CHAPTER-1

INTRODUCTION

1.1 General

The evolution in the needs for electrical energy together with the concentration of generating units, demands a continual increase of transmitted power. Despite the progress made in other forms of transmission, use of overhead lines remains the best solution for the next few decades, owing to the fact that the rated system voltages have already been raised to the levels of Ultra High Voltages (U.H.V.).

Since air is the major outdoor insulation, its importance as a dielectric medium increases as the rated system voltage moves upwards. It is particularly so, when temporary and/or transient overvoltages appear in the system. The rating of the insulation of high voltage system is given on the one hand by the stresses due to occasional transient overvoltages and on the other hand by the permanent stresses due to working voltage /1/. The working stress may also have thermal effects, caused especially by the dielectric losses in the insulation and the surface leakage currents, which may reduce the dielectric strength, as well as by internal partial discharges which destroy the organic insulants in the course of time.

Thus, one of the major factors which plays very important role in the system reliability, is the behaviour of insulation against various types of overvoltages. If the insulation were subjected to the normal operating voltage alone which varies within the narrow limits, there would have been no problems. In reality, the insulation has to withstand a variety of overvoltages with a large range of wave shapes, magnitude and durations. These various parameters of overvoltages affect the ability of the insulation to withstand them. Therefore, the knowledge of the causes of these overvoltages, their effects on insulation and the measures for preventing or limiting them is of primary importance in the design and operation of the power system /2,3/.

With the increase in transmission voltage the cost of the power equipments increases due to the insulation requirements/1/. Therefore, there is a need for optimising the insulation requirements from the economic and reliability stand point /1,2/.

It is not always economically possible to design a system/equipments which can withstand the highest stresses that may occur occasionally in the system. The economic limit always intervenes well before the technical limit. The power system engineer has to place a limit at the point at which the cost of achieving a further improvements in the reliability cannot be justified by the savings the reduced number of breakdowns may bring, which are at any rate difficult to assess in terms of money. Thus, the system design engineer has to deliberately accept a certain probability of breakdown in the design of power systems. On the other hand the design of the power system should be such that, when breakdowns are inevitable, they are confined to locations where they cause minimum damage and thereby cause least disturbance to the system operation /1/. The worst or permanent damage is caused by breakdown of solid insulation in a confined space, where as the damage is least and temporary when there is a breakdown in a self-restoring type air or SF_6 insulation system.

1.2 Overvoltages and their classification

An overvoltage is defined as any time variable voltage between one phase-to-ground and/or between phases with crest value or values exceeding the corresponding crest value derived from the highest voltage for equipment/3,4/. These overvoltages have durations ranging from some tens of microseconds to several seconds and may attain magnitude over a wide range of values.

It is convenient to classify overvoltages according to the main cause for their origin as:

a) Lightning overvoltages

b) Switching overvoltages

c) Temporary overvoltages

Overvoltages can be impressed upon a power system by atmospheric discharges, in which case they are called lightning overvoltages. Lightning overvoltages are of short duration transients having wave front and wave tail duration in the range of 0.5 to 10 μs and 10 to 150 μs respectively /1,4/. This overvoltages will be quite large if direct strokes to a line conductor, tower or an earthwire take place. The indirect strokes induces lower voltages compared to the direct strokes but the waveshape remains the same. Lightning overvoltages are as a rule independent of system voltage, while the insulation level increases with the rated system voltage. EHV lines (system voltage greater than 300kV) should therefore, be less vulnerable to lightning surges. However, within the range upto 765kV they cannot be disregarded and must be taken as a criterion for rating the insulation of the equipments of the system.

For testing purpose such lightning surges are simulated by an Internationally agreed double exponential waveshape of 1.2/50 μs/5/. The amplitude and to a lesser extent the steepness of the front of lightning surges that travel along the overhead lines are rapidly attenuated by corona losses and line capacitance. Hence it is unlikely that a single lightning surge that strikes on EHV line will overstress the insulation of more than one substation.

Switching overvoltages are due to sudden change in the system conditions brought about by the deliberate or unintentional switching operations.

Switching overvoltages are proportional to working voltages, i.e. to the instantaneous value of the switched voltage. In this respect they differ greatly from the lightning overvoltages whose amplitudes depend more on the design of the overhead lines than on the system voltage. As a consequence there is a system voltage at which the emphasis which governs the design of the insulation system of the power equipments/insulation-co-ordination changes from lightning to switching surges, this point is reached approximately at 300kV.

In contrast to lightning overvoltages, switching overvoltages have significantly longer wavefront and wavetail durations.

Overvoltages, which are generated within the system by connection or disconnection of circuit elements or due to the initiation or interruption of faults, are classified as 'temporary overvoltages', if they are of power frequency or harmonic frequency and are sustained or weakly damped, or as 'switching overvoltages' if they are highly damped and of short durations. Because of their common origin, temporary and switching overvoltages occur together and their combined effect is relevant to the insulation design. The main causes of temporary overvoltages of interest are:

a) Load rejection

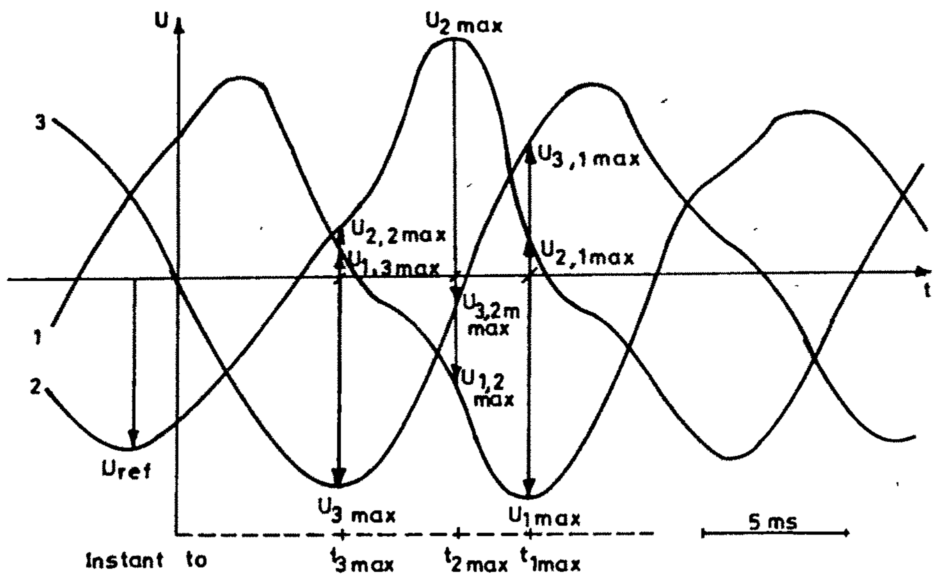
b) Ferranti effect

c) Self-excitation

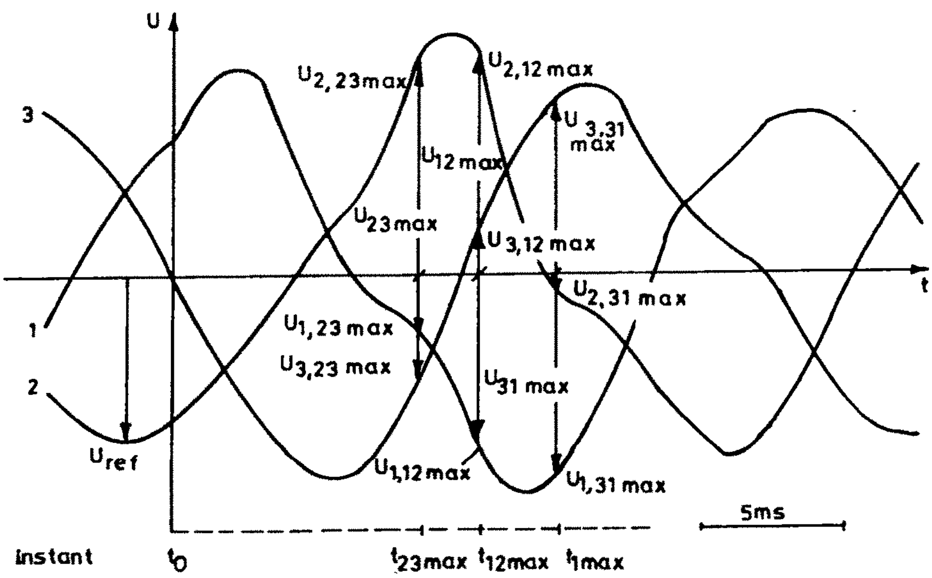
d) Ground faults

1.2.1 Characteristics of switching overvoltages

Switching surges are of a great variety of shapes, magnitude and duration, corresponding to a great variety of initiating events /1/. Their parameters are determined by both the system and the characteristics of the switching device. Figures 1.1a and 1.1b show the three phase oscillograms, which indicates peak phase-to-earth and three phase-to-phase overvoltages/8/. Figure 1.2 gives some more examples of the waveshapes/1/. The magnitude of a switching overvoltage for a given operation depends on the point on the voltage or current wave at which switching occurs.



a) Evaluation of the overvoltages phase - to - earth



b) Evaluation of the overvoltages phase - to - phase

Figure. 1.1 Evaluation of phase-to-phase and phase-to-earth overvoltages (ref. 8).

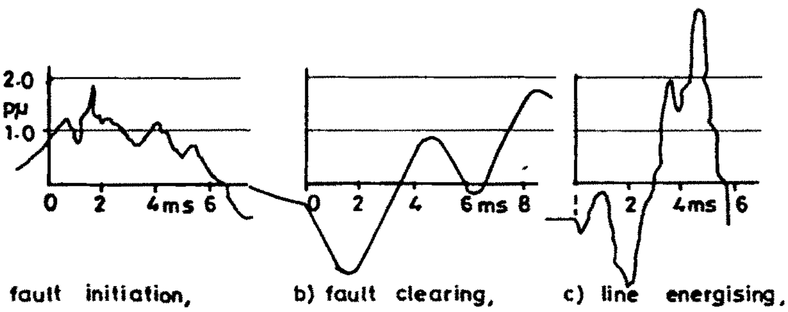


Figure. 1.2 Typical switching surge wave shapes (ref. 1).

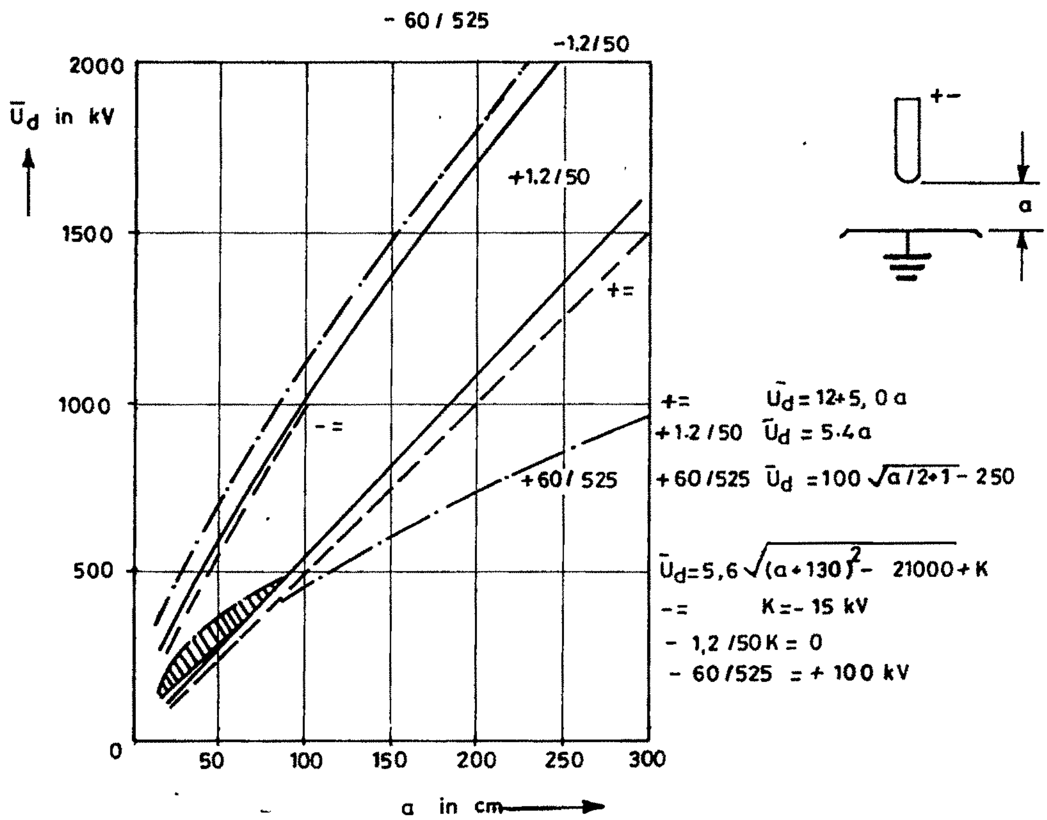


Figure. 1.3 Breakdown voltage of rod - plane spark-gap in air. Influence of the wave shape (ref. 6).

Many authors have conducted detail TNA/digital computer studies to get a clear picture/idea about the waveshapes and magnitudes of switching overvoltages/8-10/. Field tests are however, extremely valuable for verifications of the input data and of the mathematical model or simulation used and have been staged for this purpose. In India UPSEB have conducted field study under various switching conditions to check the stability/performance of the 400kV transmission line and system equipments. It was observed that all the equipments behaved satisfactorily under various switching operations. MSEB has planned to conduct field tests in collaboration with CESI and CPRI. The switching operation of greatest concern in EHV systems can be classified as follows:

a) Line energisation, with line open circuited at the far end or terminated to an unloaded transformer.
b) Line re-energisation, with trapped charge on lines from previous interruption.
c) Load rejection by circuit breaker opening at far end, possibly followed by disconnection at sending end.
d) Transformer switching at no load, or with secondary load of shunt reactors, also high voltage reactor switching.

With modern circuit breakers and correct system design only cases (a) and (b) are critical. Details regarding the cause and effect of various switching operations mentioned above are discussed at depth by many researchers/6,7/.

1.2.2 Discharge characteristic of various types of overvoltages

To design a system for better reliability, it is a must to have a knowledge of the behaviour/breakdown mechanism of various insulation systems either self-restoring type or non self-restoring type under various types of overvoltages. It is necessary to define different characteristics of the insulation system having different electrode configuration which are normally encountered in the system design. Although the mechanism of spark breakdown has been a subject of discussion for almost one hundred years, the industries and utilities are still discovering surprises by conducting various studies under different conditions. For example, below 300kV, lightning impulse used to be the important criterian for insulation design/1/. But during the development of 500kV system in early seventies it was observed that instead of lightning surges, switching surges should be considered the controlling factor for the insulation design.

A great amount of work has been done to investigate the mechanism of dielectric discharge in large air gaps subjected to impulse voltages having time-to-crest in the range between few tens and some thousands of microseconds/11-14,57-60/.

The various electrode systems which are of interest to the designer are:

a. Rod-plane gap

b. Rod-Rod gap

c. Ring-Ring gap

d. Conductor-Rod gap

e. Conductor-Conductor gap, etc. etc.

It is recognised that for a rod-plane gap, when a positive switching impulse is applied to the rod, the lowest dielectric strength is attained/15,16/. Figure 1.3 shows the breakdown voltage of the rod-plane gap in air. The results obtained under various voltage stresses were measured on the same gap in comparable surrounding conditions. Up to recent years the insulation distances of Extra High Voltage lines and high power apparatus are still determined by empirical and physical models and then verified by conducting full scale testing/17-24/. However, this approach becomes much more costly and risky for greater insulation distances and higher transmission voltages.

Some of the important factors which governs the behaviour and discharge strength of large air gaps are listed below:

- Waveshape of impulse wave, standard and non-standard waves/25-32/,
- Corona on conductors/33-41/,
- Radius of the electrodes and electrode shapes/42-45/,
- Distance of the electrodes from the surroundings/46-50/,
- Electrode configurations/44,52-56/,
- Air density and humidity/95-106/,

- Pollution

All the above mentioned factors play a vital role in deciding the sparkover characteristics of the gaps. It has been a normal practice to define discharge characteristics in the form of 50% discharge voltage U_{50} and standard deviation σ. The effect of few of the above mentioned parameters have been discussed in detail in Chapter-2.

1.2.3 Breakdown mechanism under switching impulses:

Extensive research work had been undertaken by EDF at the Les Renardieres laboratory to study the discharge mechanism of switching surges. Gap distances of the order 30 meters have been studied theoretically and experimentally and results are published /57-60/.

It has been an established fact that for long rod-plane gaps in air subjected to short and long-fronted impulses with positive polarity, the discharge path is made up of three components/16/. A bright, light intensive leader part starting from the H.V. electrode, a less luminous corona type zone starting from the leader tip and the unbridged gap from the end of the streamer zone to earthed plane. Leader usually forms a zig-zag path carrying a relatively high current (0.1 to 100 Amp), whereas streamer zone is made up of many small filaments which are associated with currents in the microampere range. When the streamers reach the plane electrode, complete breakdown of the gap will take place.

Leader and streamer model theories have been used by various authors/18,21,23,24,61-63/, to study the discharge mechanism under switching surges. The various theories developed can be extended to study the discharge behaviour for any electrode configuration.

1.3 Phase-to-phase and phase-to-ground overvoltages

In a three phase system, switching overvoltages produced on account of switching are not synchronous and have different polarity and shapes. These overvoltages stresses the phase-to-phase insulation and the stress produced is the difference of the two phase-to-ground components. It has been observed that the phase-to-ground overvoltages of two phases in the same system nearly always have opposite polarity at the times at which the overvoltages to ground reach their peak values. This indicates that the overvoltage stress between phases is generally much higher than that to ground /64-69/.

Electrical clearances adopted for HV and EHV substations tend to differ from one country to another , and even among the utilities of the same country. The co-ordination of phase-to-phase and phase-to-ground clearances is of prime importance for the EHV substations. The ratio of the phase-to-phase clearances to the phase-to-ground clearances recommended by different authors for 330-500kV system varies between 1.12 and 1.8/70-73/. No justification has been given for this wide variation. The design allowing unnecessary safety margin could lead to enormous space requirements, due to the strong saturation in the voltage withstand characteristic of air insulation.

The rational choice of the phase-to-phase clearances and their co-ordination with the phase-to-ground clearances is relatively simple as long as those are essentially dictated by the lightning overvoltages. The problem, however, becomes more complicated when the minimum air clearances are determined, as happens in EHV and UHV systems, by switching overvoltages.

For better co-ordination of the insulation, it requires both the knowledge of the withstand characteristics to switching surges of the air insulated structures used in the substations and the actual characteristics of the phase-to-phase and phase-to-ground switching surges in the electric systems. Udo/74,75/ conducted experiments by means of simultaneous application of a positive impulse to ground on one electrode and of a negative impulse to ground on the other electrode. It was observed that the dielectric strength of phase-to-phase air insulation depends both on the total voltage between phases and on the value of its phase-to ground components. Dellera and Zaffanella/76/ have suggested approaches for the design of phase-to-phase and phase-to-ground (insulation co-ordination) clearances and methods of interphase switching impulse tests on air insulation. The different test approaches, enable the designer to optimise the air clearances.

The breakdown characteristics of phase-to-phase overvoltages was studied taking care of the main characteristics of actual system overvoltages/64-71/. The influences of the following parameters on the 50% discharge voltage U_{50} of electrode configurations with different gap distances have been investigated by various researchers/78-86/.

a. Switching impulse shape, double exponential or oscillating
b. Ratio of peak value of the negative switching impulse to the sum of the peak values of positive and negative impulses (ratio α)
c. Time delay between two impulses(Δt)
d. Electrode configuration
e. Peak amplitude of the negative impulse
f. Time to half value

1.4 Longitudinal insulation

Phase-to-phase and longitudinal insulation are related types of insulation since, for both, the two electrodes in service are simultaneously subjected to over voltages of various shapes. In order to have a correct simulation of the actual stresses, both insulation types are tested with two voltage components of opposite polarity at the electrodes. The insulation is thus stressed by the difference of the two voltages/87-89/. The phase-to-phase or the longitudinal insulation configuration represents an insulation system, because it also includes the insulation of the electrodes to ground. All kinds of insulation are thus tested at the same time.

Longitudinal insulation is an open gap insulation of the circuit breaker and disconnector, which is subjected to the combined stress of the operating voltage at the one terminal and an overvoltage or an out of phase operating voltage at the other terminal.

IEC publications 56/90/ and 129/91/, and published literature/87/ specifies the following test procedure for longitudinal insulation testing:

1.4.1 Specified one terminal test

This test is also known as equivalent test. The sum of the specified value of the impulse voltage and AC voltage is applied to one terminal, the opposite terminal being grounded. IEC publications 56 and 129 also permits to raise the ground insulation in order to avoid flashovers to ground while testing the longitudinal insulation. However, it is not clearly specified how much ground insulation should be raised. By increasing the ground insulation the field configuration changes and hence exact site conditions are not simulated in order to study the dielectric withstand capability of the longitudinal insulation. The test conducted in this way gives insufficient guarantee of the performance reliability.

To conduct this test, no additional test equipments are required and hence it is very simple to simulate the test in any laboratory if required capacity of the impulse voltage generator is available. However, the side clearances required would be more, as higher voltage is being applied to one terminal and hence the cost of the laboratory building becomes very high. Various researchers/74,75/,

/87,122/ conducted extensive research work on testing of the longitudinal insulation, it has been concluded that if the equivalent test is conducted on a circuit breaker or disconnector, then the open gap clearances are to be checked by the appropriate switching impulses. This test is more severe as compared to the one which is described below:

1.4.2. Bias voltage test

The bias voltage test is also known as a two terminal test. In bias voltage test, the lightning impulse voltage or switching impulse voltage is applied to one terminal at the instant of the opposite polarity peak of the power frequency voltage applied to the other terminal.

This test calls for the requirement on the voltage distortion on the power frequency voltage resulting from the capacitive coupling between the two terminals either by stray capacitances or by the potential control capacitors. Tnis may lead to test difficulties owing to large supporting capacitance required at the transformer terminal and consequent distortion in the voltage wave.

Further more, the steep impulse generated by the breakdown of the longitudinal air gap requires a protection circuit for the test transformer. The standards do not specify what should be the location of various protective equipments required for the high voltage test transformer.Tne complete bias test circuit is shown in Figure 4.2, this may become very large and expensive. This test procedure needs additional measuring and recording equipments like damped capacitive voltage divider, double beam impulse CRO, high voltage damping resistor, lightning arrestor, point on wave control etc. etc.

1.4.3 Equivalent two-terminal tests

In this test, the lightning impulse or the switching impulse voltage is applied to one terminal and the switching impulse voltage of opposite polarity to the other terminal. Both impulses reach their crest values at the same instant.

This test procedure requires two impulse voltage generators. There are no protection problems and the complexity of the test is less as compared to the two terminal test procedure, described in section 1.4.2.

1.4.4 Testing Procedure

The longitudinal insulation may be tested in a successive steps, each more complicated than the preceding one from the point of view of the testing procedure. On the other hand, it is to be kept in mind that a simpler testing procedure involves a certain approximation both in the behaviour of the insulation tested and in the withstand voltages to be prescribed. What is gained in the testing simplicity is paid in the inaccuracy both of the results and of the prescribed withstand voltages. Generally the withstand test may consist of one of the following two methods:

a) Apply to the test object an appropriate number of impulses of a given voltage value (withstand value) to verify its withstand capability. This method is used to check the withstand capability of the non-self restoring type insulation systems.

b) Determine the maximum probable withstand voltage by calculating 50% discharge voltage U_{50} and standard deviation σ by means of a series of tests at different flashover probabilities. This method is used to obtain maximum withstand capability of the self restoring type insulation systems.

In case of two terminal test, the test results are represented in the form of 50 per cent discharge voltage between two terminals $(U^+ + U^-)_{50}$ versus α.

Where α is defined as,

$$\alpha = \frac{U^-}{U^+ + U^-} \qquad \text{........} \qquad (1.1)$$

U^- = crest value of negative impulse voltage

U^+ = crest value of positive impulse voltage

The interesting ranges of α specified in various references are/92-94/:

0.14 to 0.19 for the positive lightning impulse bias test
0.81 to 0.86 for the negative lightning impulse bias test
0.26 to 0.36 for the positive switching impulse bias test
0.64 to 0.74 for the negative switching impulse bias test
0.30 to 0.70 for the out of phase test, $U_m \geqslant$ 300kV

1.5 Atmospheric correction factors

Gaps with electrodes producing non-uniform field are used for wide applications by power utilities, such as open gap insulations with and without insulator, co-ordinating gaps for the overvoltage protection of the transformer etc.etc. The flashover voltage of any external insulation is influenced by change in the humidity content and density of the air. For this reason these effects must be taken into considerations in the design/performance of the power equipments.

IEC publication 60/5/ and IEEE standard 4-1978/95/ gives generalised correction factors for few impulse shapes and polarity for non-uniform symmetrical field gaps. The effiect of these parameters for different wave shapes and polarity, and electrodes shapes and configurations under different conditions have been studied by various researchers/96-105/. It is reported that the generalised correction factors given by IEC specifications and IEEE standard-4 change with polarity, electrodes shape and configurations. Further IEC publications 56 and 129 calls for conducting bias voltage test on the longitudinal insulation of the power equipments rated for system voltages higher than 300kV. The correction factors are applied according to IEC publication 60. However, IEC publication 60 does not describe the correction factors especially for bias voltages.This is the main difficulty encountered by industries/utilities while testing the longitudinal insulation. Presently the correction factors are being calculated separately for impulse and AC voltages according to IEC publication-60, but it is not clear whether this is the correct practice. The question as to when and how the atmospheric corrections are to be applied, has still remained unanswered/106/.

To study the influence of humidity and air density on long air gaps, generally it is necessary to conduct long run flashover tests to take the advantage of yearly natural wide variations of humidity as it is difficult to house the long air gaps in a room and create different humidity conditions artificially. Many international laboratories have conducted extensive research work on this subject/98/, /125,128,129,130,132/, and new correction methods have been suggested for phase-to-ground insulation systems/130,131/, /132,136/. This subject is further discussed at depth in Chapter-2.

1.6 Scope of work and aim

As described earlier, IEC publications 56 and 129 give two testing procedure for testing the longitudinal insulation of circuit breaker and disconnector. It has been reported in the literature that Bias testing is less severe as compared to the one terminal test procedure. If bias voltage test procedure is adopted, then it is possible to create exact site conditions in the laboratory and hence better reliability of the test results and performance of the equipments can be guaranteed.

Various International Laboratories adopted different test circuits for conducting the bias voltage test (refer Chapter-4 for various circuit configurations). There are advantages and disadvantages while using these various circuits. Since the standards do not mention clearly about the connection/position of the various equipments required for conducting bias voltage test, different test circuits have been used by utilities and industries. It was not known which circuit connections gives the reliable performance of the power equipments when tested for withstand voltage test. However, legally all the circuits do satisfy the requirements of the standards, but truly speaking they do not meet the requirement of the power systems.

The objectives of the study reported in this thesis were as follows:

- to study the different bias test circuits from systems requirement point of view and suggest the one which gives the reliable performance of the equipment when tested for withstand voltage test.
- what is the effect of the location of the high voltage damping resistor in the bias test circuit on the stress imposed on the test object. Also to check which location is most appropriate from the systems point of view. The effect of supporting capacitance C_2 (refer Figure 4.2) and the test object capacitance also need to be studied to check the impulse voltage distribution across the test object.
- what is the error introduced in applying desired voltage stresses to the longitudinal insulation when tested using different bias test circuits.
- how best the winding insulation of the high voltage test-

ing transformer can be protected from transient overvoltages during bias voltage test.

- IEC specifications/IEEE standard do not give correction factors especially for correcting bias withstand/flashover voltages. As of now no published results are available regarding humidity correction factor for bias voltages. This subject was to be studied and suitable humidity correction factor to be recommended for bias voltages.

The contents of the thesis are arranged as follows:

In Chapter-2, survey of the published literature/reports on the relevant subject is presented.

In Chapter-3, the development of bias test facility is presented.

In Chapter-4, the effect of High Voltage Damping Resistor required for the protection of the High Voltage Testing Transformer on the voltage distribution across the test object is presented.

In Chapter-5, the effect of High Voltage Damping Resistor on critical flashover voltage U_{50} and voltage distortion on AC wave is presented.

In Chapter-6, the humidity correction factor under bias voltages is developed. Also the effect of time shift between two peaks, time-to-crest of the switching impulse voltage, ratio α and effect of rain under bias voltages is presented.

Finally, in Chapter-7, the conclusion drawn from the whole investigations conducted are presented with suggestions for further scope of work, in particular with reference to breakdown phenomena under bias voltages.