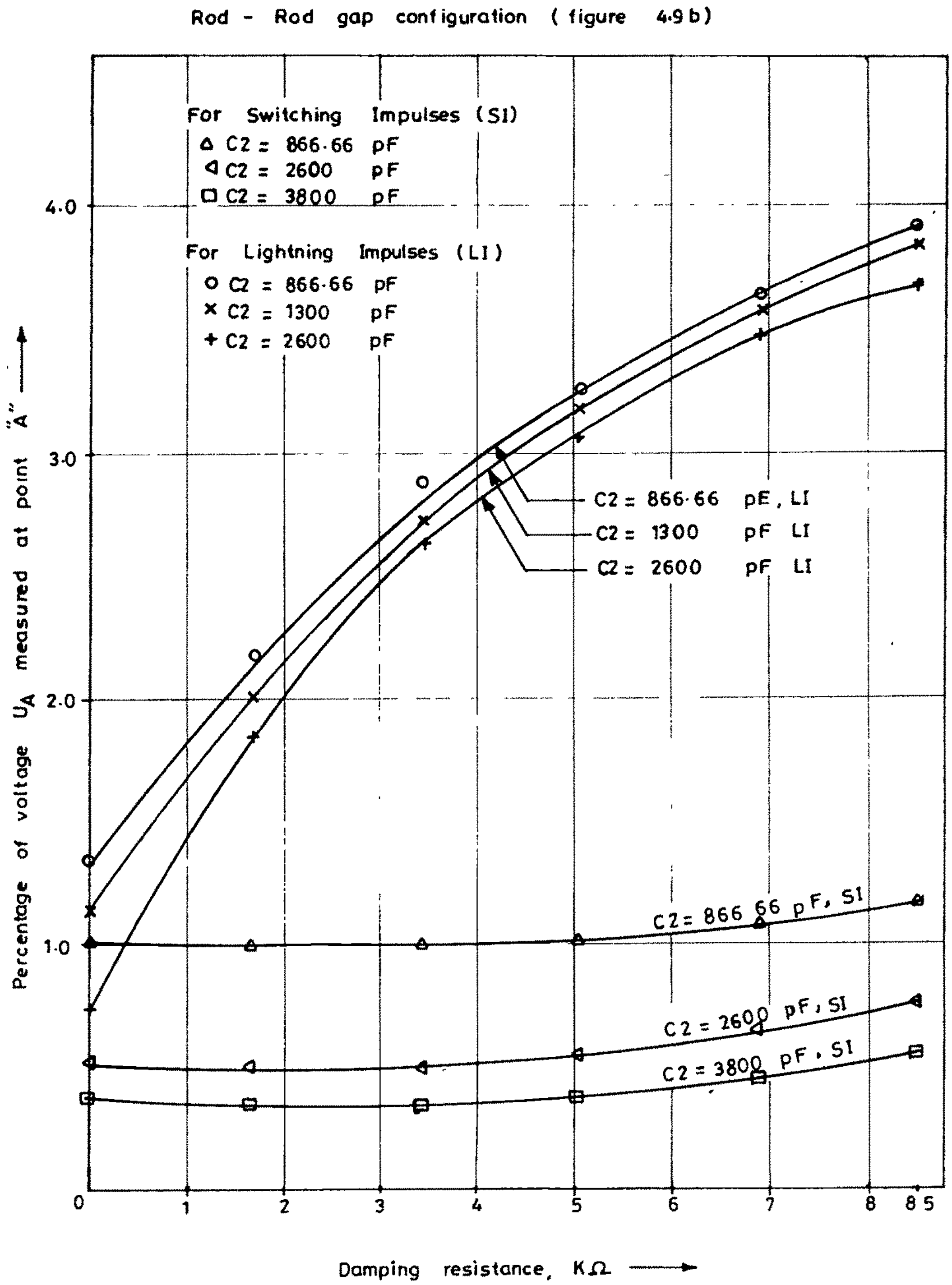


Figure. 5.17 Variation of transferred voltage U_A (LI and SI) as a function of damping resistance, rod - rod gap.

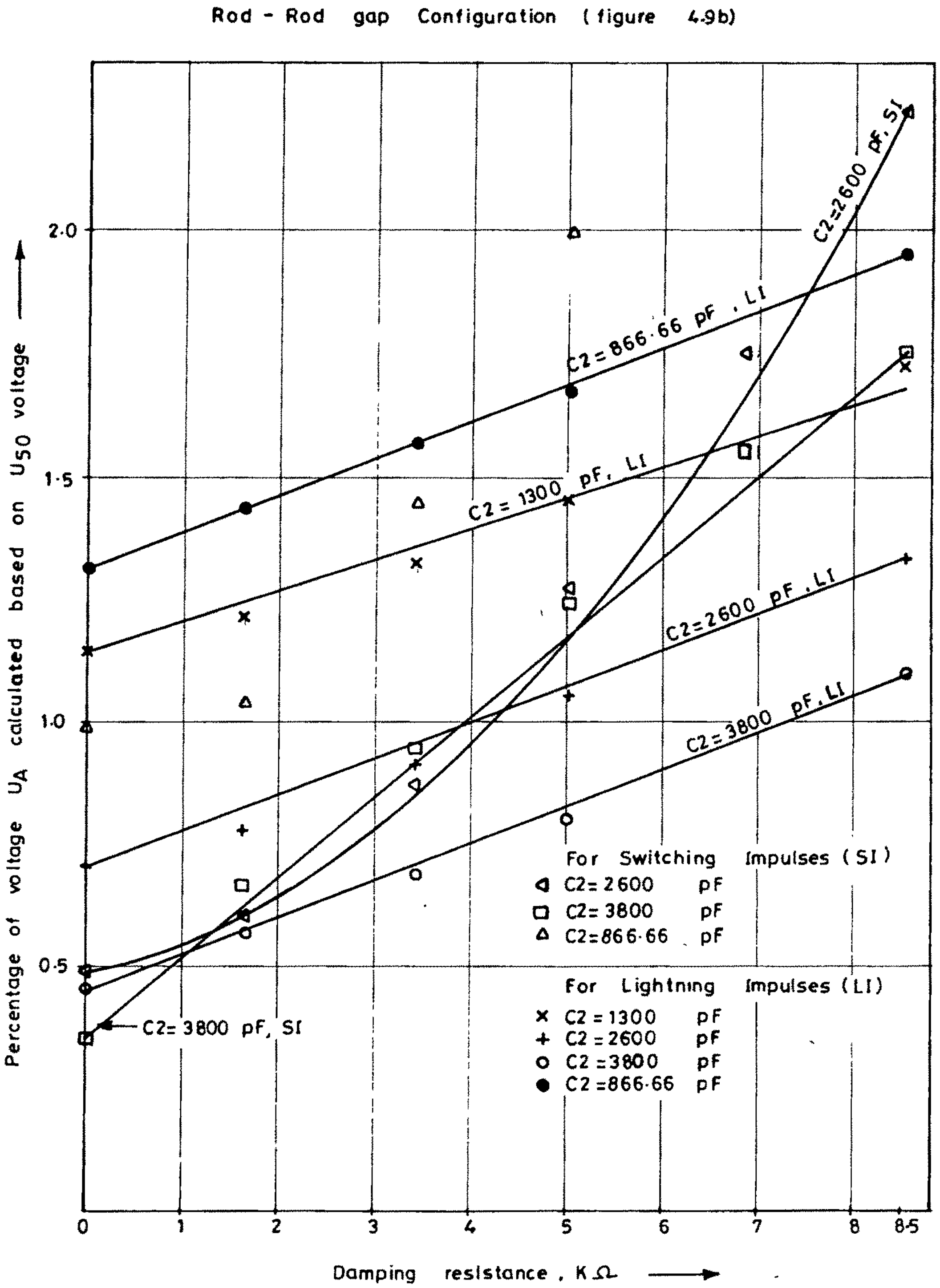


Figure. 5.18 Variation of transferred voltage U_A calculated based on U_{50} as a function of damping resistance, rod - rod gap.

a set of curves of percentage of lightning impulse transferred voltage U_A calculated based on the U_{50} values as a function of damping resistance R for various values of supporting capacitance C_2. The calculated value of voltage U_A increases linearly with the increase in damping resistance. The measured voltage at point A when a damping resistance of 8.56 Kilo Ohms is connected is 3.8 per cent of the applied impulse voltage (C_2 = 866.66pF) while the calculated value of voltage U_A is 1.97 per cent, i.e. nearly fifty per cent of the measured value.

5.5.2.2 Switching impulse voltage

Figure 5.17 also gives a set of curves of the percentage of switching impulse transferred voltage U_A as a function of damping resistance for various values of supporting capacitance. In this case the rate of increase of voltage U_A with the increase in damping resistance is very small as compared to the case of lightning impulse transferred voltage U_A. The calculated switching impulse transferred voltage U_A obtained based on U_{50} values for various combinations of damping resistance and supporting capacitance is given in Figure 5.18. The measured voltage U_A when a damping resistance of 8.56 Kilo Ohms is connected is approximately 0.8% (C_2 = 2600pF), while the calculated voltage U_A is 2.23%.

5.6 Reduction of transferred impulse voltage U_B

As discussed in Chapter-3, because of the capacitive coupling between the test object capacitance and the capacitance connected on the AC terminal, part of the applied impulse voltage to terminal D of figure 4.1, gets transferred on the AC terminal. This causes voltage distortion on the AC wave. Because of the opposite polarity of the impulse voltage, the magnitude of the AC voltage applied at the instant of impulse voltage reduces. On account of this, the test object gap is not stressed to the desired test voltages. The voltage depression on AC wave is equal to the transferred impulse voltage on AC terminal. Hence, to stress the test object gap to the required test voltages, the magnitude of power frequency voltage is increased by an amount equal to the magnitude of the transferred impulse voltage on AC terminal.

If the circuit connections for bias voltage test is made as shown in Figure 4.1, one will measure the voltage U_B and compensate for the voltage drop on AC terminal. If this is the case, it would be necessary to study the reduction of the transferred impulse voltage U_B caused by incorrect location of the damping resistor. Since there is no problem in the measurement of voltage U_B by using damped capacitive voltage divider, the percentage reduction in voltage U_B is derived from the results reported in Chapter-4.

Figure 5.19 gives a set of results of percentage decrease in voltage U_B as a function of damping resistance for various values of supporting capacitance. The test object capacitance was 600pF. As seen from this figure, in the case of switching impulse voltages, the voltage U_B does not vary with the insertion of damping resistance, it

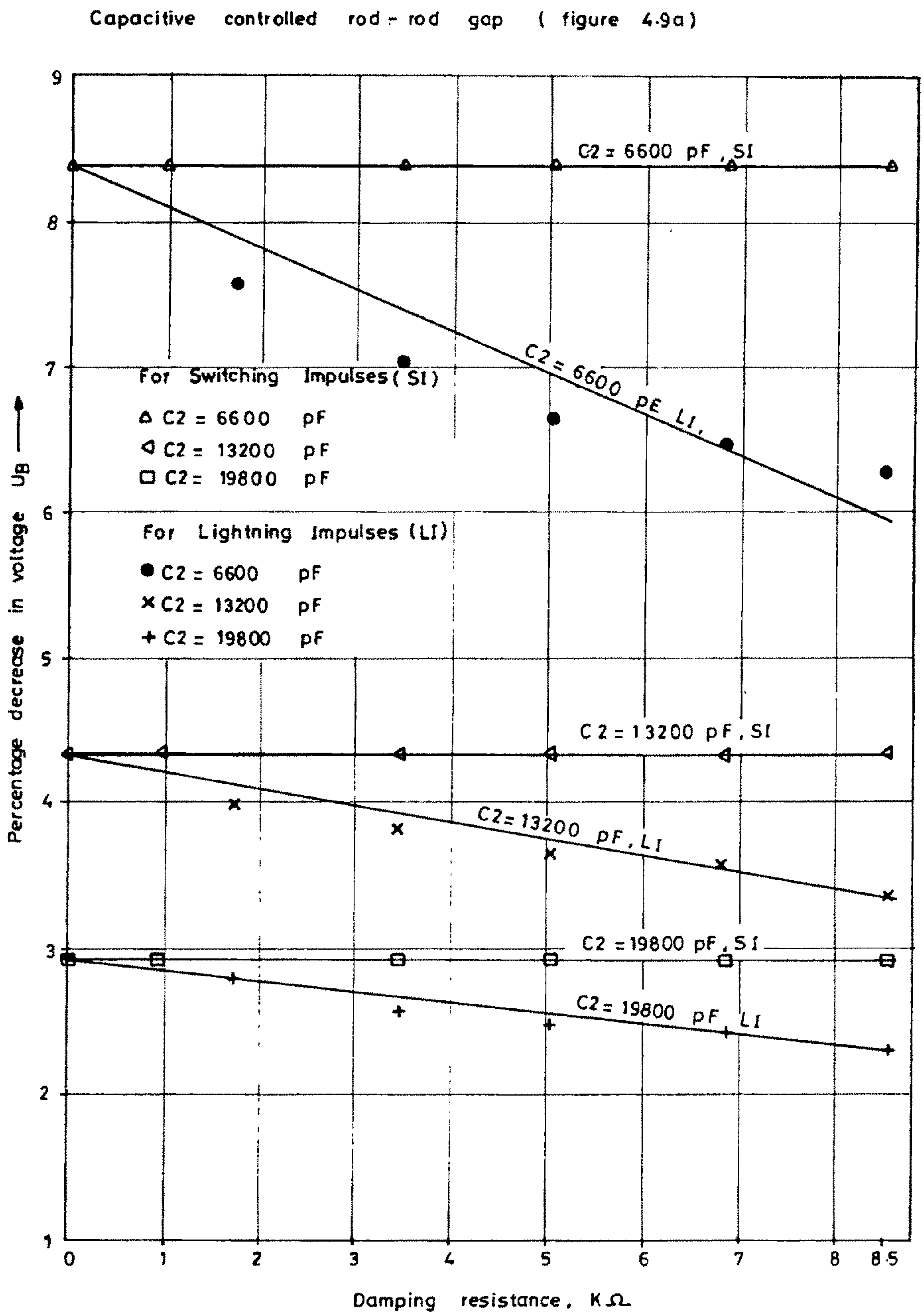


Figure. 5.19 Variation of transferred voltage U_B as a function of damping resistance, $C_1 = 600$ pF.

gives a straight line relationship. While in the case of lightning impulse voltage the voltage U_B decreases with the increase in damping resistance. The percentage decrease in lightning impulse transferred voltage U_B is approximately 2.39, 1.0 and 0.6 for supporting capacitance C_2 equal to 6600pF, 13200pF and 19800pF respectively when damping resistance of 8.56 Kilo Ohms is connected between the test object terminal and the supporting capacitor C_2.

Figure 5.20 gives a set of results of percentage decrease in voltage U_B as a function of damping resistance for rod-rod gap electrode configuration. For this type of electrode configuration also, voltage U_B does not vary for the case of switching impulse voltages by increasing the value of damping resistance. While in the case of lightning impulse voltages, the voltage U_B decreases with the increase in damping resistance. The percentage decrease in voltage U_B is approximately 0.21, 0.265 and 0.19 for supporting capacitance C_2 equal to 866.66pF,1300pF and 3800pF respectively when damping resistance of 8.56Kilo Ohms is connected between the test object terminal and the supporting capacitor C_2.

The percentage reduction of the transferred impulse voltage U_B because of damping resistance in the case of disconnector type open gap is almost negligible.However, in the case of capacitive controlled rod-rod gap,for lightning impulse bias test;the error introduced in the measurement of voltage U_B is large and cannot be neglected. For the test object capacitance equal to 600pF,the required value of the supporting capacitance will be of the order of 8800pF,for this value of

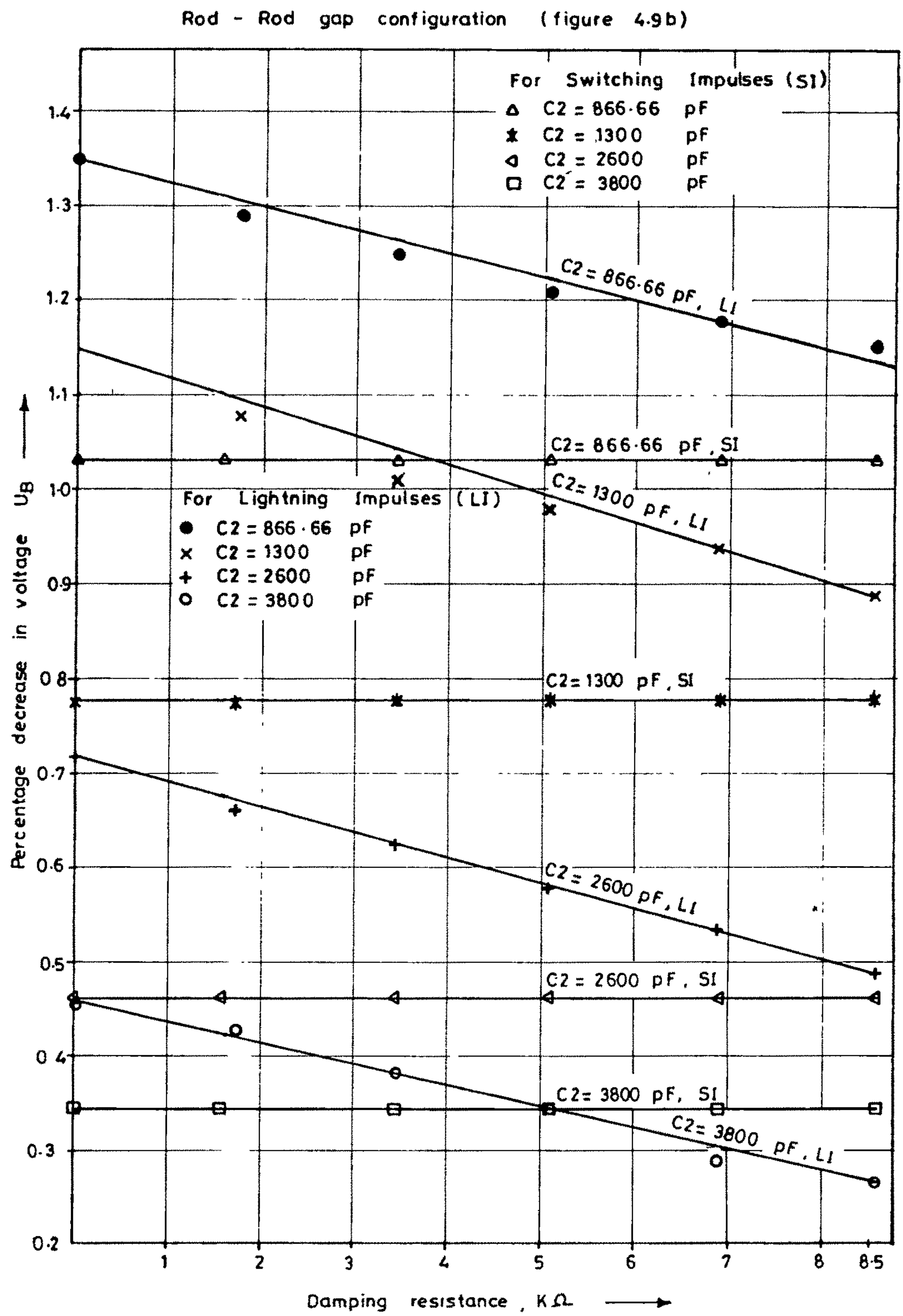


Figure. 5.20 Percentage variations of transferred voltage U_B as a function of damping resistance, rod-rod gap.

supporting capacitor C_2, the error in the measurement of voltage U_B will be of the order of 1.44% when damping resistance of 8.56 Kilo Ohms is connected between the terminals of the test object and the supporting capacitance.

5.7 Total reduction of voltage stress across the test object

It has been established now and proven that the correct test circuit for conducting bias test should be as shown in Figure 4.2. However, if the bias test circuit shown in Figure 4.1 is used, one should know the total error introduced in applying the test voltages to the test object. The error introduced is on account of the following two main aspects:

a. The voltage distribution is affected by connecting a damping resistor between the test object terminal and the supporting capacitance. Higher the value of damping resistance, lesser is the voltage applied across the test object (error e_1).

b. The error introduced in compensating for the transferred impulse voltage on AC terminal i.e. the error in the measurement of voltage U_B, which is ultimately added to the required power frequency test voltage. This error also increases with the increase in the value of damping resistor (error e_2).

For lightning and switching impulse voltages the total error can be easily calculated by using the results given in Figures 5.5 and 5.19 for capacitive controlled rod-rod gap. In the case of lightning impulse voltage, the error e_1 for C_2 = 6600pF and R = 8.56 Kilo Ohms is of the order of 19 per cent of the applied lightning impulse voltage and the error e_2 is 2.39% of the power frequency voltage.

$$\therefore \text{Total error in kV} = e_1 + e_2$$

$$= \text{impulse voltage} \times \frac{19}{100}$$

$$+ \text{power frequency peak voltage} \times \frac{2.39}{100}$$

The error e_1 mentioned above is derived based on the U_{50} values of the test object with and without damping resistance connected in the circuit. The error e_2 is obtained by measuring the voltage U_B with and without damping resistance. When the withstand voltage test is conducted on the longitudinal insulation, the gap will be stressed less by an amount of voltage equal to the total error $e_1 + e_2$.

Thus,

Actual Voltage Stress across the breaker is = Impulse voltage + power frequency peak voltage - Total error in kV

The corresponding errors introduced in the case of switching impulse voltage is of the order of 10 per cent (error e_1). The error in the measurement of voltage U_B is almost negligible (i.e. error e_2 = 0.0%).

Similarly, the total error for the case of rod-rod gap can be derived by using the results given in Figure 5.9 and 5.20. For lightning impulse voltages the error e_1 for

C_2 = 866.66pF and R = 8.56 Kilo Ohms is of the order of 0.65 per cent of the lightning impulse voltage and error e_2 is 0.21 per cent of the power frequency test voltage.

The corresponding errors introduced in the case of switching impulse voltage is of the order of 2.3 per cent (error e_1). The error in the measurement of voltage U_B is almost negligible (i.e. error e_2 = 0.0).

5.8 Standard deviation sigma and their variances

The estimation for calculation of standard deviation sigma was proposed by Dixon and Mood/150/. The formulae for calculating sigma, variance of U_{50} and variance of sigma are given in section 5.2. The measured standard deviation $\hat{\sigma}$ will converge to the true value σ_0 when the number of voltage applications is infinite. However, the measured standard deviation is biased when the number of voltage applications are finite. As described earlier the number of impulses applied to the rod-rod gap and capacitive controlled gap for obtaining U_{50} were fifty for both lightning and switching impulses. The value of standard deviation $\hat{\sigma}$, the variance of U_{50} and the variance of $\hat{\sigma}$ are summarised in Table 5.1 to 5.3 for various values of damping resistance and supporting capacitance C_2. The voltage step for lightning impulses was taken as 3 per cent of the approximately estimated U_{50} value and for switching impulses the voltage step was taken as 6 per cent of the approximately estimated U_{50} value. However, inspite of accurate estimation of starting voltage U_0 for many cases it was observed

TABLE: 5.1

Standard deviation $\hat{\sigma}$, the variance of U_{50} and the variance of $\hat{\sigma}$ for capacitive controlled rod-rod gap for switching impulse voltages, C_1=600pF.

Sr. No.	Capacitance C_2 μF	Damping resistance Kilo-Ohms	U_{50} kV	$\frac{\hat{\sigma}}{U_{50}}$ %	$\frac{\sqrt{Var50}}{U_{50}}$ %	$\frac{\sqrt{Var\hat{\sigma}}}{U_{50}}$ %
1	6600	0.0	640.4	3.285	0.7698	0.918
2	6600	5.05	690.9	2.8658	0.6568	0.8074
3	6600	6.84	702.5	2.055	0.4893	0.5698
4	6600	8.56	707.2	3.0286	0.6971	0.8465
5	13200	0.0	629.79	2.4198	0.5732	0.6709
6	13200	5.05	680.9	1.965	0.4714	0.5469
7	13200	6.84	690.4	2.5738	0.5984	0.7163
8	13200	8.56	693.09	2.155	0.5733	0.5973
9	19800	0.0	620.0	3.556	0.84	1.0196
10	19800	5.05	671.5	5.003	1.1075	1.5215
11	19800	6.84	675.35	3.839	0.8714	1.0898
12	19800	8.56	681.0	3.826	0.8727	1.0909

TABLE:5.2

Standard deviation $\hat{\sigma}$, the variance of U_{50} and the variance of $\hat{\sigma}$ for capacitive controlled rod-rod gap for lightning impulse voltages, C_1=600pF.

Sr. No.	Capacitance C_2- μF	Damping resistance Kilo Ohms	U_{50} kV	$\frac{\hat{\sigma}}{U_{50}}$ %	$\frac{\sqrt{Var50}}{U_{50}}$ %	$\frac{\sqrt{Var\,\hat{\sigma}}}{U_{50}}$ %
1	--	0.0	564.34	1.8527	0.4001	0.4607
2	6600	0.0	644.6	2.3487	0.4837	0.5885
3	6600	5.05	672.5	2.7296	0.554	0.7003
4	6600	6.84	718.5	3.7649	0.7398	1.114
5	6600	8.56	768.17	6.3	1.1833	2.369
6	13200	0.0	626.2	1.805	0.3848	0.4471
7	13200	5.05	652.2	2.3377	0.48923	0.5887
8	13200	6.84	726.5	--	--	--
9	13200	8.56	754.0	3.022	0.6034	0.7997
10	19800	0.0	608.5	1.857	0.39917	0.4601
11	19800	5.05	629.3	2.297	0.4709	0.5812
12	19800	6.84	683.0	1.8169	0.3931	0.4598
13	19800	8.56	749.0	3.4325	0.6658	1.016

TABLE 5.3

Standard deviation $\hat{\sigma}$, the variance of U_{50} and the variance of $\hat{\sigma}$, for rod-rod gap electrode configuration for switching impulse waves

Sr. No.	Capacitance C_2 μF	Damping Resistance Kilo Ohms	U_{50} KV	$\frac{\hat{\sigma}}{U_{50}}$ %	$\frac{\sqrt{Var\ 50}}{U_{50}}$ %	$\frac{\sqrt{Var\ \hat{\sigma}}}{U_{50}}$ %
1	866.66	0.0	327.47	3.148	0.6675	0.783
2	866.66	1.716	327.54	3.553	0.74189	0.8811
3	866.66	3.64	328.75	3.5923	0.7476	0.8922
4	866.66	5.05	332.76	3.9968	0.8192	1.0067
5	866.66	8.56	334.0	3.1209	0.6491	0.7784
6	0.0	0.0	304.0	2.9296	0.638	0.7322
7	2600	0.0	327.19	3.334	0.6901	0.8336
8	2600	1.716	328.09	3.374	0.7169	0.83513
9	2600	3.46	328.77	2.8697	0.6195	0.7172
10	2600	5.05	329.5	2.4613	0.5462	0.6191
11	2600	8.56	330.347	2.873	0.609	0.7122
12	3800	0.0	324.7	4.33	0.87125	1.127
13	3800	1.716	326.5	3.231	0.685	0.7993
14	3800	5.05	328.5	3.247	0.681	0.8066
15	3800	8.56	330.0	3.1587	0.656	0.7833

that the ratio $\frac{d}{\hat{\sigma}}$ was either less than 0.3 or greater than 1.7. For such cases, the voltage step d was changed and the test was repeated to derive U_{50} and $\hat{\sigma}$ to satisfy the condition $0.3 < \frac{d}{\hat{\sigma}} < 1.7$. Whenever, the test was repeated, the value U_{50} remained more or less same, only the number of voltage steps applied were changing based on the chosen voltage step-d. The average value of sigma in case of switching impulse waves were 2.808, 2.276 and 4.056 for capacitance C_2 equal to 6600, 13200 and 19800 pF respectively for test object capacitance equal to 600pF. For lightning impulse voltages the average value of sigma were 3.789, 2.38 and 2.35 for supporting capacitance C_2 equal to 6600, 13200 and 19800pF respectively for test object capacitance equal to 600pF. For rod-rod gap, the average value of sigma in case of switching impulse voltages were 3.4822, 2.9736 and 3.4916 for supporting capacitance equal to 866.66, 2600 and 3800pF respectively.

5.9 Protection of high voltage testing transformer

The protection of high voltage testing transformer in case flashover occurs across the longitudinal insulation was discussed at depth in Chapter-3. It was concluded that the time constant of the circuit should be increased in order to reduce the severity of the chopped voltage by connecting high voltage damping resistor between the terminals of the test object and the supporting capacitance C_2. Higher the value of damping resistor, the severity of the chop reduces. However, the conclusion drawn in Chapter-4 is contradictory to what has been discussed in Chapter-3.

From the testing point of view and as per the systems requirement, the damping resistance should be connected between the terminals of the high voltage testing transformer and the supporting capacitance. Then the question arises, how to protect thehigh voltage testing transformer? By connecting the damping resistance between the high voltage test transformer and the supporting capacitance, still the time constant of the circuit can be increased by increasing the value of R. However, one cannot go on increasing the value of damping resistance because of the following reasons.

1. The I^2R losses increases with increase in R

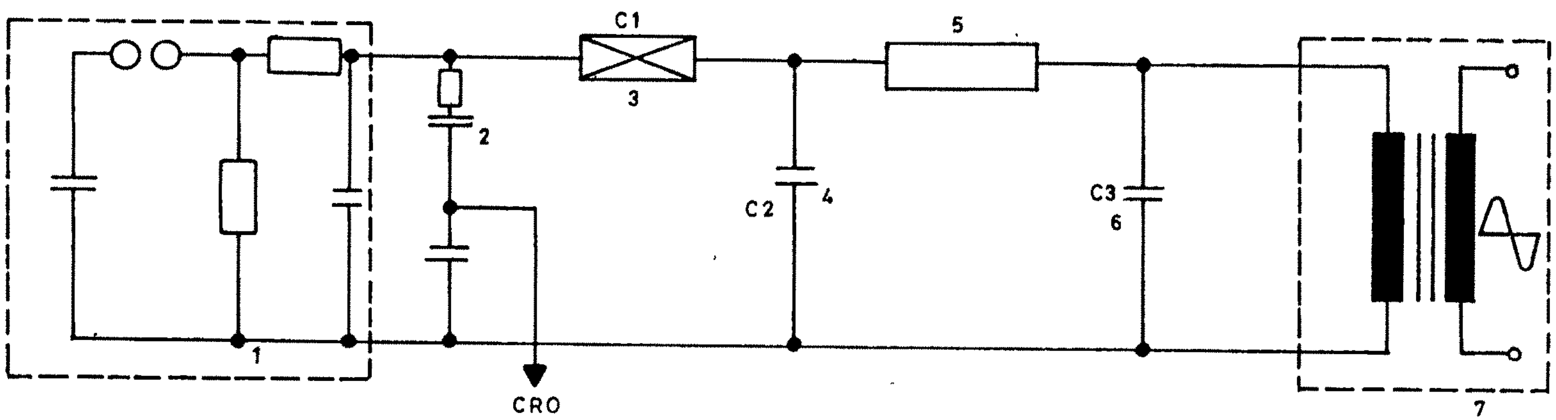
2. The sphere gap is used to protect the High Voltage testing transformer from high transient recovery over-voltages. When the open gap flashes over the sphere gap will flashover, and because of high short circuit current, the relay will operate and power supply to the testing transformer will be disconnected.

   However, if the value of damping resistance R is very high, the short circuit current may not be sufficient for the relay to operate, under such circumstances, the transformer will remain under dead short circuit for longer time till the operator trips it manually. Also, because of high impedance, premature arc extinction may takes place because of insufficient ionisation of the arc path which causes overvoltages upto twice the test voltage value. This is very dangerous and should be avoided.

3. The dimensions of the high voltage damping resistance will increase with the increase in resistance, the laboratory dimensions may not permit this.

Because of the above mentioned difficulties it was decided to increase the time constant of the circuit by connecting high voltage capacitor C_3 as shown in Figure 5.21. The capacitor C_3 can be connected only if the high voltage testing transformer has sufficient current rating.

Thus, by connecting an additional capacitor C_3, the protection problem of winding insulation of the high voltage testing transformer can be sorted out, but one has to study the effect of capacitance C_3 on the voltage distribution across the longitudinal insulation. It was aimed to study this by finding U_{50} with and without capacitor C_3. Table 5.4 gives U_{50} values for rod-rod gap and capacitive controlled rod-rod gap electrodes configuration. The maximum difference in U_{50} with and without capacitor C_3 is 0.288 per cent. It may be concluded that the capacitor C_3 has no effect on U_{50} of the test object and hence there is no harm in connecting capacitor C_3 for the protection of high voltage testing transformer. The value of C_3 will be decided based on the current capacity of the high voltage testing transformer. Higher the value of C_3, lesser is the severity of the chopped wave.



1. Impulse Voltage generator 2200 KV, 66 kj
2. Damped capacitive voltage divider 2000 KV, 713 pF
3. Test objet (either Rod - Rod gap or Capacitive controlled gap. see figure 4.9)
4. Supporting capacitor C2
5. Damping Resistor 8.56 KΩ
6. Capacitance for the protection of H.V. Testing Transformer (C3)
7. Power frequency Transformer 750 KV, 750 KVA

Figure. 5.21 Circuit layout to study the effect of capacitance C3 on the flashover voltage U_{50} of the test object.

TABLE:5.4

U_{50} Voltage with and without capacitor C_3

Sr. No.	Electrode configuration	Impulse wave	U_{50}, kV with C_3 U_{50A}	U_{50}, kV without C_3 U_{50B}	% variations $\frac{U_{50A}-U_{50B}}{U_{50A}} \times 100$ %
1	Rod-rod gap	Lightning impulse C_2=1200pF C_3=1300pF	458.72	457.70	0.222
2	Rod-rod gap	Switching impulse C_2=1200pF C_3=1300pF	330.82	331.62	- 0.242
3	Capacitive controlled gap	Lightning impulse C_2=13200pF C_3=13200pF	625.0	626.30	- 0.208
4	Capacitive controlled gap	Switching impulse C_2=6600pF C_3=6600pF	642.15	644.00	- 0.288

5.10 Conclusion

The critical flashover voltage U_{50} was derived for capacitive controlled rod-rod gap and rod-rod gap electrode configuration for both lightning and switching impulse waves. The value of damping resistor R and capacitance C_2 was varied, and few sets of results were obtained and analysed. The procedure for establishing the correct value of lightning impulse and switching impulse transferred voltage U_A and the total reduction of voltage stress across the longitudinal insulation when damping resistance is connected between the terminals of the test object and supporting capacitance is discussed.

Some of the important conclusions drawn from this study are as follows:

1. U_{50} lightning impulse voltage increases with increase in damping resistance and it decreases with the increase in supporting capacitance C_2 for capacitive controlled rod-rod gap. The percentage increase of U_{50} is as high as 23 per cent when damping resistor of 8.56 Kilo Ohms is connected between the terminals of the test object and the supporting capacitance. The increase in U_{50} value is not linear with the increase in damping resistance.

2. U_{50} switching impulse voltage also increases with increase in damping resistance and it decreases with increase in supporting capacitance for capacitive controlled rod-rod gap. The percentage increase in U_{50} for three values of supporting capacitance

6600pF, 13200 pF and 19800pF is fairly the same for a given value of damping resistance. The increase in U_{50} voltage is approximately 10 per cent when damping resistor of 8.56 Kilo Ohms is connected between the terminals of the test object and the supporting capacitance C_2.

3. It seems when damping resistance R is greater than 7 Kilo Ohms, the increase in U_{50} switching impulse voltage is reaching to a saturation level, i.e. further increase in damping resistance does not lead to increase in U_{50} for capacitive controlled rod-rod gap.

4. U_{50} lightning impulse voltage increases linearly with increase in damping resistance for rod-rod gap. The percentage increase in U_{50} is maximum 0.7 per cent when damping resistance of 8.56 Kilo Ohms is connected between the terminals of the test object and the supporting capacitance C_2. This is negligible as compared to the capacitive controlled rod-rod gap.

5. While conducting bias voltage test on rod-rod gap the damping resistor may be connected between the terminals of the test object and supporting capacitance, so that the severity of the chopped wave is not dangerous for the winding of the High Voltage test transformer.

6. U_{50} switching impulse voltage also increases with increase in damping resistance for rod-rod gap. The percentage increase in U_{50} is between 1.3 and 2.4 percent when damping resistance of 8.56 Kilo Ohms is connected between the test object terminal and the supporting capacitance C_2 ranging from 866.66pF to 3800pF.

7. The measured values of U_{50} for capacitive controlled rod-rod gap are approximately 4.5 per cent more as compared to the calculated U_{50} for both lightning and switching impulse voltages. This is attributed to the different field configurations because of change in circuit connections.

8. The measured values of U_{50} for rod-rod gap are approximately 3.8 per cent more as compared to calculated U_{50} for lightning impulses and 6.5 per cent for switching impulses.

9. For capacitive controlled rod-rod gap, it is not possible to measure the lightning impulse transferred voltage U_A accurately even by using damped capacitive voltage divider.

10. The percentage increase of lightning impulse transferred voltage U_A is of the order of 23 per cent when damping resistance of 8.56 Kilo ohms is connected between the terminals of the test object and supporting capacitor for capacitive controlled rod-rod gap. Hence, it is incorrect to connect a damping resistor

between the circuit breaker terminal and the supporting capacitor while conducting bias test.

11. For capacitive controlled rod-rod gap the calculated and measured values of switching impulse transferred voltage U_A differs only between 0.7 and 5.4% for a supporting capacitance C_2 ranging from 6600 pF to 19800 pF when damping resistance is varied from 0.0 Ohms to 8.56 Kilo Ohms. This variations may be attributed to the measurement problem.

12. The measured lightning impulse transferred voltage U_A for rod-rod gap, when a damping resistance of 8.56 Kilo Ohms is connected is 3.8 per cent of the applied impulse voltage (C_2 = 866.66 pF), while the calculated voltage U_A is 1.97 per cent, i.e. nearly fifty per cent of the measured value.

13. The measured switching impulse transferred voltage U_A for rod-rod gap is more or less independent of damping resistance. However, the calculated voltage U_A increases with the increase in damping resistance.

14. If the damping resistor is connected between the terminals of the supporting capacitor and the test object, it leads to an error in the measurement of voltage U_B which is required for compensating the voltage drop on AC terminal while conducting bias voltage test. For capacitive controlled rod-rod gap when test object capacitance C_1 is equal to

600pF, the error in the compensation of voltage drop will be approximately 1.44 per cent which is too large (C_2 = 8800pF).

15. While conducting bias voltage test on circuit breakers (C_1 = 600pF and C_2 = 13200pF) when a damping resistor of 8.56 Kilo Ohms is connected between the terminals of the test object and the supporting capacitor, the longitudinal insulation of the circuit breaker will be stressed less by approximately 20.4 per cent of the lightning impulse voltage and 1.0 per cent of the power frequency voltage while conducting lightning impulse bias test, and will be stressed less by approximately 10 per cent of the switching impulse voltage while conducting switching impulse bias test.

16. While conducting bias voltage test on rod-rod gap when a damping resistor of 8.56 Kilo Ohms is connected between the terminals of the test object and the supporting capacitor C_2 (C_2 = 866.6pF) the longitudinal insulation will be stressed less by approximately 0.65 per cent of the lightning impulse voltage and 0.21 per cent of the power frequency voltage while conducting lightning impulse bias test, and will be stressed less by approximately 2.3 percent of the switching impulse voltage while conducting switching impulse bias test.

17. The average values of standard deviation sigma for switching impulse waves were 2.8, 2.276 and 4.056

for capacitance C_2 equal to 6600, 13200 and 19800pF respectively for test object capacitance equal to 600pF, and for lightning impulse voltage, the average values of sigma were 3.39, 2.38 and 2.35 per cent for supporting capacitance C_2 equal to 6600, 13200 and 19800pF respectively.

18. For rod-rod gap the average value of sigma for switching impulse voltages were 3.48, 2.97 and 3.44 per cent for supporting capacitance C_2 equal to 866.66, 2600 and 3800pF respectively.

19. For the protection of high voltage testing transformer, an additional capacitor C_3 can be connected in parallel to the High Voltage testing transformer. This will reduce the severity of the chopped wave on the testing transformer.