Simulation of Partial Discharge Patterns Using PSPICE

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# CONTENTS

<table>
<thead>
<tr>
<th>Topic</th>
<th>Page No.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CHAPTER 1</strong></td>
<td></td>
</tr>
<tr>
<td>1.1 Partial Discharge Analysis</td>
<td>5</td>
</tr>
<tr>
<td>1.2 Causes of Partial Discharge</td>
<td>5</td>
</tr>
<tr>
<td>1.3 Partial Discharge Emissions</td>
<td>6</td>
</tr>
<tr>
<td>1.4 Effect of PD on Electrical Insulation Health</td>
<td>6</td>
</tr>
<tr>
<td>1.5 PD as a symptom of ageing</td>
<td>7</td>
</tr>
<tr>
<td>1.6 Benefits of PD monitoring</td>
<td>7</td>
</tr>
<tr>
<td>1.7 Classification of Partial Discharge</td>
<td>8</td>
</tr>
<tr>
<td>1.7.1 External Partial Discharge</td>
<td>10</td>
</tr>
<tr>
<td>1.7.2 Internal Partial Discharge</td>
<td>10</td>
</tr>
<tr>
<td>1.8 Literature Survey</td>
<td>11</td>
</tr>
<tr>
<td>1.9 Present Work</td>
<td>12</td>
</tr>
<tr>
<td><strong>CHAPTER 2</strong></td>
<td></td>
</tr>
<tr>
<td>2.1 Partial Discharge Equivalent Circuit</td>
<td>13</td>
</tr>
<tr>
<td>2.2 Simulation Model</td>
<td>22</td>
</tr>
<tr>
<td>2.2.1 Explanation of the Model</td>
<td>22</td>
</tr>
<tr>
<td>2.3 Parameters on which Partial Discharge Depends</td>
<td>23</td>
</tr>
<tr>
<td>2.3.1 Physics behind Partial Discharge</td>
<td>23</td>
</tr>
<tr>
<td><strong>CHAPTER 3</strong></td>
<td></td>
</tr>
<tr>
<td>3 Simulation Results</td>
<td>25</td>
</tr>
<tr>
<td>3.1 Simulation results for different supply voltages</td>
<td>25</td>
</tr>
<tr>
<td>3.1.1 Variation of average number of breakdown with supply voltage</td>
<td>29</td>
</tr>
<tr>
<td>3.2 Simulation results for voids of different sizes</td>
<td>30</td>
</tr>
<tr>
<td>3.3 Simulation results for different residual voltage</td>
<td>35</td>
</tr>
<tr>
<td>3.4 Simulation results for different discharge inception voltages</td>
<td>38</td>
</tr>
<tr>
<td>3.5 Simulation results for different permittivity of the dielectric</td>
<td>41</td>
</tr>
<tr>
<td>3.6 Simulation results for different supply frequency</td>
<td>43</td>
</tr>
<tr>
<td>3.7 Verifications of results with that of Field Based Results</td>
<td>46</td>
</tr>
<tr>
<td><strong>CHAPTER 4</strong></td>
<td></td>
</tr>
<tr>
<td>4.1 Conclusion</td>
<td>48</td>
</tr>
<tr>
<td>4.2 Future Scope of the Work</td>
<td>48</td>
</tr>
<tr>
<td>4.3 References</td>
<td>49</td>
</tr>
</tbody>
</table>
To
The Head of the Department
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Respected Sir,
In accordance with the requirements of the degree of Bachelor of Technology in the department of Electrical Engineering, Haldia Institute of Technology, we present the following thesis entitled “Simulation of Partial Discharge Patterns Using Pspice”. This work was performed under the supervision of Mr. Prithwiraj Das.

We declare that the work submitted in this thesis is our own and the text and reference has not been previously submitted for a degree at the institute.

Yours Sincerely,

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CHAPTER 1

1.1 PARTIAL DISCHARGE ANALYSIS

Partial discharges are electrical “sparks” that do not completely bridge the electrodes and which exist in nearly all high voltage electrical machinery. The phenomena results in high frequency, low voltage signals on the phase leads. Over time, the degradation and discharges become larger until a full discharge is obtained leading to failure of the equipment. Partial discharges are small electrical sparks that occur within the electric insulation of switchgear, cables, transformers, and windings in large motors and generators. Partial Discharge Analysis is a proactive diagnostic approach that uses partial discharge (PD) measurements to evaluate the integrity of this equipment. Each discrete PD is a result of the electrical breakdown of an air pocket within the insulation. PD measurements can be taken continuously or intermittently and detected on-line or off-line. PD results are used to reliably predict which electrical equipment is in need of maintenance. Just as every material has a characteristic tensile strength, each material also has an electrical breakdown (dielectric) strength that represents the electrical intensity necessary for current to flow and an electrical discharge to take place. Common insulating materials such as epoxy, polyester, and polyethylene have very high dielectric strengths. Conversely, air has a relatively low dielectric strength. Electrical breakdown in air causes an extremely brief (lasting only fractions of a nanosecond) electric current to flow through the air pocket. The measurement of partial discharge is, in fact, the measurement of these breakdown currents.

Electric equipment can suffer from a variety of manufacturing defects or operating problems that impair its mechanical reliability. The electrical insulation of motors and generators is susceptible to:

- Thermal stress
- Chemical Attack
- Abrasion due to excessive oil movement

In all cases, these stresses will weaken the bonding properties of the epoxy or polyester resins that coat and insulate the windings. As a result, an air pocket develops in the windings. Not only do partial discharge levels provide early warning of imminent equipment failure, but partial discharge also accelerates the breakdown process. The excessive arcing between ground and conductor within the insulation will, in time, compromise the dielectric strength and mechanical integrity of the winding insulation. Once this happens, a ground fault or a phase-to-phase fault is inevitable.

1.2 CAUSES OF PARTIAL DISCHARGE

Partial discharge can occur at any point in the insulation system, where the electric field strength exceeds the breakdown strength of that portion of the insulating material. Partial discharge can occur in voids within solid insulation, across the surface of insulating material due to
contaminants or irregularities, within gas bubbles in liquid insulation or around an electrode in gas (corona activity).

Partial discharge may originate at one of the electrode or occur in a cavity in the dielectric. The air or gas cavities are one of the most wide spread types of localized defect. Due to the fact that the dielectric permittivity of air is few times less than the dielectric filed intensity in the gas layer can considerably exceed the average field intensity in the insulator.

Therefore in the number of cases ionization process start even the working voltage. The sum total of this ionization process is called the “partial discharge” since they cover a small part of total distance between the electrodes. Once begin PD causes progressive deterioration of insulating materials ultimately leading to electric breakdown. PD can be prevented through careful design and material is confirmed using PD detector equipment during the manufacturing stage as well as periodically through the equipments useful life. PD prevention and detection are essential to ensure reliable, long term operation of HV equipment used by electric power utilities.

1.3 PARTIAL DISCHARGE EMISSIONS
Partial discharges emit energy as:

- Electromagnetic emissions, in the form of radio waves, light and heat
- Acoustic emissions, in the audible and ultrasonic ranges
- Ozone and nitrous oxide gases

1.4 EFFECT OF PD ON ELECTRICAL INSULATION HEALTH

PDs as ionization events produce different forms of energy and many types of reactive chemical species (electrons, ions, excited species, meta-stables, acidic by-products, etc). Insulating materials (dielectrics) in contact with PDs experience faster aging rates as thermal, mechanical and chemical degradations take place at the corona-to-insulation interface. The PDs can then in combination with operating and environmental stresses, “electrostatically” machine paths between the high voltage and ground. The gradual reduction in voltage withstand capability will ultimately lead to the failure of the insulation system during a voltage surge or a severe load swing for example. Vibration and contamination are also known to exacerbate the effects of PD on insulation and accelerate ageing.
1.5 PD AS A SYMPTOM OF AGEING:

It is often wrongly believed that PD by itself can quickly fail a medium or high voltage micaceous insulation system. While corona by itself contributes to that it is the combination of multiple stresses as highlighted above that creates fast insulation degradation. PD events serve as very useful indicators of how far degradation has progressed and are how fast it is progressing. An advanced PD data interpretation and a careful diagnostics work is always needed for a reliable machine health assessment. PD activity can be very sensitive to contamination due oil, conductive dust such as metal or carbon powder. It can also detect winding vibration and winding support system issues. Excessive thermal stress can also lead to a gradual degradation of stress grading systems leading to excessive local corona around the non linear voltage grading coating.

1.6 BENEFITS OF PD MONITORING:

Electrical equipments are among the most expensive and critical assets in power and process plants. Their impact is great on profit and revenue generation. Their production and management cost is high, and failures almost always lead to catastrophic losses. Electrical systems are being operated at higher stress levels (thermal and cycling), even while systems are aging - which affects both the life and the reliability of the assets. Whether continuous or periodic PD testing can enable true Condition Based Maintenance (CBM) and reduce both operating and repair costs of electrical assets. If performed over the long term and a reliable trend established PD testing can help:

- Eliminate unplanned outages and lost profit due to system downtime
- Reduce maintenance costs by extending time between planned outages
- Increase availability and operating efficiency through greater system reliability
- Improve risk management and reduce catastrophic failures
- Improve worker safety

Today’s asset managers are facing the increased challenge of maximizing profit from their aging electrical infrastructure with fewer qualified technical in-house resources, stricter regulatory requirements for worker safety, and shrinking maintenance budgets. Advances in technology, including the use of Partial Discharge testing, are giving maintenance managers new tools to achieve improved reliability and performance of critical electrical assets.
1.7 CLASSIFICATION OF PARTIAL DISCHARGE

There are various types of partial discharges.

1. **Corona Discharge** - these occur due to non-uniform field on the sharp edges of the conductor subjected to high voltage especially when the insulation provided is air or gas or liquid.

   ![Corona Discharge Diagram]

2. **Surface Discharges and discharges in laminated materials** on the interfaces of different dielectric material such as gas/solid interface as the gas gets overstressed $\varepsilon_r$ times the stress on the solid material (where $\varepsilon_r$ is the relative permittivity of solid material) and ionization of gas results.

   ![Surface Discharges Diagram]
3. **Cavity Discharges** - when cavities are formed in solids or liquid insulators, the gas in the cavities are over stressed and discharges are formed

![Cavity Discharge Diagram]

4. **Treeing Channels** - High intensity fields are produced in an insulating material at its sharp edges and this deteriorates the insulating material. The continuous partial discharges so produced are called Treeing Channels

![Treeing Channels Diagram]
1.7.1 **External Partial Discharge**

External Partial Discharge is the process which occurs external to the equipment e.g. on overhead lines, on armature.

1.7.2 **Internal Partial Discharge**

It is a process of electrical discharge which occurs inside a closed system (discharge in voids, treeing, etc). This kind of classification is essential for the PD measuring system as external discharges can be nicely distinguished from internal discharges. Partial discharge measurement has been used to assess the life expectancy of insulating materials. Even though there is no well defined relationship, yet it gives sufficient idea of the insulating property of the material. Partial discharges on insulation can be measured not only by electrical methods but by optical, acoustic and chemical methods also. The measuring principles are based on energy conversion process associated with electric discharges such as emission of electromagnetic waves, light, noise, or formation of chemical compounds. The oldest method and simplest but less sensitive method is the method of listening to hissing sound coming out of partial discharge. A high value of loss factor tan\(\delta\) is an indication of occurrence of partial discharge in the material. This is also not a reliable measurement as the additional losses generated due to application of high voltage are localized and can be very small in comparison to the volume of losses resulting from polarization process. Optical methods are used for only transparent materials. Acoustic detection methods using ultrasonic transducers have, however, been used with some success. The most modern and the most accurate methods are the electrical methods. The main objective here is to separate impulse currents associated with Partial Discharge from any other phenomenon.
1.8 LITERATURE SURVEY

The PD analysis being very important regarding the industrial point of view, it is continuously being monitored in the industry. Also there are various methods of determining the PD analysis. Tests and research has been carried out to determine the PD analysis. The PD analysis can be done by various methods such as using wavelet transform, MATLAB, PSPICE.

Even many MNCs such as General Electric, Schneider Electric have developed certain methods to determine the partial discharge and they also assist their customers. GE provides various installations and testing option for PD measurements. Using phase resolved data acquisition the insulation experts continuously monitor the equipments.

Using Principal Component Analysis (PCA) the research regarding the PD patterns has been carried out in the transformer windings. Also partial discharge analyzer DDX-9101 is used with the PCA. The PD analysis is done by locating fault in transformer and other electrical equipments. Detection of fault location and discharge magnitude of the equipment is done by PD analyzer DDX-9101. In this partial discharge analyzer, direct partial discharge magnitude, voltage level and wave shape is got by which one can easily analyze the fault location.

Also mathematical models based on MATLAB have been used for investigating the partial discharge processes in single layer solid insulation. There are chosen and calculated parameters of the model. There are done evaluation of model marginal parameters, and their influence upon the final results.
1.9 PRESENT WORK

Here we are trying to simulate the PD patterns and study its properties by using PSPICE. The void is represented by the capacitor with parallel resistor. The BJT has been used as a switching device. The BJT is initiated by the Schmitt trigger when the upper threshold voltage is reached, and the BJT is switched off when the lower threshold voltage is reached in the Schmitt trigger. The voltage follower circuit is cascaded with the Schmitt trigger to avoid loading effect.

The upper and the lower threshold voltages are determined by variation of the resistances. The n-p-n and p-n-p transistors are used for the switching purpose in positive and negative half cycles.

Once the upper threshold voltage is reached the capacitor which represents the void, discharges and thus the voltage across the capacitor reduces till the voltage reduces below the lower threshold voltage. Then again the voltage rises and same process repeats.

The voltage follower circuit is used following the Schmitt trigger and then an amplifier is used which gives sufficient voltage to trigger the base of the transistor.
CHAPTER 2

2.1 THE PARTIAL DISCHARGE EQUIVALENT CIRCUIT

If there are any partial discharges in a dielectric medium, these can be measured only across its terminal. The figure shows a simple capacitor arrangement in which a gas filled void is present. The partial discharge in the void will take place as the electric stress in the void is \( \varepsilon_r \) times the stress in the rest of the material where \( \varepsilon_r \) is the relative permittivity of the material. Due to geometry of the material various capacitances are formed as shown. Flux lines starting from electrode and terminating at the void will form one capacitance \( C_{b1} \) and similarly \( C_{b2} \) between electrode B and cavity. \( C_c \) is the cavity capacitance. Similarly \( C_{a1} \) and \( C_{a2} \) are the capacitances of the healthy portion of the dielectric on the two sides of the void. Fig-b shows the equivalent of (fig-a), where

\[
C_a = C_{a1} + C_{a2}
\]

And

\[
C_b = \frac{C_{b1}C_{b2}}{(C_{b1} + C_{b2})}
\]

Closing of switch S is equivalent to simulating partial discharge in the void as the voltage \( V_c \) across the void reaches breakdown voltage. The discharge results in a current \( i_c \).

Suppose voltage \( V \) is applied across the electrode A and B and the sample is charged to this voltage and source is removed. The voltage \( V_c \) across the void is sufficient to breakdown the void. It
is equivalent to closing the switch S. as a result the current $i_c(t)$ flows which releases a charge $\Delta q_c = \Delta V_c C_c$ which is dispersed in the dielectric material across the capacitance $C_b$ and $C_a$. Here $\Delta V_c$ is the drop in voltage $V_c$ as a result of discharge. The equivalent circuit during redistribution of charge $\Delta q_c$ is shown.

![Equivalent Circuit](image)

**EQUIVALENT OF FIG-1(A) AFTER DISCHARGE**

The voltage across AB will be

$$\Delta V = \frac{C_b}{C_a + C_b} \Delta V_c = \frac{C_b}{C_a + C_b} \frac{\Delta q_c}{C_c}$$

Ordinarily $\Delta V_c$ is in kV whereas $\Delta V$ is a few volts since the ratio $C_b/C_a$ is of the order of $10^{-4}$ to $10^{-3}$. The voltage drop $\Delta V$ even though can be measured but as $C_b$ and $C_c$ are normally known neither $\Delta V_c$ nor $\Delta q_c$ can be obtained. Also since $V$ is in kV and $\Delta V$ is in volts the ratio $\Delta V/V$ is very small $= 10^{-3}$, therefore the detection of $\Delta V/V$ is a tedious task.

Suppose that the test object remains connected to the voltage source fig-3. Here $C_k$ is the coupling capacitor. $Z$ is the impedance consisting either only of the lead impedance of or lead impedance and PD free inductor or filter which decouples the coupling capacitor and the test object from the source during discharge period only, when very high frequency current pulse $i(t)$ circulate between $C_k$ and $C_t$. $C_t$ is the total equipment capacitance of the test specimen.
It is to be noted that Z offers high impedance to circular current (impulse current) and therefore these are limited only to $C_k$ and $C_t$. However supply frequency displacement current continue to flow through $C_k$ and $C_t$ and wave shapes of currents through $C_k$ and $C_t$ are shown in the fig.

It is interesting to find that pulse currents in $C_k$ and $C_t$ have exactly same location but opposite polarities and these are of same magnitude. The amplitude of pulse depends upon the voltage applied and number of pulses depends upon the number of voids. Larger the number of faults, the higher the number of pulses over a half cycle.

During discharge, voltage across the test object $C_t$ falls by an amount $\Delta V$ and during this period $C_k$ stores the energy and releases the charge between $C_t$ and $C_k$ thus compensating the drop
\[ \Delta V \text{. The equivalent capacitance of the test specimen is } Ct = C_a + C_b \text{ assuming } C_c \text{ is negligibly small. If } C_k \gg Ct \text{ then the charge transfer is given by} \]

\[ q_c = \int i(t) dt = (C_a + C_b) \Delta V \]

Now,

\[ \Delta V = \frac{C_b}{C_a + C_b} \Delta V_c \]

\[ \Delta V = \frac{q}{C_a + C_b} \]

Therefore,

\[ \frac{q}{C_a + C_b} = \frac{C_b}{C_a + C_b} \Delta V_c \]

SO,

\[ q = C_b \Delta V_c \]

If q is known as apparent charge as it is not equal to the charge locally involved \( C_c \Delta V_c \). This charge q is more realistic than calculating \( \Delta V \), as q is independent of \( C_a \) whereas \( \Delta V \) depends upon \( C_a \).

In practice the condition \( C_k \gg Ct \) is never satisfied as the \( C_k \) will over load the supply and it will be uneconomical. However \( C_k \) is slightly greater than \( Ct \), the sensitivity of measurement is reduced as the compensating current \( i_c(t) \) becomes small. If \( C_t \) is comparable to \( C_k \) and \( \Delta V \) is drop in voltage of \( Ct \) the transfer of charge between \( C_t \) and \( C_k \) result in common voltage \( \Delta V' \).

\[ \Delta V' = \frac{C_t \Delta V + C_k \cdot 0}{C_t + C_k} = \frac{C_t \Delta V}{C_t + C_k} = \frac{q}{C_t + C_k} \]

\( \Delta V' \) is the net rise of voltage of parallel combination of \( C_k \) and \( C_t \) and therefore the charge \( q_m \) transferred to \( Ct \) from \( C_k \) will be

\[ q_m = C_k \Delta V' \]

The charge \( q_m \) is referred as measurable charge.

\[ \frac{q_m}{q} = \frac{C_k}{C_t + C_k} \]

In order to have high sensitivity of measurement i.e. high \( q_m \) it is clear that \( C_k \) should be large compared to \( C_c \), but we know that there are disadvantage in having high value of \( C_k \). Therefore this method of PD has limited applications.
The measurements of PD current pulses provide important information concerning the discharge processes in a test specimen. The time response of an electric discharge depends mainly on the nature of fault and design of insulating material. The shape of the circular current is an indication of the physical discharge process at the fault location in the test object. The principle of measurement of PD current is shown in the fig.

![PRINCIPLE OF PULSE CURRENT MEASUREMENT](image)

Here C indicates the stray capacitance between the lead of \( C_t \) and the earth, the input capacitance of amplifier and other stray capacitances. The function of high pass amplifier is to suppress the current \( i_K(t) \) and \( I_c(t) \) and to further amplify the short duration current pulse. The delay cable is electrically disconnected from R. Suppose during a partial discharge a short duration pulse current \( i(t) \) is produced and results in apparent charge \( q \) on \( C_t \) which will be redistributed between C, \( C_t \) and \( C_k \). The circuit for the same is given by:

![EQUIVALENT CIRCUIT AFTER DISCHARGE](image)

Potential across

\[
C_t = \frac{q}{\frac{C_c}{C_t+C_k}}
\]
Therefore voltage across C will be

\[
V = \frac{q}{Ct + Ck} \cdot \frac{Ck}{Ct + Ck} = \frac{q}{Ct(C + Ct) + CkCt}
\]

\[
= \frac{qCt}{CkCt + CkCt + CkCt} = \frac{q}{C + C(Ck + \frac{Ck}{C})}
\]

And because of resistance R the expression for voltage across R will be

\[
V(t) = \frac{q}{C + C(Ck + \frac{Ck}{C})} e^{-t/\tau}
\]

\[
\tau = (C + \frac{Ck}{C} + \frac{C}{Ck})R
\]

The voltage across the resistance R indicates a fast rise and is followed by an exponential decay. The circuit elements have just deferred the original current wave shape especially the wave tail side of the wave and therefore the measurement of pulse current \(i(t)\) is a difficult task.

Also the PD pulse current gets corrupted due to the various interferences present in the system. The power frequency displacement current \(i_k(t)\) and \(i_r(t)\) are the
major sources of interferences. Higher harmonics in the supply and pulse current in the thyristorised control circuits are always present which will interfere with the PD currents. On load taps in a transformer, carbon brushes in generator are yet other sources of noise in the circuits.

Mainly interference can be classified as follows:

- Pulse shaped noise signals: These are due to impulse phenomenon similar to PD currents.
- Harmonic signals: These are mainly due to power supply and thyristorized controller.

We are taking apparent charges as the index level of the partial discharges which is integration of PD pulse currents. Therefore continuous alternating current of any frequency would disturb the integration process of measuring circuit and hence it is important that these currents must be suppressed before the mixture of currents is passed through the integrating circuits. The solution of the problem is obtained by using filter circuits which may be completely independent of integrating circuits.

In the following fig. two different ways in which the measuring impedance $Z_m$ can be connected in the circuits.
In fig $Z_m$ is connected in series with $C_t$ and provides better sensitivity. However, even the disadvantage is that in case of puncture of the test specimen the measuring circuit will also be damaged. Especially for this reason the second arrangement in which $Z_m$ is connected between $C_t$ and the ground and is the circuit most commonly used.

The apparent charge is obtained by integration of circular currents $i_c(t)$. This operation is carried out on PD pulses using ‘Wide Band’ and ‘Narrow Band’ measuring systems. These are basically band pass filters with amplifying option. If we examine the frequency spectrum of pulse current, it will be cleared why band pass filters are suitable for integrating PD pulse currents.

We know that for a non-periodic pulse current $i(t)$, the complex frequency spectrum of current is given by Fourier transform as
Here the current is approximated by an exponentially decaying curve, neither \( i(t) \) nor \( I(jw) \) vanish and so a new measure of pulse width required. The time constant \( \tau \) is a measure of the width of \( i(t) \), a line tangent to \( i(t) \), a line tangent to \( i(t) \) at \( t=0 \) intersects the line \( i=0 \) at \( t= \tau \) as shown in the fig.

From the above expression and fig. it is clear that \( \omega \to 0 \) \( I(jw) \to I_0 \tau \) which means that dc content of the frequency spectrum equals apparent charge in the pulse current. Therefore the frequency spectrum of PD pulse current contains complete information concerning the apparent charge in low frequency range. In order to have proper integration of the pulse current, the time constant \( \tau \) of the pulse should be greater than the time constant of measuring circuit or the band width (upper cut off frequency) of the measuring system should be much lower than that of spectrum of pulse currents to be measured.
2.2 SIMULATION MODEL

The simulation model for the partial discharge analysis is given below:

![Simulation Model Diagram]

**Figure (a)**

2.2.1 EXPLANATION

Figure 1 represents the simulation model where V1 represents the supply voltage, C3 represents the void. The Schmitt trigger is used for setting the lower and the upper threshold voltages. The upper threshold voltage represents the voltage at which the breakdown in the void occurs and the inception of partial discharge occurs. Once the partial discharge starts the voltage across the void starts decreasing and when it reaches the lower threshold voltage the voltage becomes insufficient for the breakdown process and partial discharge extinct again the voltage build up starts with the supply voltage. The n-p-n and p-n-p transistors are used as the switching devices for the positive and the negative half cycles respectively when fed by the positive and negative pulses from Schmitt Trigger.
2.3 PARAMETERS ON WHICH PARTIAL DISCHARGE DEPENDS

The various parameters on which partial discharge depends are:

- Supply voltage
- Area of the void
- Supply frequency
- Upper threshold voltage of the Schmitt trigger
- Lower threshold voltage of the Schmitt trigger.

2.3.1 PHYSICS BEHIND THE PARTIAL DISCHARGE

- **Dependence on supply voltage:**

  The partial discharge patterns are dependent on the magnitude of the supply voltage. The greater the supply voltage more is the slope and early the partial discharge occurs. And if the supply voltage is reduced the slope decreases and there is some delay in partial discharge.

- **Dependence on the supply frequency:**

  The partial discharge is also dependent on the supply frequency. If we raise the supply frequency, the rate of change of the voltage becomes high and the partial discharge occurs at lower voltage.

- **Dependence on the upper and lower threshold voltage:**

  The partial discharge patterns are also dependent on the upper threshold voltage and the lower threshold voltage (of the Schmitt trigger used here). The PD patterns are mainly dependent on the difference of the upper and the lower threshold voltage as the charge transfer is dependent on the difference:

  \[ Q \propto (V_{UT}-V_{LT}) \]

  More is the difference between \( V_{UT} \) and \( V_{LT} \) more early the PD occurs. If we fix the \( V_{UT} \) and start increasing the \( V_{LT} \) the PD starts at higher voltage and vice versa. Same case occurs when we fix the \( V_{LT} \) and start decreasing \( V_{UT} \).
• **Dependence on the Area of the void**

The partial discharge patterns are heavily dependent on the area of the void i.e. the void size. The relative permittivity of the void is nearly equal to 1, as the void is mainly the air gaps present in the dielectric. If there is no void then the electric field line would go straight without any deviation, and there will be no partial discharge.

![Electric field line](image)

When the void size is very small then deviation is observed in the patterns of the electric field lines. Instead of going straight these lines bend towards the higher permittivity region as they have the tendency to pass through the higher permittivity. The bent field lines gives rise to the horizontal and the vertical component of the voltage. The vertical voltage is mainly responsible for the breakdown. As the overall voltage is divided into horizontal and the vertical voltages, the vertical component gets reduced and thus more amount of voltage is required for the inception of the partial discharge.

![Vertical component](image)

When the void size is quite large, there is absence of horizontal component and the vertical component is mainly present. So less amount of voltage (as compared to the previous case) is required for the inception of partial discharge.

![Vertical component](image)
CHAPTER 3

3.0 SIMULATION RESULTS:

3.1 Simulation results for different voltages

<table>
<thead>
<tr>
<th>Supply Voltage (in Volts)</th>
<th>Angle of Inception (in degrees)</th>
<th>Angle of Extinction (in degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>26.55</td>
<td>46.72</td>
</tr>
<tr>
<td>12</td>
<td>20.34</td>
<td>56.62</td>
</tr>
<tr>
<td>16</td>
<td>15.64</td>
<td>62.46</td>
</tr>
<tr>
<td>18</td>
<td>14.09</td>
<td>67.51</td>
</tr>
<tr>
<td>20</td>
<td>12.51</td>
<td>70.43</td>
</tr>
</tbody>
</table>

Variation of Angle of Inception and Angle of Extinction with Supply Voltage
1. \( V_s=10\text{V}, f=50\text{Hz}, C_1=2500\text{pF}, C_2=300\text{pF}, C_3=10\text{pF}, C_4=300\text{pF}, V_{UT}=6\text{V}, V_{LT}=3\text{V} \)

**OUTPUT:**

**OBSERVATIONS:**
- Average no. of Breakdowns per half cycle: 4.3°
- Angle of Inception: 25°
- Angle of Extinction: 72°
- Partial Discharge Band: 47°
2. $V_s=12\,\text{V}, \, C_1=2500\,\text{pF}, \, C_2=300\,\text{pF}, \, C_3=10\,\text{pF}, \, C_4=300\,\text{pF}, \, V_{UT}=6\,\text{V}, \, V_{LT}=3\,\text{V}$

**OUTPUT:**

![Graph with data points labeled V(1) and V(4)]

**OBSERVATIONS:**
- Average no. of Breakdowns per half cycle: 5
- Angle of Inception: $20.34^0$
- Angle of Extinction: $79.83^0$
- Partial Discharge Band: $59.49^0$
3. $V_s=14V$, $f=50Hz$, $C_1=2500pF$, $C_2=300pF$, $C_3=10pF$, $C_4=300pF$, $V_{UT}=6V$, $V_{LT}=3V$

**OUTPUT:**

![Graph showing voltage over time with labeled axes and markers for $V(1)$ and $V(4)$]

**OBSERVATIONS:**
- Average no. of Breakdowns per half cycle: 5.3
- Angle of Inception: 20.34°
- Angle of Extinction: 65.48°
- Partial Discharge Band: 45.14°
3.1.1 Variation of average number of breakdown per half cycle with the supply voltage

<table>
<thead>
<tr>
<th>Supply Voltage (in volts)</th>
<th>Average No. of Breakdown per Half Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>4.5</td>
</tr>
<tr>
<td>12</td>
<td>5.3</td>
</tr>
<tr>
<td>16</td>
<td>6.9</td>
</tr>
<tr>
<td>18</td>
<td>7.6</td>
</tr>
<tr>
<td>20</td>
<td>9.1</td>
</tr>
</tbody>
</table>

Variation of Average no. of breakdown per Half Cycle with Supply Voltage
### 3.2 Simulation results for different void sizes.

<table>
<thead>
<tr>
<th>Area of the Void (Ad)</th>
<th>Average no. of breakdown per half cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05A</td>
<td>2.5</td>
</tr>
<tr>
<td>0.10A</td>
<td>2.3</td>
</tr>
<tr>
<td>0.15A</td>
<td>2.2</td>
</tr>
<tr>
<td>0.20A</td>
<td>2</td>
</tr>
<tr>
<td>0.30A</td>
<td>1.9</td>
</tr>
</tbody>
</table>

#### Variation of Average no. of breakdown per Half Cycle with Area of the Void

![Graph showing variation of average number of breakdown per half cycle with area of the void](graph.png)
1. $V_s = 10\text{V}$, $f = 50\text{Hz}$, $C_1 = 210\text{pF}$, $C_2 = 115\text{pF}$, $C_3 = 170\text{pF}$, $C_4 = 115\text{pF}$, $V_{UT} = 6\text{V}$, $V_{LT} = 3\text{V}$ ($\varepsilon_r = 3$, $A_d = 0.20\text{A}$)

**OUTPUT:**

![Graph showing voltage versus time for different voltage levels and time intervals.]

**OBSERVATIONS:**

- Average no. of Breakdowns per half cycle: 1.7
- Angle of Inception: $43.83^0$
- Angle of Extinction: $51.46^0$
- Partial Discharge Band: $7.63^0$
2. $V_s=10\text{V}, f=50\text{Hz}, C_1=210\text{pF}, C_2=116\text{pF}, C_3=131\text{pF}, C_4=116\text{pF}, V_{UT}=6\text{V}, V_{LT}=3\text{V}$ ($\varepsilon_r=4, A_d=0.20\text{A}$)

OUTPUT:

OBSERVATIONS:
- Average no. of Breakdowns per half cycle: 1.9
- Angle of Inception: $42.4^\circ$
- Angle of Extinction: $62.6^\circ$
- Partial Discharge Band: $20.2^\circ$
3. $V_s=10V$, $f=50\text{Hz}$, $C_1=100\text{pF}$, $C_2=100\text{pF}$, $C_3=145\text{pF}$, $C_4=100\text{pF}$, $V_{UT}=6V$, $V_{LT}=3V$ ($\varepsilon_r=3$, $A_d=0.30\text{A}$)

**OUTPUT:**

[Graph showing waveforms for $V(1)$ and $V(4)$ over time.]

**OBSERVATIONS:**
- Average no. of Breakdowns per half cycle: 1.4
- Angle of Inception: $23.34^\circ$
- Angle of Extinction: $61.05^\circ$
- Partial Discharge Band: $37.71^\circ$
4. $V_s=10\text{V}, f=50\text{Hz}, C_1=190\text{pF}, C_2=180\text{pF}, C_3=200\text{pF}, C_4=180\text{pF}, V_{UT}=6\text{V}, V_{LT}=3\text{V}$ ($\varepsilon_r=4, A_d=0.30\text{A}$)

**OUTPUT:**

**OBSERVATIONS:**
- Average no. of Breakdowns per half cycle: 2.3
- Angle of Inception: 39.13°
- Angle of Extinction: 53.22°
- Partial Discharge Band: 14.09°
### 3.3 Simulation results for different lower threshold voltage for fixed upper threshold voltage

<table>
<thead>
<tr>
<th>Lower Threshold Voltage (in volts)</th>
<th>Angle of Inception (in degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>14.22</td>
</tr>
<tr>
<td>4</td>
<td>15.30</td>
</tr>
<tr>
<td>5</td>
<td>18.52</td>
</tr>
<tr>
<td>6</td>
<td>20.36</td>
</tr>
<tr>
<td>8</td>
<td>23.45</td>
</tr>
</tbody>
</table>

**Variation of Angle of Inception with lower threshold voltage keeping upper threshold voltage constant**
1. $V_s=10\text{V}, f=50\text{Hz}, C_1=2500\text{pF}, C_2=300\text{pF}, C_3=10\text{pF}, C_4=300\text{pF}, V_{UT}=6\text{V}, V_{LT}=1\text{V}$

**OUTPUT:**

![Graph showing voltage over time](image)

**OBSERVATIONS:**
- Average no. of Breakdowns per half cycle: 2.3
- Angle of Inception: 30°
- Angle of Extinction: 72°
- Partial Discharge Band: 42°
2. $V_s=10\text{V}, f=50\text{Hz}, C_1=2500\text{pF}, C_2=300\text{pF}, C_3=10\text{pF}, C_4=300\text{pF}, V_{UT}=6\text{V}, V_{LT}=2\text{V}$

OUTPUT:

OBSERVATIONS:
- Average no. of Breakdowns per half cycle: 2.8
- Angle of Inception: $28^\circ$
- Angle of Extinction: $68.4^\circ$
- Partial Discharge Band: $40.4^\circ$
3.4 Simulation results for different upper threshold voltages keeping the lower threshold voltage fixed.

<table>
<thead>
<tr>
<th>Upper Threshold Voltage (in volts)</th>
<th>Angle of Inception (in degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>17.21</td>
</tr>
<tr>
<td>5</td>
<td>18.36</td>
</tr>
<tr>
<td>6</td>
<td>20.34</td>
</tr>
<tr>
<td>8</td>
<td>20.41</td>
</tr>
</tbody>
</table>

Variation of Angle of Inception with upper threshold voltage keeping lower threshold voltage constant

![Graph showing the variation of Angle of Inception with upper threshold voltage keeping lower threshold voltage constant]
1. \( V_s=10\,\text{V}, f=50\,\text{Hz}, C_1=2500\,\text{pF}, C_2=300\,\text{pF}, C_3=10\,\text{pF}, C_4=300\,\text{pF}, V_{UT}=5\,\text{V}, V_{LT}=2\,\text{V} \)

OUTPUT:

![Graph showing voltage over time](image)

OBSERVATIONS:

- Average no. of Breakdowns per half cycle: 4.0
- Angle of Inception: 24.8°
- Angle of Extinction: 54°
- Partial Discharge Band: 29.2°
2. \( V_s=10\,V, f=50\,Hz, C_1=2500\,pF, C_2=300\,pF, C_3=10\,pF, C_4=300\,pF, V_{UT}=7\,V, V_{LT}=2\,V \)

OUTPUT:

![Graph showing V(1) and V(4) over time](image.png)

OBSERVATIONS:

- Average no. of Breakdowns per half cycle: 2.6
- Angle of Inception: \( 31.32^\circ \)
- Angle of Extinction: \( 60.96^\circ \)
- Partial Discharge Band: \( 29.64^\circ \)
3.5 Simulation results for different values of permittivity

1. \( V_s=10\text{V}, f=50\text{Hz}, C_1=230\text{pF}, C_2=55\text{pF}, C_3=85\text{pF}, C_4=55\text{pF}, V_{UT}=6\text{V}, V_{LT}=3\text{V}, \varepsilon_r=3 \)

OUTPUT:

OBSERVATIONS:
- Average no. of Breakdowns per half cycle: 1.2
- Angle of Inception: 36°
- Angle of Extinction: 67.5°
- Partial Discharge Band: 31.5°
2. $V_s=10\text{V}$, $f=50\text{Hz}$, $C_1=220\text{pF}$, $C_2=70\text{pF}$, $C_3=60\text{pF}$, $C_4=70\text{pF}$, $V_{UT}=6\text{V}$, $V_{LT}=3\text{V}$, $\varepsilon_r=4$

OUTPUT:

OBSERVATIONS:
- Average no. of Breakdowns per half cycle: 2
- Angle of Inception: $40.69^\circ$
- Angle of Extinction: $72^\circ$
- Partial Discharge Band: $31.31^\circ$
3.6 Simulation results for different values of frequency

1. $V_S=10\text{V}, f=25\text{Hz}, \ C_1=2500\text{pF}, \ C_2=300\text{pF}, \ C_3=10\text{pF}, \ C_4=300\text{pF}, \ V_{UT}=6\text{V}, \ V_{LT}=3\text{V}$

OUTPUT:

OBSERVATIONS:
- Average no. of Breakdowns per half cycle: 3
- Angle of Inception: $50.08^0$
- Angle of Extinction: $106.43^0$
- Partial Discharge Band: $56.35^0$
2. \( V_S = 10\text{V}, \ f = 100\text{Hz}, \ C_1 = 2500\text{pF}, \ C_2 = 300\text{pF}, \ C_3 = 10\text{pF}, \ C_4 = 300\text{pF}, \ V_{UT} = 6\text{V}, \ V_{LT} = 3\text{V} \)

OUTPUT:

![Graph Image]

OBSERVATIONS:

- Average no. of Breakdowns per half cycle: 3.1
- Angle of Inception: 12.38°
- Angle of Extinction: 37.08°
- Partial Discharge Band: 24.7°
3. $V_S=10V$, $f=200Hz$, $C_1=2500pF$, $C_2=300pF$, $C_3=10pF$, $C_4=300pF$, $V_{UT}=6V$, $V_{LT}=3V$

OUTPUT:

**OBSERVATIONS:**
- Average no. of Breakdowns per half cycle: 3.6
- Angle of Inception: $6.37^0$
- Angle of Extinction: $11.07^0$
- Partial Discharge Band: $4.7^0$
3.7 VERIFICATION OF PSPICE BASED SIMULATED RESULTS WITH THAT OF FIELD COMPUTATION RESULTS

Let us consider a specimen of dielectric constant of 5 and dimension 50 x 50 x 35m$^3$ with the void being placed exactly at the center with the dimension 35 x 35 x 1m$^3$. The equivalent capacitances are calculated and w.r.t figure (a)

C1=330pF  
C2=245pF  
C3=220pF  
C4=245pF

The PSPICE simulated output is:
The results obtained by this particular method have been compared with the results obtained from a C++ program, which is based on field computation results. In a C++ program language following parameters are considered:

- Critical voltage for discharge inception
- Residual voltage for discharge extinction
- Critical voltage for discharge propagation
- Size of the void
- Location of the void within dielectric

The results are compared in terms of angle of inception obtained. It can be seen from the table:

<table>
<thead>
<tr>
<th>Angle of inception by PSPICE (in degree)</th>
<th>Angle of inception by C++</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The results obtained are quite close which validates the model in particular sense.
CHAPTER 4

4.1 CONCLUSION

- From the above simulation model we see that the partial discharge largely depends on the supply voltage, supply frequency, size of the void, upper threshold voltage and the lower threshold voltage.

- From the observations we see that with the increase of supply voltage the angle of inception decreases as the slope of the voltage profile is increased and the PD occurs earlier. Also the average numbers of breakdown rises i.e. the more amount of PD patterns are observed.

- Increase of supply frequency causes more rate of change of voltage profile so the PD patterns occur earlier. Also the average number of breakdown per half cycle increases.

- As the size of the void is small, more amount of voltage is needed for inception of PD patterns as the voltage gets divided into horizontal and vertical components and the vertical components are responsible for the breakdown. So as the void size increases the horizontal component of the voltage decreases and the vertical component increases so PD patterns starts early.

- As the upper threshold voltage rises, the PD patterns starts later as more time is required to reach that high voltage. And PD patterns start earlier when the upper threshold voltage is lower.

- The PD patterns depend on the difference between the upper threshold voltage and the lower threshold voltage. So as the lower threshold voltage is increased keeping the upper threshold voltage fixed, the PD pattern starts later and vice versa.

4.2 FUTURE SCOPE

Here only the PSPICE simulated model is represented. The hardware model can be made and compared with the simulated model. To simulate partial discharge patterns for multiple voids, spherical voids and cylindrical voids. The angle of extinction can be matched with the C++ language.
4.3 REFERENCES

- SPICE: Users guide and reference, edition 1.3 by Michael B. Steer
- High Voltage Engineering by C.L. Wadha
- Partial Discharge theory and applications to electrical equipment by Gabe Paoletti
  Investigation of the Voltage Influence on Partial Discharge Characteristic Parameters in Solid Insulation by P. Valatka, V. Sučila
- High-voltage test techniques – Partial discharge measurements