The Influence of Tropical Operating Conditions on the AC and Impulse Breakdown Strength in Gas Insulated Substation (GIS)

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Abstract

In a densely populated area, a gas insulated substation (GIS) is more favorable than an air insulated substation (AIS) due to some reasons, e.g. its compact size and less maintenance requirements.

The ambient temperature and humidity can influence the insulating gas condition inside the GIS. The increase of ambient temperature increases the gas temperature, thus also increases gas pressure inside the GIS. The increase of ambient humidity can increase the gas humidity, particularly for those having leakage in seal. This varied condition which is very likely to occur in tropical countries could influence the breakdown strength of the gas.

A protrusion inside the GIS will decrease the breakdown strength considerably. Therefore, it is important to check if the GIS is still safe to be operated in the presence of protrusion especially under varied conditions.

In this thesis, an investigation for such situation is performed. As insulating gas, CO₂ is used instead of SF₆. A risk assessment is then accomplished as a tool for making a decision whether the GIS is safe to be operated under such varied conditions.
# Table of Contents

Acknowledgment ........................................................................................................... i

Abstract ....................................................................................................................... ii

Table of contents ........................................................................................................... iii

Chapter 1 Introduction ................................................................................................. 1
  1.1 General .................................................................................................................. 1
  1.2 The problem definition ......................................................................................... 2
  1.3 The objective of thesis ......................................................................................... 2
  1.4 The Thesis layout ................................................................................................. 3

Chapter 2 Discharging Process in Gas as Insulating Material ................................. 5
  2.1 General ................................................................................................................ 5
  2.2 Ionization processes ............................................................................................. 6
    2.2.1 Ionization by electron collision ...................................................................... 6
    2.2.2 Ionization by radiation (photo-ionization) ..................................................... 6
    2.2.3 Ionization by interaction with meta-stable atoms ........................................ 7
    2.2.4 Thermal ionization ....................................................................................... 8
    2.2.5 Electron detachment .................................................................................... 8
  2.3 Deionization processes ........................................................................................ 8
    2.3.1 Deionization by recombination .................................................................... 9
    2.3.2 Deionization by diffusion .............................................................................. 9
    2.3.3 Electron attachment ..................................................................................... 9
  2.4 Pre-breakdown phenomena in gases ................................................................... 9
    2.4.1 Electron avalanches generation .................................................................... 10
    2.4.2 Secondary electrons .................................................................................... 11
3.2 The properties of carbon dioxide (CO₂) ......................................................... 31
3.3 The properties of hexafluoride (SF₆) ................................................................. 31
3.4 Conclusion ............................................................................................................. 32

Chapter 4 The test setup and procedures ................................................................. 33
4.1 General ................................................................................................................ 33
4.2 The test object ..................................................................................................... 34
  4.2.1 The configuration of the test object .............................................................. 34
  4.2.2 The electric field ......................................................................................... 36
4.3 The test circuit ..................................................................................................... 36
  4.3.1 AC breakdown test circuit ......................................................................... 37
  4.3.2 Partial discharge measurement circuit ....................................................... 39
  4.3.3 Bias test circuit ......................................................................................... 39
4.4 The test procedures ............................................................................................ 41
  4.4.1 AC breakdown test procedure .................................................................... 41
  4.4.2 Partial discharge measurement procedure ................................................ 42
  4.4.3 Bias test procedure .................................................................................... 43
    4.4.3.1 The applied AC voltage calculation ....................................................... 43
    4.4.3.2 The impulse setting ............................................................................ 44
4.5 Parameters controlling ....................................................................................... 47
  4.5.1 Protrusion length controlling ....................................................................... 47
  4.5.2 Humidity controlling .................................................................................. 47
  4.5.3 Pressure controlling ................................................................................... 48
  4.5.4 Temperature controlling ............................................................................ 48
4.6 Conclusion .......................................................................................................... 50

Chapter 5 The result and analysis of the AC breakdown tests and the partial discharge measurements ........................................................................................................ 51
5.1 The result and analysis of the AC breakdown strength ........................................ 51
5.1.1 The influence of the protrusion length ................................. 52
5.1.2 The influence of the gas temperature .................................. 58
5.1.3 The influence of the gas humidity ..................................... 63
5.1.4 The influence of the gas pressure ..................................... 68
5.2 The result and analysis of the partial discharge measurements ................................. 72
5.3 Conclusion ........................................................................ 79

Chapter 6 The Result and analysis of the bias test ................................................. 81
6.1 The result and analysis .................................................................. 82
6.2 Conclusion ........................................................................... 85

Chapter 7 The SF₆ breakdown test ......................................................... 87
7.1 The test setup and procedures .................................................... 87
7.2 The result and analysis ............................................................... 87
7.3 Conclusion ........................................................................... 88

Chapter 8 The Risk Assessment .......................................................... 89

Chapter 9 Conclusion and Recommendation ........................................... 95
9.1 Conclusion ........................................................................... 95
9.2 Recommendation .................................................................... 96

References .................................................................................. 97
Chapter 1
Introduction

1.1 General

Electricity is seen as a primary need for human beings. It is generated at a power plant, transmitted to other sites over transmission lines and then distributed to consumers as end points. To deliver the electricity from the generating plant to the consumers, substations are needed as "terminals" for incoming and outgoing lines. Electricity from the incoming lines can either be transformed up/down and then forwarded to the outgoing lines or just forwarded to other outgoing lines.

There are two well known types of substation: air insulated substations (AIS) and gas insulated substations (GIS). In AIS type, the apparatus are put in the open air which means that the air acts as an insulating material. By contrast, in GIS type the apparatus are put inside enclosures filled with compressed gas as insulating material (Figure 1.1). For the same level of power or voltage, a GIS needs much less space than does an AIS. This is a significant benefit especially for installations in densely populated areas. Another benefit is the lower maintenance requirements with GIS because the apparatus are enclosed from the environment.

Figure 1.1 A gas insulated substation (GIS)
1.2 The Problem Definition

In an ideal condition, a GIS should be defect-free and be operated under certain steady level of temperature, pressure and humidity. The electrodes surface should be smooth and clean. However, in practice, some defects such as protrusions, free particles or floating parts may be present inside a GIS. This can occur due to, for example, poor machining during fabrication or due to scraping of electrode surfaces during on-site assembly. Operation of contacts during service life is also considered as a reason for the protrusion presence inside a GIS.

The protrusions change electric field inside a GIS considerably. They locally intensify the electric field, which in turn can decrease the breakdown strength of the GIS. This situation thus puts the GIS into a severe condition.

Due to circumstance influence, a GIS may operate under varied level of temperature, pressure and humidity or moisture content. A change from one season to other season, as an example from rainy season to dry season in tropical countries, can alter the ambient temperature which in turn can also alter the temperature of the GIS. The GIS temperature increase affects on an increase in the pressure for they are linearly proportional. [9, p.2]

Ambient humidity can give an important role for the moisture content of a GIS, mainly on a leakage-sealed GIS. The more humid the ambient air is, the easier the water vapor infiltrates into the GIS. Thus, in rainy season the GIS has a higher probability to get humid than in dry season.

The increase of temperature and humidity can influence the gas breakdown strength. It can also initiate corrosions of the electrodes inside the GIS, which is not discussed in this thesis.

1.3 The Objective of Thesis

The objective of this thesis is to investigate the influence of pressure, temperature, moisture content, and protrusion length on the breakdown of GIS
installation. An artificial protrusion will be put on one electrode which will be
described in detail in Chapter 4. The temperature, pressure and moisture
content are set to a certain level which depicts the tropical condition. The
breakdown voltage will be investigated by applying AC voltage between the
electrodes. As in practice the installation could experience not only AC voltage
but also impulse voltage, in this thesis impulse voltage superposed on AC voltage
will be applied as well.

The presence of the protrusion makes the electric field between the electrodes
becomes very in-homogenous. There is a high concentration of electric field
around the protrusion which in turn produces corona. This is also another point
of investigation in this thesis.

Gas used as insulating material in a GIS has to meet several criteria such as
chemically and thermally stable, good heat transfer and quenching properties. In
industrial use, sulfur hexafluoride (SF₆) has been chosen because it has very
good properties for that purpose. However, its byproducts produced during
breakdown are very toxic that introduce a threat to the health of people who
come into contact with them. [16]

In this thesis project an alternative gas, CO₂, will be used instead. The tests will
be done under different levels of moisture content, pressure and temperature
and under different protrusion length. For comparison reason, test using SF₆ will
be conducted as well in a limited number. Analysis will be presented by
comparing the results with literatures.

Based on the test result, a risk assessment will be accomplished as a tool to make
a decision whether a GIS is safe to be operated.

1.4 The Thesis Layout

- Some background theory of gas as insulating material will be presented in
  Chapter 2.
Chapter 1: Introduction

- The properties of CO$_2$ and SF$_6$ as insulating gases will be given in Chapter 3.

- Chapter 4 describes the test setup and procedures. How to control the parameters will be explained here.

- Chapter 5 contains the test results and analysis of the AC breakdown test and partial discharge measurement of CO$_2$.

- Chapter 6 contains the test results and analysis of the bias (impulse voltage superposed on AC voltage) breakdown test of CO$_2$.

- In Chapter 7, the result and analysis of breakdown test of SF$_6$ is given.

- The risk assessment is presented in Chapter 8.

- Finally, conclusions and recommendation are put in Chapter 9.
Chapter 2
Discharging Process in Gas as Insulating Material

2.1 General

At a normal state, a gas put in between two electrodes behaves almost as a perfect insulator. However, a gaseous dielectric always contains free electrons due to radio-active radiation, light or cosmic radiation [2, p.67]. In the absence of electric field, the free electrons move randomly with velocities ranging from zero to a fraction of the light velocity. In this way, collisions occur between the free electrons.

The average distance for electrons traverse between two successive collisions is called the mean free path. It is directly proportional to gas temperature and inversely proportional to gas pressure.

If a voltage is applied between the electrodes and thus an electric field is present, the free electrons gain energy and are accelerated in the field toward the anode, hence in opposite direction of the field. When the voltage is increased, the electric field increases. Increasing the voltage until a certain level will make the insulating gas cannot withstand the electric field. Electrical breakdown occurs. This can be regarded as the result of ions, thus electrons, generation by electron collision, photo-ionization, interaction with meta-stable atoms, thermal ionization, electron detachment and furthermore by secondary ionization. The processes are called ionization. Therefore ionization can be defined as a process of releasing an electron from a gas molecule. However there is also a process of annihilating the electron by recombination, by diffusion, and for certain gases, by electron attachment. This process is named deionization.
2.2 Ionization Processes

2.2.1 Ionization by Electron Collision

Ionization by electron collision is considered as the most important ionization process for a gas discharge. When the electron traverses, the gas molecule may be hit by the electron. This collision can result, depending on the electron energy, elastic or inelastic collision. If the electron energy is less than ionization energy of the molecule, elastic collision occurs. On contrary, inelastic collision takes place when the electron energy is higher than that of the molecule.

Ionization energy is the amount of energy needed to liberate one electron from a neutral atom or molecule. In elastic collision, there is no internal change of energy in the colliding particles. Energy exchange is always kinetic which involves only redistribution of the kinetic energy of the colliding particles. The electron could change direction and is reaccelerated until the next collision. No excitation or ionization results in elastic collision.

In inelastic collision, the gas atom becomes excited or ionized by the energy acquired from the hitting electron. There is an internal change of energy experienced by the molecule. The total kinetic energy of the particles is now different from what it was before the collision. A part of the kinetic energy of the electron due to collision is converted to potential energy of the atom.

Each collision, due to the exceeding energy of electron, produces a positive ion and an extra electron. This process can be represented as:

\[ A + e \rightarrow A^+ + 2e \]

Where A is the atom or molecule, \( A^+ \) is the positive ion and e is the electron.

2.2.2 Ionization by Radiation (Photo-ionization)

Ionization by radiation concerns the interaction of radiation with matter. When an atom or molecule absorbs an amount of radiation energy above its ionization energy, photo-ionization happens. The radiation absorption can happen due to excitation of the atom to a higher energy state. The reaction can be written as:
\[ A + e \rightarrow A^* + e \]

where \(A^*\) represents the excited atom.

When the excited atom returns to its lower state or ground state within a short time (\(10^{-7} - 10^{-10}\) seconds), it radiates a quantum of energy of photon \((hv)\) which in turn could ionize another atom whose ionization energy is equal or less than the photon energy.

The process can be expressed as

\[ A^* \rightarrow A + hv \]

\[ B + hv \rightarrow B^* + e \]

Here \(A^*\) represents the excited state of atom \(A\), \(hv\) is the photon energy and \(B^*\) represents the excited state of another atom \(B\).

This process continues as the photons energy exceeds or is equal to the ionization potential of the other atoms or molecules. The process is known as photo-ionization.

### 2.2.3 Ionization by Interaction with Meta-stable Atoms

A meta-stable atom is an excited particle whose lifetime is very large (\(10^{-3}\) s) compared to that of ordinary atom (\(10^{-8}\) s). This atom has a certain energy level to which an electron may be started but from which it cannot go back easily to its normal or previous state energy level. Electrons can be released from a metal surface by the impact of meta-stable (excited) atoms which have a relatively high potential energy and are therefore able to ionize neutral particles.

Ionization by interaction with meta-stable atoms comes into operation long after excitation. It has been shown by some research works that these processes are responsible for the long time lags of breakdown observed in some gases.[1, p.320]
2.2.4 Thermal Ionization

If a gas is heated to a sufficiently high temperature, its particles will move faster and as a result may cause ionization on collision between gas atoms. Thermal ionization can be written

\[ A + W_t \rightarrow A^+ + e \]

where \( W_t \) represents the thermal energy.

This type of ionization is the main reason for the ionization in flames/spark and high-pressure arcs. [1, p.320]

2.2.5 Electron Detachment

The presence of radiation may cause an electron detachment from a negative ion. The photon energy of the radiation, \( h\nu \), is absorbed by the negative ion and, as a result, a fast-moving atom \( A \) and an electron are produced, as follows:

\[ A^- + h\nu \rightarrow A + e \]

It is known that the kinetic energy is directly proportional to mass and to the square of the speed. Therefore, the electron has much higher kinetic energy than the negative ion. In this way, the electron can trigger further ionization.

Moreover, there is a probability that the fast-moving atom \( A \) collides with another negative ion. This collision results in other fast-moving atom and electron, as shown below:

\[ A^- + A \rightarrow 2A + e \]

If this process continues, the ionization will develop more intensely. [6, p.27]

2.3 Deionization Processes

Deionization is the process of decreasing the number of charged particles, especially the electrons, in a certain gas volume. It is important to prevent the
avalanche growth, which will be discussed in section 2.4. There are three processes of the deionization: recombination, diffusion, and as additional for electronegative gases, electron attachment.

2.3.1 Deionization by Recombination

If positively and negatively charged particles are present, there is a tendency for these particles to recombine to form neutral atoms. When an electron is captured it loses kinetic energy which is emitted as a quantum of radiation. [7, p.38] It can be written as

\[ A^+ + B^- \rightarrow AB + h\nu \]

2.3.2 Deionization by Diffusion

Diffusion is a process to get equilibrium in a non-uniform concentration of ions. Charged particles move from regions of higher concentration to regions of lower concentration. This process will cause a de-ionizing effect in the regions of higher concentrations and ionizing effect in regions of lower concentrations.[1, p.332]

2.3.3 Electron Attachment

Certain atoms in gaseous states can easily capture slow moving free electrons to form a stable negative ion. These gases are known as electronegative gases. The process can be written as follows which is opposite to the detachment process [6, p.29]:

\[ A + e \rightarrow A^- \]

2.4 Pre-breakdown Phenomena in Gases

There are many literatures describing the pre-breakdown phenomena in gases. Among them is Industrial High Voltage Volume 1, written by F. H. Kreuger, which will be summarized in this section. [2, pp 67-76]
2.4.1 Electron Avalanches Generation

If the ionization of the atoms occurs repeatedly, there will be a multiplication in the number of electrons. This can be described as follows. When ionization happens, electrons move from the cathode towards the anode. Suppose an amount of $N_0$ electrons leave the cathode and then arrive at a distance $x$. The number of electrons at $x$, $N_x$, can be calculated as shown in figure 2.1.

![Diagram of electron avalanches](image)

**Figure 2.1** The number of electrons, $N_x$, in layer $dx$ at a distance $x$ from the cathode

Let $\alpha$ (ionization coefficient) be the average number of ionizations per cm travel of an electron in the direction of the field. It is known as the Townsend's first ionization coefficient which is also equal to the number of new electrons over a certain distance.

This coefficient depends on the electric field ($E$) and the gas pressure ($p$):

$$\alpha = A \cdot p \cdot e \cdot \left( \frac{E}{B \cdot p} \right)$$

(2.1)

where $A$ is the saturation ionization in the gas at a particular $E/p$ and $B$ is related to the excitation and ionization energies.

It can be seen that $\alpha$ increases exponentially as the electric field increases. This ionization coefficient is thus constant for a homogenous electric field.
At a distance $x$ from cathode let the number of electrons be $N_x$. If these $N_x$ electrons move further in a layer $dx$, an amount of extra electrons ($N_x \alpha \, dx$) will be generated. Thus we have:

$$d \, N_x = N_x \alpha \, dx$$

Integration from cathode to the layer $dx$, in homogenous electric field, results:

$$N_x = N_0 e^{(\alpha x)}$$

Therefore the number of electrons arriving at the anode, at a distance $d$ from cathode, can be written as:

$$N_0 = N_0 e^{(\alpha d)}$$

(2.2)

This equation can also be expressed in the term of current as it is numerically proportional to the number of electrons moving per second. Suppose $I_0$ is current leaving the cathode, the current arriving at the anode ($I_a$) is

$$I_a = I_0 e^{(\alpha d)}$$

The number of electrons enhances exponentially and the current as well.

The increasing of electrons by $e^{(\alpha d)}$ is called electron avalanche. It is a figure of the number of electrons generated by one electron in moving from the cathode to the anode. The head of the avalanche is built up of electrons whereas the tail is dominated by positive ions.

### 2.4.2 Secondary Electrons

The electron avalanches cause leakage currents. However, a breakdown does not occur by only those avalanches. A feedback mechanism is necessary to release new starting electrons which in turn will create further avalanches. In this way, breakdown will take place. There are several feedback mechanisms such as electron emission by positive ion and electron emission by photon impact as will be described later. The electrons produced by these mechanisms are called secondary electrons.
2.4.2.1 Feedback by \( \gamma \) Process (Electron Emission by Positive Ion)

The positive ions move much slower than electrons. The ions have a speed about 1 mm/\( \mu \)s, whereas that in the electrons is about 100 mm/\( \mu \)s. Thus after ionization, in traveling from cathode toward anode, the ions are left behind the electrons. These ions are then accelerated by the electric field and move toward the cathode.

As the ions hit the cathode, depending on the kinetic energy there is a probability \( \gamma \) that an electron will be emitted from the cathode surface. It is known as Townsend’s second ionization coefficient \( \gamma \) and defined as the net number of secondary electrons produced for each primary electron leaving the cathode. There are many factors influencing the probability \( \gamma \) such as the field strength and cathode material.

The effect of secondary process on the electrons or current growth can be considered as follows. Let initially a number of \( N_o \) electrons leave the cathode. Based on Equation 2.2, the amount of electrons reaching the anode is \( N_o e^{(a_d)} \).

The number of ions formed then is \( N_o (e^{(a_d)} - 1) \) which will be attracted to and thus hit the cathode. With the probability \( \gamma \), these ions will release secondary electrons, \( N_s \) as many as

\[
N_s = \gamma N_o (e^{(a_d)} - 1)
\]

(2.3)

These secondary electrons move toward the anode and create new avalanches and further processes repeat. Let \( \gamma (e^{(a_d)} - 1) \) is replaced by \( q \), the whole electrons formed can be written as

\[
N_a = N_o + N_o q + N_o q^2 + N_o q^3 + N_o q^4 + \ldots
\]

It can be seen that if \( q \) is greater than 1 the electrons are produced infinitely and thus breakdown occurs. Increasing the field strength to a certain level is one way to reach this condition.
2.4.2.2 Feedback by Photon (Electron Emission by Photon-ionization)

When a number of electrons travel through a layer $dx$, they excite atoms and create photons. Here a factor $\theta$ is introduced. It is the number of atoms per unit length excited by the fast-moving electrons in the electric field. Because the excited atom will produce a photon, $\theta$ can also represent the number of released photons per unit of length.

Not all the photons will reach the cathode. There is photon absorption by the gas in amount of $\mu$ and thus only a part $g$ of photons reaches the cathode. A part $\delta$ of these reaching-cathode photons then produces electrons capable of leaving the surface.

Referring to figure 2.1, the number of electrons produced in layer $dx$ in this way is introduced as follows.

$$dN = N_0 \cdot e^{(\alpha x)} \cdot \theta \cdot g \cdot e^{(-\mu x)} \cdot \delta \cdot dx$$

The total number of electrons can be calculated by integrating from cathode to anode which yields:

$$N_a = N_0 \frac{\theta g \delta}{\alpha - \mu} (e^{(\alpha - \mu) d} - 1)$$

If we use $\Gamma$ to replace $\frac{\theta g \delta}{\alpha - \mu}$ and if $\mu << \alpha$ then the equation can be written as:

$$N_a = N_0 \Gamma (e^{\alpha d} - 1)$$

This is similar to Equation 2.3.

In practice both electron emissions by positive ion and by photon may occur at the same time. However, at low pressure the photon-ionization effect on the growth of electrons, and thus of current, can usually be ignored.
2.4.3 Current-Growth Equations

Now, let \( \Gamma \) be the representation of the combined effects of several feedback mechanisms for creating secondary electrons. Suppose at first a number \( N_o \) of electrons will produce \( N_o(e^{\alpha x} - 1) \) new electrons as they leave the cathode at a distance \( x \). If we denote \( N_s \) as the number of secondary electrons generated at the cathode and \( N_t \) as the number of total electrons leaving the cathode, then we can write

\[
N_t = N_o + N_s
\]

Here we can have \( N_s \) by referring to Equation 2.2 and replacing \( \gamma \) with \( \Gamma \). So,

\[
N_s = \Gamma \cdot N_o(e^{\alpha x} - 1)
\]

Rearranging those equations, the total number electrons (\( N_t \)) is

\[
N_t = \frac{N_o}{1 - \Gamma(e^{\alpha d} - 1)}
\]

If the gap (cathode – anode) distance is \( d \), referring the Equation 2.1, the number of electrons reaching the anode (\( N_a \)) is

\[
N_a = \frac{N_o e^{\alpha d}}{1 - \Gamma(e^{\alpha d} - 1)}
\]

So the current is

\[
I_a = \frac{I_o e^{\alpha d}}{1 - \Gamma(e^{\alpha d} - 1)} \tag{2.4}
\]

2.5 Breakdown in Gases

The voltage applied across a dielectric gas results in an electric field either uniform or non-uniform. It depends on factors such as the shape of the electrodes, the smoothness of the electrodes and the cleanliness of the gap. In a uniform field gap the electric field is homogenous. It means that the field is the
same everywhere. Contrary to uniform field gap, in non-uniform situation there is a concentration of electric field in certain area. This leads to in-homogenous field.

2.5.1 Breakdown in a Uniform Field

There are two typical gas breakdown mechanisms mostly accepted: Townsend mechanism and streamer mechanism.

2.5.1.1 The Townsend Mechanism

For a low pressure gas, breakdown process can be explained with Townsend mechanism. Figure 2.2 shows the current-voltage relationship in pre spark region. This was first studied by Townsend using two parallel plate electrodes [1, pp.313-314].

![Current-voltage relationship in pre spark region](image)

At first the current increases slowly when the voltage rises, as shown in region 1. The current, in region 2, then remains almost constant at a value \( I_0 \) which is designated as the saturation current. The value \( I_0 \) also represents the emitted photocurrent if the cathode is exposed to an ultraviolet light.
Further increasing in the voltage, beyond $V_2$, causes an increasing in the electric field and, thus, in the ionization coefficient ($\alpha$) as well according to the Equation 2.1. This eventually leads to an increasing in the current exponentially as shown in region 3.

In region 4, due to the presence of secondary electrons by feedback mechanisms, a small increasing in the voltage beyond $V_3$ can result much increasing in the current so that the gap breaks down.

The states of region 3 and region 4 can be explained using the Equation 2.4. In the absence of the Townsend secondary-mechanism ($I = 0$) the current increases exponentially ($I_a = I_0 e^{(\alpha d)}$) as can be seen in region 3. In region 4, breakdown occurs when the current is infinite ($I_a = \infty$). This is called Townsend breakdown criterion. Referring Equation 2.4, it can be reached when:

$$ I' (e^{(\alpha d)} - 1) = 1 $$

(2.5)

Apparently the Townsend secondary-mechanism ($I'$) contributes to give much more electrons.

It can be said that in the Townsend mechanism there are three steps for breakdown [2, p.73]:

1. The presence of starting electrons.

2. The multiplication of electrons leading to an avalanche. This can be obtained by means of sufficiently high electric field.

3. Feedback mechanisms to produce more electrons from the cathode.
2.5.1.2 The Paschen Law

In low pressure gas, there is a dependence of breakdown voltage on the product of pressure and gap distance \((pd)\). This was concluded by Paschen. He conducted an extensive study of air, CO_2, and H_2 over varied values of \(pd\). He revealed that the breakdown voltage is a function of \(pd\). This is known as the Paschen's law as will be described here. [7, p.61]

Equation 2.5 shows the Townsend breakdown criterion where the coefficients \(\Gamma\) and \(\alpha\) are the functions of \(E/p\), say:

\[
\frac{\alpha}{p} = f_1\left(\frac{E}{p}\right)
\]

\[
\Gamma = f_2\left(\frac{E}{p}\right)
\]

Since in a uniform field \(E = V/d\), we can write those equations

\[
\frac{\alpha}{p} = f_1\left(\frac{V}{pd}\right)
\]  \hspace{1cm} (2.6)

\[
\Gamma = f_2\left(\frac{V}{pd}\right)
\]  \hspace{1cm} (2.7)

Rearranging the Equations 2.6 and 2.7 and rewriting the Equation 2.5 in the expressions for \(\alpha\) and \(\Gamma\), a new equation is revealed:

\[
f_2\left(\frac{V}{pd}\right) e^{pd f_1\left(\frac{V}{pd}\right)} - 1 = 1
\]  \hspace{1cm} (2.8)

There is a relationship between \(V\) and \(pd\). Variation in \(pd\) will result variation in breakdown voltage. In this way, for a particular \(pd\) there is one value of breakdown voltage \((V)\). This can be written as:

\[
V = f(pd)
\]  \hspace{1cm} (2.9)

The Equation 2.9 presents that for a particular gas, the breakdown voltage is a function of pressure and gap distance product. This equation is known as the Paschen law.
The Paschen law can be expressed in a curve named the Paschen curve, with \( V \) and \( pd \) at logarithmic scales. Examples are shown in figure 2.3 for air, \( \text{H}_2 \) and \( \text{Ne} \) [2, p.75]. Each gas has its own Paschen curve.

![Figure 2.3 Paschen curve](image)

There is a unique situation in the Paschen curve. Increasing \( pd \) will decrease \( V \), but at particular level of \( pd \) it reaches a minimum breakdown voltage and there from it increases as \( pd \) increases. This situation can be explained as follows.

For the left part of the minimum point, the number of atoms available is so small that the electrons crossing the gap have little opportunity to make collision with gas molecules. Ionizations occur rarely. In order to create ionization more intensely, thus to break down eventually, higher electric field is required. This can be accomplished by increasing the voltage.

Contrary to the left part, for the right part of the minimum voltage there is lot of electrons colliding with the gas molecules more frequently. However, the distance passed is so small that the electrons do not gain sufficient velocity. As a result, ionization exists in small amount. Higher electric field is then needed to reach breakdown.

The Paschen curve is valid for low pressure gas up to about 1 atm x 5 mm. For higher \( pd \) product the Paschen curve is not acceptable. Other breakdown mechanism takes place as will be described below.
2.5.1.3 The Streamer Mechanism

The Townsend mechanism is not appropriate for $pd > 5$ atm.mm. In practice there are several phenomena which cannot be explained by the Townsend mechanism. Time lag to breakdown is in order of $10^{-8}$ s which is much shorter than that in the Townsend mechanism ($10^{-5}$ s). The breakdown channel is filamentary and sharp while in the Townsend mechanism it has a very diffused form. Moreover, the cathode material does not give contribution to the breakdown voltage.

The streamer mechanism was proposed by Raether, Loeb and Meek independently to explain those phenomena. [7, pp.79-82] It was observed that if the number of ions in the avalanche head reaches $10^8$ a space charge field is formed with the same magnitude as the electric field. This may lead to the initiation of streamer. The number of $10^8$ ions is named as critical length for a streamer.

Figure 2.4 illustrates an avalanche consisting of fast moving electrons (100 mm/μs) and slow moving ions (1 mm/μs). Due to the different velocities, ions are left and still at the position where they were formed when the electrons are extinguished. This creates a positive space charge accumulated at the head of the avalanche.

![Figure 2.4 Space charge of an avalanche](image)

If the number of ions exceeds the critical length, there is a significant enhancement on the electric field. Extra ionizations and creation of photons occur. These photons will be absorbed by gas molecules and causes new ionizations in adjacent gas molecules. This in turn generates auxiliary avalanches.
Chapter 2: Discharging Process in Gas as Insulating Material

As auxiliary avalanches are produced, further extra ionizations and photons creation take place. This process occurs repeatedly. The new avalanches combine with the previous avalanches and positive ions space charge develop in direction to the cathode. Hence the ionizations will grow from the anode to the cathode creating a channel called streamer. Eventually the gap breaks down.

The electrons do not engage to the previous avalanches in straight line. The path created is a branched and zigzag line. It is caused by random avalanche process. Many avalanches may be generated almost simultaneously. However, only one avalanche will reach the cathode. Figure 2.5 shows the development of a streamer into a breakdown. [2, p.80]

![Diagram of avalanche development](image)

Figure 2.5 Development of a streamer into a breakdown:

a. Photons are radiated from the tip of the streamer. A new avalanche can be started in line with the streamer or at an angle stochastically.

b. Two avalanches may start simultaneously an cause branching on the streamer.

c. When moving closer to the cathode, the intensive field causes electrons and emission electrons.

d. Negative electrons and positive ions mix and form a conductive path, thus the gap breaks down.

e. An arc is formed at higher short-circuit currents.
2.5.2 Breakdown in a Non-uniform Field

The electric field strength in a uniform field gap is equal everywhere. In this condition, a discharge leads to a complete breakdown. By contrast, in a non-uniform electric field, for instance in a point-plane configuration, the field strength varies across the gap. Thus the Townsend's first ionization coefficient $\alpha$ varies as well according to the integral of $\alpha$ over the gap. The Equation 2.5 can then be written as in Equation 2.10 by replacing $ad$ with $\int_{a}^{b} \alpha dx$. [8, p.31]

$$\Gamma\left(e^{\int_{a}^{b} \alpha dx} - 1\right) = 1$$

(2.10)

In the non-uniform distributed $\alpha$, the breakdown or the inception of discharge criterion for general case can be written as

$$e^{\int_{a}^{b} \alpha dx} = N_{cr}$$

(2.11)

where $N_{cr}$ is the critical number of electrons needed for starting a streamer (i.e. $10^8$), $x_c$ is the path of the avalanche to reach $N_{cr}$ and $d$ is the gap length. This situation is illustrated in Figure 2.6.

Figure 2.6 An electrical field distribution in a non uniform field gap
2.5.3 The Influence of Gas Temperature on the Breakdown Voltage

In general, the breakdown voltage of gas is a function of the product of relative gas density $\delta$ and the electrodes' gap length $d$, which is expressed as [14, pp.48-50]

$$U_{bd} = A\delta d + B\sqrt{\delta d}$$  \hspace{1cm} (2.12)

Where $A$ and $B$ are constants which depend on the gas type.

As increasing the gas temperature will decrease the relative gas density, it can be seen from Equation 2.12 that increasing the gas temperature will decrease the breakdown voltage.

2.5.4 The Influence of Gas Humidity on the Breakdown Voltage

According to Kuffel [1, p104], the presence of water vapor in gas will increase the breakdown strength. This may be due either to the increasing of the electron attachment to the water molecules, or the decreasing of the secondary ionization coefficient $I'$ resulted from photons absorption by water molecules.

At humidity above 90%, water condensation can take place which result negative impacts on the breakdown voltage. [2, p.85] Therefore, the humidity should be kept below that value.

2.6 Breakdown in Gases under Impulse Voltage

2.6.1 The Wave Shape of the Impulse Voltage

Impulse over-voltages can occur in a power system due to lightning or switching impulses. They are unidirectional and can be represented with a general shape as shown in Figure 2.7.
Figure 2.7 General shape of an impulse voltage. \( T_1 \): front time, \( T_2 \): half-value or tail time.

In this figure, there are two kinds of time: front time \((T_1)\) and half-value or tail time \((T_2)\). According to the IEC specifications, front time, also known as rise time, is defined as \(1.67T\) which is measured between 0.3 and 0.9 of the peak value, at point A and B respectively. Half-value time is the time measured at 0.5 of the peak value (at point C).

Based on the values of the front times \((T_1)\) and the half-value time \((T_2)\), a difference can be made between lightning and switching impulse. Lightning impulses are specified at \(T_1 = 1.2\) \(\mu\)s and \(T_2 = 50\) \(\mu\)s with a tolerance of about 30% for \(T_1\) and 20% for \(T_2\). This is also known as 1.2/50 \(\mu\)s wave shape. Switching impulses are specified at \(T_1 = 250\) \(\mu\)s and \(T_2 = 2500\) \(\mu\)s with a tolerance of about 20% for \(T_1\) and 60% for \(T_2\), thus named as 250/2500 \(\mu\)s wave shape. [1, pp.53-56]

### 2.6.2 The Time Lag for the Breakdown

The breakdown mechanisms under impulse voltage and under steady DC or power frequency AC are different. This is related to the presence of an initiatory electron needed to start an avalanche which in turn leads to a breakdown.

With slowly rising voltage, DC or 50 Hz AC, there is no difficulty in finding an initiatory electron from natural sources, for example cosmic rays or detachment negative electrons. However, under impulse voltage with short duration, in the order of \(\mu\)s, the natural sources may not be sufficient to provide the initiatory electron. Therefore the gap does not break down when the peak voltage reaches...
the lowest static breakdown value \((V_s)\) which is the breakdown level of the gap after a long time of the voltage application. In this condition, the voltage level has to be increased higher than \(V_s\) to reach the breakdown.

The time that passes between the application of the voltage higher than \(V_s\) and the breakdown is called the time lag \((t)\). It consists of two components: the statistical time-lag \((t_s)\) and the formative time-lag \((t_f)\). The statistical time lag is the time that passes during the application of the voltage higher than \(V_s\) until an initiatory electron appears. After such an electron appears the subsequent time, the formative time-lag, is required for a breakdown. The time lag components of a breakdown under an impulse voltage are depicted in Figure 2.8. [1, p.383]

![Figure 2.8 The time lag components of a breakdown under an impulse voltage](image)

### 2.6.3 The Breakdown Probability under Impulse Voltage

When a number of impulses of a peak \(V_p\), see Figure 2.8, are applied to a gap, due to the statistical nature of the time lags there is only a certain percentage that the gap will breakdown. This is known as the breakdown probability of an impulse voltage, represented as \(U_{\text{p}}\). [6, p51] For example, \(U_{50\%} = 26 \text{ kV}\). It means that at applied impulse voltage of 26 kV the probability that the gaps will breakdown is 50\%.

### 2.7 Partial Discharge in Gases

The presence of defects in an insulating gas causes local field concentration which often results in partial discharge. According to IEC 60270 "High-voltage
test techniques – Partial discharge measurements", a partial discharge is defined as \textit{localized electrical discharge that only partially bridges the insulation between conductors and which can or cannot occur adjacent to a conductor}. [10, p.15] Initially the discharge usually appears in small magnitude. Through continuous process it can grow and damage the dielectric material. Eventually the insulating system collapses.

There are four types of partial discharges: corona discharges, surface discharges, internal discharges and electrical treeing. As this thesis will deal with corona discharges in gas, it will be discussed more detail than the others.

2.7.1 Surface Discharges

Surface discharges may occur parallel with dielectric interfaces, either in gas or in oil, if a strong tangential stress component exists. Some examples are shown in Figure 2.9. [4, p.2]

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{surface_discharges.png}
\caption{Surface discharges}
\end{figure}

2.7.2 Internal Discharges

These discharges occur in cavities in solid insulating material. The cavities are usually gas-filled. Some examples are given in Figure 2.10. [4, p.2]

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{internal_discharges.png}
\caption{Internal discharges}
\end{figure}

\begin{enumerate}
\item Flat cavity, perpendicular to the electrical field and completely surrounded by the dielectric
\item Spherical cavity
\item Long cavity, parallel to the electrical field
\item In an interface with a longitudinal field
\end{enumerate}
2.7.3 Electrical Treeing

Electrical treeing originates from conducting particles or from defects in solid insulation. Figure 2.11 shows an example of electrical treeing. [4, p.14]

![Figure 2.11 Electrical treeing](image)

2.7.4 Corona Discharges

The presence of a sharp metallic point on an electrode in an electric field can initiate corona discharges. The inception of the corona is a function of absolute voltage instead of field strength. Figure 2.12 represents a corona discharge. [4, p11]

![Figure 2.12 Corona discharge](image)

The corona discharge process depends on the polarity of the applied voltage which will be described as follows.

2.7.4.1 Negative Corona

When a negative voltage applied to point-plane electrodes (the sharp metallic point) reaches a certain level in which the critical field is established, electron avalanches occur and move towards the anode leaving behind the positive ions. When the electrons enter the low field region, negative ions are formed and therefore a space charge field is created. If the difference between the applied electrostatic field and the field due to space charges, named as the effective field,
is less than the critical field value, the discharge stops. After the space charges drift away, the field around the point recovers and the discharge repeats. This situation occurs repeatedly. Corona current pulses are thus formed. Increasing the voltage will increase the number of pulses per second.

The next mode is the negative glow mode. If the voltage is increased further, the effective field is always higher than the critical field. The discharge becomes continue and therefore results in a pulseless current, a steady glow discharge.

With an increase in the applied voltage, the discharge takes place more intensively until breakdown occurs.

2.7.4.2 Positive Corona

Now, if a positive voltage is applied to the point-electrodes and reaches a certain level in which the critical field is established, electron avalanches are produced which will get directed to the anode. At the anode, the electrons will be absorbed quickly while the positive ions are left and accumulate around the anode. This first mode is called onset streamer.

If the voltage is further increased, a cloud of negative ions may form around the anode. The onset streamer will be so high that it can cause discharges in the form of a glow that shield the anode. This is called positive glow corona.

At higher voltage, incomplete streamers occur which can result so called positive pre-breakdown streamer mode corona. If the voltage is further increased, a complete breakdown takes place.

The corona under positive polarity appears at higher voltage than that under negative one.

2.7.4.3 AC Corona

At AC voltage, there is periodic change in direction of the applied field. The modes as both in positive and negative polarities described above can appear under AC voltage as well.
For the point-plane electrodes configuration, when the voltage is increased, negative corona occurs first: the discharges appear at the cathode. If the voltage is again increased the number and the amplitude of discharges then increases. The discharges appear at the negative half cycle. This is shown in Figure 2.13a.

![Figure 2.13 Corona at AC voltage for point-plane electrodes](image)

Further increasing the voltage will result the discharges appearing at the positive half cycle as well, shown in Figure 2.11.b.

In the case of reversed electrodes configuration (plane-point), a reversed pattern will appear: the discharges will appear first at the positive half cycle.

### 2.7.4.4 Corona Stabilization

In the case of slowly increasing voltage, such as in AC voltage, the so called corona stabilization takes place which relies on many parameters like the protrusion geometry and the gas pressure. When the voltage is applied, streamers arise in the gas at the tip of the protrusion and leave positive space charges. A space charge cloud is formed there which shields the tip from the field and therefore reduces the electric field around the tip. As a result, further ionization and, thus, further discharge process are stopped. In this case, higher voltage is needed to initiate a breakdown. This type of breakdown is called corona-stabilized breakdown.

The corona-stabilized breakdown applies up to a certain gas pressure $p_m$. If the gas pressure is increased above $p_m$, according to Works and Dakin, corona streamer propagation between the electrodes is enhanced by reduced positive-
ion diffusion and photo-ionization is a more effective secondary process at higher gas density. This would lead to a breakdown without any stable corona which is called corona-free breakdown. As a result the breakdown voltage decreases as the pressure increases. [5, section5.4]

2.8 Conclusion

The following conclusion can be made:

- Discharging in gas as insulating material may occur if there are free electrons and sufficient electric field. Electrons multiplication can lead to electrons avalanche and eventually, by feedback mechanism, to a breakdown.

- There are two breakdown mechanisms, i.e. the Townsend and streamer mechanisms. The Townsend mechanism applies in low pressure gas, while streamer applies in high pressure gas.

- According to IEC Recommendation, lightning and switching impulses can be represented as 1.2/50 μs and 250/2500 μs wave shapes, respectively.

- Due to very short rising time (in the order of micro seconds) of an impulse voltage, a time lag is needed for a breakdown.

- Under a certain applied voltage, there is a certain probability that the gap will breakdown.

- A protrusion on an electrode in an electric field can introduce corona discharges and eventually breakdown. The polarity of the voltage influences the breakdown voltage. The corona under positive polarity appears at higher voltage than that under negative one. At AC voltage, breakdown occurs when the protrusion is positive.

- At a certain condition, corona stabilization occurs which increases the breakdown voltage.
Chapter 2: Discharging Process in Gas as Insulating Material
Chapter 3

The Properties of CO₂ and SF₆ as Insulating Gases

3.1 General

There are some requirements needed for a gas to be used as an insulating medium in a GIS. For high voltage applications, the insulating gases have to possess high dielectric strength, good thermal stability, non-flammability, low condensation temperature, good heat transfer and availability at reasonable cost. SF₆ has been commonly used as it has most of the above requirements.

However, the byproducts of SF₆ which could be present due to the breakdown process are toxic. Moreover, it is a greenhouse gas with a high global warming potential (GWP) of 23900 [11]. Therefore, in this experiment set-up, CO₂ (GWP of 1) gas will be used as the main course instead of SF₆. Limited experiments with SF₆ will be performed as well for a comparison purpose.

In this chapter the properties of both gases will be presented.

3.2 The Properties of Carbon dioxide (CO₂)

Carbon dioxide (CO₂) consists of two oxygen atoms bonded to a single carbon atom. At standard temperature and pressure (15 °C and 1 atm) it is in gas state. It is found in small proportions in the atmosphere with typical concentration is about 0.036% or 360 part per million volume (ppmv). CO₂ gas is colorless, inert, non flammable, odorless. It is toxic in high concentration. CO₂ freezing point is -78.5 °C. [15]

3.3 The Properties of Sulfur Hexafluoride (SF₆)

SF₆ is colorless, odorless, nontoxic in normal conditions, nonflammable and inert gas. It has a symmetric, octahedral structure in which six fluorine atoms are attached to a central sulfur atom. At atmospheric pressure, SF₆ is chemically
stable up to 500°C. At higher temperature which could be caused by an electrical discharge, it can decompose into several byproducts. In the presence of water vapor and oxygen, oxidation will take place. Some possible reactions are listed below.

\[
\begin{align*}
\text{SF}_6 + e & \rightarrow \text{SF}_4 + 2F + e \\
\text{SF}_6 + e & \rightarrow \text{SF}_2 + 4F + e \\
\text{SF}_6 + e & \rightarrow \text{SF}_5 + F + e \\
\text{SF}_5 + \text{SF}_5 & \rightarrow \text{S}_2\text{F}_{10} \\
\text{SF}_4 + \text{H}_2\text{O} & \rightarrow \text{SOF}_2 + 2\text{HF} \\
\text{SF}_4 + \text{O} & \rightarrow \text{SOF}_4 \\
\text{SOF}_4 + \text{H}_2\text{O} & \rightarrow \text{SO}_2 + 2\text{HF}
\end{align*}
\]

SF6 can start desiccation due to an electrical discharge. For instance, the products of the decomposition tend to recombine very quickly to reform SF6. Therefore, the dielectric strength of the gas returns to its original level. [6, section 4.2]

Some SF6 byproducts are toxic and corrosive and could pose a significant health threat.

### 3.4 Conclusion

- SF6 is commonly used nowadays as insulating gas because it can fulfill most of the required properties.
- CO2 might be interesting for future application as its GWP is much lower than that of SF6.
Chapter 4
The Test Setup and Procedures

4.1 General

In this thesis work, the influence of environmental conditions on the operation of a GIS in tropical area is investigated. In particular the influence of temperature, humidity, gas pressure and fast transients is studied. Moreover, the influence of small defects on the breakdown strength is investigated as well.

The temperature of the gas was set at 20, 30 and 40 °C. These values represent the temperature in tropical countries, such as Indonesia. The gases used contained 1500 part-per-million volume (ppmv) humidity or 500 ppmv humidity and were compared to dry gas as well. These levels of humidity are taken into account as the relative humidity in Indonesia is very high. It can reach above 90% (source: www.bmg.go.id). This high-level ambient humidity could influence the humidity inside a GIS, especially that with aged seal.

The effect of the gas pressure will be studied by setting the value at 6 and 8 bars. The last parameter, the protrusion length is 4, 2, 1 and 0.5 mm. These parameters are listed in Table 4.1. It can be seen that for the AC breakdown test, there will be 72 configurations of parameters.

<table>
<thead>
<tr>
<th>Protrusion Length (mm)</th>
<th>Pressure (bar)</th>
<th>Humidity (ppmv)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>8</td>
<td>1500</td>
<td>40</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>500</td>
<td>30</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>Dry gas</td>
<td>20</td>
</tr>
<tr>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The test object as was used for all tests is described in the following section.
4.2 The Test Object

4.2.1 The Configuration of the Test Object

A vessel, as shown in Figure 4.1, is used as the object for all tests. Basically, plane-plane electrodes with Rogowski profile are put inside the vessel (Figure 4.2.a). In order to simulate the presence of protrusion inside the vessel, a needle is mounted on the lower electrode.

![Figure 4.1 The test object](image1)

![Figure 4.2.a The electrodes inside the vessel](image2)
The material chosen for the protrusion is tungsten since it has very high melting point (~3400°C) compared to other needle material, i.e. steel (~1370°C). The needle is shaped in such a way that the tip’s radius is about 100 μm.

To ensure that the needle will be fixed on the electrode, it is screwed on a driving plate which in turn will be screwed on the electrode. The needle can be adjusted to get the required length of the protrusion. This is shown in Figure 4.3.
4.2.2 The Electric Field

The electric field distribution between the electrodes can be expected as non homogenous field. The highest field will be around the tip of the protrusion. This is conformed to the two-dimension field calculation using electric field calculation software, Ansoft Maxwell Student Version (Figure 4.4).

![Figure 4.4 Field plotting between the electrodes](image)

This non homogenous field can also be checked at the high-voltage electrode surface. There are many pits around the electrode center which resulted from breakdowns occurring only in that area (Figure 4.5).

![Figure 4.5 The surface of the high voltage electrode after several breakdowns](image)

4.3 The Test Circuit

Three kinds of tests will be performed: AC breakdown test, partial discharge measurement and bias test (AC voltage with superimposed impulse voltage test). In this section, the circuit for each test will be described. Basically, the circuits for
the AC breakdown test and the partial discharge measurement are the same while for the bias test is quite different.

4.3.1 AC Breakdown Test Circuit

In Figure 4.6, a basic circuit for AC breakdown test is shown. It consists of low voltage and high voltage sides. Voltage regulation is done at the low voltage side by means of a voltage regulator. The test object is placed at the high voltage side.

![Image of AC Breakdown Test Circuit]

Figure 4.6 Basic circuit for AC breakdown test

For each test, the voltage is increased from zero until it reaches its breakdown level. When the breakdown occurs at the test object, here at the protrusion, energy is released. However, the circuit does not always trip shortly after the breakdown so that the releasing energy continues. It often trips after further increasing the voltage.

Having suffered several energy-extensive-released breakdowns, the protrusion can melt. The originally sharp protrusion becomes rounded. The comparison before and after melting is shown in Figure 4.7 and 4.8.

![Image of Original Shape]

Figure 4.7 The original shape

![Image of Melted Shape]

Figure 4.8 The melted shape
For consistent results, it is important to keep the protrusion at the same, or relatively the same, shape and dimension during the whole experiments of a certain configuration of parameters. To obtain this, the circuit has to be switched off as soon as possible. Therefore an improvement has been made on the basic circuit. A “protective circuit” is added to the circuit as can be seen in Figure 4.9.

![Figure 4.9 The improved circuit for AC breakdown test](image)

If a breakdown occurs at the test object, current flows to earth. This current is sensed by means of a current transformer (CT) which is placed just after the test object. The sensing unit then gives “switch on” command to the normally-open tripping unit. Thus, a closed loop is created at the low voltage side and no more voltage appears at the high voltage side. Afterwards, the low voltage is switched off by turning the regulator to its zero position. Now, there is no voltage at both low and high voltage sides.

This improvement can prevent the protrusion from melting since the circuit will trip directly after a breakdown occurs.

Figure 4.10 shows the comparison of the protrusion shapes before and after some series of breakdowns. The shapes are relatively still the same. From this figure we can expect that the results will be consistent and comparable.

![Figure 4.10 The shape before and after some series of breakdowns](image)
4.3.2 Partial Discharge Measurement Circuit

Basically, the circuit for partial measurement is the same with that for the AC breakdown test. A partial discharge measuring unit is added as shown in Figure 4.11. Since the maximum applied is 80% of breakdown voltage, the "protective circuit" is not needed here.

![Figure 4.11 Partial discharge measurement circuit](image)

The capacitance $C_k$ is 1973 pF - 100 kV. The quadripole is set to be 1 nF - 1 mA.

4.3.3 Bias Test Circuit

The basic circuit for bias test is shown in Figure 4.12. It consists of two parts, i.e. AC and impulse parts.

![Figure 4.12 The basic circuit for bias test](image)
Chapter 4: The Test Setup and Procedures

The AC voltage is supplied from the AC circuit to the bottom side of the test object, thus the vessel body will experience the voltage as well. Therefore, the vessel has to be isolated from earth.

The impulses used in this thesis are positive ones which are injected from the impulse generator to the test object through the upper electrode. To protect the AC circuit from the impulse current when a breakdown occurs, a “protective gap” is added into this circuit. The current will then be delivered to earth rather than to the AC circuit.

The complete circuit is shown in Figure 4.13.

![Circuit Diagram](image)

**Figure 4.13 The complete circuit for bias test**

The values of capacitors and resistors of impulse part are set to obtain lightning or switching impulse. The values are listed in Table 4.2.

<table>
<thead>
<tr>
<th>Component</th>
<th>LI</th>
<th>SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{II}$: internal front  resistor</td>
<td>35 Ω</td>
<td>3400 Ω</td>
</tr>
<tr>
<td>$R_{II}$: external front resistor</td>
<td>240 Ω</td>
<td>13400 Ω</td>
</tr>
<tr>
<td>$R_{I}$: tail resistor</td>
<td>140 Ω</td>
<td>6000 Ω</td>
</tr>
<tr>
<td>$C_{extra}$: extra capacitor</td>
<td>-</td>
<td>1000 pF</td>
</tr>
<tr>
<td>$C_{div}$: divider capacitor</td>
<td>1600 pF</td>
<td>1600 pF</td>
</tr>
<tr>
<td>$C_{g}$: generator capacitor</td>
<td>0.25 μF</td>
<td>0.5 μF</td>
</tr>
</tbody>
</table>
The values of capacitors and resistors for switching impulse are larger than those for lightning impulse. This is due to the wave-shape of the impulses: switching impulse has larger front and half times than lightning impulse.

4.4 The Test Procedure

The test procedures are different for AC, bias tests and partial discharge measurement. However, the two latter tests can be conducted after completing the AC test. It will be discussed in the following sections.

4.4.1 AC Breakdown Test Procedure

For AC breakdown test, there are 72 configurations of parameters, thus 72 series to be done.

The voltage is increased from zero until the gas breaks down. The rate of the voltage rise is determined around 1 kV/sec. This rate is applied for all series.

Each series consists of seven breakdown tests. To get comparable and consistent results, it is important to keep the gas at the same condition for each test. This can be obtained by letting the gas recover after suffering a spark. A recovery time, three minutes between two successive breakdowns, is then needed. This has been used by other researcher [11, p654] and has also been proved by the author (see Table 4.3). One or two-minute recovery time yielded quite deviated results, whereas the three, four or five-minute recovery time gave similar results with small deviations.

Table 4.3 Comparison of breakdown voltage for different time interval series at dry gas, 8 bars, 20°C with 4mm protrusion

<table>
<thead>
<tr>
<th>Time interval (minutes)</th>
<th>Breakdown Voltage (kV)</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>28 25 25 22 24 21 22</td>
<td>23.9</td>
<td>2.23</td>
</tr>
<tr>
<td>1</td>
<td>27 27 24 23 25 22 23</td>
<td>24.4</td>
<td>1.84</td>
</tr>
<tr>
<td>2</td>
<td>25 25 25 25 24 25 26</td>
<td>25.0</td>
<td>0.53</td>
</tr>
<tr>
<td>3</td>
<td>26 24 25 25 25 25 25</td>
<td>25.1</td>
<td>0.64</td>
</tr>
<tr>
<td>4</td>
<td>24 24 25 25 25 26 25</td>
<td>24.9</td>
<td>0.64</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The average of the seven breakdown voltages is then calculated and is determined as the breakdown voltage of the configuration. The standard deviation of each series is also calculated to see the scattering of the result.

4.4.2 Partial Discharge Measurement Procedure

Partial discharge (PD) measurement is performed directly after completing the AC breakdown test. The AC breakdown level has to be known before doing the PD measurement because the maximum applied voltage is set at 80% of the breakdown level. This is important to ensure no breakdowns occurring during the PD measurement which otherwise could harm the PD detector.

The voltage is increased slowly until partial discharge starts to occur. This is called the PD inception voltage. The discharge is then recorded for two-minute time interval.

The PD at higher voltage, i.e. at 40, 50, 60, 70 and 80% of breakdown level is measured and recorded. As an example, Table 4.4 shows the voltage level of PD measurements for one configuration.

<table>
<thead>
<tr>
<th>Breakdown voltage (BDV)</th>
<th>23 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>PD inception voltage (PDIV)</td>
<td>8.8 kV</td>
</tr>
<tr>
<td>40% of BDV</td>
<td>9.2 kV</td>
</tr>
<tr>
<td>50% of BDV</td>
<td>11.5 kV</td>
</tr>
<tr>
<td>60% of BDV</td>
<td>13.8 kV</td>
</tr>
<tr>
<td>70% of BDV</td>
<td>16.1 kV</td>
</tr>
<tr>
<td>80% of BDV</td>
<td>18.4 kV</td>
</tr>
</tbody>
</table>

Table 4.4 PD measurements voltage level for the configuration of 4 mm protrusion, 1500 ppmv humidity, 8 bar pressure, 40°C temperature
4.4.3 Bias Test Procedure

In the bias test, AC voltage is applied to the test object as the normal operating stress and at a certain moment an impulse is injected which will superpose on the AC voltage. The applied AC voltage level is determined in such a way that the electric field between the electrodes will be the same with the highest electric field occurring in the industrial GIS. A calculation, as described in the following section, results that the applied nominal voltage is 26.5 kV.

4.4.3.1 The Applied AC Voltage Calculation

The cross section dimension of a one-phase GIS is shown in Figure 4.13. It consists of two coaxial cylinders. The conductor radius, \( R_{in} \), is 64 mm and the enclosure radius, \( R_{out} \), is 267 mm.

![Figure 4.13 The cross section dimension of a one-phase GIS](image)

Let the phase-to-phase voltage applied on this GIS, \( U \), be 380 kV. For an arbitrary long period, a maximum voltage, \( U_m \), between the phases could be present which is about 10% higher than \( U \) in average. This maximum voltage is thus 420 kV.

Before calculating the electric field inside the GIS, the nominal voltage, \( U_o \), between the conductor and earth needs to be calculated as follows:

\[
U_o = \frac{U_m}{\sqrt{3}}
\]

\[U_o = 242 \text{ kV}\]

The well-known expression to calculate the electric field, \( E \), between two coaxial cylinders is then used [2, p15].
\[ E = \frac{U_o}{x \ln \frac{R_{out}}{R_{in}}} \]

where \( x \) is the distance of the calculated field location from the cylinder center.

From Equation 4.1, it can be seen the highest electric field occurs at the surface of the conductor, i.e. \( x = R_{in} \). Inserting all values into the equation, the electric field is 2.65 kV/mm. This is known as the nominal electric field of the GIS which will further be used to calculate the applied voltage for the test object, as described below.

Figure 4.14 shows the dimension of the electrodes of the test object. The distance between the electrodes, \( d \), is 10 mm.

![Cross-section dimension of the electrodes of the test object](image)

Figure 4.14 The cross-section dimension of the electrodes of the test object

From this figure, the electrodes can be regarded as two parallel plates. A simple field strength calculation can then be used.

\[ E = \frac{U_o}{d} \]

In order to set the nominal electric field of the GIS as calculated above (2.65 kV/mm) on the test object, a certain level of AC voltage has to be applied on the electrodes. From Equation 4.2, the nominal voltage is 26.5 kV. It introduces the normal operating stress on the test object.

### 4.4.3.2 The Impulse Setting

After the nominal AC voltage is applied on the electrodes, at a certain moment an impulse is injected to the test object. The impulse could enter at any point of the AC voltage wave. However, the worst case is the injection at the peak of the AC voltage wave. A positive impulse which enters at the positive peak of the AC
voltage wave will result the highest superposition voltage over the positive half of the AC voltage wave. The gap then suffers the highest stress.

The highest stress can also be obtained by injecting a negative impulse at the peak of negative AC voltage wave. Figure 4.15A and B depict the highest stresses at the positive and negative half-cycles, respectively.[13, p23]

![Figure 4.15 The superposition voltage for bias test](image)

The situations above are valid if both the AC and impulses are put into the test object from the same electrode. As the AC and impulse voltages, in this thesis, are put into the test object from opposite electrodes, a different approach is applied to obtain the highest stress over the gap. The highest stress is reached when the potential difference between the electrodes is maximal. This can be resulted by applying the positive impulse when the AC voltage reaches the negative's peak, as shown in Figure 4.16.
Figure 4.16 Applying a positive impulse (37 kV) at AC negative peak (-36 kV)

In Figure 4.16 the impulse magnitude is 37 kV applied at the upper electrode where the AC negative peak is 36 kV applied at lower electrode. The stress over the gap is then 73 kV.

At a certain level of impulse voltage, there is a probability that a breakdown will occur or not occur. Thus, having a certain breakdown probability is of importance. A method, up and down method, is used for this purpose. A 50% probability of breakdown ($V_{50}$) is obtained in this way.

**Up and Down Method**

An impulse, $V_i$, which is close to the estimated $V_{50}$ is applied to the test object. If this impulse does not cause breakdown, the next impulse should be $V_i + \Delta V$, where $\Delta V$ is the voltage step and is about 3% of $V_i$. If still no breakdown occurs, the impulse is further increased with $\Delta V$ step until the first breakdown occurs. After the first breakdown, the next impulse is $V_i - \Delta V$. This procedure is continued, increasing or decreasing the impulse by $\Delta V$, until 20 impulses have been applied since the first breakdown. The average is calculated and is determined as the $V_{50}$. 
4.5 Parameters Controlling

In order to get comparable data from all tests and measurements, the parameters have to be controlled. This can be done as will be described below.

4.5.1 Protrusion Length Controlling

The protrusion length is measured from the electrode surface to the tip of the electrode. The length can be simply controlled by adjusting it at the driving plate, as shown in Figure 4.3.

4.5.2 Humidity Controlling

To get a certain humidity level, humidity controlling is essential. An amount of water is added to dry CO₂ gas. The more water is added the more humid the gas is.

A calculation of the required amount of water to be added to the dry gas is presented in [12]. It was based on the ideal gas law. Since in practice the gas is not ideal, there is a deviation between the calculated and the actual required amount of water. In this section, the actual required amount of water is discussed.

In the laboratory, 5 ml water is added to the dry CO₂ gas to obtain 1500 ppmv under 8 bars and 30 °C, and for 500 ppmv 3.6 ml water is needed.

As the temperature is increased up to 40 °C for another configuration, the humidity and the pressure are increasing. Thus, the humidity and the pressure have to be decreased down to the original level. The humid gas is slowly released meanwhile the dry gas is added into the vessel. This process has to be monitored until the desired humidity is reached. Figure 4.17 depicts the process.
The vessel has to be vacuumed before the CO₂ gas and the water are put into it. This aims to release the air inside the vessel and to help the water evaporates. It is known that at the lower pressure the water evaporates easier. The evaporation can even be developed faster by heating the vessel.

For time and used-gas saving purpose, the vacuuming process is not repeated at each gas pressure. It is done only at the highest pressure, i.e. 8 bars. For lower gas pressure, i.e. at 6 bars, the required humidity can be achieved by performing the humidity controlling explained above.

### 4.5.3 Pressure Controlling

The pressure of the gas can be controlled by adding/releasing the gas into/from the vessel. A digital pressure reader is used to monitor the pressure of the gas.

### 4.5.4 Temperature Controlling

Since the temperature needed is higher than the ambient temperature, heating bands are needed to increase the temperature of the gas. The heating bands are placed over the vessel surface. To confine the heat in the vessel, a thermal
insulation, made of glass-fiber material, is used to cover the vessel. Thus, a relatively constant temperature during the measurement is obtained.

To monitor the gas temperature level, two thermocouples are used: inside and outside the vessel. The inside thermocouple measures the gas temperature directly. The other one is placed on the frame which measures the temperature of vessel frame.

When the heating is just started, there is a big difference on the reading of both thermocouples. The temperature of the frame will be higher than that of the gas as the heating band heats the frame directly and thus immediately, whereas the gas inside the vessel gets the heat from the frame by heat conduction. So, the gas needs more time to be heated.

The gas tends to equalize its temperature with that of the frame. This, of course, takes time. When the readings of both thermocouples are the same or almost the same, it can be said that the temperature of the gas has been stable.

Decreasing the temperature can be done by means of a fan or an air compressor which will blow air to the vessel surface. The heat then released from the vessel to the ambient. During decreasing the temperature, the heat insulation should be removed.

The temperature controlling is depicted in Figure 4.18.
4.6 Conclusion

It is important to have consistent and comparable results. This can be obtained by:

- A suitable test set up,
- Performing an appropriate test procedure for each kind of test, and
- Controlling all parameters.
Chapter 5

The Result and Analysis of the AC Breakdown Tests and the Partial Discharge Measurements

In this chapter, the result of the AC breakdown tests and the partial discharge measurements are presented and analyzed in sections 5.1 and 5.2, respectively.

5.1 The Result and Analysis of the AC Breakdown Strength

In this section, the results of the AC breakdown tests at various parameters, i.e. the protrusion lengths, gas temperatures, humidity levels and pressures, are presented and analyzed.

The results are presented in graphs for each parameter, as shown in figures in this section. The breakdown voltage shown represents the mean value of each series. To see the scattering of the breakdown voltage for each series, a standard deviation is used which is represented by a vertical line at each breakdown value. The length of the line depends on the scatter value: the less scatter the result the shorter the line.

To see the effect of varying the parameter value on the breakdown voltage, a multiplication factor is calculated. This multiplication factor is the ratio of the breakdown voltages between parameter variations and is presented in tables in this chapter.

The influence of each parameter on the breakdown voltage is presented in each separated sub-section: from subsection 5.1.1 to 5.1.4. At the end of each subsection, a conclusion is made.
5.1.1 The Influence of the Protrusion Length

The influence of the protrusion length on the CO₂ gas breakdown strength is shown on Figure 5.1 – 5.6. Each figure displays the breakdown voltage at one pressure value, one humidity level and at various temperatures. The 0 (zero) protrusion-length indicates the plane-plane electrodes without protrusion. Its breakdown voltage is taken from [12].

![Figure 5.1 The breakdown voltage versus protrusion length at 8 bars and 1500 ppmv](image1)

![Figure 5.2 The breakdown voltage versus protrusion length at 8 bars and 500 ppmv](image2)
Figure 5.3 The breakdown voltage versus protrusion length at 8 bars and dry gas

Figure 5.4 The breakdown voltage versus protrusion length at 6 bars and 1500 ppmv

Figure 5.5 The breakdown voltage versus protrusion length at 6 bars and 500 ppmv
Figure 5.6 The breakdown voltage versus protrusion length at 6 bars and dry gas.

From those figures, by comparing the breakdown voltage at 0 and 0.5 mm protrusion lengths, it can be seen that the breakdown voltage decreases considerably as the protrusion is present. In those figures, the presence of a protrusion with a length only 5% of the electrodes distance reduces the breakdown voltage more than 50% of that without protrusion. This steep decrease is due to the field enhancement and non-homogeneity around the protrusion's tip.

The effect of the protrusion length can be observed as well. From Figure 5.1 – 5.6 it can be seen that the decrease of the breakdown voltage is larger for longer protrusion. The decrease is related to the field enhancement caused by the protrusion: the longer the protrusion the higher the field and, as result, the lower the breakdown voltage.

It can also be seen that the decreasing of the breakdown voltage is not linear with the increasing the protrusion length. This can be explained as follows.

In the book of F.H. Kreuger Volume I [2], the effect of protrusion length on the field enhancement in a vacuum as insulator is discussed. The field enhancement factor $\beta$ depends on the shape of the protrusion according to

$$\beta \approx 2 \frac{h}{w}$$

where $h$ and $w$ are the length and radius of the protrusion, respectively.
According to this formula, increasing the length of the protrusion, while keeping the radius remain the same, will increase the field enhancement linearly. As a result, the breakdown strength will decrease linearly as well.

However, as in this thesis the insulating material used is CO$_2$ gas instead of vacuum, the relation between $\beta$ and $h$ is not linear. This is due to the corona stabilization at the tip of the protrusion occurring when gas is used as insulator medium (see subsection 2.7.4.4) which impede the field enhancement. Therefore, the field enhancement in CO$_2$ gas, thus the decreasing of the breakdown strength, is not linear as that in vacuum.

This nonlinearity can be checked by comparing the breakdown voltage of all protrusion lengths to the breakdown voltage of the 0.5 mm protrusion length, as shown in Table 5.1.a. At the end of the table, the average value is calculated which represents the breakdown voltage ratio of all configurations of each protrusion length.
Chapter 5: The Result and Analysis of the AC Breakdown Tests and the Partial Discharge Measurements

Table 5.1.a The breakdown voltage ratio of all protrusion lengths to the 0.5 mm protrusion length

<table>
<thead>
<tr>
<th>Protrusion Length (mm)</th>
<th>0.5</th>
<th>1</th>
<th>2</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500 ppmv, 8 bar, 20 C</td>
<td>1</td>
<td>0.76</td>
<td>0.60</td>
<td>0.50</td>
</tr>
<tr>
<td>1500 ppmv, 8 bar, 30 C</td>
<td>1</td>
<td>0.77</td>
<td>0.63</td>
<td>0.48</td>
</tr>
<tr>
<td>1500 ppmv, 8 bar, 40 C</td>
<td>1</td>
<td>0.77</td>
<td>0.62</td>
<td>0.46</td>
</tr>
<tr>
<td>1500 ppmv, 6 bar, 20 C</td>
<td>1</td>
<td>0.85</td>
<td>0.76</td>
<td>0.53</td>
</tr>
<tr>
<td>1500 ppmv, 6 bar, 30 C</td>
<td>1</td>
<td>0.86</td>
<td>0.75</td>
<td>0.52</td>
</tr>
<tr>
<td>1500 ppmv, 6 bar, 40 C</td>
<td>1</td>
<td>0.86</td>
<td>0.76</td>
<td>0.52</td>
</tr>
<tr>
<td>500 ppmv, 8 bar, 20 C</td>
<td>1</td>
<td>0.77</td>
<td>0.61</td>
<td>0.48</td>
</tr>
<tr>
<td>500 ppmv, 8 bar, 30 C</td>
<td>1</td>
<td>0.76</td>
<td>0.60</td>
<td>0.47</td>
</tr>
<tr>
<td>500 ppmv, 8 bar, 40 C</td>
<td>1</td>
<td>0.76</td>
<td>0.61</td>
<td>0.45</td>
</tr>
<tr>
<td>500 ppmv, 6 bar, 20 C</td>
<td>1</td>
<td>0.90</td>
<td>0.68</td>
<td>0.47</td>
</tr>
<tr>
<td>500 ppmv, 6 bar, 30 C</td>
<td>1</td>
<td>0.88</td>
<td>0.68</td>
<td>0.45</td>
</tr>
<tr>
<td>500 ppmv, 6 bar, 40 C</td>
<td>1</td>
<td>0.88</td>
<td>0.73</td>
<td>0.47</td>
</tr>
<tr>
<td>dry gas, 8 bar, 20 C</td>
<td>1</td>
<td>0.84</td>
<td>0.66</td>
<td>0.52</td>
</tr>
<tr>
<td>dry gas, 8 bar, 30 C</td>
<td>1</td>
<td>0.87</td>
<td>0.64</td>
<td>0.51</td>
</tr>
<tr>
<td>dry gas, 8 bar, 40 C</td>
<td>1</td>
<td>0.92</td>
<td>0.67</td>
<td>0.53</td>
</tr>
<tr>
<td>dry gas, 6 bar, 20 C</td>
<td>1</td>
<td>0.63</td>
<td>0.58</td>
<td>0.42</td>
</tr>
<tr>
<td>dry gas, 6 bar, 30 C</td>
<td>1</td>
<td>0.62</td>
<td>0.57</td>
<td>0.42</td>
</tr>
<tr>
<td>dry gas, 6 bar, 40 C</td>
<td>1</td>
<td>0.66</td>
<td>0.61</td>
<td>0.43</td>
</tr>
<tr>
<td>The average of the breakdown voltage ratio</td>
<td>1</td>
<td>0.80</td>
<td>0.65</td>
<td>0.48</td>
</tr>
</tbody>
</table>

If the insulating medium were vacuum, the breakdown voltage ratio between all protrusion lengths would be linearly proportional to the protrusion length. The estimated breakdown voltage ratio based on the field enhancement is shown in Table 5.1.b.

Table 5.1.b The estimated breakdown voltage ratio of all protrusion lengths to the 0.5 mm protrusion length in vacuum

<table>
<thead>
<tr>
<th>Protrusion Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
</tr>
<tr>
<td>Breakdown voltage ratio</td>
</tr>
</tbody>
</table>
From both tables, it can be seen that in the case of vacuum as insulating medium, the breakdown voltage decreasing is linear with the protrusion length where it is not in the case of CO₂.

To quantify the breakdown voltage decreasing regarding the protrusion length increasing, protrusion-length multiplication-factors are constructed in Table 5.2a and 5.2b. All multiplication factors are less than unity indicating the decreasing in breakdown voltage.

Table 5.2a The protrusion-length multiplication-factors of CO₂ gas breakdown

<table>
<thead>
<tr>
<th>Gas Pressure</th>
<th>Humidity</th>
<th>Dry gas</th>
<th>500 ppmv</th>
<th>1500 ppmv</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Temperature (°C)</td>
<td>Temperature (°C)</td>
<td>Temperature (°C)</td>
<td>Average</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>30</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>6 bar</td>
<td>0-&gt;0.5 mm</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>0-&gt;1mm</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>0-&gt;2mm</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>0-&gt;4mm</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>8 bar</td>
<td>0-&gt;0.5 mm</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>0-&gt;1mm</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>0-&gt;2mm</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>0-&gt;4mm</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Table 5.2b The average of protrusion-length multiplication-factors of CO₂ gas breakdown

<table>
<thead>
<tr>
<th>Protrusion Length</th>
<th>Multiplication factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-&gt;0.5mm</td>
<td>0.47</td>
</tr>
<tr>
<td>0-&gt;1mm</td>
<td>0.38</td>
</tr>
<tr>
<td>0-&gt;2mm</td>
<td>0.32</td>
</tr>
<tr>
<td>0-&gt;4mm</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Conclusion

It can be concluded that:

- The presence of protrusion will reduce the breakdown strength considerably.
The longer the protrusion, the lower the breakdown strength.

Due to corona stabilization, the relation between the protrusion length and the breakdown strength is not linear.

### 5.1.2 The Influence of the Gas Temperature

The breakdown strength versus the gas temperature is shown in Figure 5.7-5.14. Each figure consists of breakdown voltage at one pressure level, one protrusion length and at various humidity levels.

![Figure 5.7 The breakdown voltage versus temperature at 8 bars and 0.5 mm protrusion](image1)

![Figure 5.8 The breakdown voltage versus temperature at 6 bars and 0.5 mm protrusion](image2)
Chapter 5: The Result and Analysis of the AC Breakdown Tests and the Partial Discharge Measurements

Figure 5.9 The breakdown voltage versus temperature at 8 bars and 1 mm protrusion

Figure 5.10 The breakdown voltage versus temperature at 6 bars and 1 mm protrusion

Figure 5.11 The breakdown voltage versus temperature at 8 bars and 2 mm protrusion
Figure 5.12 The breakdown voltage versus temperature at 6 bars and 2 mm protrusion

Figure 5.13 The breakdown voltage versus temperature at 8 bars and 4 mm protrusion

Figure 5.14 The breakdown voltage versus temperature at 6 bars and 4 mm protrusion
From Figure 5.7-5.14 it can be seen that:

1. At 0.5 mm protrusion, the breakdown voltage decreases as the temperature increases. This applies for all measured humidity levels and both 6 and 8 bar pressure levels (Figure 5.7 and 5.8).

2. At 1 mm protrusion, the breakdown voltage decreases as the temperature increases except:
   - At 8 bars, 1500 ppmv: the breakdown voltage increases when the temperature increases from 20 °C to 30 °C (see Figure 5.9).
   - At 6 bars, dry gas: the breakdown voltage increases when the temperature increases from 30 °C to 40 °C (see Figure 5.10).

3. At 2 mm protrusion, the breakdown voltage decreases as the temperature increases except:
   - At 8 bars, 1500 ppmv: the breakdown voltage increases when the temperature increases from 30 °C to 40 °C. This also applies for the temperature increasing from 20 °C to 30 °C (see Figure 5.11).
   - At 6 bars, dry gas: the breakdown voltage increases when the temperature increases from 30 °C to 40 °C (see Figure 5.12).
   - At 6 bars, 500 ppmv: the breakdown voltage increases when the temperature increases from 30 °C to 40 °C (see Figure 5.12).

4. At 4 mm protrusion, the breakdown voltage decreases as the temperature increases except:
   - At 6 bars, 500 ppmv: the breakdown voltage increases when the temperature increases from 30 °C to 40 °C (see Figure 5.14).

To quantify the breakdown voltage changes, the temperature multiplication factors are constructed as shown in Table 5.3. The multiplication factor less than unity indicates a decreasing in breakdown voltage, whereas more than unity indicates an increasing in breakdown voltage. No change is indicated by unity
multiplication factor. In this table, the factor values more than, equal to and less than unity are marked with blue, yellow and red blocks, respectively.

<table>
<thead>
<tr>
<th>Gas humidity</th>
<th>Temperature change</th>
<th>0.5 (bar)</th>
<th>1 (bar)</th>
<th>2 (bar)</th>
<th>4 (bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>6 8 6 8</td>
<td>6 8 6 8</td>
<td>6 8 6 8</td>
<td>6 8 6 8</td>
</tr>
<tr>
<td>Dry gas</td>
<td>20 → 30</td>
<td>0.97 0.96</td>
<td>0.96 0.99</td>
<td>0.96 0.92</td>
<td>0.96 0.94</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>500 ppmv</td>
<td>20 → 30</td>
<td>0.97 0.98</td>
<td>0.95 0.98</td>
<td>0.98 0.97</td>
<td>0.93 0.96</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1500 ppmv</td>
<td>20 → 30</td>
<td>0.97 0.98</td>
<td>0.96 0.97</td>
<td>0.95 1.00</td>
<td>0.95 0.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

To see the general effect of the increasing of the temperature on the breakdown voltage, the average of multiplication factors is calculated, which is 0.97. This value means increasing the temperature 10 °C in the range of 20-40 °C will decrease the breakdown voltage 3%.

This is due to the decrease of the gas density as the temperature increases while the volume and the pressure are kept constant (see section 2.5.3).

**Conclusion**

In general, increasing the temperature, at the same volume and pressure, will decrease the breakdown strength. This is related to the decreasing of the gas density.
5.1.3 The Influence of the Gas Humidity

In this subsection, the influence of the gas humidity on the breakdown test is discussed and depicted in Figure 5.15-5.22. Each figure shows the influence at one pressure level, one protrusion length and at various temperatures.

![Figure 5.15](image1.png)

Figure 5.15 The breakdown voltage versus gas humidity at 8 bars and 0.5 mm protrusion

![Figure 5.16](image2.png)

Figure 5.16 The breakdown voltage versus gas humidity at 6 bars and 0.5 mm protrusion
Figure 5.17 The breakdown voltage versus gas humidity at 8 bars and 1 mm protrusion

Figure 5.18 The breakdown voltage versus gas humidity at 6 bars and 1 mm protrusion

Figure 5.19 The breakdown voltage versus gas humidity at 8 bars and 2 mm protrusion
Figure 5.20 The breakdown voltage versus gas humidity at 6 bars and 2 mm protrusion

Figure 5.21 The breakdown voltage versus gas humidity at 8 bars and 4 mm protrusion

Figure 5.22 The breakdown voltage versus gas humidity at 6 bars and 4 mm protrusion
From Figure 5.15-5.22, it can be seen that:

1. At 0.5 mm protrusion, the breakdown voltage increases as the humidity increases except:
   - At 6 bar and 20 °C, increasing the humidity from dry gas to 500 ppmv keeps the breakdown voltage constant.
   - At 6 bar and 30 °C, increasing the humidity from dry gas to 500 ppmv reduces the breakdown voltage strength.

2. At 1 mm protrusion, different trends can be observed between 6 and 8 bars.
   - At 6 bars, the breakdown strength increases as the humidity increases except at 20 °C. In this temperature, the breakdown voltage decreases when the humidity increases from 500 to 1500 ppmv.
   - At 8 bars, the breakdown strength decreases as the humidity increases, except at 30 °C and 40 °C. In these temperature levels, the breakdown voltage increases as the humidity increases from 500 to 1500 ppmv.

3. At 2 mm protrusion, the breakdown voltage increases as the humidity increases, except:
   - At 8 bars and 20 °C, increasing the humidity from dry gas to 500 ppmv does not change the breakdown voltage. Increasing the humidity from 500 to 1500 ppmv results an increasing in breakdown voltage which is also applied for the increasing from dry gas to 1500 ppmv.

4. At 4 mm protrusion, the breakdown voltage increases as the humidity increases, except:
   - At 8 bars, 20 °C and 40 °C, increasing the humidity from dry gas to 500 ppmv results a decreasing in breakdown voltage.

Similar to that in previous section, to quantify the breakdown voltage changes, the humidity multiplication factors are created as shown in Table 5.4.
Table 5.4 The humidity multiplication factors of CO₂ breakdown strength

<table>
<thead>
<tr>
<th>Gas Temperature</th>
<th>Humidity change (ppmv)</th>
<th>0.5</th>
<th>1</th>
<th>2</th>
<th>4</th>
<th>Average</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>8</td>
<td>6</td>
<td>8</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>dry → 500</td>
<td></td>
<td>1.00</td>
<td>1.09</td>
<td>1.43</td>
<td>1.01</td>
<td>1.18</td>
<td>1.00</td>
</tr>
<tr>
<td>dry → 1500</td>
<td></td>
<td>1.04</td>
<td>1.01</td>
<td>0.98</td>
<td>1.01</td>
<td>1.17</td>
<td>0.98</td>
</tr>
<tr>
<td>dry → 500</td>
<td></td>
<td>0.99</td>
<td>1.11</td>
<td>1.42</td>
<td>0.98</td>
<td>1.20</td>
<td>1.05</td>
</tr>
<tr>
<td>dry → 1500</td>
<td></td>
<td>1.04</td>
<td>1.01</td>
<td>1.02</td>
<td>1.02</td>
<td>1.14</td>
<td>1.01</td>
</tr>
<tr>
<td>dry → 500</td>
<td></td>
<td>1.01</td>
<td>1.15</td>
<td>1.35</td>
<td>0.95</td>
<td>1.71</td>
<td>1.05</td>
</tr>
<tr>
<td>dry → 1500</td>
<td></td>
<td>1.04</td>
<td>1.02</td>
<td>1.02</td>
<td>1.03</td>
<td>1.09</td>
<td>1.04</td>
</tr>
</tbody>
</table>

To see the general effect of the humidity increasing on the breakdown voltage, the average of multiplication factors is calculated, as follows:

- Increasing the humidity from dry gas to 500 ppmv will increase the breakdown voltage 10%.
- Increasing the humidity from dry gas to 1500 ppmv will increase the breakdown voltage 5%.

It means that an increase in humidity level will result in an increase in the breakdown voltage. This is related to the amount of the captured free electrons by the water molecules. In higher humidity level there are more water molecules available. As water molecules have an ability to capture free electrons, more water molecules will capture more free electrons. This will delay the growth of the amount of free electrons, thus will increase the breakdown voltage. [1, p104]

Further increasing the humidity does not always increase the breakdown strength (compare the multiplication factors for 500 ppmv and 1500 ppmv). There is a certain humidity level from which further increasing the humidity will decrease the breakdown strength. See subsection 2.5.4.
Conclusion

In general, increasing the humidity will increase the breakdown level. This is due to the ability of water molecules to capture free electrons.

5.1.4 The Influence of the Gas Pressure

The breakdown voltage versus the gas pressure is presented in Figure 5.23-5.28. Each figure presents the influence of the gas pressure at one humidity level, one protrusion length and at various temperatures.

Figure 5.23 The breakdown voltage versus the pressure at dry gas, 1 mm protrusion and at various temperatures

Figure 5.24 The breakdown voltage versus the pressure at 500 ppmv, 1 mm protrusion and at various temperatures
Figure 5.25 The breakdown voltage versus the pressure at 1500 ppmv, 1 mm protrusion and at various temperatures

Figure 5.26 The breakdown voltage versus the pressure at dry gas, 4 mm protrusion and at various temperatures
Figure 5.27 The breakdown voltage versus the pressure at 500 ppmv, 4 mm protrusion and at various temperatures

Figure 5.28 The breakdown voltage versus the pressure at 1500 ppmv, 4 mm protrusion and at various temperatures

From Figure 5.23-5.28 it can be seen that:

1. At 1 mm protrusion length, the breakdown voltage increases as the pressure increases. The breakdown voltage increasing is not linear. It can be observed that the increasing breakdown voltage in the range of 8-10 bars is smaller than that in lower measured pressure ranges.
2. At 4 mm protrusion length, increasing the pressure will increase the breakdown voltage. However, in the range of 8-10 bars, the breakdown voltage decreases as the pressure increases except at dry gas and 500 ppmv, both under 40 °C.

The breakdown voltage changes can be quantified with pressure multiplication factors, as presented in Table 5.5. A factor higher than unity, which is marked with blue block, means an increasing in the breakdown voltage whereas the factor less than unity, marked with red one, represents a breakdown voltage decreasing.

| Table 5.5 The pressure multiplication factors of CO₂ breakdown strength |
|-------------------------|-------------------------|---------|---------|
|                         | Protrusion length       |         |         |
|                         |                         | 1 mm    | 4 mm    |
|                         | Humidity                |         |         |
|                         | Dry gas                 | 500 ppmv| 1500 ppmv|
| Gas Temperature        | Pressure change (bar)   |         |         |
| 20 °C                   | 4 → 6                   | 1.307   | 1.233   | 1.209   |
|                         | 6 → 8                   | 1.541   | 1.068   | 1.077   |
|                         | 8 → 10                  | 1.035   | 1.007   | 1.018   |
| 30 °C                   | 4 → 6                   | 1.317   | 1.227   | 1.278   |
|                         | 6 → 8                   | 1.591   | 1.097   | 1.100   |
|                         | 8 → 10                  | 1.064   | 1.051   | 1.014   |
| 40 °C                   | 4 → 6                   | 1.324   | 1.178   | 1.264   |
|                         | 6 → 8                   | 1.576   | 1.112   | 1.128   |
|                         | 8 → 10                  | 1.100   | 1.080   | 1.025   |

To check the total effect of the gas pressure increasing on the breakdown voltage, the percentage of the breakdown voltage changing is calculated in similar way with that in previous subsections. The percentage is listed in Table 5.6.
Table 5.6 The total effect of the increasing of the gas pressure on the breakdown voltage (BDV)

<table>
<thead>
<tr>
<th>Gas pressure changing (bar)</th>
<th>% of BDV increasing (blue blocks)</th>
<th>% of BDV decreasing (red blocks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 → 6</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>6 → 8</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>8 → 10</td>
<td>60</td>
<td>40</td>
</tr>
</tbody>
</table>

It can be observed from Figure 5.4.1-5.4.6 and Table 5.5-5.6 that increasing the pressure in a certain range, from the lowest measured range, will increase the breakdown voltage. However, further increasing the pressure does not always increase the breakdown voltage. At a certain pressure level, it will reach the maximum value from which increasing the pressure will decrease the breakdown voltage. This decreasing is related to corona-free breakdown (see 2.7.4.4).

Conclusion

Increasing the gas pressure up to a certain level will increase the breakdown voltage. Due to corona-free breakdown, further increasing the gas pressure will result in a decreasing in the breakdown voltage.

5.2 The Result and Analysis of the Partial Discharge Measurements

In this section, the results of the partial discharge measurements are presented and discussed. All partial discharges, in this thesis, appear at the positive half of the voltage wave. This is due to the protrusion located at the low voltage electrode (see 2.7.4.3).
Figure 5.29 - 5.34 show the graphs of the discharge magnitude versus applied voltage relative to nominal voltage ($U/U_0$) at certain pressure levels, certain humidity level, various temperatures and various protrusion lengths. In these graphs, the effect of the temperature and the protrusion length is investigated.

In these figures, the minimum value of each graph shows the partial discharge at the inception voltage where the maximum value shows the partial discharge at 80% of the breakdown voltage. It should be noted that not all graphs have partial discharge inception point or 80% of breakdown voltage discharge point. As shown in Figure 5.33, the configuration of 0.5 mm protrusion, 6 bars, 500 ppmv and 30 °C has only partial discharge inception point, i.e. at its 80% of breakdown voltage. Furthermore, no discharge at all occurs in the configurations of 0.5 mm protrusion length, 6 bars, dry gas, both at 30 °C and 40 °C (see Figure 5.34).

![Graph](image)

Figure 5.29 The discharge magnitude versus applied voltage relative to nominal voltage ($U/U_0$) at 8 bars, 1500 ppmv and at various temperatures and protrusion lengths
Figure 5.30 The discharge magnitude versus applied voltage relative to nominal voltage ($U/U_0$) at 8 bars, 500 ppmv and at various temperatures and protrusion lengths.

Figure 5.31 The discharge magnitude versus applied voltage relative to nominal voltage ($U/U_0$) at 8 bars, dry gas and at various temperatures and protrusion lengths.
Figure 5.32 The discharge magnitude versus applied voltage relative to nominal voltage ($U/U_o$) at 6 bars, 1500 ppmv and at various temperatures and protrusion lengths.

Figure 5.33 The discharge magnitude versus applied voltage relative to nominal voltage ($U/U_o$) at 6 bars, 500 ppmv and at various temperatures and protrusion lengths.
From Figure 5.29-5.34, the influence of the protrusion length on the partial discharges can be observed. The longer the protrusion, the lower the ratio $U/U_0$ needed for the appearance of partial discharges. Moreover, the graph is steeper which indicates that for the longer protrusion, the increasing of the voltage by the same $\Delta U/U_0$ steps will result greater magnitude of the discharges than that for shorter protrusion. This is due to the field enhancement regarding the shape of the protrusion: the longer the protrusion, the greater the field enhancement around the protrusion’s tip, and as a result, the greater the discharges [2, p60].

It can be seen that for all configurations, the partial discharge inception and the partial discharge of the 80% of the breakdown voltage of each protrusion length are present at a certain $U/U_0$ which are tabulated in Table 5.7.
Table 5.7 The value of U/U₀ for partial discharge inception voltage (PDIV) and the partial discharge of the 80% of the breakdown voltage (80%BDV)

<table>
<thead>
<tr>
<th></th>
<th>4 mm</th>
<th></th>
<th>2 mm</th>
<th></th>
<th>1 mm</th>
<th></th>
<th>0.5 mm</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PDIV 30°C</td>
<td>80% BDV</td>
<td>PDIV 30°C</td>
<td>80% BDV</td>
<td>PDIV 30°C</td>
<td>80% BDV</td>
<td>PDIV 30°C</td>
<td>80% BDV</td>
</tr>
<tr>
<td>8 bar,</td>
<td>0.29</td>
<td>0.26</td>
<td>0.67</td>
<td>0.66</td>
<td>0.67</td>
<td>0.62</td>
<td>0.89</td>
<td>0.90</td>
</tr>
<tr>
<td>dry gas</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 bar,</td>
<td>0.36</td>
<td>0.34</td>
<td>0.73</td>
<td>0.66</td>
<td>0.68</td>
<td>0.64</td>
<td>0.94</td>
<td>0.92</td>
</tr>
<tr>
<td>500 ppmv</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 bar,</td>
<td>0.37</td>
<td>0.35</td>
<td>0.74</td>
<td>0.72</td>
<td>0.71</td>
<td>0.68</td>
<td>0.98</td>
<td>0.95</td>
</tr>
<tr>
<td>1500 ppmv</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 bar,</td>
<td>0.32</td>
<td>0.25</td>
<td>0.52</td>
<td>0.52</td>
<td>0.54</td>
<td>0.55</td>
<td>0.70</td>
<td>0.70</td>
</tr>
<tr>
<td>dry gas</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 bar,</td>
<td>0.34</td>
<td>0.29</td>
<td>0.60</td>
<td>0.57</td>
<td>0.56</td>
<td>0.56</td>
<td>0.84</td>
<td>0.86</td>
</tr>
<tr>
<td>500 ppmv</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 bar,</td>
<td>0.40</td>
<td>0.34</td>
<td>0.67</td>
<td>0.64</td>
<td>0.60</td>
<td>0.58</td>
<td>0.95</td>
<td>0.92</td>
</tr>
<tr>
<td>1500 ppmv</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From this table, it can be seen that, in general:

1. Increasing temperature will decrease the partial discharge inception voltage and the 80% of breakdown voltage as well. This is related to the decreasing of the gas density (see 2.5.3).

2. Increasing the humidity will increase the partial discharge inception voltage and the 80% of breakdown voltage as well. This is due to the attachment of electrons to water molecules and as a result the electron multiplication is prevented or delayed (see 2.5.4).

Now, if a linear regression is applied on each graph, a line, and subsequently its linear equation, is resulted. From that equation, the gradient of the line is obtained which represents the steepness of the line, and therefore represents the steepness of the graph as well.

As examples, Figure 5.35 shows the linear regressions on the graphs taken from Figure 5.32. The linear equations are not valid below the minimum value because in this value partial discharge does not occur yet.
Figure 5.35 Examples of linear regression on the graphs taken from Figure 5.32

All gradients of the graphs, from Figure 5.29-5.34, are listed in Table 5.8.

<table>
<thead>
<tr>
<th>Table 5.8 The gradient of the graph</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 mm</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>8 bar, 1500 ppmv</td>
</tr>
<tr>
<td>8 bar, 500 ppmv</td>
</tr>
<tr>
<td>8 bar, dry gas</td>
</tr>
<tr>
<td>6 bar, 1500 ppmv</td>
</tr>
<tr>
<td>6 bar, 500 ppmv</td>
</tr>
<tr>
<td>7 bar, dry gas</td>
</tr>
</tbody>
</table>

The combination of the value of $U/U_0$ for partial discharge inception voltage (PDIV) and the partial discharge of the 80% of the breakdown voltage (80%BDV) with the steepness of the graph can be used to determine the length of
protrusion inside the test object. A low value of PDIV and of 80%BDV and high steepness indicates a long protrusion whereas a high value of PDIV and of 80%BDV and low steepness indicates a short protrusion (compare the lines in Figure 5.35).

This kind of information is useful when performing an after laying test for a GIS. By having such partial discharges measurement values, the presence, and the length as well, of a protrusion can be determined. Thus, a decision can be made whether the GIS is accepted to be operated.

Conclusion

- The length of protrusion affects in:
  a. Partial discharge inception voltage (PDIV): the longer the protrusion the lower the PDIV.
  b. The magnitude of the partial discharge: the longer the protrusion the greater the magnitude.

- Increasing temperature will increase the partial discharge magnitude.

- Increasing humidity will decrease the partial discharge magnitude.

- The influence of those parameters on the partial discharge is similar to that on the breakdown voltage. Therefore, it can be said that there is a correlation between the partial discharge and breakdown

5.3 Conclusion

From this experiment it can be concluded that:

1. The presence of protrusion on the electrode decreases the breakdown voltage considerably.
2. The longer the protrusion, the larger the discharges and as result, the lower the breakdown strength.

3. Increasing the temperature enlarges the partial discharges which in turn decreases the breakdown strength.

4. Increasing the humidity reduces the partial discharge magnitude. Therefore, the breakdown strength increases.

5. Increasing the pressure increases the breakdown strength. At higher measured pressure range, it will reach the maximum level. Further increasing the pressure beyond this maximum point will decrease the breakdown strength.

6. There is a correlation between partial discharge and breakdown voltage. The larger the partial discharge magnitude the lower breakdown strength.
Chapter 6
The Result and Analysis of the Bias Test

The result of the bias (impulse voltage superposed on AC voltage) test is presented and analyzed in this chapter. In this test, the configurations used are 8 bars, dry gas or 1500 ppmv, 30 or 40 °C, and plane-plane, plane-0.5 mm or plane-1 mm protrusions (see Table 6.1).

The applied AC voltage is 37 kV_{peak} at the low voltage electrode. The impulse is positive lightning impulse (LI) or positive switching impulse (SI) which is applied on the opposite electrode.

To determine the $V_{50}$, the up and down method of 20 impulse shots is applied on the test object. An example is shown in Figure 6.1 which is applied on the plane-0.5mm-protrusion electrodes at 8 bars, dry gas and 40 °C. The impulse is positive lightning impulse. In this configuration, the $V_{50}$ is 76 kV.

![Figure 6.1 Up-and-down method of 20 impulse shots superposed on 37 kV_{peak} AC.](image)
6.1 The Result and Analysis

The result of the test is presented in Table 6.1.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>LI (kV)</th>
<th>SI (kV)</th>
<th>SI/LI</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 mm, 8bar, dry gas, 30°C</td>
<td>144</td>
<td>127</td>
<td>0.88</td>
</tr>
<tr>
<td>0 mm, 8bar, dry gas, 40°C</td>
<td>135</td>
<td>115</td>
<td>0.86</td>
</tr>
<tr>
<td>0 mm, 8bar, 1500ppmv, 30°C</td>
<td>138</td>
<td>124</td>
<td>0.90</td>
</tr>
<tr>
<td>0 mm, 8bar, 1500ppmv, 40°C</td>
<td>135</td>
<td>119</td>
<td>0.88</td>
</tr>
<tr>
<td>0.5 mm, 8bar, dry gas, 30°C</td>
<td>78</td>
<td>50</td>
<td>0.64</td>
</tr>
<tr>
<td>0.5 mm, 8bar, dry gas, 40°C</td>
<td>76</td>
<td>44</td>
<td>0.58</td>
</tr>
<tr>
<td>0.5 mm, 8bar, 1500ppmv, 30°C</td>
<td>101</td>
<td>61</td>
<td>0.60</td>
</tr>
<tr>
<td>0.5 mm, 8bar, 1500ppmv, 40°C</td>
<td>85</td>
<td>58</td>
<td>0.68</td>
</tr>
<tr>
<td>1 mm, 8bar, dry gas, 30°C</td>
<td>60</td>
<td>35</td>
<td>0.58</td>
</tr>
<tr>
<td>1 mm, 8bar, dry gas, 40°C</td>
<td>57</td>
<td>32</td>
<td>0.56</td>
</tr>
<tr>
<td>1 mm, 8bar, 1500ppmv, 30°C</td>
<td>63</td>
<td>40</td>
<td>0.63</td>
</tr>
<tr>
<td>1 mm, 8bar, 1500ppmv, 40°C</td>
<td>59</td>
<td>37</td>
<td>0.63</td>
</tr>
</tbody>
</table>

From this table, it can be seen that the switching impulse magnitude (SI) is lower than the lightning impulse magnitude (LI). This is related to front time of each impulse. A switching impulse has larger front time, 250 μs, than a lightning impulse, 1.2 μs. Therefore, the voltage rising in the switching impulse is slower than that in the lightning impulse, and as a result finding an initiatory electron in the case of switching impulse is easier than that in the case of lightning impulse. This eventually causes a lower breakdown voltage for switching impulse (see section 2.6.2).

The ratio of SI to LI magnitude (SI/LI) in the case of protrusion is different with that in the case of no protrusion, as follows:

- No protrusion: SI/LI is between 85% and 90%
• 0.5 mm protrusion: SI/LI is between 60% and 70%

• 1 mm protrusion: SI/LI is between 55% and 65%

It is obviously seen that the SI/LI ratio gets lower with the presence of protrusion. Furthermore, the ratio decreases as the protrusion length increases. This is related to the combination of the field enhancement occurring in the case of protrusion and the front time of SI and LI.

The changing of the breakdown voltage of the bias test as the protrusion length, temperature or humidity changes is quantified as multiplication factors, shown in following Table 6.2a – 6.4b.

Table 6.2a The influence of protrusion length on the breakdown voltage of LI bias test

<table>
<thead>
<tr>
<th>Protrusion change</th>
<th>Dry gas</th>
<th>1500 ppmv</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30 °C</td>
<td>40 °C</td>
</tr>
<tr>
<td>0 → 0.5mm</td>
<td>0.54</td>
<td>0.56</td>
</tr>
<tr>
<td>0 → 1mm</td>
<td>0.42</td>
<td>0.42</td>
</tr>
</tbody>
</table>

Table 6.2b The influence of protrusion length on the breakdown voltage of SI bias test

<table>
<thead>
<tr>
<th>Protrusion change</th>
<th>Dry gas</th>
<th>1500 ppmv</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30 °C</td>
<td>40 °C</td>
</tr>
<tr>
<td>0 → 0.5mm</td>
<td>0.39</td>
<td>0.38</td>
</tr>
<tr>
<td>0 → 1mm</td>
<td>0.27</td>
<td>0.28</td>
</tr>
</tbody>
</table>

From Table 6.2a and 6.2b it can be seen that the presence of protrusion will decrease the breakdown strength considerably. For longer protrusion, the breakdown strength furthermore decreases. This is related to the field enhancement as discussed in section 5.1.1.
The influence of temperature on the breakdown voltage of the bias test is shown in Table 6.3a and 6.3b. In this table, all multiplication factors are less than unity which means that increasing the temperature will decrease the breakdown strength. This is related to the decrease of the gas density as the temperature increases. See also section 5.1.2.

Table 6.3a The influence of temperature on the breakdown voltage of LI bias test

<table>
<thead>
<tr>
<th>Humidity</th>
<th>Temperature change</th>
<th>LI 0 mm</th>
<th>LI 0.5 mm</th>
<th>LI 1 mm</th>
<th>Average</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry gas</td>
<td>30 → 40 ºC</td>
<td>0.94</td>
<td>0.97</td>
<td>0.95</td>
<td>0.95</td>
<td>0.01</td>
</tr>
<tr>
<td>1500 ppmv</td>
<td>30 → 40 ºC</td>
<td>0.98</td>
<td>0.84</td>
<td>0.94</td>
<td>0.96</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Table 6.3b The influence of temperature on the breakdown voltage of SI bias test

<table>
<thead>
<tr>
<th>Humidity</th>
<th>Temperature change</th>
<th>SI 0 mm</th>
<th>SI 0.5 mm</th>
<th>SI 1 mm</th>
<th>Average</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry gas</td>
<td>30 → 40 ºC</td>
<td>0.91</td>
<td>0.88</td>
<td>0.91</td>
<td>0.90</td>
<td>0.01</td>
</tr>
<tr>
<td>1500 ppmv</td>
<td>30 → 40 ºC</td>
<td>0.96</td>
<td>0.95</td>
<td>0.93</td>
<td>0.95</td>
<td>0.01</td>
</tr>
</tbody>
</table>

The influence of humidity on the breakdown voltage of the bias test is shown in Table 6.4a and 6.4b. In the case of no protrusion, three situations occur: the breakdown voltage increases, decreases or remains the same as the humidity increases. In the cases of protrusion, increasing the humidity will increase the breakdown strength.
Table 6.4a The influence of humidity on the breakdown voltage of the LI bias test

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Humidity change</th>
<th>0 mm</th>
<th>0.5 mm</th>
<th>1 mm</th>
<th>Average</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 °C</td>
<td>Dry gas $\rightarrow$ 1500 ppmv</td>
<td>0.96</td>
<td>1.30</td>
<td>1.05</td>
<td>1.10</td>
<td>0.14</td>
</tr>
<tr>
<td>40 °C</td>
<td>Dry gas $\rightarrow$ 1500 ppmv</td>
<td>1</td>
<td>1.12</td>
<td>1.04</td>
<td>1.05</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Table 6.4b The influence of humidity on the breakdown voltage of the SI bias test

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Humidity change</th>
<th>0 mm</th>
<th>0.5 mm</th>
<th>1 mm</th>
<th>Average</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 °C</td>
<td>Dry gas $\rightarrow$ 1500 ppmv</td>
<td>0.98</td>
<td>1.22</td>
<td>1.14</td>
<td>1.11</td>
<td>0.10</td>
</tr>
<tr>
<td>40 °C</td>
<td>Dry gas $\rightarrow$ 1500 ppmv</td>
<td>1.04</td>
<td>1.32</td>
<td>1.16</td>
<td>1.17</td>
<td>0.12</td>
</tr>
</tbody>
</table>

In general it can be seen that increasing the humidity will increase the breakdown strength. This is related to electrons attachment to the water molecules, thus the growth of electron is delayed. See also section 5.1.3.

6.2 Conclusion

The bias tests are done at plane-plane electrodes, plane-0.5 mm or plane-1 mm protrusion electrodes, at 8 bars, dry gas or 1500 ppmv, 30 or 40 °C, and. The 50% probability of breakdown ($V_{50}$) is obtained by using up-and-down method with 20 shots for each series. Some conclusions are made:

- The presence of protrusion will decrease the breakdown voltage significantly. The longer the protrusion, the lower the breakdown strength.

- Increasing the temperature will decrease the breakdown strength.

- Increasing the humidity will, in general, increase the breakdown strength.
Chapter 6: The Result and Analysis of the Bias Test
Chapter 7
The SF₆ Breakdown Test

In previous chapters, the experiments with CO₂ gas as insulating material have been presented. Now, in this chapter, a short figure of the breakdown voltage of SF₆ gas is presented. Due to some limitations, i.e. the toxicity of SF₆ byproducts produced during the breakdown and the high global warming potential of SF₆, the usage of the gas in this experiment is set to a small amount, i.e. at 4 bars. In this way, the wasted SF₆ is small as well.

Instead of comparing the breakdown voltage of SF₆ to that of CO₂, this chapter aims to investigate the influence of parameter used in previous chapters on the breakdown strength of SF₆. However, due to the limited time available for the experiments, the varied parameter is only the humidity. A general trend for the influence of humidity is then made and compared to that of CO₂.

7.1 The Test Setup and Procedures

Basically the test setup and procedures used are similar to that in CO₂ experiments. However, due to the restricted capability of the test object bushing (maximum 200 kV peak), it is important to set the breakdown voltage below this maximum level. As SF₆ has high breakdown strength, this can be obtained by reducing the electrodes’ gap. Therefore, the gap is set at 5 mm instead of 10 mm.

A 1 mm protrusion is placed on the low voltage electrode, similar to that in CO₂ experiments. The gas pressure is set at 4 bars under room temperature. The humidity is varied at four levels: 680, 2000, 2800 and 4400 ppmv.

The procedures for AC and bias test and for partial discharge measurement used are similar to that in CO₂ experiments.

7.2 The Result and Analysis

The result of the test is shown in Table 7.1. It consists of AC and bias breakdown tests and partial discharge measurement.
Table 7.1 The SF₆ test results

<table>
<thead>
<tr>
<th></th>
<th>680 ppmv</th>
<th>2000 ppmv</th>
<th>2800 ppmv</th>
<th>4400 ppmv</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Breakdown Voltage (kV peak)</td>
<td>60</td>
<td>60</td>
<td>61</td>
<td>62</td>
</tr>
<tr>
<td>PDIV</td>
<td>23 kV</td>
<td>27 kV</td>
<td>24 kV</td>
<td>24.9 kV</td>
</tr>
<tr>
<td>3 pC</td>
<td>3 pC</td>
<td>3 pC</td>
<td>2.2 pC</td>
<td>3 pC</td>
</tr>
<tr>
<td>50% BDV</td>
<td>30 kV</td>
<td>30 kV</td>
<td>30.5 kV</td>
<td>31 kV</td>
</tr>
<tr>
<td>8 pC</td>
<td>8.8 pC</td>
<td>8.8 pC</td>
<td>8.8 pC</td>
<td>6.5 pC</td>
</tr>
<tr>
<td>80% BDV</td>
<td>48 kV</td>
<td>48 kV</td>
<td>48.8 kV</td>
<td>49.6 kV</td>
</tr>
<tr>
<td>17 pC</td>
<td>13 pC</td>
<td>13 pC</td>
<td>13 pC</td>
<td>10 pC</td>
</tr>
<tr>
<td>SI-Bias BDV (kV peak)</td>
<td>36</td>
<td>37</td>
<td>--</td>
<td>37</td>
</tr>
<tr>
<td>LI-Bias BDV (kV peak)</td>
<td>44</td>
<td>44</td>
<td>--</td>
<td>44</td>
</tr>
</tbody>
</table>

From this table, it can be seen that increasing humidity from 680 up to 2000 ppmv does not increase the breakdown strength. Further increasing the humidity up to 4400 ppmv results in only slight increasing of the breakdown voltage (3% in AC, 3% in SI bias test and unchanged in LI bias test).

This is quite different with that in CO₂ experiments. Increasing humidity level up to 500 ppmv increases the AC breakdown voltage by 10%. Increasing humidity level up to 1500 ppmv increases the SI and LI breakdown voltage by 14% and 8%, respectively. It may be due the electronegative property of the gases. As SF₆ is an electronegative gas, adding certain humidity does not increase its electronegative property. This is in contrast to CO₂ in which adding certain humidity can increase the electronegative property of CO₂, thus increase its breakdown strength.

7.3 Conclusion

The conclusion for the SF₆ test is that increasing SF₆ humidity does not increase the breakdown strength significantly.
Chapter 8
The Risk Assessment

It is important to assess if a GIS is still allowed to operate under some variations of ambient condition as described in previous chapters. A simple knowledge rule can be used for this purpose which, in this thesis, is constructed from multiplication factors.

The first step is to check if there is a protrusion inside the GIS. This is done by means of partial discharge measurements. If no partial discharge is measured, it can be said that in general the GIS is safe for the ambient condition variations. The steps for the decision making are shown in Figure 8.1.

![Figure 8.1 The steps for the risk assessment](image)

The protrusion length can be determined by constructing a graph and, consequently, its linear equation as shown in 5.2, where the temperature and humidity levels are obtained by direct measurement.

The multiplication factors for AC are presented again here:

- Increasing temperature by 10 °C will decrease the breakdown strength by 3% (multiplication factor: 97%).

- Increasing the humidity by 100 ppmv, from dry gas up to 500 ppmv, will increase the breakdown strength by 2% (multiplication factor: 102%).
• Increasing the humidity by 100 ppmv, from 500 to 1500 ppmv, will increase the breakdown strength by 0.5% (multiplication factor: 100.5%).

• The multiplication factors for protrusion length:

<table>
<thead>
<tr>
<th>Protrusion Length</th>
<th>Multiplication factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 → 0.5mm</td>
<td>0.47</td>
</tr>
<tr>
<td>0 → 1mm</td>
<td>0.38</td>
</tr>
<tr>
<td>0 → 2mm</td>
<td>0.32</td>
</tr>
<tr>
<td>0 → 4mm</td>
<td>0.22</td>
</tr>
</tbody>
</table>

An example is given below for AC, LI and SI risk assessment calculations.

Suppose the measured humidity and temperature levels are 300 ppmv and 25 °C, respectively. If there is no protrusion inside the GIS, the AC breakdown strength is, let's say, BDAC₁.

Now if from the partial discharge measurement, in the same humidity and temperature levels, a protrusion is detected, let's say 0.5 mm, new breakdown strength BDAC₂, can be calculated as follows:

\[
BDAC₂ = 0.5 \text{ mm protrusion multiplication factor} \times BDAC₁
\]
\[
BDAC₂ = 0.47 \times BDAC₁
\]

If the gas temperature and humidity change to be 35 °C and 1500 ppmv, the breakdown strength changes (BDAC₃) as well:

\[
BDAC₃ = 0.47 \times 97\% \times 111\% \times BDAC₁
\]
\[
BDAC₃ = 0.51 \times BDAC₁
\]

The multiplication factors for LI bias test are shown as follows:

• Increasing temperature by 10 °C will decrease the breakdown strength by 5% (multiplication factor: 95%).

• Increasing the humidity from dry gas up to 1500 ppmv will increase the breakdown strength by 8% (multiplication factor: 108%).
• The multiplication factors for protrusion length:

<table>
<thead>
<tr>
<th>Protrusion Length</th>
<th>Multiplication factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 → 0.5mm</td>
<td>0.62</td>
</tr>
<tr>
<td>0 → 1mm</td>
<td>0.44</td>
</tr>
</tbody>
</table>

Similar to the calculation above, the effect of varied parameters on the LI bias breakdown strength (BDLI) can be calculated:

\[
\text{BDLI}_2 = 0.62 \times \text{BDLI}_1
\]

\[
\text{BDLI}_3 = 0.62 \times 95\% \times 108\% \times \text{BDLI}_1
\]

\[
\text{BDLI}_3 = 0.64\times\text{BDLI}_1
\]

The multiplication factors for SI bias test are shown as follows:

• Increasing temperature by 10 °C will decrease the breakdown strength by 7% (multiplication factor: 93%).

• Increasing the humidity from dry gas up to 1500 ppmv will increase the breakdown strength by 14% (multiplication factor: 114%).

• The multiplication factors for protrusion length:

<table>
<thead>
<tr>
<th>Protrusion Length</th>
<th>Multiplication factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 → 0.5mm</td>
<td>0.44</td>
</tr>
<tr>
<td>0 → 1mm</td>
<td>0.3</td>
</tr>
</tbody>
</table>

The effect of varied parameters on the LI bias breakdown strength (BDSI) can be calculated as follows:

\[
\text{BDSI}_2 = 0.44 \times \text{BDSI}_1
\]

\[
\text{BDSI}_3 = 0.62 \times 93\% \times 114\% \times \text{BDSI}_1
\]

\[
\text{BDSI}_3 = 0.66\times\text{BDSI}_1
\]
Chapter 8: The Risk Assessment

The calculated results above are listed in Table 8.1.

<table>
<thead>
<tr>
<th></th>
<th>BDAC</th>
<th>BDLI</th>
<th>BDSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 mm protrusion with initial temperature and humidity (25°C and 300 ppmv)</td>
<td>0.47 x BDAC_1</td>
<td>0.62 x BDLI_1</td>
<td>0.44 x BDSI_1</td>
</tr>
<tr>
<td>0.5 mm protrusion with increased temperature and humidity (35°C and 1500 ppmv)</td>
<td>0.51 x BDAC_1</td>
<td>0.64 x BDLI_1</td>
<td>0.66 x BDSI_1</td>
</tr>
</tbody>
</table>

It can be seen that in the presence of 0.5 mm protrusion, the breakdown strength for all voltage forms is decreasing. Increasing both temperature and humidity increases the breakdown strength. This is due the influence of humidity is more dominant than that of temperature.

Now, the next step is to compare this result with the operating voltages. BDAC is compared to operating AC voltage; BDSI is compared to transient overvoltage that may occur due to switching process; BDLI is compared to transient overvoltage that may occur due to lightning. If these values are higher than the operating voltages/overvoltage, it can be said that the GIS is safe to be operated under the situation above (0.5 mm protrusion, temperature and humidity variations).

Special attentions should be paid to the GIS' operating in countries in which many lightning and switching processes occur, for example in Indonesia. Because both types of transient overvoltage are likely to occur often here, the calculation of BDSI and BDLI as shown above is of importance.

The risk assessment calculated above is done for CO_2. The same steps can also be done for SF_6. However, due to the limited parameters and, thus, the experiments, it is less favorable to calculate the BDAC, BDLI and BDSI in this thesis. To do so, further experiments with more parameters are needed.
Conclusion

Risk assessment is important to decide whether a GIS is safe to be operated. A simple risk assessment can be performed by multiplying the related factors/parameters and comparing the result with the operating voltage.
Chapter 9
Conclusions and Recommendation

The objective of this thesis is to investigate the influence of the tropical conditions on the AC breakdown strength and on the AC-combined-impulse breakdown strength in the presence of small protrusion inside a GIS. CO\textsubscript{2} gas is used instead of SF\textsubscript{6} because of the toxicity of SF\textsubscript{6} byproducts produced during the breakdown. However, to give a short figure of the SF\textsubscript{6} breakdown voltage, some experiments are also performed with SF\textsubscript{6}.

In this chapter the conclusions and recommendations are made.

9.1 Conclusions

From the experiments in this thesis, some conclusions (points 1-4 are for CO\textsubscript{2}, point 5 is for SF\textsubscript{6}) can be drawn:

1. The effects of protrusion length, temperature and humidity are similar on the AC breakdown and AC-combined-impulse breakdown, as follows:
   - The presence of protrusion will decrease the breakdown considerably. The longer the protrusion, the lower the breakdown voltage.
   - Increasing the temperature will decrease the breakdown voltage.
   - Increasing the humidity will increase the breakdown voltage.

2. The effects of protrusion length, temperature and humidity on partial discharges are as follows:
   - The longer the protrusion, the greater the magnitude of partial discharges and the lower the AC voltage needed for the appearance of the partial discharge.
• Increasing the temperature will increase the partial discharges magnitude and decrease the AC voltage needed for the appearance of the partial discharge.

• Increasing the humidity will decrease the partial discharges magnitude and increase the AC voltage needed for the appearance of the partial discharge.

3. There is an inverse relation between the AC breakdown voltage and the partial discharge magnitude: if the partial discharge magnitude is great, the AC breakdown voltage is low.

4. The effect of gas pressure on the AC breakdown voltage is as follows:

• Increasing the pressure, at certain range of pressure, will increase the AC breakdown strength. At higher range of pressure, the breakdown voltage will reach the maximum level. Further increasing the pressure will decrease the breakdown voltage.

5. There is no significant influence of humidity on the breakdown strength of SF$_6$.

6. A risk assessment is important to decide whether a GIS containing a certain length protrusion under altered ambient parameters (temperature and humidity) is still safe to be operated.

7. The overvoltage risk assessment is mandatory for GIS operated in countries in which switching and lightning overvoltage occur frequently.

### 9.2 Recommendation

As in high voltage GIS SF$_6$ is the mostly used as the insulating gas, further experiments with SF$_6$ are needed to investigate the influence of tropical conditions on the SF$_6$ breakdown strength. The risk assessment can be performed then.
References


15. CIGRE Working Group 03 of Study Committee 15 (Insulating Materials), “BREAKDOWN OF GASES IN UNIFORM FIELDS Paschen curves for nitrogen, sulfur hexafluoride, hydrogen, carbon dioxide and helium” 1977