THE ELECTRICAL BREAKDOWN CHARACTERISTICS OF
OIL/PAPER INSULATION
UNDER FAST FRONT IMPULSE VOLTAGES

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ABSTRACT

Gas Insulated Substation (GIS) and Gas Insulated Transmission Line (GITL) have found broad application in power system over the last twenty years. Disconnect switch operations in this equipment causes transient voltages with rise times as fast as 5 to 20 nanoseconds and magnitudes as high as 2.5 pu. There is very little information on the effect of these transients on oil/paper insulated equipment connected to the GIS and GITL. There have been reports of transformer and bushing failures which may have been caused by these transients.

In the investigation reported in this thesis, the electrical breakdown properties of oil/paper insulation under fast front impulse were studied. A test system was built to generate a high voltage fast front (rise time less than 10 ns) and to apply this voltage to oil/paper samples. The breakdown characteristics of oil/paper insulation was investigated using different types of paper, types of oil and number of layers of paper. Insulation breakdown voltage vs breakdown time (V-t) data was obtained with the fast front step waveform and $V_{50}$ breakdown data was obtained with the fast front waveform and lightning and switching impulse waveforms.

The V-t data was analyzed using the histogram, Weibull distribution and equal area criterion methods. A 2% probability V-t curve was generated and fits the data well. The $V_{50}$ test results showed that the fast front impulse waveform has the lowest breakdown voltage and the switching impulse has the highest breakdown value.
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1. INTRODUCTION

Gas Insulated Substations (GIS) and Gas Insulated Transmission Lines (GITL) have found a broad application in power systems over the last twenty years. GIS and GITL are based on the use of a coaxial conductor arrangement with the inner conductor supported on insulators in an aluminium sheath. Sulphur hexafluoride (SF$_6$) has been used in GIS and GITL as insulation since it has a much higher dielectric strength compared to air and other dielectric gases.

The technology of SF$_6$ Gas Insulated Substations has some significant advantages. It greatly reduces the size of the substations. GIS are about ten times smaller than conventional substations because large clearances are not required. It also has other advantages. It has independence from environmental effects. Environmental pollution will not cause flashover in the bus. The lack of flammable insulation such as oil means it is not a fire hazard. Its small size allows more flexibility in the selection of a site within the power system. Personnel safety is enhanced because they are not directly exposed to the energised components. Also it has a long service life, short time from planning to commissioning and high reliability. Both GIS and GITL are used in extra high voltage (EHV) and ultra high voltage (UHV) transmission. The voltage range of GIS in service is from below 69 kV to 550 kV [1]. The normal operating pressure in GIS systems is between 0.3 and 0.5 MPa (3-5 atmosphere) absolute.
GIS and GITL systems contain: a high voltage bus, circuit breakers, isolators, disconnect switches, current transformers, potential transformers and surge arresters. A typical GITL consists only of a coaxial bus with bushings at the ends.

GIS systems have some special problems not found in conventional switchgear substations. For example, it has been found that the gas-insulator-electrode junction quite often constitute the weakest point in the system. At this junction, micro-discharges start and lead to surface flashover. Some research has been done in this area [2,3].

Fast transients generated by disconnect switch operation also cause problems. These transients may be a danger to people who work around the GIS since they cause high transient voltages in ground systems. They may also cause damage to electronic equipment connected to the GIS or using the same ground return. As a result, worldwide investigations have been carried out on this subject both in the field and in laboratories. Some research has been done on the characteristics of these transients [4,5,6]. During switching of small capacitive charging current by disconnecters, a large number of pre-strikes and re-strikes occur (from less than 10 up to hundreds). Every ignition triggers an electromagnetic transient, the amplitude and time characteristics of which are dependant on the circuit configuration. These waves are reflected at every abrupt change of surge impedance in the GIS system. Disconnect switch operation in GIS generates the largest line to ground voltage transients...
imposed on the switchgear during normal operation. The magnitude of transients induced by disconnect operation can be as high as 2.5 pu [7]. The main features of this type of transient are the initial steepness with a risetime between 5 and 20 nanoseconds as well as a subsequent oscillation with frequencies of the dominating fundamental component up to 40 Mhz and of the superimposed harmonics to more than 100 MHz [8,9].

Figure 1.1 A Disconnect Switch Induced Transient

Some work has been done on the calculation and measurement of these transients in GIS [4,5,10,11,12], but there is little published information on the effect of disconnect switchgear transients on conventional equipment connected to GIS.
During the last ten years, a series of transformer and bushing failures have occurred [13 to 17] in Brazil and the U.S after a period of daily GIS switching operations. These experiences lead to the alarming concern that gradual damage may by caused in conventional insulation by repeated impact of transients resulting from normal disconnect switch operation. This process may lead to eventual failure of conventional (oil/paper) insulation in bushings, transformers, cables and other apparatus connected to GIS.

Cellulose impregnated paper insulation is the traditional and most widely used insulation in power transformers and bushings. Many manufacturers and users hesitate to change materials at substantially higher prices when the conventional oil/paper material has proven to work well [18].

In the investigation reported in this thesis, the electric breakdown properties of oil/paper insulation under fast front impulses were studied. A test system to produce a uniform electrical field was designed for the breakdown tests. The test arrangement did not directly simulate the systems used in power equipment. Instead a uniform field geometry was used. This was done so that the basic characteristics of oil/paper insulation under fast front impulses could be investigated. Insulation breakdown voltage vs breakdown time (V-t) data was obtained with different voltage levels. Different numbers of layers insulation were tested and compared to a single layer. In addition, different kinds of paper samples and different impregnants were
investigated in this work. In addition to the tests with fast front impulse (rise time less than 10 ns) (FFI), tests were done with lightning impulse (LI) and switching impulse (SI). $V_{50}$ breakdown values were also measured with different applied voltage waveforms. The $V$-$t$ test results are plotted in histogram and with Weibull distribution. The equal area criterion was used to analyze the fast front $V$-$t$ data, and the low breakdown probability characteristics were calculated. The experimental observations are discussed in the context of known physical breakdown processes for oil/paper insulation and suggestions for future investigation are offered.
2. LITERATURE REVIEW

Cellulose impregnated paper insulation has been widely used in electrical equipment such as cables, transformers, bushings and capacitors, for many years. Although there have been some new materials developed to replace the kraft paper insulation, the traditional oil/paper insulation still plays a major role in power systems. Oil/paper insulation has a relatively low cost and reliable dielectric characteristics. Many manufacturers and users hesitate to change to materials with unestablished long term performance at substantially higher prices if the conventional materials work satisfactorily [18].

SF₆ switchgear operation in power systems cause fast transient overvoltages. They are generated mainly by switching operations of disconnecters. These very fast transients stress components such as bushings and transformers directly connected to the GIS. These transients are characterized by risetimes down to several nanoseconds (5-20 ns) with short duration and amplitudes as high as 2.5 pu [4, 19]. The effect on oil-paper insulated equipment is of particular concern. A literature survey on failures of oil-paper insulated equipment related to the operation of SF₆ switchgear and on the electrical breakdown characteristics of oil-paper dielectric was carried out.
2.1. Field Experience with Failures under Fast Front Transients

There have been reports of some transformer and bushing failures in service due to fast transients generated by disconnect switching in GIS. American Electric Power (AEC) has experienced unacceptably high 765 kV transformer failures at the Rockport 765 kV installation since early 1984. Five 765/25 kV, 500 MVA generator step-up transformers [17] and two 765/138/34.5 kV, 80 MVA reserve auxiliary transformers have failed. All but one of these failures occurred during quiescent system conditions. It was suggested that some transient events caused incipient dielectric damage which later developed into a complete failure under normal system voltage.

There were failures in high voltage bushings and 500/132/13.8 kV 200 kVA single phase transformers connected to the gas insulated switchgear installed at the Grajau substation in Brazil [15,16]. 500 kV oil impregnated paper bushings exploded after being in service for less than two years. It was suggested that high frequency surges, which developed during disconnect switch operation in the GIS could be the cause of bushing insulation deterioration [15]. Some field tests were done and they showed that transients with 25 ns risetimes appeared on the top of the 500 kV transformer bushing during SF6 disconnect switch operations [16].

Fast rise time transients can also affect distribution systems and may endanger distribution transformers [13, 14] and cause anomalous failures. Reference [20]
reports that distribution arrester operation levels for 100 ns risetime transients exceed the standard test wave voltages by 30% for ZnO arresters and 62% for SIC arresters. Thus, it appears that ordinary distribution insulation will need considerably higher short duration withstand capability, compared with standard lightning performance, if it is subjected to fast transients.

2.2. Breakdown Mechanisms in Solid and Liquid Insulation

The breakdown process in combinations of solid and liquid insulation is a very complicated phenomenon. There is not much published information to explain the breakdown mechanisms in solid liquid combinations. However, there is some published theoretical information on solid and on liquid breakdown giving insight into physical phenomena responsible for failure. Such knowledge of failure mechanisms is of great practical importance and will be reviewed in the following sections.

2.2.1. Solid Breakdown Mechanisms

In industrial environments, the same solid materials are found to exhibit a wide range of dielectric strengths. The measured breakdown voltage is influenced by a large number of external factors such as temperature, humidity, duration of test, waveform or voltage applied, pressure applied to the electrodes and many other factors. The fundamental mechanisms of breakdown in solids are not understood as well as those in gases; nevertheless, several mechanisms have been identified and
treated theoretically [21, 22, 23]. Generally speaking there are three kinds of breakdown occurring in solid insulation. They are electrochemical breakdown, thermal electron breakdown and intrinsic breakdown. The dominant mechanism is dependant on the duration of the applied voltage. The regions over which the different mechanism apply are shown in Figure 2.1.

![Figure 2.1 - Variation of Breakdown Strength in Solids with Duration of Stress](image-url)
2.2.1.1. Electrochemical Breakdown

Electrochemical breakdown is caused by partial discharge in solid dielectrics. Solid dielectric material invariably contains some cavities or voids either within the insulation or on boundaries between the layers of dielectric or between the solid and electrodes. These cavities are generally filled with a medium (liquid or gas) of lower breakdown strength than the solid dielectric. Moreover, the dielectric constant of the filling medium is often lower than that of the solid insulator thus making the field in the cavity higher than that in the solid dielectric. Accordingly, under normal working stress, the voltage across the cavity may exceed its breakdown strength and the dielectric breaks down [24,25].

Electrochemical breakdown is a long term breakdown process. Failure by this process can take from several hours to several years.

2.2.1.2. Thermal Breakdown

In insulating materials dielectric losses occur when an electric field is applied to the insulation. The losses include conduction, polarization and ionization losses. These losses increase the temperature of the dielectric and are themselves temperature dependent. In regions where the dielectric losses increase steeply with temperature, the solid insulating material may become overheated and may eventually break down. To obtain the basic thermal breakdown equation, a cube of face area $A$ ($m^2$) within
the dielectric is considered. Assume the heat flows in the x-direction, in Figure 2.2 [24, 25].

For energy balance, the heat input equals the heat conducted away plus the heat used to raise it is temperature $T$.

That is:

$$C_v \cdot \frac{dT}{dt} + K \cdot \frac{dT}{dx} = \sigma \cdot E^2$$

Where $C_v$ is the specific heat of the dielectric

$\sigma$ is the electrical conductivity
K is the thermal conductivity

To solve it, we assume that a critical condition arises and the solid becomes fully conducting. Two limiting cases are considered for equation (2.1).

Case 1 - Assume heat loss can be neglected. The equation reduces to

\[ C_v \cdot \frac{dT}{dt} = \sigma \cdot E^2 \]  (2.2)

Solving equation (2.2) the critical field \( E_c \) can be obtained

\[ E_c = \frac{1}{2} \cdot \frac{3 \cdot C_v \cdot k \cdot T_0^2}{\sigma_0 \cdot U \cdot t_c} \cdot \exp \left( \frac{U}{2 \cdot k \cdot T_0} \right) \]  (2.3)

where \( \sigma_0 \) is the conductivity at ambient temperature \( T_0 \)

\( T_c \) is critical temperature

In this case, the critical temperature \( T_c \) is reached by a fast rise in temperature.

Case 2 - Assume the temperature of the dielectric is at the ambient.

Equation (2.1) becomes

\[ \sigma \cdot E^2 = \frac{d}{dx} \left( K \cdot \frac{dT}{dx} \right) \]  (2.4)

Then the breakdown voltage can be obtained as
$V_c^2 = 8 \frac{K}{\sigma_0 T_0} \int_0^{T_c} \exp \left( \frac{U}{2kT_0} \right) \, dt$  \hspace{1cm} (2.5)

$T_c$ is the critical temperature at which the material decomposes. Under AC fields the heat loss is much greater than under DC fields. Consequently, thermal breakdown strength for an AC field is usually lower than for a DC field, and it decreases with increasing frequency.

### 2.2.1.3. Intrinsic Breakdown

The mechanism which leads to a sudden loss of insulating capability even after a short period of voltage without appreciable pre-heating and without partial pre-discharges is called intrinsic breakdown.

Early theories assumed an ionic mechanism or mechanical destruction as a consequence of field forces on the lattice ions. Intrinsic breakdown must be anticipated in homogeneous, predominantly crystalline materials, and especially during short periods of voltage application [26]. The degree of inhomogeneity of an insulating material has a significant effect on intrinsic breakdown. Unfortunately, the processes involved are not well enough known to enable the design of practical high voltage insulation systems. Several theoretical models have been proposed in an attempt to predict the critical value of the field which causes intrinsic breakdown, but no completely satisfactory solution has yet been obtained. For example, intrinsic
breakdown with times as low as $10^8$ second have been postulated to be electronic in nature. The stresses required for an intrinsic breakdown are well in excess of $10^6$ V/cm. The breakdown criterion is formulated by solving an equation for the energy balance between the gain of energy by conduction electrons from the applied field and loss to the lattice. The models used by various workers differ in the proposed mechanisms of energy transfer from conduction electrons to the lattice, and also by the assumptions made concerning the distribution of conduction electrons.

Early work by Von Hippel [27] forms the basis for a number of theories of intrinsic breakdown. If it is assumed that there will always be a small number of free electrons in an insulating solid which are thermally excited from the valence band to the conduction band. These electrons will be accelerated in an applied electric field. During their general drift, energy will be lost to the lattice of the crystalline material. In this model breakdown occurs when the average rate of energy gain exceeds the energy lost to collisions. Figure 2.3 shows rates of gain and loss of energy as a function of electron energy, W.
A family of curves describes the average rate of gain for various applied fields.

Von Hippel's low energy criterion corresponds to $A(E_c)$, where the rate of gain always exceeds the rate of loss $B$, for all electrons, and no equilibrium is reached. Some experimental data were analyzed by this theory, but the fit is not good [28].

Frohlich [29] developed a high energy breakdown criterion for a pure homogeneous dielectric. This theory is based on the fact that if electrons in thermal equilibrium are distributed then ionizing collisions will take place. Figure 2.3 shows that if $W' < W < W_1$, then energy will be lost to the lattice until stability is gained at energy
For a chance fluctuation creating an electron having an energy in the range $W_1 < W < W_p$, the energy rate gained from the field will be greater than that dissipated. This results in instability and leads to breakdown. At lower fields, energy is lost faster than it can be gained. The highest field for which an equilibrium can be obtained is the high energy criterion adopted by Frohlich.

Streamer breakdown is another short term breakdown mechanism in solid dielectrics. Under certain uniform field conditions, with electrodes embedded in a specimen, breakdown may result after the passage of a single avalanche. An electrode entering the conduction band of the dielectric at the cathode will drift towards the anode under the influence of the field, gaining energy between collisions and losing it on collisions. On occasions the free path may be long enough for the energy gain to exceed the lattice ionization energy and an additional electron is produced on collision. The process is repeated and may lead to the formation of an electron avalanche similar to that in gases.

Under fast transients, intrinsic breakdown mechanisms predominate. The other two mechanisms require much longer formation times.

2.2.2. Breakdown in Liquid

General knowledge of breakdown in liquids is less well established than for gases or solids. Many aspects of liquid breakdown have been investigated over the last
several years [68 to 71]. The electrical breakdown of liquid dielectrics is a complicated process and there is no single theory that explains all the experimental results. The behaviour of insulation liquids is fundamentally different from that of gases and solids. It is governed by impurities and by the ageing process as well as by space charges.

Goodwin and Macfadyen [30] have found that the relationship between breakdown strength $E_{bd}$ and pulse duration can be expressed in the form

$$E_{bd} = C(\tau - \tau_0)^a$$

(2.6)

where C, a and $\tau$ are constants for a given liquid. For impulses with time duration longer than $\tau$, the breakdown stress does not change with the pulse duration and may be compared with the statistical value of breakdown stress.

In general, electrical breakdown in liquids depends on two phenomena [31]:

1. Electron emission from the cathode surface
2. The mechanism of the formation of an avalanche of electrons and ions

Lewis [32] investigated liquid breakdown phenomena and proposed a breakdown theory for an insulating liquid.

According to Lewis, energy can take place quite easily when an electron has energy which corresponds to one of the vibration energies of the molecules. The breakdown stress $E_{bd}$ must satisfy the following relationship:
where $e$ is the electronic charge

$\lambda$ is the mean free path of an electron in the liquid

$h\nu$ is one of the vibration energies of the molecule

$K$ is a constant

The mean free path of an electron can be obtained from the following equation:

$$\frac{1}{\lambda} = \frac{\rho}{M} \cdot N \cdot \sum_{i} n_i \cdot Q_i$$  \hspace{1cm} (2.8)

Where $\rho$ is the density of the liquid

$N$ is the number of molecules per cm$^3$

$M$ is the molecular weight and expression

$\sum_{i} n_i Q_i$ gives the sum of active cross sections for inelastic collisions with those parts of the molecule.

Then

$$E_{bd} = K \cdot N \cdot \nu \cdot e^{-1} \sum_{i} n_i \cdot Q_i$$  \hspace{1cm} (2.9)
The loss of an electron energy on path passing through a potential barrier in a molecule is shown in figure 2.4.

![Figure 2.4 Variation of $\Delta E/\lambda$ with $E$](image)

The energy an electron gains from the field is shown in the straight line AB. The electron continues to gain energy from the field to the ionization energy level, $I$, for energy greater than B. The condition $B=I$ was accepted by Frohlich and Lewis as the breakdown criterion. Based on this, Lewis [32] developed a theory of breakdown for a group of saturated hydrocarbons. A critical energy level for electrical
breakdown is assumed. He obtained the following expression for breakdown stress, $4E_{bd}$, for this group of liquids:

$$E_{bd} = k \cdot N \left( n_1 Q_1 + n_2 Q_2 + n_3 Q_3 \right)$$  \hspace{1cm} \text{(2.10)}$$

Where $n_i$ is the number of groups of type $i$ in the molecule and $Q_i$ is the active cross section for energy exchange for group $i$.

Another breakdown theory in liquid has been proposed by Adamczewski [34]. This theory is based on the assumption that the active cross section for the retardation of electrons accelerated by the field is proportional to the longitudinal geometric cross sectional area of the molecule. The breakdown criterion is based on the assumption that the energy gained by the electron on its mean free path $\lambda$ from the electric field $E$ ($L = eE \lambda$) is not less than the energy which retards the electron on this path:

$$e \cdot E \cdot \lambda = E_0 - h \cdot \nu$$  \hspace{1cm} \text{(2.11)}$$

since

$$A (n - 1) \cdot \frac{\rho}{M} = \frac{1}{\lambda}$$
We obtain

\[ e \cdot E = h \cdot v \cdot A(n-1) \frac{\rho}{M} \]  \hspace{1cm} (2.12)

Where \( A = 2rh_0N \) is a constant for a whole series of the liquids.

The final equation for breakdown stress in term of the parameters characterizing a given liquid (\( \rho \), \( M \), \( n \)) has the following form:

\[ E = E_{bd} = \frac{h \cdot v}{e} A(n-1) \frac{\rho}{M} = B(n-1) \frac{\rho}{M} = B \cdot Z \]  \hspace{1cm} (2.13)

Where \( A = 2rh_0N \)

\( B = \frac{A}{(h \cdot v / e)} \)

\( Z = (n-1) \frac{\rho}{M} \)

\( \rho \) - the density of liquid

\( M \) - the molecular weight of the liquid

\( N \) - Avogadro's number
Ward and Lewis [35] proposed a statistical theory for liquid breakdown. A breakdown probability is given at time $t$ between the limits $t$ and $t + dt$

$$P(E)\, dt = W \cdot I \cdot \exp[-W \cdot I \cdot (t - t_1)]\, dt$$

(2.14)

This equation is based on a step function voltage being applied to a liquid. In this equation, $t_1$ is the formative time lag and $1/W$ is the mean statistical time lag. The parameters $I$ and $W$ will be functions of the electric stress and a threshold stress $E_0$ is assumed below which $P(E) = 0$.

The probability of breakdown occurring when a pulse of duration $T$ is applied to the liquid is:

$$P(E) = 1 - \exp[-W \cdot I \cdot (T - t_1)]$$

(2.15)

The probability $P(E) = 0$ if $E < E_0$ or $T < t_1$.

If at each level of the voltage $N$ pulses are applied then the probability of breakdown occurring in the range $E$ to $E + dE$ is:

$$P_m = 1 - (1 - p_m)^N + 1 - \exp[-I_m W_m TN]$$

(2.16)
An expression for breakdown probability for this type of test can be more conveniently expressed in terms of a continuous variable $Q(E)$. If $Q(E)dE$ is the probability of breakdown occurring in the range $E$ to $E+dE$ then

$$Q(E) = \lambda \cdot P(E) \cdot \exp \left[ -\lambda \int_{E_a}^{E} P(E') \, dE' \right]$$

(2.17)

Where $\lambda$ is the number of pulse applications in a unit interval of stress.

A streamer theory was used by Breitfelder [36] to study the breakdown behaviour of transformer oil under high frequency voltages and compared it with lightning and switching impulses voltages. Breakdown measurements and V-t characteristics with square wire and circular wire-plane electrodes in different insulating oils were obtained for AC, LI and SI voltages. The authors concluded that:

Breakdown voltages in dry clean oil for AC and SI can be described by a streamer theory and for 1.2/50 $\mu$s and 1/10 $\mu$s impulses the volt-time area law can be used with satisfactory conformity to the measurements.

Kojima and co-workers developed a theory of impulse breakdown of oil-filled cable [37]. They proposed that the breakdown is caused by the stress increase due to the propagation of partial breakdown. The theory is based on past experimental data and is capable of explaining the observation that the breakdown strength decreases with increased conductor size.
Knorr and co-workers [38] applied streamer theory to AC and impulse breakdown in dry transformer oil. The streamer theory states that a primary electron sets off an electron avalanche. This avalanche changes the original electric field. If the space charge field of the avalanche is sufficiently high, secondary avalanches arise from photo ionization. A rapidly advancing conducting plasma is formed in this way.

The classical work on this subject has been carried out by Halpern [39, 40, 41] who investigated experimentally and theoretically the field emission and field ionization process in various liquids. Several other papers on this subject include a variety of insulating liquids [42 to 46].

Beside electron emission from the cathode surface into the liquid, the phenomena of collisional ionization and avalanches in the liquid itself are also important. The theory of these phenomena is based on the theory of ions in gases, which has been extensively studied and confirmed. A review of these studies is given by Von Engel [66].

2.3. Influence of Parameters

The following section reviews the effect of the different parameters on the breakdown voltage. Factors such as the physical properties of the paper and impregnant, electrode shape and material, applied waveforms and polarity as well as charge accumulation are considered to be relevant to the breakdown phenomena.
2.3.1. Effect of Thickness of Solid Paper Dielectric

Standring and co-workers did some work on breakdown under impulse voltages of solid and liquid dielectrics in combination (such as oil impregnated paper and pressboard) [48]. They investigated different solid dielectrics. The results show that for single sheets and for N sheets of thickness of t in contact with each other, the puncture voltage of pressboard between electrodes spaced N×t apart is roughly proportional to \(N^{0.9} \times t^{0.8}\). For two or more sheets separated by oil the puncture voltage increases with the oil gap at a rate which is greater for thin than for thick sheets. The samples used in Standring's tests were single sheets of pressboard and phenol-formaldehyde-resin-bonded paper containing 50% resin.

Hall investigated impulse strength of lapped impregnated paper dielectric using a model cable [49]. Variations of the physical properties of paper, such as thickness, density and permeability of the paper, were investigated. Under 1/50 µs impulse voltages, the impulse breakdown stress reduces approximately linearly as the thickness of paper increases. The impulse breakdown stress increases as the paper density increases. Although the impulse strength increases with increase of impermeability and uniformity the separate effects are smaller than that of density alone. He pointed out that for impulse strength, the effect of the thickness of the paper is more important than all other properties of the paper.
Gazzana Priaroggia [50] investigated oil impregnated paper breakdown properties under 1/50 $\mu$s impulse voltages using a plate capacitor model. Paper impermeability, density and sheet thickness were investigated. The main results are: When the impermeability is increased from $2 \times 10^5$ to $2 \times 10^6$ EU (40 to 300 Gurley seconds), the impulse strength increased from 105 to 132 kV/mm.

2.3.2. Effect of Paper Density

Gazzana [50] showed that within the density limits of 0.70 to 0.85 g/cm$^3$ appreciable variations in impulse strength is not observed. However, there is no data related to high density paper having the same impermeability. The investigation also showed that the impulse strength decreases with increase in sheet thickness.

Nelson and co-workers investigated impulse breakdown of oil-paper insulation in transformer oil duct spacer insulation [51]. This work helped to determine the effects of geometrical factors and examined the nature of the pre-breakdown light emission under 1/50 $\mu$s impulses. An oil duct was modelled by using two copper conductors covered with lapped kraft paper and separated by pressboard spacers. Breakdown voltage was obtained as a function of kraft paper thickness with constant duct spacing and as a function of constant kraft paper thickness with different duct spacing. The authors concluded that the failure under impulse voltage excludes the mode of failure reliant on a cavitation model. It is suggested that failures remote
from the spacer for the parallel duct configuration are the result of the volume-area effect.

2.3.3. Effect of Electrode

An investigation by Strandring found that the puncture voltage of solid dielectric sheet or pressboard appears to be independent of the shape of the electrode [48]. His test arrangement was a single sheet of pressboard and phenolformaldehyde-resin-bonded paper containing 50% resin, with one electrode a plane and the other a sphere of 50 mm diameter or a sharp-edged cylinder.

Hall [49] did tests on lapped oil impregnated paper insulation with a simple coaxial electrode system. The inner H.V. electrode was a hollow tube and the outer electrode was formed by a layer of metallic foil. The inner electrode had a length of 12 inch and an external diameter of 5/8 inch. Three kinds of H.V. electrode material (copper, aluminum, rhodium) were examined. The results showed that the impulse strength was independent of the inner electrode material. He also examined different outer electrodes (lead, tin, aluminum and copper). These results showed that the highest impulse strength value occurred with lead and the lowest occurred with tin and aluminum.

The results of this experimental investigation included the effect of electrode area. The statistical analysis shows that there is a significant linear relationship between
impulse strength and the logarithm of electrode length (for a fixed 5/8 inch diameter), the breakdown strength decreased by 2% as the electrode length was doubled.

Gazzana [50] examined the influence of the surface finish of the electrode. He used a flat smooth surface electrode and a flat surface with a radius of curvature of either 0.5 or 1 mm in his investigation. The results show that the impulse strength decreases from 132 kV/mm for plane electrodes to 105 kV/mm for electrodes having corrugations with a radius of curvature of 1 mm. It does not show a difference between results obtained with a radius of curvature of 0.5 mm and those obtained with a radius of 1 mm on the inner electrode surface.

Some research work has been done by Naidu on oil impregnated paper insulation [51]. Various electrode systems were used to obtain a better understanding of the processes involved in the breakdown phenomenon. The electrode systems were:

a) rod (10 mm dia.)-plane electrode,

b) modified rod-plane electrode (12.7 mm dia. rod with a 2 mm dia. needle),

c) uniform field, epoxy-cast, composite electrode system (16 mm dia. cylindrical electrode with 3 mm radius rounded edge) and
d) nonuniform field, epoxy-cast, composite electrode system (16 mm dia. cylindrical electrode with sharp edge).
He tested a single layer of oil impregnated paper. The lightning impulse breakdown probabilities were obtained. The author indicates that the general behaviour of the breakdown probabilities, as a function of the normalised gradient, appears to support a model based on charge injection from the cathode followed by the generation of intense local fields arising from structural fluctuations.

2.3.4. Effect of Polarity

In Standring's investigation [48], the puncture voltage of solid dielectric sheets and pressboard was found to be independent of voltage polarity in an arrangement with one electrode a plane and the other a sphere of 50 mm diameter or a sharp-edged cylinder.

On single conductor mass-impregnated paper insulated cable, a comparison of the mean negative and positive puncture voltage showed that the positive puncture voltage exceeds the negative value by 5 to 7% [52].

Hall also examined the effect of impulse polarity on oil-impregnated paper dielectric cable [49]. It was found that the polarity of the conductor has no significant effect upon the impulse strength.
2.3.5. Effect of Repeated Impulses

The results from some solid and liquid dielectrics in combination [48] show that accumulation effects do exist. The 100 shot puncture voltage with impulses of one polarity is about 15% below the single shot value. With impulses of alternate polarity the reduction is about 25%. For mass-impregnated paper insulated cables, the test results show that an increase in the number of applications at each voltage level from two to a hundred causes a reduction of approximately 10% in the puncture voltage [52].

Hall [49] found that there is a decrease of approximately 13% in the breakdown strength, as the number of applications, at each voltage level, is increased from 1 to 200.

Davis [53] observed a similar reduction using groups of 200 impulses.

2.3.6. Effect of Waveform

The puncture voltage of two 1.6 mm phenol-resin-bonded paper and pressboard is not affected by voltage duration at small spacings but is some 30% higher for 1/5 $\mu$s than for 1/50 $\mu$s impulses at large spacings [48]. This is consistent with time lags observed with 1/50 $\mu$s waves, which were of the order of a microsecond at small spacings and up to 50 $\mu$s. at large spacings.
Impulse puncture results of mass-impregnated paper insulated cables under different waveshapes ranging from 1/5 $\mu$s to 1/250 $\mu$s as well as 11/85 $\mu$s are shown in table 2.1 [52]. The samples are 0.5, 0.25 and 0.15 in single-conductor mass-impregnated paper-insulated cables. The differences in puncture voltage for the different waveshapes was not significant.

Table 2.1 Effect of Waveshape on Negative Puncture Voltage

<table>
<thead>
<tr>
<th>Waveshape</th>
<th>0.15 in² cable</th>
<th>0.5 in² cable</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of cable Samples</td>
<td>Puncture voltages</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>Minimum</td>
</tr>
<tr>
<td>1/5</td>
<td>10</td>
<td>615</td>
</tr>
<tr>
<td>1/50</td>
<td>10</td>
<td>600</td>
</tr>
<tr>
<td>1/250</td>
<td>10</td>
<td>615</td>
</tr>
<tr>
<td>11/85</td>
<td>6</td>
<td>610</td>
</tr>
</tbody>
</table>

Work done by Grzegorz [67] focused on the effect of different risetimes of switching impulse voltages on oil-paper insulation breakdown. During these tests the impulse rise time was changed from 1.5 $\mu$s to 1200 $\mu$s. The results show the mean value of the breakdown voltages of the tested oil-paper insulation at steep switching impulses (rise time about 1.5 $\mu$s) is lower than that for a standard switching impulse. The differences measured for the individual test series were approximately 4% to 17%. According to the above report, the breakdowns accumulate in the front part of the wave for steep impulses. For impulses with long fronts (although the breakdowns accumulate mainly near the peak value) a great number of them also occur after longer times.
In the opinions of the authors, the test results indicate that there are different mechanisms of discharge development in oil/paper insulation. These differences are caused by the rate of voltage increase on the front of the switching impulse, not by the duration of the voltage.

Gazzana discussed the difference between 1/50 μs lightning impulses and several oscillating switching surges (from 600 Hz to 2500 Hz). The results show that the dielectric strength values do not change for this frequency range, and the dielectric strength values under switching surges are substantially lower (from 7% to 20%) than the lighting impulse strength value [55].

Watson did some research on the electric strength of Perspex as a function of voltage rise time [56]. The test results are shown on Figure 2.5.

![Figure 2.5 The Electric Strength of Perspex](image)

A, Sphere-Sphere Electrodes; B, Point-Plane Electrodes, Negative; C, Point-Plane Electrodes, Positive
The conclusions are:

The impulse strength of Perspex depends on voltage rise time for both sphere-sphere and point-sphere electrodes. The observations are consistent with the accumulation of space charges close to the electrode, positive at the anode and negative at the cathode, reaching their maximum values in a time between 177 $\mu s$ and 1000 $\mu s$. Charge migration is assumed to be responsible for the subsequent fall in electric strength at longer rise times.

Dzikowski [54] investigated the breakdown strength of three different models of oil-paper insulation. Those models closely approximated some features of interturn insulation of transformers. The 50% breakdown voltage for the 1.5 $\mu s$ risetime lightning impulse was lower than for the switching impulse (250/2500 $\mu s$) by at least 5% with a maximum difference of 17%. From the time-lags of breakdown it was observed that for fast impulses the breakdown occurred during the rising portion of the impulse whereas with slow impulses it occurred during the tail portion of the wave.

2.3.7. Effect of Impregnant

Hall [49] found that the impulse strength of lapped impregnated paper increases with oil viscosity.
Gazzana's work [50] shows that for impregnated paper the impulse strength varied from 132 kV/mm for treatment with thin mineral oil to 161 kV/mm for a compound of thick cable oil plus 30% resin.

2.4. Test System

Several kinds of test systems have been used in testing oil-impregnated paper insulation. One type is the plate capacitor test system [50] which consists of two circular flared electrodes made of steel with plane circular surfaces facing each other and having a 7 cm diameter. The electrode surfaces can be made purposely smooth or corrugated, and the dielectric interposed between the electrodes consists of a number of circular paper disks. This capacitor is set in a cylindrical container which is air-tight and has a cover connected to a H.V. bushing. Another test cell system described by Gazzana [50] is a cylindrical capacitor test system. This test system consists of a 2 metre long metal rod inner electrode, and around this inner electrode insulated paper tapes are helically wound in order to build up a certain dielectric thickness. The outer electrode is obtained by means of a helically wound metal tape. The edge effect is minimized by two impregnated paper "stress cones" at the ends of the rod. Test results with these two systems show good agreement [50].

The test system used in Hall's investigation [49] was a coaxial electrode system. The inner electrode was a hollow tube and the outer electrode was formed by a layer of
metallic foil. The inner electrode was 12 in. long and 5/8 in. diameter. The thickness of dielectric used was 0.02 in.

Standring [48] used a similar plate capacitor system to test pressboard. In his system, one electrode is a plane and the other a sphere of 50 mm. diameter or a sharp-edged cylinder.

In Naidu's test system [57], a parallel electrode system was used. The high voltage electrode was a stainless steel rod with a rounded edge and was encapsulated in epoxy. The ground electrode was a stainless steel plate. The paper sample under test could be moved between the electrodes by a drive system, after each breakdown.

2.5. Time to Breakdown of Oil/Paper and Oil Insulation under Fast Front Waveform

There is not much work done on time to breakdown of oil/paper insulation and the breakdown characteristics are not well understood in this area. The research done on oil and oil/paper insulation under fast front impulses in the microsecond to submicrosecond range in recent years is reviewed in the following section.

Claire Vincent did a project on oil breakdown with steep-front voltage transients [58]. Two impulse waveforms were used in the tests (standard lightning 1.2/50 µs and steep-front 60-90 ns/7 µs). A sphere-plane gap and a needle-plane gap were selected
for the tests. About 100 breakdowns tests were made at different voltage levels to obtain the V-t characteristics of the test gaps.

The results show that the V-t curve of the sphere-plane gap is quite flat over the range of time-to-breakdown investigated (0.2 - 1.7 µs), for positive polarity lightning impulses. For longer time-to-breakdown values, the lower breakdown voltages indicate a decreasing trend for the V-t curve. The lightning impulse V-t data is shown in Figure 2.6. On the other hand, with a steep front impulse, the V-t curve for the sphere-plane gap shows an increasing trend over the range from 30 to 250 ns as shown in Figure 2.7.

The needle to plane gap results are shown in Figures 2.8 and 2.9. The main conclusion from this work is that the V-t curve results with quasi-uniform and non-uniform field configurations show a tendency of increasing breakdown voltage with shorter time to breakdown and they suggest that additional data are needed for other insulation materials used in power equipment. It is also pointed out that oil-paper insulating systems are very vulnerable, especially power transformers, because of susceptibility to breakdown. Time to repair and high costs are consequences of breakdown.
Figure 2.6  V-t Curve under Lightning Impulse (Sphere-Plane Electrodes) [58]
Figure 2.7 V-t Curve under Steep Front Impulse Voltage

(Sphere-Plane Electrodes) [58]
Figure 2.8 V-t Curve under Steep Front Impulse
(Needle-Plane Electrodes) [58]
Figure 2.9 Extension of the V-t Curve under Steep Front Impulse

(Needle-Plane Electrodes) [58]
Herstad did some work on solid transformer winding insulation and liquid and solid interwinding insulation systems [59] that shows a steep increase of the breakdown voltage with shorter times-to-breakdown of between 0.3 and 1 $\mu$s.

National Institute of Standards and Technology of USA (NIST) did research work on fast front pulse breakdown in oil, [60]. The objective of their research was to understand the mechanisms of electrical failure in practical insulation materials used in power systems apparatus. The test results show a V-t curve as shown in Figure 2.10.

![Figure 2.10 Time to Breakdown in Oil](image_url)
The electrode system used in the test (NIST) is a needle with 3 μm radius placed 5 mm from a sphere. As the breakdown time decreased to the range of a few microseconds, the breakdown voltage began to decrease. When the breakdown times decrease and become significantly shorter than one microsecond, the breakdown voltage continues to increase figure 2.10. The explanation for the observed V-t characteristics is that the breakdown voltage depends on the relative time the streamer spends in the slow and fast propagation modes. There is no definition of slow and fast propagation modes in the paper. The breakdown voltage increases dramatically when the streamer is entirely in the fast mode and the time to breakdown is forced to decrease further [60].

The author believed that the fast propagation modes are more energetic than the slower modes. It is hypothesised that a piece of paper insulation may stop the slower mode, but may not stop the faster mode. In the same investigation, some tests were done by interposing a paper interface between the needle electrode and the spherical electrode. The position of the paper in the gap can be varied relative to the electrodes. The authors were unable to determine whether or not a fast pulse can break down a paper interface at a lower voltage than a slow pulse can; thus pointing out the need for more work. There is, however, some evidence that fast pulses can produce anomalously low voltage failure of an interface.
The authors indicate:

If partial discharge activity is present in power apparatus, then particles (carbon particles) are being generated and results indicate an increased susceptibility to anomalous failure due to fast pulses which generate the fast streamer processes. The authors indicated more work is needed to isolate the parameters which may combine to permit an anomalous failure.

Some measurements have been done on time to breakdown of oil impregnated paper insulation under fast front step voltages [51, 57, 61]. The purpose of the work was to study the dielectric breakdown of oil-impregnated paper insulation in the submicrosecond and microsecond regime. The tests were done in oil on 0.13 mm thick paper between a plane electrode and a plane electrode, 10mm in diameter with a rounded edge, embedded in filled epoxy resin. The tests were done with standard lightning impulse and with a step voltage with a rise time of about 5 ns. A model has been proposed for the breakdown time lag probabilities [57]. The proposed model relies on charge injection from the cathode followed by generation of intense local fields arising from structural fluctuations within the dielectric. The time to breakdown results and calculated probability curves are shown in Figure 2.11. Another method used to analyze the test data is a two stage breakdown model [61]. By using this model, it is supposed that with the same group of data low probability curves can be calculated.
Figure 2.11 Fast Front Breakdown V-t Characteristics

for 0.13 mm Thick Oil/Paper Insulation
2.6. Purpose of the Research Program

The literature review found a number of major trends in the breakdown characteristics of oil/paper insulation:

- The breakdown strength decreases as paper thickness increases.
- For pressboard the puncture voltages tend to be independent of shape of electrode.
- The breakdown strength of oil/paper insulation with smooth electrode surfaces has a higher value than the one with corrugated surface. As electrode area increases, the breakdown strength decreases slightly.
- It was found that polarity of applied voltage has no significant effect on breakdown strengths.
- Results show there are significant accumulation effects. The breakdown strength is significantly reduced when the insulation is subjected to multiple impulses.
- The trend is that as the rise time of the waveform increases the breakdown strength decreases.

This review shows that fast front voltages, such as those produced during routine switching operations in GIS equipment, appear to have caused major failures in conventional oil/paper insulated equipment connected to the GIS. There has been very little work done on investigating the properties of oil/paper insulation subject to fast front transient overvoltages. The work that has been done gives some
indication that the breakdown strengths under fast front impulses may be lower than the breakdown strength under longer rise time waveforms.

A lot of work has been done on lightning and switching breakdown characteristics. The lightning impulse withstand test generally applies to all equipment and this test voltage is defined as the B.I.L (Basic Insulation Level). However, for the fast front transient more work needs to be done on determining the V-t characteristics of breakdown strength of oil/paper insulation. This investigation gives basic information useful for the manufacture design of equipment such as transformers, bushings etc.

In electric power apparatus/systems the insulation is designed in two ways. One is to limit the overvoltages with protective devices. The other is to choose the insulation for the components such that they will withstand the overvoltages encountered in the system. Conventional methods of insulation coordination provide a margin of protection between electrical stress and electrical strength based on the predicted maximum overvoltage and minimum breakdown strength. The dielectric strength of insulations is usually determined by laboratory tests. The electrical breakdown is governed by statistical laws and it has a random character. The risk of failure for the insulation or equipment can be determined by the following calculation
\[ R = \int_0^{\infty} P_b(V_k) \cdot P_0(V_k) \, du \]

\( P_b(V_k) \cdot P_0(V_k) \, du \) is the probability that insulation will breakdown at an overvoltage \( V_k \). The description of the risk of failure is shown in Figure 2.12.

![Figure 2.12 Method of Describing the Risk of Failure](image)

The focus of this investigation is to determine the electrical breakdown characteristics of oil/paper insulation under fast front impulses. Practical equipment such as transformers have complex insulation structures and the electric field distribution is not uniform under fast transients. There are many factors that contribute to insulation breakdown. This investigation focuses on the effect of fast impulses on a simple structure of oil/paper insulation in a uniform field. In this investigation the
breakdown strength is measured under different waveforms such as fast front impulses, lightning and switching impulses, and V-t data is collected under different voltage levels. Different kinds of paper, different thickness of paper and different number of layers as well as different impregnant were investigated in this work.
3. GENERATION OF FAST FRONT IMPULSE VOLTAGES

In this section the generation of fast front impulse voltages and measuring systems for these voltages will be discussed.

3.1. Fast Front Waveforms

There are several types of fast front voltage waveforms used for research and testing of power system equipment and insulation. One of the most familiar fast front waveforms used is the lightning impulse. It has a risetime from several tens of nanoseconds to several microseconds. The IEEE standard waveform for lighting impulses is $1.2/50\ \mu s$ [62] (see Figure 3.3).

A second type of fast risetime waveform that has been used is the transient that is caused by disconnect switching in GIS systems. The risetime of this transient is from 5 to 20 ns and has an oscillating characteristic. The fast front step waveform is widely used in experimental physics research as a power pulse sources. It is not commonly used in high voltage electrical research. This type of waveform is much more difficult to produce than the standard lightning impulse. There is no "standard" method for producing this type of waveform.
3.2. Fast Front Waveform Generators

3.2.1. The Marx Impulse Generator

There are several basic circuits used to build fast front voltage pulse generators. The one most widely used is the Marx circuit which has been in use for more than fifty years. In earlier days, Marx generators were mainly built for the testing of high voltage equipment to insure that they could withstand the high voltage surges caused by lightning, switching and short circuit faults. Marx generators are relatively easy to design and build, and function reliably for long periods. Modern Marx generators built for laboratory use in the UHV-range operate at up to 6000 kV [63]. Lightning and switching impulse voltages can be generated by this generator.

In addition to being used directly to produce the required voltage waveform a number of other fast front pulse generators are based on using the Marx generator as an input high voltage source.

The basic circuit of a single stage impulse generator is shown in Figure 3.1. In this circuit, C1 is much greater than C2 and R2 is much greater than R1. The front time
of the impulse depends mainly on $R_1$ and $C_2$. The tail time of the impulse depends mainly on $R_2$ and $C_1$. The output voltage is described by the following equation (the waveform is shown in Figure 3.2):

$$V(t) - V_{c_1} [e^{-\frac{-t}{R_2.C_1}} - e^{-\frac{-t}{R_1.C_2}}] \quad (3.1)$$

Figure 3.1 - Single Stage Impulse Generator Circuit
Figure 3.2 - The Impulse Voltage Wave and its Components

The single-stage circuit was not suitable for generating high voltage impulses greater than about 250 kV because of the difficulties in obtaining high dc voltages for initial charging. In order to get higher output voltages, Marx suggested a circuit in which a number of capacitors are charged in parallel through resistances and discharged in series through spark gaps. This type of generator is commonly given his name.

The advantages of the Marx generator are that it can generate a very high output voltage (up to several MV), reasonably high power (several hundreds of kJ), it is straightforward to construct and it functions reliably. One of the major
disadvantages of the conventional Marx circuit is that it is very difficult to generate a waveform which has a front time in the nanoseconds range. The risetime is usually greater than 100 ns. This is caused by the series inductance and stray capacitance as a result of physical size of the circuit and the inherent time-delay in spark initiation in the various spark gaps.

3.2.2. Cable or Pulse Forming Network (PFN) Generators

Cable generators have been used to generate high voltage square pulses for many years. The basic circuit for cable pulses generators is shown in Figure 3.3.

![Cable Generator Circuit](chart.png)

Figure 3.3 - Cable Generator Circuit
This circuit operates as follows:

A length of cable is charged from a power supply, either DC or AC, until its voltage reaches a chosen value. Then the switch is closed and the cable discharges through the resistive load. If the resistance value is chosen to equal to the surge impedance of the cable, a square voltage pulse is developed across the load resistance. The pulse duration is twice the transit time of the cable. In a matched condition the pulse voltage is equal to \( V_0/2 \) (where \( V_0 \) is the charging voltage of the cable).

In practice, the coaxial cable can be replaced by a pulse-forming-network (PFN). The PFN consists of a series of lumped capacitances and inductances. The operation principle is similar to the cable pulse generator. In order to obtain higher output voltage pulses, two PFN's can be charged in parallel through the inductances and discharged in series through a rotational gap and a stationary gap. With proper design the cable and PFN pulse generator can give a very steep front square pulse waveform and the circuit is not complicated. However, the output voltage is limited by the cable or PFN voltage rating.

### 3.2.3. SF\(_6\) Insulated Steep Front Pulse Generator

In recent years, a large number of fast front SF\(_6\) transient generators have been built in various laboratories. These generators have been used for SF\(_6\) research work such as investigating the behaviour of SF\(_6\) insulation and traditional insulation connected to SF\(_6\) equipment.
The SF$_6$ fast front transient generator is similar to the cable pulse generator. An SF$_6$ bus replaces the normal pulse cable. Compact SF$_6$ bus can be operated at high voltages and the spark gap in the pressurized SF$_6$ has a sharp breakdown voltage. These characteristics of the SF$_6$ bus and gap endow the SF$_6$ pulse generator with unique features.

One example of such a fast risetime generating system, designed by the Graz University of Technology [64], is shown in Figure 3.4. It is used for testing different dielectrics under fast transients. This pulse generating system consists of a pulse forming network and a charging voltage source. The pulse forming network consists of a 19 metre coaxial line, which is charged to twice the test pulse voltage, and a 71 metre coaxial test line. The test line and charging line are connected by a SF$_6$ spark gap. The end of the test line is terminated by its surge impedance to avoid disturbing reflections. By changing the SF$_6$ gap distance and the pressure, a 10 kV voltage pulse with a 1 ns risetime and 146 ns duration can be generated in the system. The risetime can be changed by installing a coaxial smoothing capacitance behind the spark gap.
A coaxial measuring device was constructed to measure the output of this generating system. It is designed for fitting into the coaxial test line. The high voltage capacitance of the divider is formed between the high voltage electrode and the tapping layer of the probe. The low voltage capacitance of the divider is formed by a Polyethylene Terephthalate (PETP) foil of 100 micrometer thickness. The foil and tapping layer of the probe is pasted on to the tube wall. The dimensions of the tapping layer in the axial direction is designed with regard to making the upper cut off-frequency as high as possible. The arrangement has a defined surge impedance,
so a plane wave front can be assumed. To obtain high natural frequencies the low voltage capacitance was small. In this system the high voltage capacitance C1 was about 0.03 pf, and the low voltage capacitance, C2, about 37 pf. The measuring circuit is given in Figure 3.5.

![Diagram of Capacitance Divider and Measuring Circuit]

Figure 3.5 - Measuring Circuit

Another very fast transient (VFT) generating system was built at the Technical University of Munich [65]. This system consisted of 420 kV GIS components. A Marx generator was employed as a voltage source. A variable spark gap separated the SF₆ bus into a charging line and a load. The length of both sides was variable, using different bus sections L1 and L2. The fundamental frequency of the generated
VFT waveform could be changed from 10 MHz to 45 MHz. A 24 kilo-ohm resistor was inserted into the vertical part of the source side. This resistor created an open end for travelling waves inside the GIS. In this way, the bushing was protected and the damping of the VFT amplitude is reduced to about 2% per cycle. The measuring system was formed by a capacitive divider and an active FET probe. It provided a bandwidth up to 500 MHz at measuring point M1. The signals were stored in a digitizer with a sampling rate of 1 Gigasample/s and 8 kbyte memory for each channel. This system has been used to study the statistical time-lag of SF₆ breakdown under strong very fast transient inhomogeneous fields.

In conclusion:

1. The Marx circuit is a very useful circuit. It can generate a very high voltage impulse with a risetime of several hundred nanoseconds. By using a special Marx generator, a very fast pulse can be generated with a risetime of a few nanoseconds. In this case, the output voltage is usually several hundred kilovolts. The Marx circuit can also be used as the high voltage source for another pulse generator.

2. Cable and pulse forming network pulse generators can generate very fast pulses with risetimes of about a nanosecond, but the output voltage is limited and the cable and load impedances have to be matched. It is usually used for lower voltage and to generate fast risetime square pulse waveforms.
3. SF$_6$ insulated fast risetime pulse generators have been developed recently. Different waveforms can be generated by changing the configuration of the SF$_6$ bus. The SF$_6$ insulated generator can be used to generate very high voltage pulses with very fast risetime from a few nanoseconds to several tens of nanoseconds. Single or recurrent pulses can be generated by SF$_6$ pulse generators.

4. It is not feasible to measure the fast risetime pulse with conventional impulse dividers. The built-in capacitive divider and measuring system suffices to measure the fast risetime pulse. This kind of measuring system has a very fast response time and a wide bandwidth.
4. EXPERIMENTAL ARRANGEMENT AND PROCEDURE

4.1. Introduction

The experimental set up used for the research program will be discussed in detail. It includes a description of the fast front voltage generation and measuring system as well as a description of the oil/paper insulation test cell set up, electrodes, geometries etc.

4.2. Description of the Fast Front Waveform Generator

4.2.1. Fast Front Waveform Generator

The generating system consists of four main parts; the Marx impulse generator, the SF$_6$ bus and the SF$_6$ chamber. The generating system configuration is shown in Figure 4.1.

The generating system circuit is shown in Figure 4.2. The Marx impulse generator has 5 stages. The capacitor in each stage can be charged up to 100 kV. By changing the front resistance R1 and tail resistance R2, the output waveform can be changed. The front capacitance (C1) is 1600 pF. The number of stages used is determined by the voltage required.
Figure 4.1 - Generating System Configuration
Figure 4.2 - Generating System Circuit Layout
A 6 meter long 230 kV GIS bus is used in this generating system as the fast front waveform forming part, with a Marx generator as the high voltage charging source. The Marx generator was configured so the output wave tail is about 2300 \( \mu \text{s} \) and the front time is about 1 \( \mu \text{s} \).

The voltage from the Marx generator is injected into the bus through a SF\(_6\) insulated bushing. A test chamber is located on the other end of the bus. The test chamber includes a series spark gap and a high voltage electrode connected to ground through a 250 megohm resistor. The spark gap consists of a fixed 5 cm diameter sphere attached to the bus and a movable 1 cm diameter stud. The gap can be adjusted from 0 to 5 cm from the outside of the chamber. The test chamber is air-tight and can be pressurized separately from the rest of the bus. It has good electrical shielding from outside noise.

The high voltage electrode in the chamber is a 30 cm diameter disk on an insulating support. The test object can be placed on the top of this high voltage electrode.

In order to generate the proper fast front waveform, the design of the spark gap in the SF\(_6\) chamber is very important. The original design used a 5 cm diameter sphere at the bushing side of the gap and a 1 cm diameter sphere on the high voltage test electrode side. This arrangement produced a good waveform with a steep rise time (5-10 ns). However, the gap did not break down consistently on the tail of the
applied impulse waveform. Some of the breakdowns occurred on the front of the impulse waveform. This resulted in a non-square test waveform.

Replacing the 1 cm sphere with a needle produced a consistent breakdown on the tail of the impulse waveform but the test waveform risetime was too long (20-30 ns). The needle was then replaced with a 0.6 cm diameter stud. This gap has a consistent breakdown on the relatively flat tail of the waveform when it is correctly adjusted. The risetime of the test waveform generated is also very good (5-10 ns). When this gap was pressurized with SF$_6$ gas at 1.3 kPa the gap spacing could be kept small for the higher test voltages, which ensured that the risetime remained low. The gap breakdown was not highly sensitive to gap spacing. This meant that setting the gap for a given voltage was not difficult. This gap design was used for all the tests. It is shown in Figure 4.3.
4.2.2. Waveform Measurement

The pulse generator utilizes a specially designed voltage measuring system. A built-in capacitive voltage divider is mounted on one side of the test chamber. It is placed in such a position that the HV electrode shields it from the series gap and the GIS bus conductor. The HV capacitance, $C_1$, of the divider is formed between a rounded disk extension of the HV electrode and a 5 cm diameter circular area on the top surface of a 0.010 inch thick PTFE insulated double sided circuit board. The LV capacitance, $C_2$, is formed between the two sides of the circuit board. A special coating technique (vapor-reaction film) has been employed to bond copper on the two sides of the teflon board. This technique produces no gaps between the teflon
and the copper. In this way the value of C2 is kept constant. The ratio of the capacitive divider can be changed by adjusting the size of the opening in the wall of the test chamber in front of the teflon board. Reducing the size of this aperture reduces the magnitude of C1.

The output of C2 is connected to a buffer amplifier mounted on the back of the teflon board. It has a 10 GΩ input impedance and a 50 ohm output impedance. The output signal from this buffer is fed into a 500 MHz wide band fibre optic link, and by remotely switching the built-in input attenuation, the signal to noise ratio can be maintained at 100:1. The optically transmitted signal is recorded in a shielded control room by displaying it on a Tektronix 7104 oscilloscope equipped with a digitizing camera system connected to a personal computer. This oscilloscop/camera system has a 1 GHz bandwidth and produces a 512 sample waveform digitized to 12 bits (.03%) resolution. The overall accuracy of the system is limited to about 1% by the noise limit of the fibre optic link, and the bandwidth limit of the capacitive divider sets the overall system risetime to 2 ns. The triggering time is very critical for measuring the very fast rise time waveform with different breakdown time in this system. An external triggering system was used. An antenna was built into the inside of the SF₆ chamber lid. This antenna received the triggering signal from the SF₆ spark gap. A coaxial cable connected the antenna from the outside of the SF₆ chamber to the 7104 oscilloscope external triggering terminal. By adjusting the triggering level on the oscilloscope and the length of the triggering cable, a suitable
triggering time can be obtained. In this way, the system can avoid triggering too soon or too late. Figure 4.4 shows the waveform recorded in this test system with and without breakdown of the insulation test sample.

![Figure 4.4 - Fast Front Waveform Measured with System](image)

4.3. Oil Paper Test Cell

A test cell was built to test single or multiple layers of oil impregnated paper. The function of this test cell is to do multiple breakdown tests on oil impregnated paper without changing paper between tests. A test cell which holds rolls of paper and with
a mechanism to move the paper between a pair of electrodes was designed. After each breakdown the paper has to be moved without mechanical damage. The test cell contains four main parts, a plastic oil container, a brass plate, paper holder and moving mechanism and test electrodes.

The profile of the test cell is shown in Figure 4.5 and 4.6.

Figure 4.5 - Oil Paper Test Cell Profile
The electrode system used in the test cell consists of two different electrodes designed to give a uniform electric field. The high voltage electrode consists of a 16 mm diameter disk with 3 mm radius edge made of Elconite. Elconite is a silver/molybdenum alloy which has very good arc resistance. This is embedded in epoxy resin to reduce edge effects during the breakdown process. The overall diameter of the epoxy encapsulated electrode is 45 mm. The design of the high
voltage electrode is based on the work done by Naidu [57]. The ground electrode is a 29 mm diameter Elconite disc press fitted into a 45 mm diameter brass disk. The configuration of the high voltage and ground electrodes are shown in Figure 4.7.

![Figure 4.7 - High Voltage and Ground Electrodes Configuration](image)

To keep the high voltage and ground electrodes parallel during the test, the ground electrode is mounted on a swivel joint. The ground electrode has a 4.9 kg weight on it to maintain a constant pressure on the paper. The pressure is 3.1 g/mm².

Both electrodes are thoroughly cleaned and polished to 600 grit before each test series. The paper drive system utilizes an AC motor driving a takeup reel to move
the paper. There are paper guides in the receiving end to ensure that the paper goes straight through the test cell. A solenoid, mounted on the side of the test cell and attached to a lever, lifts the electrode up before the paper starts moving. This prevents damage to the paper during movement. The test cell is air tight and can support a vacuum down to 30 millitorr. It can be put in the SF$_6$ chamber, and sits on top of the high voltage disk of the chamber. The top of the test cell is grounded. Figure 4.8 shows the test cell in position in the SF$_6$ chamber.

Figure 4.8 - Test Cell in the SF$_6$ Chamber
4.4. Test Sample Preparation Procedure

The paper to be tested is cut to a width of 70 mm and a length from 5 to 10 metres. The paper is dried for 72 hours at 75°C and then vacuumed for 72 hours down to 50 millitorr. At the end of the 72 hours it is impregnated with oil under vacuum and kept under vacuum for a further 24 hours. The paper is then stored under oil in a closed container until used. The paper to be tested is put in the test cell and then it is vacuumed down to 50 millitorr for a minimum of 12 hours. The test cell is then filled with degassed oil under vacuum. Finally the vacuum in the test cell is released and the cell is placed in the test chamber.

4.5. Test Procedures

The following tests were done on different kinds of paper samples.

- Fast front impulse $V_{50}$ breakdown tests
- Lightning impulse $V_{50}$ breakdown tests
- Switching impulse $V_{50}$ breakdown tests
- AC breakdown tests
- DC breakdown tests
- Fixed voltage level fast front impulse breakdown tests

During the fast front test, the gap in the SF$_6$ chamber is open to generate the fast front pulse. The impulse generator charging voltage is kept at a constant value, and the gap in the SF$_6$ chamber is set at a suitable distance the impulse generator is fired.
At the end of the SF₆ gap, a less than 10 ns rise time impulse can be obtained. For the time-to-breakdown test a constant breakdown voltage level of the gap has to be maintained. The fast front generating and measuring system and functions are described in detail in Chapter 4. A typical fast front waveform is shown in Figure 4.4.

For the lightning and switching $V_{50}$ tests, the circuit parameters are listed below.

For the Lightning Impulse Tests:

$C_1 = 0.2 \mu F$, $C_2 = 1750 \mu F$, $R_1 = 195 \Omega$,

$R_2 = 330 \Omega$, $R = 75 \mathrm{k\Omega}$

A measured output voltage is $1.2/50 \mu s$. It is shown in Figure 4.9.
For the switching impulse tests:

\[ C_1 = 0.2 \mu F, \quad C_2 = 3300 \text{ pF}, \quad R_1 = 17 \text{ k}\Omega \]

\[ R_2 = 17 \text{ k}\Omega, \quad R = 75 \text{ k}\Omega \]

The output waveform is 250/2500 \( \mu \text{s} \). It is shown in Figure 4.10.
A low damped capacitive divider was used to measure the $V_{50}$ breakdown voltage. A Tektronix 7834 storage scope was used to record the waveform. The up-and-down method was employed to obtain the $V_{50}$ value for the test sample.

The up-and-down method is described as follows:

A voltage $V_e$ is chosen which is estimated to be approximately equal to the $V_{50}$ breakdown voltage. A voltage interval $dV$, approximately 3 percent of $V_e$, is chosen. One impulse is applied at the level $V_e$. If this does not cause a breakdown, the next impulse should have the level $V_e + dV$. If a breakdown occurs at the level $V_e$, the next impulse should have a level equal to $V_e - dV$. This procedure is continued, the
level of each impulse being thus determined by the result of the previous one until
a sufficient number of observations have been recorded. For each test sample 30 to
40 observations were made. The $V_{50}$ value is given by:

$$V_{50} = \frac{\sum n_v V_v}{\sum n_v} \quad 4.5.1$$

and the standard deviation is calculated by:

$$\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (V_v - \bar{V})^2} \quad 4.5.2$$

Where mean value $V$ is given by:

$$\bar{V} = \frac{1}{n} \sum_{i=1}^{n} V_v \quad 4.5.3$$

Here $V_v$ is a series of $n$ voltage values.

After each test shot, the paper was moved about 5 cm. There was a minimum wait
of 5 minutes before the next impulse after each impulse shot with a breakdown.
When there was no breakdown there was a minimum wait of 2 minutes before the
next impulse.
For the fast front V-t test, several fixed voltage levels were used. The time to breakdown was measured for 10 to 50 impulses at each voltage level. For each sample 4 to 7 voltage levels were used.

For the AC and DC breakdown tests, the voltage was raised at a fixed rate (40 kV/min) until breakdown occurred. For these tests, 10 breakdowns were measured for each sample. From 100 to 150 breakdowns were done for each load of paper.

4.6. Test Samples

Six different kinds of samples were tested. They were one, two and three layers of 0.076 mm thick kraft paper (TMC Dennison), one layer of 0.254 mm thick kraft paper (Cottrell Paper), one layer of 0.76 mm thick Nomex paper (EHV Weidmann) and one layer of 0.254 mm thick Melinex (polyester). The information on the paper samples is listed in table 4.1.

Two kinds of impregnants were used in the investigation. One is Voltesso 35 mineral oil and the other is R-Temp Fluid synthetic oil. Data on these impregnants are listed in table 4.2.
Table 4.1 Paper Sample Data

<table>
<thead>
<tr>
<th>Paper Type</th>
<th>Thickness (mm)</th>
<th>Density (g/cm(^3))</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncoated Kraft Paper</td>
<td>0.076</td>
<td>1.001</td>
<td>TMC Dennision</td>
</tr>
<tr>
<td>Nomex</td>
<td>0.076</td>
<td></td>
<td>EHV Weidmann</td>
</tr>
<tr>
<td>Uncoated Kraft Paper</td>
<td>0.254</td>
<td>1.25-1.35</td>
<td>Cottrell Paper</td>
</tr>
<tr>
<td>Melinex (Polyester)</td>
<td>0.254</td>
<td></td>
<td>EHV Weidmann</td>
</tr>
</tbody>
</table>

Table 4.2. Impregnant Sample Data

<table>
<thead>
<tr>
<th>Impregnant Trade Name</th>
<th>Voltesso 35</th>
<th>R-Temp Fluid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
<td>WEMCO</td>
<td>RTE Fluids</td>
</tr>
<tr>
<td>Oil Type</td>
<td>Mineral Oil</td>
<td>High Flammability Oil</td>
</tr>
<tr>
<td>Viscosity (cst)</td>
<td>8.0 (at 40°C)</td>
<td>140.0 (at 40°C)</td>
</tr>
<tr>
<td>Power Factor</td>
<td>0.5% (at 100°C)</td>
<td>0.16% (at 100°C)</td>
</tr>
<tr>
<td>Relative Permittivity</td>
<td>2.2</td>
<td>2.2</td>
</tr>
</tbody>
</table>
5. TEST RESULTS AND ANALYSIS

5.1. Introduction

The results of the investigation are presented and analyzed in the following sections. The effect of test parameters, $V_{50}$ test results and the fast front $V-t$ test results are studied.

5.2. Effect of Test Cell Parameters

5.2.1. Oil Deterioration

To determine if the oil in the test cell deteriorates during a series of breakdown tests, a set of standard oil tests were done on Voltesso 35 mineral oil used in the test cell before and after a series of oil/paper breakdown tests. The oil breakdown voltage, power factor and water content was measured. The oil breakdown voltage was determined by using the ASTM D-1816 test method. This method uses 36 mm diameter spherical (25 mm radius) VDE electrode at 2 mm spacing. The results of these tests are shown in Table 5.1.

These results show that if the number of breakdowns for each test series is less than 180 the oil deterioration is acceptable.
Table 5.1 Oil Test Results

<table>
<thead>
<tr>
<th>OIL TYPE</th>
<th>Breakdown Voltage (kV)</th>
<th>POWER FACTOR (%)</th>
<th>WATER (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>New Oil</td>
<td>53</td>
<td>0.57</td>
<td>17</td>
</tr>
<tr>
<td>Oil after 180 breakdowns</td>
<td>39</td>
<td>0.74</td>
<td>22</td>
</tr>
<tr>
<td>(out of 337 Shots)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil with 350 breakdowns</td>
<td>16</td>
<td>0.61</td>
<td>24</td>
</tr>
<tr>
<td>(out of 600 shots)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.2.2. Electrode Surface

Examination of the electrode surfaces for the breakdowns done with 0.076 mm thickness paper found that the breakdowns were very uniformly distributed over the electrode surface. This was not the case with the original electrode design which did not have a flexible joint as used in these tests. With the fixed joint electrode the breakdowns were concentrated at the interface between the electrode and the epoxy. Figure 5.1 shows the flexible joint electrode surfaces after about 150 breakdowns. This distribution of the breakdowns shows that the electrical field in this test arrangement is very uniform. It also showed that for the thicker paper or multiple layers the breakdowns tend to concentrate more towards the edge.
a. One layer of 0.076 mm oil/paper breakdown surface
b. Two layers of 0.076 mm oil/paper breakdown surface
c. Three layers of 0.076 mm oil/paper breakdown surface

Figure 5.1. - High Voltage Electrode Breakdown Surface
5.2.3. Effect of Number of Breakdown on $V_{50}$

The switching impulse $V_{50}$ of one layer of kraft paper was measured at the beginning and the end of a load of paper in the test cell to determine if there was significant reduction in the test result as a result of a deterioration in the oil and electrode condition. Table 5.2 shows the results.

Table 5.2. $V_{50}$ Data Before and After a Test Series

<table>
<thead>
<tr>
<th>Test Sample</th>
<th>$V_{50}$ at start of the test</th>
<th>$V_{50}$ after 120 shots</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.076 mm kraft paper impregnated with Voltesso 35 oil</td>
<td>188 kV/mm</td>
<td>208 kV/mm</td>
<td>10%</td>
</tr>
</tbody>
</table>

The results show the $V_{50}$ breakdown value after 120 shots increased 10% rather than decreasing. This may indicate the electrode surface condition changed and show the effect of space charge in the paper surface and in the oil as well as the effect of oil deterioration. This test determines the overall condition of the test sample setup after a series of shots. The overall condition for less than 100 shots indicated only small errors.

5.3. $V_{50}$ Test Data and Analysis

In this section, the $V_{50}$ data and analysis under fast front, lightning and switching impulses, as well as the AC and DC data and analysis are presented.
5.3.1. V_{50} Test Data

Figure 5.2 shows a plot of the results of the V_{50} tests. In order to compare the effect of different waveforms, especially rise time, on the breakdown voltage, three to five different waveforms were used for the tests. Switching impulse 250/2500 \( \mu \)s, lighting impulse 1.2/50 \( \mu \)s, 5.7/130 \( \mu \)s impulse, 120/1400 \( \mu \)s impulse and fast front impulse 10 ns/2500 \( \mu \)s as well AC and DC were used in the study. Different numbers of layers and thicknesses of paper and different types of paper and impregnant were investigated. The results are presented in the following sections.
Figure 5.2 - $V_{50}$ Test Results
5.3.2. Effect of Polarity

Tests were done on one layer of 0.076 mm kraft paper (impregnated with Voltesso 35) with both positive and negative polarities with the fast front, lightning and switching waveforms. The results are shown in Table 5.3.

Table 5.3 Effect of Polarity on One Layer of 0.076 mm Kraft Paper

<table>
<thead>
<tr>
<th>Polarity</th>
<th>FFI (kV/mm)</th>
<th>LI (kV/mm)</th>
<th>SI (kV/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>155.3</td>
<td>182.4</td>
<td>210.0</td>
</tr>
<tr>
<td>-</td>
<td>160.5</td>
<td>179.8</td>
<td>211.0</td>
</tr>
<tr>
<td>Difference</td>
<td>3.3%</td>
<td>-1.4%</td>
<td>0.48%</td>
</tr>
</tbody>
</table>

For this test sample, the polarity effect is not significant. The difference between positive and negative polarity is less than 2% for lightning impulse and less than 0.5% for switching impulse. The difference is less than 4% for the fast front impulse. These results prove that the electric field between the electrodes is uniform.

5.3.3. The Effect of Rise Time for Sample Impregnated with Voltesso 35

All the tests done were based mainly on three waveforms, fast front, lightning and switching impulses. The rise times were respectively 10 ns, 1.2 μs and 250 μs. For one layer of 0.076 mm thick kraft paper, the \( V_{50} \) tests were done also on two other waveforms. They were 5.7/130 μs and 120/1400 μs. By adding these two waveforms more information was obtained on overall rise time effect. The rise time vs \( V_{50} \)
breakdown voltage series of tests is show in Figure 5.3. For each sample AC and DC tests were done as bench marks.

The general trend for all the data is that the fast front $V_{50}$ value has the lowest value and the $V_{50}$ breakdown value for the switching impulse is the highest.

For one, two and three layers of 0.076 mm paper, the fast front impulse has the lowest value and all are very close together. These results indicate that the breakdown processes has the same pattern for different number of layers. The breakdown strength increases as the front time increases. The tail time is seen to not be critical in determining the breakdown value since the fast front and switching impulse had the same tail time while the lightning impulse has a much shorter tail time. This shows that the breakdown process is mainly related to the rise time of the waveforms. The AC breakdown strengths have the lowest value for all the waveforms and for all the samples. The DC breakdown strengths have the highest values for all the samples except for the one layer of 0.076 mm kraft paper and the Nomex paper. From thermal breakdown theory, under AC voltage the heat loss is much greater than under DC voltage, so this makes the AC breakdown strength lower than the DC breakdown strength.

It is observed that paper samples of the same thickness have similarly shaped curves for breakdown strength vs risetime. All the curves are shown in Figure 5.2.
Comparing the FFI and LI, the $V_{50}$ strengths increased from 7% to 18% for kraft paper, 10% for Nomex paper and 28% for polyester. Comparing FFI and SI, the $V_{50}$ strengths increased from 13% to 36% for kraft paper, 28% for Nomex paper and 36% for polyester.

Table 5.4 and Figure 5.2 show the comparison for all the samples under FFI, LI and SI.

### Table 5.4 Effect of Rise Time

<table>
<thead>
<tr>
<th>Sample</th>
<th>Layers</th>
<th>FFI (base)</th>
<th>LI</th>
<th>SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.076 mm paper</td>
<td>one</td>
<td>1</td>
<td>1.18</td>
<td>1.36</td>
</tr>
<tr>
<td></td>
<td>two</td>
<td>1</td>
<td>1.07</td>
<td>1.24</td>
</tr>
<tr>
<td></td>
<td>three</td>
<td>1</td>
<td>1.07</td>
<td>1.25</td>
</tr>
<tr>
<td>0.254 mm paper</td>
<td>one</td>
<td>1</td>
<td>1.1</td>
<td>1.13</td>
</tr>
<tr>
<td>0.076 mm Nomex</td>
<td>one</td>
<td>1</td>
<td>1.1</td>
<td>1.28</td>
</tr>
<tr>
<td>0.254 mm polyester</td>
<td>one</td>
<td>1</td>
<td>1.28</td>
<td>1.36</td>
</tr>
</tbody>
</table>

The $V_{50}$ results are in agreement with other research work [54]. The work done by Dzikowski [54] shows the mean value of the breakdown voltages of oil paper
insulation models at steep switching impulse (rise time is 1.5 μs) is lower than their strength for impulses of the shape close to the standard switching impulse.

A conclusion that can be drawn from the results is that the $V_{50}$ breakdown value for the kraft paper, Nomex and polyester are dependent mainly on the rise time of the waveform. In the range tested (10 ns to 250 μs), the steeper the rise time the lower the breakdown strength is. This characteristic of oil paper insulation gives some disadvantages. Since the volt-time curve of the arresters protecting the equipment goes up at the short times to breakdown.

There are different mechanisms of discharge development in oil paper insulation. These differences are mainly caused by the speed of voltage increase on the front of the impulse but not by the duration of the voltage.

The results would indicate an increased susceptibility to anomalous failure if the fast transients generated in SF$_6$ system propagate into power apparatus.
Figure 5.3 - Effect of Different Waveforms for One Layer of 0.076 mm Kraft Paper
5.3.4. The Effect of Thickness of Paper

In the tests two different thicknesses of one layer of kraft paper were used. One was 0.076 mm thick and the other was 0.254 mm thick. The test results are shown in Table 5.5.

Table 5.5 The Results for Different Thickness of Paper

<table>
<thead>
<tr>
<th>Sample Voltesso 35 impregnant</th>
<th>FFI Breakdown Strength (kV/mm)</th>
<th>LI Breakdown Strength (kV/mm)</th>
<th>SI Breakdown Strength (kV/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.076 mm</td>
<td>154.9</td>
<td>182.4</td>
<td>210.0</td>
</tr>
<tr>
<td>0.254 mm</td>
<td>142.0</td>
<td>155.9</td>
<td>160.2</td>
</tr>
<tr>
<td>Difference</td>
<td>8.3%</td>
<td>14.5%</td>
<td>23.7%</td>
</tr>
</tbody>
</table>

The effect of thickness under fast front impulse is less than under lightning and switching impulse. Among these three waveforms, the breakdown strength under switching impulse has the largest difference. This may show there are different breakdown mechanisms between fast front and switching impulses. The test results show that the breakdown strength decreases as the paper thickness increases.
5.3.5. The Effect of Type of Paper

Four types of paper were used in the test. They are shown in Table 5.6.

Table 5.6 Test Sample

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kraft Paper</td>
<td>0.076 mm</td>
<td>TMC Dennison</td>
</tr>
<tr>
<td>Nomex</td>
<td>0.076 mm</td>
<td>EHV Weidmann</td>
</tr>
<tr>
<td>Kraft Paper</td>
<td>0.254 mm</td>
<td>TMC Dennison</td>
</tr>
<tr>
<td>Polyester</td>
<td>0.254 mm</td>
<td>EHV Weidmann</td>
</tr>
</tbody>
</table>

The results for one layer these papers (in table 5.6), impregnated with Voltesso 35, and the difference in the $V_{50}$ breakdown strengths are shown in Table 5.7 and Table 5.8 as well as Figure 5.4 and Figure 5.5.

Table 5.7 Test Results for Different Types of Paper

<table>
<thead>
<tr>
<th>Sample</th>
<th>FFI (kV/mm)</th>
<th>LI (kV/mm)</th>
<th>SI (kV/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.076 mm Kraft Paper</td>
<td>154.9</td>
<td>182.4</td>
<td>210.0</td>
</tr>
<tr>
<td>0.076 mm Nomex</td>
<td>106.3</td>
<td>116.8</td>
<td>136.5</td>
</tr>
<tr>
<td>Difference</td>
<td>31.4%</td>
<td>36%</td>
<td>35%</td>
</tr>
</tbody>
</table>

For the same thickness, the $V_{50}$ breakdown strength of the Nomex paper is much lower than for kraft paper (31 to 36 percent lower) under FFI, LI and SI. However, the percentage difference is almost the same under all three waveforms.
Figure 5.4 - Thin Kraft Paper and Nomex Paper $V_{50}$ Curves
The curves of strength vs waveform rise time (Figure 5.4) have a similar shape for these two types of paper, but the breakdown strength value is shifted down (about 30%) for the Nomex. It is hypothesised that the Nomex and kraft paper with the same thickness have the same breakdown process.

Table 5.8 Thick Kraft Paper and Polyester

<table>
<thead>
<tr>
<th>Sample</th>
<th>FFI (kV/mm)</th>
<th>LI (kV/mm)</th>
<th>SI (kV/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kraft Paper</td>
<td>142.0</td>
<td>155.9</td>
<td>160.2</td>
</tr>
<tr>
<td>0.254 mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polyester</td>
<td>94.9</td>
<td>121.7</td>
<td>129.5</td>
</tr>
<tr>
<td>0.254 mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Difference</td>
<td>33.2%</td>
<td>22%</td>
<td>19%</td>
</tr>
</tbody>
</table>

A comparison of the thick kraft paper and of the polyester film (Figure 5.5) shows that the breakdown strength of the polyester is also lower than that for the same thickness of kraft paper.

The shape of the $V_{50}$ strength curve for polyester is different than the one with the same thickness of kraft paper.
Figure 5.5 - Thick Kraft Paper and Polyester $V_{50}$ Curves
5.3.6. Effect of Number of Layers of Paper

From the results, it is shown that for fast front impulse, the $V_{50}$ breakdown stresses for one, two and three layers of 0.076 mm kraft paper are very close together. The results are shown in Table 5.9 and Figure 5.6.

Table 5.9 Effect of Number of layers on $V_{50}$ Value

<table>
<thead>
<tr>
<th>Sample</th>
<th>FFI</th>
<th>LI</th>
<th>SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>One Layer(base)</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Two Layer</td>
<td>96.6%</td>
<td>88.2%</td>
<td>88.1%</td>
</tr>
<tr>
<td>Three Layer</td>
<td>93.6%</td>
<td>85.4%</td>
<td>86.5%</td>
</tr>
</tbody>
</table>
Figure 5.6 - Effect of Number of Layers
The $V_{50}$ fast front impulse breakdown value for two layers of 0.076 mm thick paper is 3.4% lower than for one layer of paper. It is 6.4% lower for three layers of paper.

For lightning and switching impulses, the difference between one and two layers is significantly larger. The difference between two and three layers is not large (2.8% and 1.6%). From the $V_{50}$ test, it can be concluded the results for one layer of paper can be applied to multiple layers of paper under fast front impulses but not for lighting and switching impulses. The results for two layer of paper can be applied to multiple layer for all three impulse waveforms.

5.3.7. Effect of Different Impregnants

Two different kinds of impregnant were used in the investigation. One is Voltesso 35, a standard mineral oil used in oil filled power equipment and the other is R-Temp fluid, an oil with a high flammability point. The specifications for these impregnants are listed in Table 4.2. Fast front impulses, lightning and switching impulses, as well as DC and AC breakdown tests were done with 0.076 mm kraft paper impregnated with these two kinds of oil. The $V_{50}$ results are shown in Table 5.10. A graph comparing these two kinds of impregnants is shown in Figure 5.7. The results show that curve of $V_{50}$ values with the R-Temp Fluid is much flatter than the one with mineral oil.
To study the difference in breakdown phenomena between these two impregnants, the surface charge potential voltage decay rate was measured. The surface of test samples of paper were charged to a DC voltage and the change in charge with time was recorded. Dry paper, paper impregnated with Voltesso 35 and paper impregnated with R-Temp fluid were tested. Figure 5.8 shows the surface charge decay rates.

The measurement shows the R-Temp fluid has a decay rate about 10 times faster than Voltesso 35 mineral oil. The charge is difficult to build up with the R-Temp fluid since the charge decay rate is very fast. There is less effect with different waveforms for R-Temp fluid. This may explain why the variation in $V_{50}$ values with different waveforms for paper impregnated with R-Temp fluid is less than for paper impregnated with Voltesso 35.

The time scale of the charge measurements is much larger than the test waveform (minutes vs $\mu$s). However since the decay rate is a exponential function it is believed that the relative decay rate in the two impregnants would be the same in the shorter
Figure 5.7 - Effect of Different Impregnants with Kraft Paper
Figure 5.8 - Surface Charge Decay Curves with Kraft Paper

Δ - Voltesso 35 (Mineral Oil)
◊ - R-Temp Fluid (Synthetic Oil)
□ - Dry Paper
time scale of the test waveforms. It was impractical to do the measurements in the time scale of the waveforms.

5.3.8. Discussion of $V_{50}$ Data

From the $V_{50}$ tests, we obtained several sets of very interesting data. The $V_{50}$ tests show that the fast front impulse has the lowest breakdown voltage compared to lightning and switching impulses. The results show that the breakdown value depends mainly on the rise time of the waveform and is not governed by the duration of the waveform. Five waveforms are used for the tests with one layer 0.076 mm of kraft paper. The waveforms were 10 ns/2500 $\mu$s, 1.25$\mu$s/50 $\mu$s, 5.7$\mu$s/130 $\mu$s, 120 $\mu$s/1400 $\mu$s and 250 $\mu$s/2500 $\mu$s. The results show that as the rise time increases the breakdown voltage value increases. Dzikowski also found a similar phenomenon in his investigation [54]. His hypothesis was that the phenomenon is related to charge build up between the electrodes. When the voltage rises very rapidly, the charge has no time to build up. When the voltage rises slowly, the charge can build up and distort the original electric field. It then requires a higher voltage to produce breakdown. The $V_{50}$ breakdown curves for different impregnants and their surface charge decay rate give support to this breakdown theory. R-Temp fluid has a relatively flat $V_{50}$ breakdown curve compared to Voltesso oil. The voltage rise time has less effect. The measurements show that the surface charge decay rate of R-Temp oil is ten times faster than that of Voltesso 35 oil. This means that the charge is difficult to build up in R-Temp oil. The electric field has less distortion with long
rise time waveforms which results in the $V_{50}$ curve for R-Temp oil being flat. Watson observed a similar phenomenon in Perspex [56]. He explained that the phenomenon was related to the space charge. For future investigations, more complicated models that are close to bushing and transformer insulation systems should be tested instead of only basic insulating material tests.

Different paper but with the same thickness have $V_{50}$ breakdown curves with similar shapes, but the $V_{50}$ values are different. Impregnated kraft paper has the highest $V_{50}$ breakdown value, as compared with Nomex and polyester, from fast front impulses to switching impulses.

The $V_{50}$ breakdown stresses with different number of layers under fast front impulses are very close. The $V_{50}$ under fast front impulses for two layers of paper is 3.4% lower than for one layer and for three layers it is 6.4% lower than one layer. For lightning impulses, two layers is 11.8% lower than one layer and three layers is 14.6% lower than one layer. These results show that there may be a different breakdown mechanism under fast front impulses than under lightning and switching impulses. Also there may be a different mechanism for one layer under lightning and switching impulses than for two other layers under lighting and switching impulses.

It was found that the thick paper has a lower impulse breakdown strength than the thin paper. In addition the difference in $V_{50}$ values between the thin (0.076 mm)
paper and the thick (0.254 mm) paper was less for the fast rise time impulses than for the other waveforms.

5.4. Fast Front V-t Results and Analysis

In this section, the V-t data under fast front impulse are presented and analyzed.

5.4.1. Test Results

At each voltage level, about 50 breakdowns have been measured for kraft paper. For each sample 4 to 7 voltage levels have been measured. V-t tests were done on the following samples:

1. One layer of 0.076 mm thick kraft paper
2. Two layer of 0.076 mm thick kraft paper
3. One layer of 0.254 mm thick polyester

The main purpose of the project is to investigate the characteristics of oil impregnated paper, so that the polyester V-t test was done only for comparison. Ten measurements were done at each voltage level for the polyester samples. The results of the polyester tests are shown in Figure 5.9. Figure 5.10 shows the results for one layer of 0.076 mm kraft paper and Figure 5.11 shows the results for two layers of 0.076 mm kraft paper.
Figure 5.9 - Polyester Film V-t Data
Figure 5.10 - One Layer 0.076 mm Kraft Paper V-t Data
Figure 5.11 - Two Layers 0.076 mm Kraft Paper V-t Data
The V-t curve for one layer of 0.076 mm thick kraft paper shows an increasing trend starting around 80 to 90 ns. For two layers of 0.076 mm kraft paper, the increasing trend starts around 100 ns. The V-t curve for one layer has a discontinuity between 45 to 55 ns and the V-t curve for two layers has a discontinuity between 50 to 60 ns.

5.4.2. Fast Front Test Results Analysis

In this section the histogram, Weibull distribution and equal area criterion methods are used to analyze the V-t data.

5.4.2.1. Histogram

Statistical methods are frequently used for analysis of electrical insulation breakdown for purposes such as predicting life expectancy and the ability of the insulation system to withstand voltage. The testing data can be plotted in a histogram. Using a histogram to look at the distribution of breakdown times at each fixed voltage level gives a general idea of how the breakdown times are distributed. It also shows whether enough test data has been obtained. Histograms of the V-t test data from this investigation are plotted on histograms at each voltage level in Figures 5.12 to 5.24. The histograms are useful for further analysis.
Figure 5.12 - One Layer 0.0762 mm Kraft Paper Three Dimensional Histogram
Figure 5.13 - Two Layers 0.076 mm Kraft Paper Three Dimensional Histogram
Figure 5.14 - Single Layer 0.076 mm Kraft Paper E = 174 kV/mm
Figure 5.15 - Single Layer 0.076 mm Kraft Paper $E = 191$ kV/mm
Figure 5.16 - Single Layer 0.076 mm Kraft Paper E=204 kV/mm
Figure 5.17 - Single Layer 0.076 mm Kraft Paper E=217 kV/mm
Figure 5.18 - Single Layer 0.076 mm Kraft Paper E=229 kV/mm
Figure 5.19 - Single Layer 0.076 mm Kraft Paper $E = 242$ kV/mm
Figure 5.20 - Single Layer 0.076 mm Kraft Paper E=255 kV/mm
Figure 5.21 - Two Layers 0.076 mm Kraft Paper $E = 164$ kV/mm
Figure 5.22 - Two Layers 0.076 mm Kraft Paper E = 178 kV/mm
Figure 5.23 - Two Layers 0.076 mm Kraft Paper $E = 190 \text{ kV/mm}$
Figure 5.24 - Two Layers 0.076 mm Kraft Paper E=204 kV/mm
5.4.2.2. Weibull Distribution

There are many different kinds of statistical distributions used in various branches of science and engineering but only three are commonly used in the evaluation of electrical insulation systems: the Normal, the Log-Normal, and the Weibull distributions.

In the field of electrical insulation, the Weibull distribution is generally accepted as the one which best fits time to failure and dielectric strength data. It is asymmetrical, and three parameters are required to uniquely specify it. The three parameters of the Weibull distribution are the scale ($\alpha$), shape ($\beta$), and location ($\gamma$). The scale parameter is analogous to the mean of the normal distribution, and the shape parameter is analogous to the standard deviation. In many cases in the field of electrical insulation, the value of the location parameter is assumed to be zero, but this is not always completely justified. The cumulative Weibull distribution is defined by the mathematical relationship

$$F(x) = 1 - \exp \left[ -\left( \frac{x-\gamma}{\alpha} \right)^\beta \right]$$

Where $x$ is the time at failure, $\alpha$ is the scale parameter, $\beta$ is the shape parameter, and $\gamma$ is the location parameter. $F(x)$ indicates the proportion of specimens that will fail up to time $(x)$. The failure time is then used to calculate estimates of the
parameters. The Weibull plots of the fast front time breakdown data at different voltage levels are shown in Figure 5.25 to 5.35.
Figure 5.25 - Single Layer Kraft Paper at $E = 171 \text{ kV/mm}$
Figure 5.26 - Single Layer Kraft Paper at $E = 184$ kV/mm
Figure 5.27 - Single Layer Kraft Paper at E = 197 kV/mm
Figure 5.28 - Single Layer Kraft Paper at E=211 kV/mm
Figure 5.29 - Single Layer Kraft Paper at E=224 kV/mm
Figure 5.30 - Single Layer Kraft Paper $E=237 \text{kV/mm}$
Figure 5.31 - Single Layer Kraft Paper E = 250 kV/mm
Figure 5.32 - Two Layer of Kraft Paper $E = 164 \text{ kV/mm}$
Figure 5.33 - Two Layers of Kraft Paper $E = 178$ kV/mm
Figure 5.34 - Two Layers of Kraft Paper $E = 191 \text{kV/mm}$
Figure 5.35 - Two Layers of Kraft Paper E = 204 kV/mm
The Weibull parameters can be obtained from the test data and this information can be used for further analysis.

The Weibull distribution calculation shows all the data at one voltage level can not be fitted in one group of Weibull parameters, especially for the V-t data for two layers. This means that there may be more than one process involved in the breakdown.

The lower the applied voltage, the larger the scatter of the Weibull plots.

5.4.2.3. Equal Area Criterion Method

The equal area criterion method is usually used in analyzing V-t data in gas dielectrics. There is a lack of suitable theories to model the liquid/solid breakdown as a result, in this work, the equal area criteria theory is used in the analysis of the V-t data.

5.4.2.3.1. Equal Area Criterion Fundamentals

Suppose the breakdown of oil paper insulation is governed by the streamer mechanism. Breakdown takes place when the number of free electrons in an avalanche exceeds a critical number. To start a critical electron avalanche an effective primary electron is necessary. The ignition consists of the statistical time lag $t_{sn}$, the discharge formation time $t_d$ and the spark formation time $t_s$ (Figure 5.36).
Figure 5.36 - Ignition Time Lag

$t_{st}$ - statistical time

t_d - discharge formation time

t_s - spark formation time

It is assumed that there is a constant number of free electrons per unit volume and time and that it is independent of electrical field strength. The probability of starting a critical avalanche by a primary electron is

$$W_v(t) = 1 - \exp\left(-\frac{\varepsilon}{n_0} \int V_w dt\right)$$  \hspace{1cm} (5.1)

$W_v(t)$ describes the probability of an effective primary electron at a certain time $t$. $V_w$ is called the Weighted Volume
\[ V_w = \int_{(V_c)} \left(1 - \frac{\alpha}{\eta} \right) dV \quad (5.2) \]

where:

\[ \alpha = \text{ionization coefficient} \]
\[ \eta = \text{attachment coefficient} \]

\( V_c \) is the critical volume where the critical field strength is exceeded.

The probability of field emission of electrons is given by:

\[ w_e(t) = 1 - \exp \left( k_2 \int_{0}^{t} A_w dt \right) \quad (5.3) \]

\( k_2 \) is a constant dependent on the material and surface roughness of the cathode, \( A_w \) is the weight area.

\[ A_w(E) = \int_{(A)} \left( \frac{1}{2} + \frac{1}{\pi} \arctan(k_1) \left( E - E^* \right) \right) dA \quad (5.4) \]

Where \( k_1 \) and \( E^* \) are two constants to describe the field dependence of electron emission.

At shorter times to breakdown, theoretical calculations of the formative time lag are not yet possible. However, an empirical technique exists and has been used with
apparent success in calculating the formative times for conventional surges. This volt-time area criterion assumes that the area underneath the applied voltage waveform and above the minimum breakdown voltage, from the moment of the appearance of an initiatory electron to the time of voltage collapse is constant.

Discharge Formation Time - The discharge formation time may be described by the voltage-time area law. This criterion is based on the assumption that for a given arrangement a certain voltage value $U_r$ exists below which no breakdown can occur. A certain voltage-time area above $U_r$ has to be exceeded before breakdown conditions are fulfilled. This is described mathematically as follows:

$$A_d = \int_{t(U_r)}^{t_b} (u(t) - U_r) \, dt$$

(5.6)

$A_d$ represents the voltage-time area which is a constant independent of impulse shape.
In the calculation of impulse voltage-time curves the equal area criterion [24, 72, 73] has proved to be a useful assumption in many cases.

5.4.2.3.2. Voltage - Time Characteristics

For the calculation of V-t characteristics in oil-paper insulation, the statistical time lag and the discharge formation time are to be taken into account. A model is used, which combines the two procedures describing the statistics of the effective primary electron and the formation of the avalanche. The lower limiting curve of the V-t characteristics is calculated by applying the voltage-time area criterion.
scattering is governed by the probability of an effective primary electron according to (5.1), (5.3). The calculation procedure is shown in Figure 5.38.

The calculation starts from a given impulse shape. The probability $W$ of a primary electron, which starts a critical avalanche, is calculated. At the same time the voltage-time area criterion is applied. In this way one point on the lower limiting curve of the V-t characteristics is determined. This procedure is used for several
amplitudes of the impulse voltage. In this way, the complete V-t characteristic can be obtained.

In this particular case, the applied voltage is almost a square waveform. The waveform calculation can be simplified. By combining the $V_{50}$ data and the Weibull distribution, the equal area criterion constant can be derived. The different probability V-t curves can be derived from the equal area criterion. The 2% curve are plotted in Figure 5.39 and Figure 5.40.
Figure 5.39 - One Layer of Kraft Paper V-t Data and 2% V-t Curve
Figure 5.40 - Two Layer of Kraft Paper V-t Data 2% V-t Curve
5.4.3. Discussion on the V-t data

The V-t results give general information on oil/paper insulation breakdown time for one electrode arrangement. It is observed that there is a gap in the V-t test results. For one layer of paper the location is between 45 to 55 ns. For two layers of paper, the gap is between 50 to 60 ns, except at one voltage level. This indicates that there may be two breakdown mechanisms in the breakdown process. One is a fast breakdown mechanism in the time range less than 45 ns and the other is a slower breakdown mechanism in the time range greater than 55 ns. The V-t data for the steep front impulse tests done by IREQ [58] on oil also show a gap between 100 ns to 200 ns.

By using fast rise time and long tail impulses, almost a square waveform, the breakdowns were forced at the peak value. In this way there are less factors affecting the results. Mazzetti [66] in his study on time to breakdown in transformer oil under impulse found two basic regimes. They depended on whether breakdown occurred on the rise of the impulse or on its tail. The first regime occurs at much higher voltages than the latter one and it usually occurs at small electrode separations. In addition, the time to breakdown decreased with increased peak voltage in the first regime. The time to breakdown shows statistical fluctuations in the second regime. In their present study it was found that the times to breakdown were not altered in a statistically significant manner by a 25% increase in the pulse...
amplitude. This statement is limited to breakdown processes occurring in the tail end of the pulse.

The Weibull calculation in this investigation indicates that the breakdown has more than one process. Two set of parameters are used for the Weibull curve fitting. One is for the short time range and the other is for the longer time range. Since the most critical part is the low probability breakdown V-t curve, the short time range Weibull parameters are used for the equal area criterion V-t curve calculation.

The histograms show the general trend of breakdown time distribution at different voltage levels.

By using the time range from Weibull calculation and equal area criterion method a 2% low probability V-t curve was generated and it fits the test data well.

5.5. Summary of Observations

The following review gives a summary of the test results and analysis:

- Oil deterioration
It was found that if the number of breakdowns in the test cell are less than 180 the oil deterioration level is acceptable.

- Electrode surfaces

Damage to the electrodes from the insulation breakdowns were uniformly distributed over the surface of the electrodes when a flexible joint was used on the ground electrode.

- Effect of overall insulation condition

The effect of the overall insulation deterioration in the test cell was determined by measuring the $V_{50}$ switching impulse value at the beginning and end of a test series. The results shows that if less than 100 breakdowns are done the overall test cell deterioration did not introduce large errors.

- $V_{50}$ test
  - Effect of polarity on the test results

  There was no significant polarity effect for one layer of 0.076 kraft paper. The differences were 0.5% for switching impulse, 2% for lightning impulse and 4% for fast front impulse.
• Effect of rise time

For switching, lightning and fast front impulses, the fast front impulse has the lowest breakdown value for all the samples. The \( V_{50} \) breakdown curve has the same shape for two and three layers of paper. For one layer of paper, the breakdown strength increases faster than for two and three layers of paper, as the rise time increase. AC has the lowest breakdown strength and DC has the highest breakdown strength for all but one test sample. Nomex paper has the same shape of curve as kraft paper with same thickness but has lower breakdown values.

• Effect of thickness of paper

The biggest difference in breakdown stress as a function of paper thickness occurred for switching impulses and the smallest difference for fast front impulses. The thicker the paper the lower the breakdown strength.
• Effect of paper type

The $V_{50}$ breakdown strength of the Nomex paper is much lower than for kraft paper of the same thickness under FFI, LI and SI. A comparison of the 0.254 mm kraft paper and polyester film shows that the breakdown strength of the polyester is lower than kraft paper.

• Effect of different impregnants

The results show that the curve of $V_{50}$ values with the R-Temp fluid are much flatter than the one with mineral oil. R-Temp fluid has a faster surface charge decay rate than Voltesso 35 mineral oil.

• Fast front V-t results

V-t data were obtained for one and two layers of 0.076 mm thick kraft paper. There is a significant discontinuity in the data for one layer of kraft paper and it shows a discontinuous line on the Weibull plots. This indicates that there may be two breakdown processes, a fast one and a slower one. When the voltage is increased, the breakdowns tend toward the fast process. A 2% probability V-t curve was generated and fit the test data well by using the equal area criterion. It gave a good fit to the test data.
6. CONCLUSIONS AND FUTURE WORK

This thesis investigated oil/paper insulation electrical characteristics under fast front impulses. Some very useful information was obtained from this investigation. The following sections discuss the conclusions from this investigation and make recommendations for future work.

In order to carry out this work, a fast front impulse generating and measuring system was implemented. A fast front impulse was generated through a unique SF$_6$ spark gap. The fast front waveforms were successfully measured through a fibre optic measuring system equipped with a high speed oscilloscope and digital camera system.

$V_{50}$ breakdown strength and time to breakdown characteristics under fast front impulse were investigated. The $V_{50}$ breakdown strength under slower rise time impulses were studied for comparison with fast front impulses. Different types of paper, number of layers, and thicknesses as well as impregnants were examined. The V-t data was analyzed by using Weibull distribution. This showed a discontinuous curve. Analysis using equal area criterion was also done. This was used to generate a 2% probability V-t curve.

6.1. $V_{50}$ Breakdown Characteristics

Some general electrical characteristics of oil/paper insulation have been obtained from the $V_{50}$ tests. The effect of rise time of the waveform is very important. In the
basic arrangement of oil/paper test setup, the fast front impulse has the lowest $V_{50}$ breakdown strength, as compared with switching and lightning impulses. This is true for all the test samples including different numbers of layers, types of paper and thicknesses. The results is alarming as it has been generally assumed in the past that the oil/paper insulation breakdown strength increases as the impulse rise time decreases.

The results indicate that the different types of paper (impregnated with mineral oil) with the same thickness have similarly shaped curves for rise time vs $V_{50}$ values, but the $V_{50}$ values are different. Kraft paper has the highest $V_{50}$ breakdown strength when compared with Nomex paper and polyester film.

The $V_{50}$ strength with one, two and three layers under fast front impulse have much less difference (less than 6.5%, showed in Table 5.9 and Figure 5.6) when compared with the differences between one, two and three layers under lightning and switching impulses (greater than 11%, Table 5.9). The thinnest single layer of kraft paper (0.076 mm) has the highest $V_{50}$ breakdown strength compared with the thick kraft paper (0.254 mm) (see Figure 5.2 and Table 5.5).

The $V_{50}$ breakdown strengths with R-Temp fluid have a flat curve of rise time vs strength for fast front, lightning and switching as well as for DC (Figure 5.7). This is believed to be due to the surface charge decay rate being much faster for the R-
Temp fluid than for the Voltesso 35 oil (see Figure 5.8. These two types of oil have very different viscosities as well. These differences in breakdown characteristics indicate that the shape of the breakdown voltage vs rise time of oil/paper insulation mainly depends on the oil, not the paper.

6.2. V-t Characteristics Under Fast Front Impulses

In this investigation, basically two sets of V-t data were obtained. One is for a single layer and the other is for two layers of 0.076 mm kraft paper. For one layer of kraft paper the breakdown time ranged from 15 ns to 1 $\mu$s with a breakdown strength from 171 kV/mm to 249 kV/mm. For two layers of paper the data the breakdown time range is from 15 ns to 4 $\mu$s and the voltage range from 164 kV/mm to 203 kV/mm.

The equal area criteria combined with the breakdown time histograms have been used to generate V-t curves. The V-t curves thus obtained fit the data well. The Weibull distribution was also used to analyze the data, however it did not fit the test results well with a single group of Weibull parameters. As a result, one curve is used for the shorter breakdown time range and an other for the longer breakdown time range. The V-t data for one layer of paper showed a discontinuity between 45 ns and 55 ns. It may indicate that the fast front breakdown processes has two mechanisms. One is a fast regime under 45 ns and the other is over 55 ns. The two layer paper V-t results show the same phenomena except at one voltage level.
6.3. Future Work

The results of this work show that further work should be done in the following areas:

a) Develop a more realistic physical model to simulate oil/paper insulation systems in power apparatus under fast front waveform.

b) The fast front square impulse used in the investigation eliminated the tail voltage decay effect. In this study the effect of frequency was not studied. Several oscillating waveforms should be used to test oil/paper insulation systems. This will show the combined effect of a fast front voltage and oscillating voltages.

c) Non-uniform electrode systems should be used (such as needle to plane and needle to needle electrode systems) in future tests to identify non uniform electric field breakdown effects.

d) The cumulative effect of fast front impulses on oil/paper insulation should be studied to determine long- term performance of the insulation.

e) More work needs to be done to obtain V-t data with different impregnants.

f) Extend the tests to more than three layers of paper.
7. REFERENCES


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