THE DETECTION OF PARTIAL DISCHARGES IN TRANSFORMER OIL

by

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ABSTRACT

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The level, meaning the number and the intensity of partial discharges that occur in transformer oil per time period of applied pulse when a high voltage is applied can be used as a measure of the quality and remaining life of the oil. The level of partial discharges at a given applied voltage can be correlated with the degree of contamination of the oil by impurities such as water and conductive particles and can be used as an indicator of the proximity of the oil to breakdown. There are several approaches to the detection of partial discharges, e.g., acoustic measurements, electromagnetic measurements, and charge measurements.

In this study, a comparison was made among different types of partial discharge detectors. The radiated radio frequency (rf) emission of the partial discharges in the oil was simultaneously measured with the partial discharge currents detected by a capacitively-coupled detector. The discharges were measured under uniform field conditions and using a sinusoidal voltage of 60 Hz. A second experiment was run in which the currents due to the partial discharges were

measured inductively and compared with those measured by the capacitively-coupled detector. The second experiment was run using an impulse voltage and a nonuniform field geometry. In both experiments, it was observed that the detector with capacitive coupling had greater sensitivity than either of the other two systems.

A discussion of the reasons for the differences in sensitivity along with a comparison of other discharge detection methods is included.

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CHAPTER I.

INTRODUCTION

The prevention of electrical failure in power transmission and distribution systems is essential to avoid the interruption of service. Power transformers usually fail when the insulation system becomes conductive and allows large currents to pass between conductors which may induce other failure modes. There are several mechanisms that contribute to the failure of the insulation system as a whole, but this thesis will focus on the transformer oil, which is used for the dual purposes of insulating and cooling the coils in the transformer. Initially, the transformer oil is a very good electrical insulator, but when the transformer is energized, the oil and other insulating elements are subjected to great electrical and thermal stresses. The oil goes through heating and cooling cycles and is exposed to voltage stresses in the 10^3 to 10^6 volt range. These processes have a degrading effect on the liquid causing decomposition or aging of the oil with the resultant formation of gases and other conductive species. The presence of gas and contaminants reduces the insulating quality of the oil and if the contamination becomes large enough, it leads ultimatly to failure of the oil in a process known as electrical breakdown.

The degradation processes giving rise to breakdown are very long term in nature. A precursor of the total failure of transformer oil is the injection of small quantities of charge into the liquid, in a mechanism referred to as partial discharge or corona. Once in the liquid, these charges are accelerated by the electric field, causing ionization. The reactions of the ions form new chemical compounds which do not have the same insulating properties as the original oil.

There are many approaches to determining the deterioration of the oil. A gas-in-oil analysis analysis can be performed on a sample of the oil to measure the degree of gas formation. Chemical analyses can be made to determine the quantity of chemical contaminants that have been formed. Surface tension and other physical parameters of the oil sample can be measured and compared to their initial values. The sample can be tested to determine the voltage at which it will fail using standard ASTM (American Standards for Testing and Materials) methods. Finally, the magnitude and rate of partial discharges can be measured in the oil sample while it is electrically stressed. Alternatively, and more important, the partial discharge measurements can be performed in situ on the entire oil volume in the transformer. A comparison of the various techniques used for the measurement of partial discharges both in the transformer and in a laboratory sample is the subject of this thesis.

In the next section, background information is provided on the relevant chemical and physical properties of transformer oils along with a description of their use as electrical insulation. A presentation of current theories of the degradation and breakdown mechanisms in transformer oils is then made followd by a discussion of the methods of partial discharge detection and the experimental work carried out in this study. The paper is concluded with a discussion of the relative merits and shortcomings of the individual techniques.

CHAPTER II.

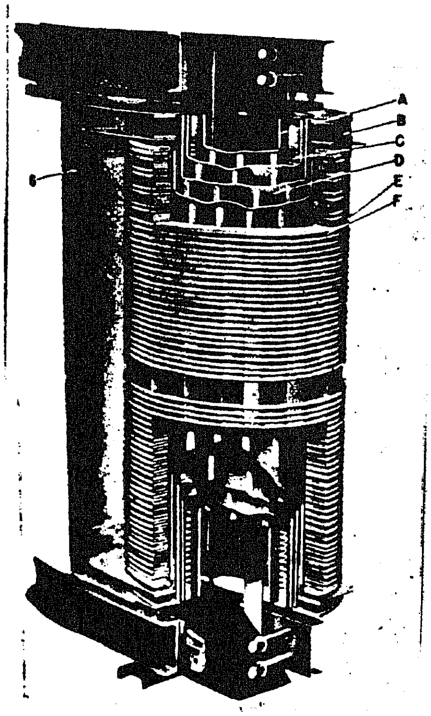
BACKGROUND

Transformer oil is used as as a coolant and an electrical insulator in a typical transformer such as that depicted in figure 1. The transformer consists of concentric sets of coils surrounding the core. The coils are wrapped with paper or fiberglass tape and separated from each other by radial spacers made of pressboard paper, porcelain, glass fabric, or paper-filled plastic laminates. The high or low voltage coils are also insulated from one another by tubes of oil-impregnated pressboard or paper with slots in them to permit oil circulation. The coils and core are housed in a steel-walled tank that is filled with transformer oil.

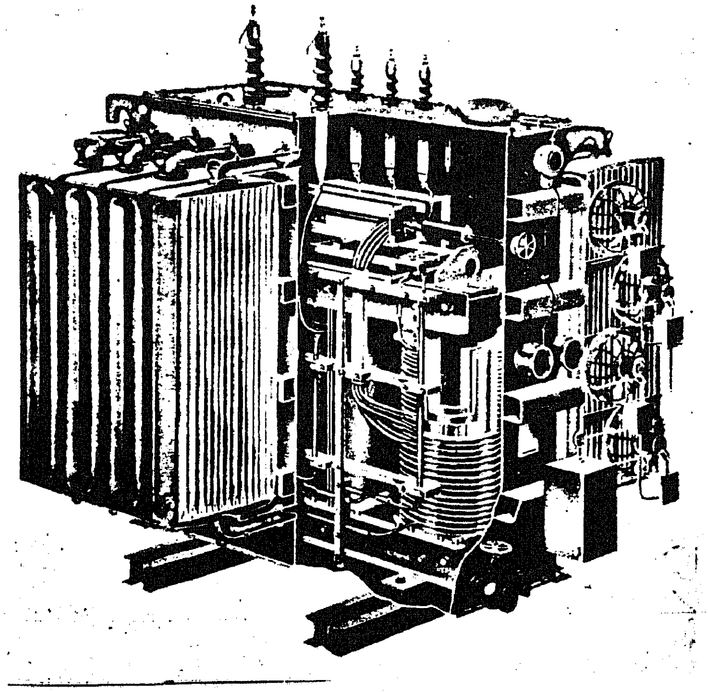
Heat is generated in the coils and core by the currents that are present when the transformer is energized. The heat is transported away from the core by the oil mainly via convective processes. The heated oil flows out of the coils to the walls of the tank where it is cooled by contact with the external environment through the cooling fins of the tank. Some transformers have fans which force air past the fins to enhance the cooling of the oil and to increase the power rating of the transformer. In order to maintain its cooling properties, the transformer oil must flow freely under the operating conditions of the transformer. The oil must remain stable under thermal cycling and must not chemically react with any of the elements of the transformer. The cost must also be reasonable . In addition to the physico-chemical property requirements, the oil must have good electrical properties as it must remain electric-

Figure 1

Core and Windings of a Power Transformer



a) Core And Windings



b) Cutaway View of a Power Transformer

ally insulating under normal operating voltages as well as impulse voltages arising from lightning strokes or switching surges.

Transformer oil is a mixture of different types of hydrocarbon molecules produced from crude oil. The crude oil is divided into fractions through distillation processes according to boiling point ranges of the various components. Transformer oil is a part of the lubricating oil fraction and is composed of three types of molecules : 1) linear chain and branched chain paraffins , 2) cyclical paraffins (naphthenes), and 3) cyclical structures containing carbon-carbon double bonds (aromatics). Transformer oils are categorized as either paraffinic or naphthenic according to their dominant components. Table I gives typical compositions of the two types of transformer oils. The relative percentages of paraffinic and naphthenic components are determined by the source of the crude oil. Despite differences in composition, the physical properties of both types of oil are similar and these values are listed in Table II. Considering the oil as a coolant, the important physical properties are the density, viscosity, cloud point (the temperature at which wax forms), and pour point (the temperature at which the oil no longer flows in a standard test), since these properties are related to the oil's ability to flow freely. If the flow of oil is impeded, the transformer can overheat and form hot spots, and fail through thermal mechanisms. The low viscosity, cloud point, pour point , and low

TABLE I

PERCENTAGE COMPOSITIONS OF TWO TYPES OF TRANSFORMER OIL

	Paraffinic (% composition)	Naphthenic (% composition)
Paraffins	60	20
Naphthenes	25	65
Aromatics	15	15

TABLE II

PHYSICAL PROPERTIES OF TRANSFORMER OIL

Index of Refraction, k	2.1-2.7
Density, 15 C (g/cc)	0.876
Viscosity, 40 C (cSt)	9.48
Cloud Point (°C)	-54
Pour Point (°C)	-54
Sulfur (wt. %)	0.05
Wax Content (-40°C)	0

wax content indicate that the oil will flow freely at operating temperatures in most environments.

The electrical properties of transformer oil are given in Table III. The breakdown electric field strength, E, of the oil is defined as either the crest or rms voltage, V, at which breakdown occurs, divided by the gap spacing :

$$E = \frac{V}{d}$$

The gap spacing, d, is the electrode separation used in the specific test. Several ASTM tests (35-82, 8-81) are used to determine breakdown strength, and the one chosen to test the oil depends on the type of voltage withstand strength to be tested, i.e., impulse or sine wave. The breakdown strength depends on the degree of contamination. A brief description is now given.

ASTM test procedure D3300 (8-81) is followed to test the impulse breakdown strength of the oil. The oil is placed in a test cell such as that shown in figure 2. A steel phonograph needle and a stainless steel ball bearing separated by 1" are used for electrodes. An impulse voltage having a 1.5 µs rise time and a 50 µs fall time to half the crest value is applied and the crest voltage is increased in steps of 5 or 10 kV until breakdown occurs. The breakdown strength determined by this test depends on the polarity of the electrodes. With the needle positive, the strength usually is lower than for the needle negative, as shown in

TABLE III

ELECTRICAL PROPERTIES OF TRANSFORMER OIL

Resistivity, 80 C, (Ω - cm)	10^{13}
Tan δ	.002
Corona inception level (kV)	22.4
AC Breakdown Voltage (kV/")	400
Impulse Breakdown Voltage, Positive Needle (kV/.25")	30
Impulse Breakdown Voltage, Negative Needle (kV/.25")	50

Figure 2

Impulse test cell as specified by ASTM test D3300

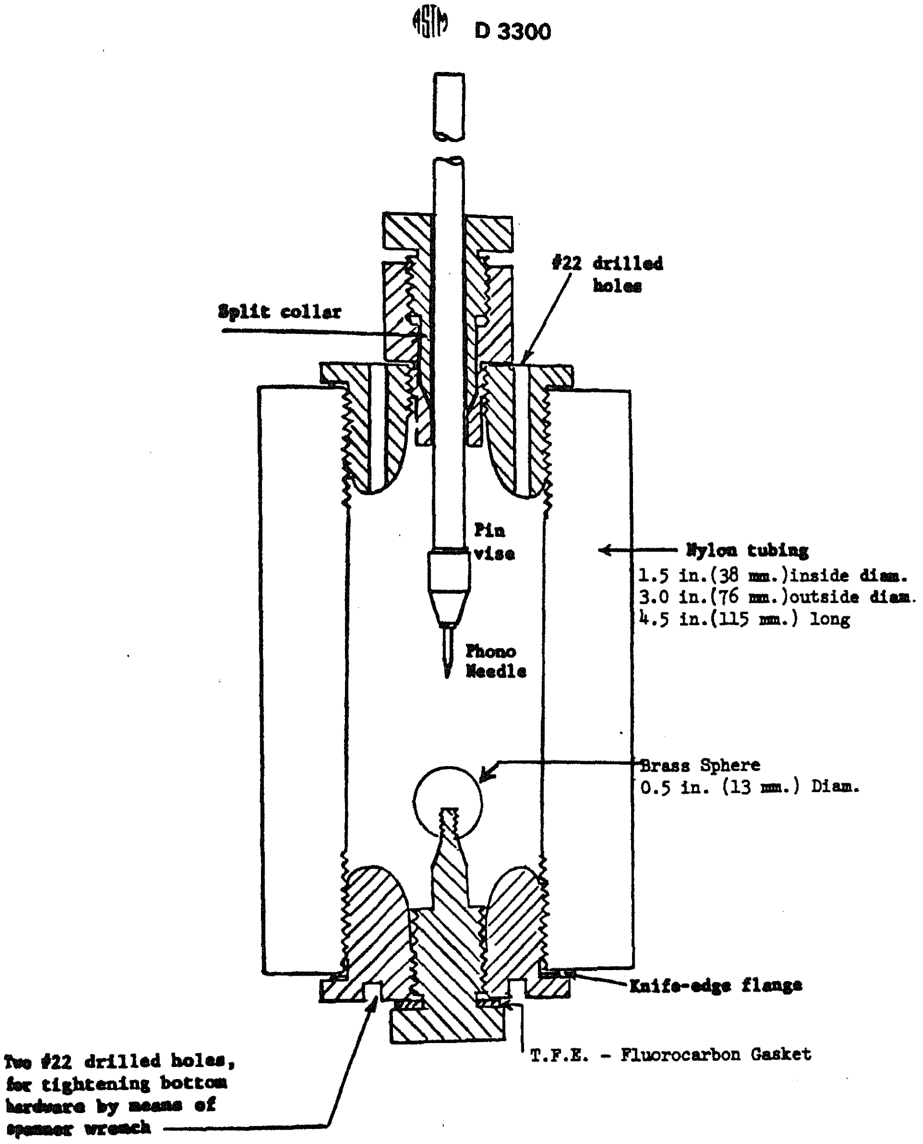


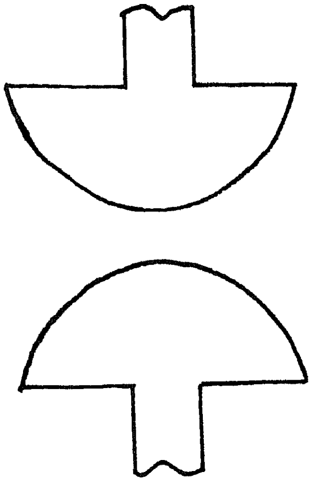
Table III, which also lists the resistivity, tan δ, and corona inception levels for a typical transformer oil. This difference in the voltage at which the oil breaks down indicates that there is a different breakdown mechanism for each polarity.

AC breakdown strength is covered by two other ASTM tests. For very clean oil with a high anticipated breakdown strength, ASTM procedure D1816 (8-81) is used. The test specifies that the oil be placed in a test cup between rounded electrodes that are oriented in a parallel fashion as shown in figure 3a. An alternating voltage is applied and increased at a rate of rise of 500 volts per second until the current exceeds a predetermined value of 0.5 to 5.0 mA.

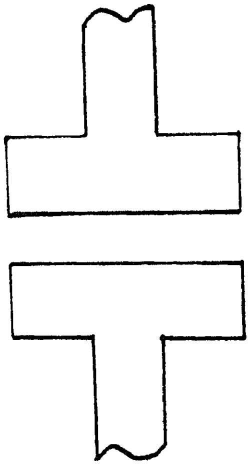
For contaminated oil, procedure D877 (8-81) requires the use of a different electrode configuration as illustrated in figure 3b. The ac voltage is applied in a similar manner to D1816, but with a higher rate of rise of 3 kilovolts per second. The ac breakdown voltages are more sensitive to contaminants in the oil than is the breakdown voltage measured with the impulse test. Another difference between the two is that the impulse strength is lower than the ac breakdown strength for both positive and negative polarities. This is not only due to the difference in the voltage waveforms but is also attributable to the differences in the electric field distributions used in each test. The field in the liquid is nonuniform for the impulse test electrode configuration while it is uniform in the configur-

Figure 3

Electrode Configurations for ASTM Tests D1816 and D877



a) VDE Electrodes for Test D1816



b) Electrodes for Test D877

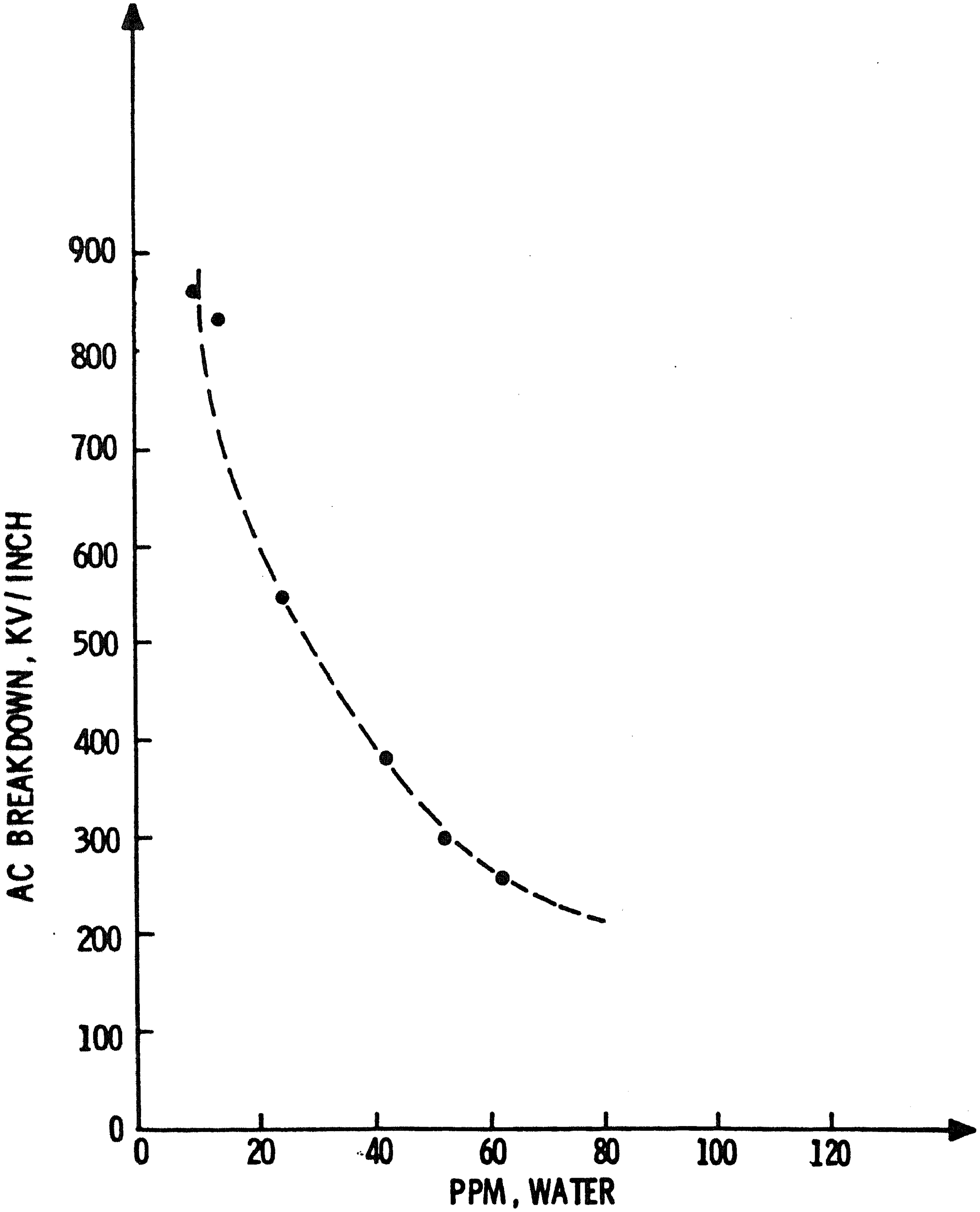
ation of the ac breakdown test. It has been shown experimentally that for the same gap spacing, the breakdown strength under uniform field conditions will be higher than that for nonuniform field conditions in most cases (2-82).

Water has a critical effect on the ac breakdown strength of transformer oil, as shown in figure 4. An increase in water concentration from 20 to 60 ppm causes a reduction in the ac breakdown strength to about one-third of its original value. This figure emphasizes the need to minimize the water concentration in the oil before introducing it into the transformer and also preventing the exposure of the oil to water once the transformer has been filled.

Oxidation is also one of the degradation processes that occur in the transformer in service. Oxygen causes chemical reactions with the oil at high temperatures. Although exposure to oxygen in the transformer is minimized and the oil is dried, degassed, and nitrogen filled instead of air, some oxygen is always present. Oxidation reactions form peroxides, weak organic acids, and water. The water and acids can corrode metal surfaces while all three may cause deterioration of the insulation. Oxidation can be retarded through the use of a sealed transformer or by filling the gas space in the larger transformers with nitrogen. Oxidation inhibitors such as di-tertbutyl phenol (DBP) and di-tertbutyl paracresol (DBPC) are used predominantly in sealed transformers placed on poles to be left for years without maintenance.

Figure 4

AC breakdown as a function of water content



Sludge, which is a high molecular weight reaction product of organic molecules, also presents a problem in transformers. It is formed from the molecules that have been ionized by partial discharges. It precipitates at the coils and walls and reduces the flow of oil. In extreme cases, the flow of the oil is impeded so that the transformer eventually fails completely.

CHAPTER III.

THEORY OF PARTIAL DISCHARGES

The partial discharge is the first step in a sequence of events leading to complete insulation failure. Originally, the insulation failure was believed to be a runaway ionization process. Today, photographic evidence has shown the details of the mechanisms of partial discharges and electrical breakdown (4-83, 4-82, 11-81, 4-81). These studies have used a high-speed image converter camera to obtain a series of photographs that show the initiation and development of partial discharges. These events are described in the following paragraphs.

In the case of a metal in contact with a liquid, the tendency is to reduce the free electron concentration in the metal by injecting electrons from the metal into the liquid, where, unlike the metal, in good insulating oil there are virtually no free electrons. This injection process occurs even in the absence of any externally applied electric field and provides the liquid with several free electrons. Upon the application of an external electric field, a force acts on the charges and their resultant motion causes the formation of low density oil regions. It is the presence of these low density regions which facilitates further charge injection and thus the initiation of a partial discharge. The field-induced charge injection occurs at optimum sites on the interfaces between the liquid and metal surfaces, such as the walls of the transformer tank or the surface of conductive particles in the oil, or at the interfaces of the liquid and an insulator such as the wires of the transformer coils. For the latter to occur, a conductive path through the insulator must be established to allow the transfer of charge from the metal windings to the oil-paper interface. Although the transformer is designed to avoid any large field gradients, the microscopic roughness of the interfaces alter and enhance the electric field at certain points on these surfaces. Thus, the electric field is locally increased and thereby facilitates the charge injection.

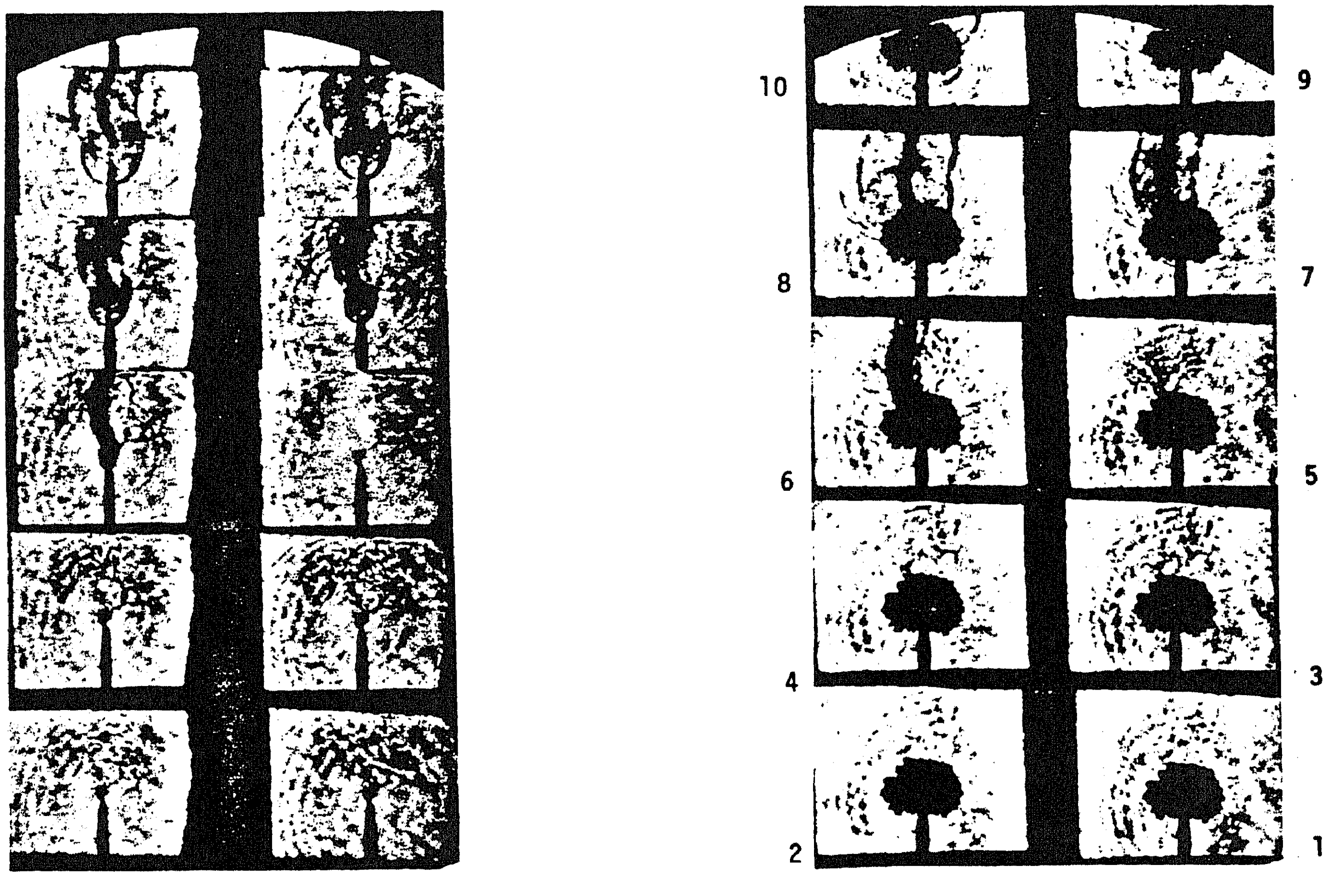
The formation of these low density regions by the movement of electrons in response to the applied field is necessary for partial discharges to occur. In a solid insulation, partial discharges occur in gaseous voids trapped within the dielectric. The constant bombardment of the inside surfaces of these voids causes ionization and the degradation of the insulator. Eventually, cracking can occur and a conductive path may be formed through the solid. Similarly in a liquid, the acceleration of the electrons also causes ionization to occur with subsequent production of more free electrons. These charges cause further expansion of the low density region, which in turn increases charge injection and ionization, and finally an ion-filled, highly conductive path bridges the conductors.

There are two processes that occur in partial discharges depending upon the polarity of the interface at which the partial discharge initiates. The initiating mechanism is believed to be the same in both cases : electrons already present in the liquid are accelerated by the field causing ionization and the creation of a low density region. In the case where the initiating surface is of positive polarity, as shown in figure 5a, the electrons are drawn from the liquid into the surface, leaving behind a low density region of predominantly positive ions. This positive ion cloud acts as an extension of the interface into the liquid and further ionization occurs at the tip of this positive streamer. The free electrons are conducted from the tip of the streamer back to the point of initiation. The resultant structure, as seen in the figure consists of a large number of finely separated branches which form a hemispherical bush-like shape. This streamer grows at a fairly constant rate of the order of 10^5 cm/s (43-78) and, in small gaps of the order of 2-3 mm, traverses the gap to cause complete breakdown.

The partial discharge mechanism is different for the negative polarity case, an example of which is seen in figure 5b. Here, once the low density region is formed, the electrons are injected from the interface into the liquid causing further ionization and growth of the discharge channel. The final shape is not quite as symmetrical or dense as it is in the positive polarity case. The branching is not so closely spaced either and the growth is erratic rather than constant. In small gaps, the streamer does not necessarily traverse the liquid, but it can stop growing before completing the path between the conductors and eventually it can dissipate into tiny bubbles.

Figure 5

Impulse Breakdown in Non-uniform Field Geometry



a) Positive Point

b) Negative Point

The experimental evidence of the factors that influence breakdown in insulating liquids can be understood in light of the two mechanisms that have just been described. At reduced ambient pressure, the breakdown strength of the liquid is lowered (2-51). The lower pressure facilitates the formation of the low density regions so that partial discharges can be initiated at lower applied voltages. As mentioned previously, the breakdown field strength of an insulator is higher for a uniform field geometry than for a nonuniform one (2-82). The reason for this is that although the low density regions are still formed upon voltage application, the local field enhancement, and hence charge injection at the interface is greater under nonuniform field conditions than for uniform field conditions. Thus, a higher applied voltage is required to achieve the same charge injection in a uniform field.

The breakdown strength of the oil is lowered by the presence of contaminants (2-82), of which there are four basic types in transformer oils : 1) gas bubbles and particles (dust, copper, and cellulose) that are present when the transformer is filled with the oil, 2) gas bubbles and particles that are produced by partial discharges, 3) water, and 4) additives to the oil such as oxidation inhibitors. The ac breakdown strength of the oil is affected more by the presence of particles than is the impulse strength. The ASTM tests described in the previous section recognize the effect of particles on the breakdown strength by requiring that the oil be changed after each breakdown. Gas bubbles present in the oil lower its breakdown strength and although the oil is degassed before it is introduced into the transformer, gas is produced by partial discharges. Water is another contaminant that lowers the breakdown strength of the oil as demonstrated by figure 4. Particles also provide initiation sites for partial discharges as well as distort the electric field near the interfaces and enhance the discharges there. They also can cause discharges when making and breaking contact with metal or insulator surfaces. To reduce the effects of these contaminants, the oil must be degassed, dried, and filtered before use and then regularly maintained.

Some components of the oil have stabilizing effects on the partial discharges. The aromatic compounds that are present in the oil can accomodate free electrons and form stable ions. The aliphatic compunds, which are the principal components of the oil , have a tendency to form gases when subjected to partial discharges, and thus lower the breakdown electric field. Spectral evidence of the light emitted from partial discharges and during breakdown indicate that the same processses occur in both of them. Chemical bonds are broken and new bonds are formed from the ionized species which create contaminants having electrical properties that are different from those of the original oil. Major byproducts of partial discharge activity are methane, ethane, propane, butane, which are all gases, and graphitic structures, which are conductive particles. They, in turn, increase the intensity of partial discharges and cause the production of more contaminants. The partial discharge intensity is therefore a measure of the quality of the electrical insulation. As a precursor of complete insulation failure, it can be used to indicate the proximity to breakdown. The detection of partial discharge energy in its different forms is discussed in the next section.

CHAPTER IV.

EXPERIMENTAL METHODS

Partial discharges have several different types of energies associated with them. The major types of energies of partial discharges and the techniques used for their detection are now discussed.

1) Acoustic detection. Acoustic waves are generated by the expansion of the low density region formed by the partial discharge. The shock waves have frequency components from the subsonic range ($<$20 Hz) to the ultrasonic range ($>$ 20 kHz). Acoustic measurements have been found to be useful for partial discharge detection in oil-filled transformers, where the transducer can be either placed directly into the liquid or attached to the transformer tank walls. The transducers that are used usually have narrow bandwidths in the ultrasonic range, near 40 kHz.

Detection of partial discharges in air using transducers at a distance of one meter from the discharge source could detect pressure pulses having amplitudes of $\sim$.01 μbar (23-79). The discharge pulses had an equivalent charge magnitude of about 20 pC (10^{-12} C). The lower discharge limit for which acoustic pulses could be detected was estimated to be 5pC.

Although attenuation of the acoustic pulses in air is greater than it is in transformer oil, when the transducers are mounted outside the transformer tank wall, the acoustic pulses must pass through both the oil and the wall before they can be measured. The sensitivity of the measurement is usually determined by the degree of the reflections at the oil-metal interface for which the reflection coefficient, R_o , is defined as :

$$R_o = \frac{\rho_1 c_1 - \rho_2 c_2}{\rho_1 c_1 + \rho_2 c_2}$$

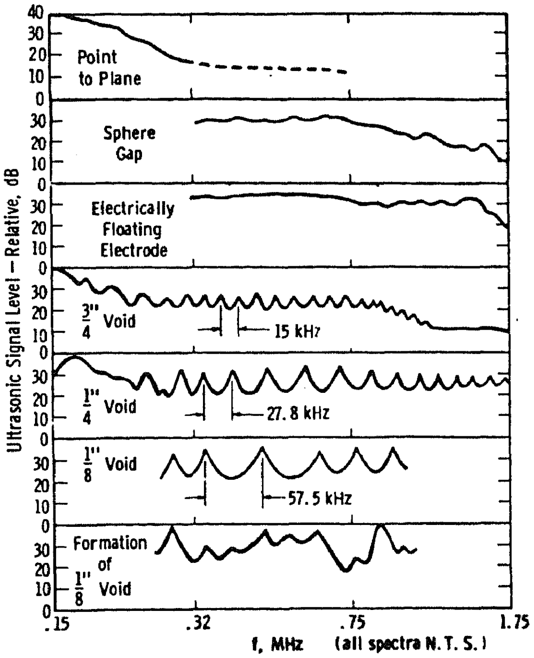
where ρ_i is the density of medium i, and c_i is the speed of sound in medium i. The product ρc is known as the acoustic impedance of the medium. For an acoustic wave going from the oil to the metal tank, the reflection coefficient is .89. Since this means that only 11% of the incident energy is transmitted to the tank wall, much of the acoustic energy is lost at this interface. If the thickness of the metal wall is about one-half the wavelength of the transmitting frequency, the percentage of incident energy that is transmitted can be much higher. In addition to the energy lost through reflections at the wall, the sound wave is also attenuated in the oil. The attenuation has been found to be inversely proportional to r, the distance from the emitting site.

Typical acoustic spectra for partial discharges in mineral oil are shown in figure 6 (3-79). Unlike the spectra for partial discharges in voids in solid dielectrics, there are no distinguishing features for the spectra in mineral oil. The spectra for discharges in solid dielectrics has distinct peaks where the increment in frequency between peaks is related to the void size.

One of the disadvantages of acoustic measurements

Figure 6

Ultrasonic Spectra for Discharges in Mineral Oil



(3-79)

is that the measured amplitude of the pressure pulse varies considerably even though the magnitude of the discharge is constant. Harrold (3-79) has found that acoustic pressure varies by as much as ten to one for constant ac discharges in mineral oil. The acoustic pressure measured in the 100 to 300 kHz frequency range has been found by Ogihara (4-64) to be proportional to the square root of the magnitude of the discharge.

High energy discharges have been found to have acoustic spectra peaks in the 120 Hz to 2000 Hz range in air and microdischarges show spectral peaks in the 20-40 kHz range. Partial discharge spectra in mineral oil , however , show the largest magnitudes in the 10-20 kHz range regardless of the charge magnitude (3-79).

Acoustic detectors have the advantage of being less susceptible to electrical noise than other types. These partial discharge detectors are therefore suited for environments such as substations near EHV power lines. Also, through the use of an array of microphones outside of the transformer, the partial discharges occurring within the transformer can be located with reasonable accuracy.

2) Optical detection. Partial discharges can also be detected optically (4-83, 4-82, 3-82, 6-80, 3-77) but, in general, optical detection schemes are best suited for idealized systems in the laboratory. A photomultiplier tube can be used to detect the light emitted from the partial discharge, but recently the development of partial dischar-

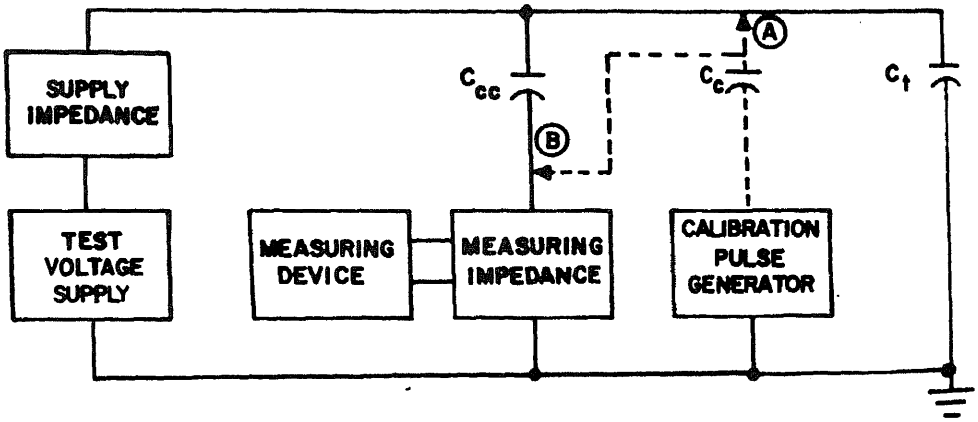
ges can be monitored with high speed photograhic techniques using laser illumination as figures 5a and 5b show. The optical techniques provide the fastest resolution, but can only be used in the controlled environment of the laboratory.

3) Charge detection. The most commonly used partial discharge measurement method is the charge measurement appraoach (8-82, 5-82, 6-82, 12-81, 13-81, 2-80). This technique makes the system under test a part of the measurement circuit and detects the currents caused by the partial discharges. Ther are essentially two types of charge measurement detectors : the straight type of detector and the bridge type of detector.

a) Straight type detector. The straight type of detection is shown in figure 7. Here the detector is placed in series or in parallel with the system to be tested and is capacitively coupled to the insulation system. The radio influence voltage (RIV) is the voltage that appears at the terminals of the insulation under test. For RIV tests, the detector has a relatively narrow bandwidth of 9 kHz that is centered at about 1 MHz, which is approximately the midpoint of the AM broadcast band. RIV measurements are made in units of microvolts quasi-peak (μVQP) as determined with an RIV meter. Partial discharge meters, on the other hand, measure the response of and inductive-resistive-capacitive (LRC) or resistive-capacitive (RC) circuit to the partial discharge. This measurement is made with a broad band amplifier in the frequency range from 15 kHz to 300 kHz. The meter is cali-

Figure 7

Straight Detection Circuit



(6-82)

brated by using a square wave generator to inject a known quantity of charge into the circuit at the same point as the test specimen. The output of the detector can be displayed on an oscilloscope. The straight detection method is described by ASTM test D1868 (6-82). The test covers measurement of partial discharge levels by use of either a peak-reading voltmeter or by reading the peak discharge level directly from the oscilloscope trace. The average discharge current can be found by dividing the sum of the discharges occurring in a time interval T, by the interval. The apparent power loss is then the product of the average discharge current and the RMS voltage. The partial discharge meter is used to find the current inception voltage (CIV) and the current extinction voltage (CEV). The CIV is the voltage at which partial discharges occur consistently in every cycle as the voltage is increased. The CEV is the voltage at which partial discharges no longer occur consistently as the voltage is lowered. The CEV is usually considerably lower than the CIV so that although operating below CIV, a sudden voltage surge may initiate continuous discharges that are not extinguished until the voltage falls below the CEV again. The CIV and CEV together determine safe operating voltages for an insulation system and they can also be used as indicators of any chemical or physical changes in the dielectric while in use.

<u>b) Bridge type.</u> The second type of measurement of electrical energy of partial discharges is the bridge tech-

nique of ASTM procedure D3382 (6-82). Typical bridge circuits used in this technique are shown in figures 8a and 8b. There are two approaches to the bridge measurement, namely the balanced method and the unbalanced method.

i) Balanced bridge. The first approach balances the bridge to determine the capacitance, C, and the dissipation factor, tan δ , of the test specimen at a voltage below the CIV level, that is, in the absence of any partial discharges. The voltage is the raised above the CIV level and the bridge is again balanced. The power loss due to the partial discharges is then calculated using :

$$P = \omega V_2^2 (C_{x_1} \tan\delta_2 - C_{x_2} \tan\delta_1)$$

where ω is the angular frequency, V_2 is the higher voltage (above the CIV level), and the subscripts 1 and 2 represent the measurements made below and above the CIV respectively. The change in dissipation factor,

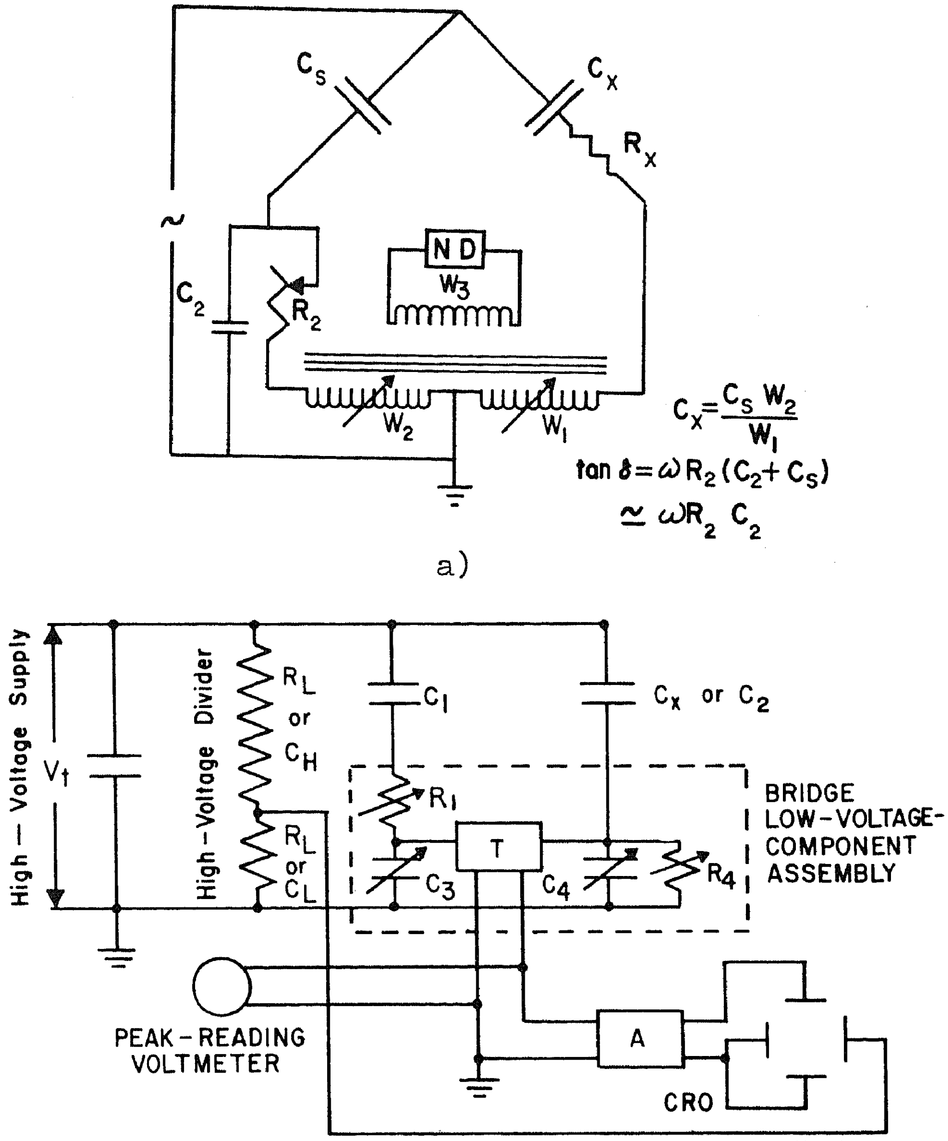
$$\Delta \tan\delta = \tan\delta_2 - \tan\delta_1$$

can be used as an index of partial discharge intensity.

ii) unbalanced bridge. The second bridge method is the unbalanced approach. The bridge circuit is balanced at an applied voltage below CIV. The voltage is again raised above the CIV but the bridge is not rebalanced as in the first case. Instead, the unbalanced voltage of the bridge is displayed on the oscilloscope. An illustrative trace is shown in figure 9. The integrated charge per half-cycle can be calculated from this trace once a calibration has been

Figure 8

Bridge Circuits



$$C_X = \frac{C_S W_2}{W_1}$$

$$\tan\delta = \omega R_2 (C_2 + C_S)$$

$$\simeq \omega R_2 C_2$$

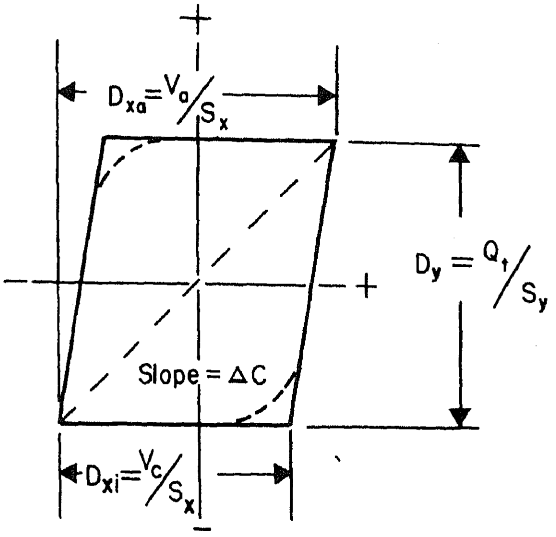
a)

b)

(6-82)

Figure 9

Bridge Circuit Oscilloscope Trace



V_c = discharge inception voltage peak to peak
V_a = applied voltage peak to peak
$D_y S_y$ = Q_t coulombs per half cycle
$S_y S_x A$ = W joules per cycle
A = area = $D_{xi} D_y$
ΔC = slope = $C_x' - C_x = D_y S_y / D_{xa} S_x$

(6-82)

made using the following :

$$Q = D_y S_y$$

where D_y is the vertical displacement shown in figure 9, and S_y is the system's sensitivity calibrated in coulombs per centimeter. The average energy in joules per cycle can be found from :

$$W = D_{x_i} D_y S_x S_y$$

where D_{x_i} is the horizontal displacement of the figure and S_x is the calibrated system sensitivity.

Of these two types of partial discharge detection schemes, the straight type of detector is more commonly used because the individual corona pulses can be monitored. Many high voltage test systems come with the straight type of detector as a standard item.

4) Electromagnetic detection. The radiated partial discharge radio frequency (rf) energy can be measured with an antenna and amplifier. This approach is useful where direct coupling of the detector circuit to the insulation system is not practical, such as for the measurement of discharges from overhead transmission lines.

CHAPTER V.

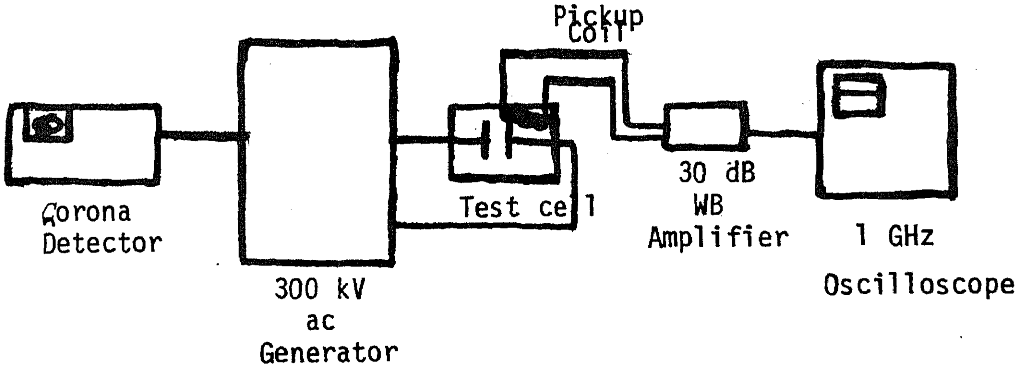
EXPERIMENTAL MEASUREMENTS PERFORMED

Measurements of partial discharges were made using two different experimental setups. The first set of measurements used an alternating high voltage and partial discharges were simultaneously recorded using a capacitively coupled detector and a radio frequency (rf) detector. The second set of measurements used an impulse voltage and the partial discharges were picked up by a current transformer.

AC Measurements. The setup used in this experiment is shown in figure 10. A Hipotronics 300 kV ac generator, model 7300 was used to apply a high voltage to the test cell which was an open plastic cup having two high voltage feedthroughs terminated in parallel plane electrodes of the type illustrated in figure 3b. The test cup was constructed according to the specifications of ASTM test D877. The cup was filled with Exxon Univolt 60 transformer oil and a copper coil was immersed into the oil and positioned near the electrode gap, which was set at 2.54 cm. The oil was used as received without any special purification. The pickup coil was connected by a 50Ω coaxial cable to a Sencore model WBA52 30 dB gain amplifier. The bandwidth of the amplifier extended from 10^6 Hz to 1.3×10^9 Hz and the amplifier output was connected to a Tektronix 7604 oscilloscope having a 500 MHz bandwidth. A commercially-available discharge detector, Hipotronics mode CDO-77A, was capacitively coupled to the test cell to make simultaneous measurements of the partial discharges. This detector had a discharge sensitivity of about 1 picocoulomb (1 pC = 10^{-12} C) and

Figure 10

Pickup coil-oscilloscope partial discharge detector setup



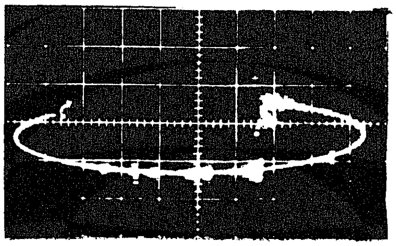
displayed the partial discharges on an elliptical loop where the position of the discharges on the loop corresponds to the phase of the applied ac voltage. The Hipotronics detector had a high gain amplifier with a band extending from 1 kHz to 500 kHz. It also had a peak-reading voltmeter and the peak discharge level was displayed on a digital readout.

The high voltage was applied at the 25 kV level and increased in increments of 10 kV up to 55 kV. Typical oscilloscope traces are shown in figures 11a and 11b. Figure 11a shows the output of the Hipotronics detector at 35 kV applied voltage. Discharges can be seen at several points along the trace on both the positive and the negative cycles. As seen in figure 11b, the trace from the pickup coil detector showed very few discharges, even at the greatest sensitivity of the oscilloscope. The Hipotronics corona detector measured peak discharge levels of between 30 and 150 pC at applied voltages below breakdown, and levels of 300 pC were measured just prior to breakdown.

Impulse measurements. The second detection scheme used an impulse voltage generator, as illustrated in figure 12. A Pearson current transformer having an output of .1 volt per ampere was inserted on the ground side of the test cell, which consisted of one spherical electrode and one needle electrode contained in a plastic case. The test cell was made according to specifications for ASTM test D3300, with a typical cell being shown in figure 2. The current

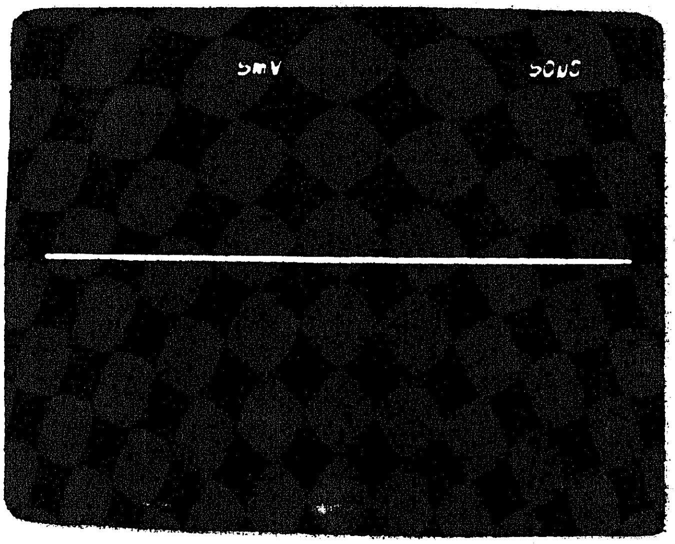
Figure 11

Typical Oscilloscope Traces



a) Partial Discharges Detected by Hipotronics Corona Detector

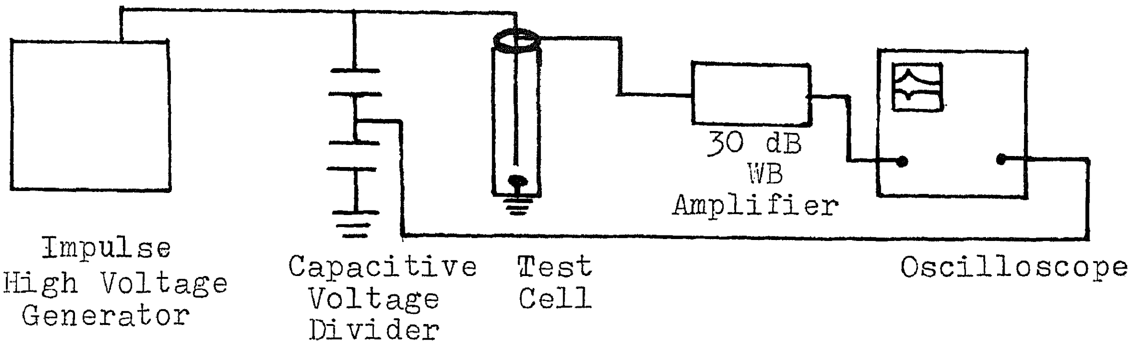
35 kV Applied Voltage



b) Partial Discharges Detected by Pickup Coil-Oscilloscope Setup

Figure 12

Partial Discharge Detection Setup with Impulse Voltage Generator



transformer was connected to a Phillips model PM550 oscilloscope with a bandwidth of 60 MHz through the 30 dB Sencore amplifier used in the previous experiment. The applied impulse voltage had a crest value of 160 kV and a rise time of 2 us. The test liquid for this experiment was Exxon Marcol 52, which is a highly refined mineral oil. The applied crest voltage was increased on successive impulses from 160 kV to 200 kV in 10 kV increments while both the high voltage waveform and the current transformer output were simultaneously measured and displayed on the oscilloscope. The oscilloscope and amplifier together had an estimated lower detection limit of about 20 μV (10^{-6} volts), which corresponds to a discharge current of about .2 mA. The total charge dissipated is found from the following calculation, which assumes a pulse duration of one microsecond:

$$.2 \text{ mA} = 2 \times 10^{-4} \text{ C/s}$$

$$2\text{x}10^{-4} \text{ C/s} \times 10^{-6} \text{ s} = 2 \times 10^{-10} \text{ C}$$

$$2\text{x}10^{-12} \text{ C} = 200 \text{ pC}$$

The lower detection limit of 200 pC estimated for the current transformer is about two orders of magnitude higher than that of the Hipotronics corona detector used in the first experiment, which had a lower detection limit of near 1 pC.

Using the current transformer detection setup, the output of the current transformer and the high voltage waveform were displayed simultaneously on the oscilloscope. From the current transformer output, the charging current was seen to follow the applied impulse voltage. There were also small "spikes" present on the current trace, but they were of such small magnitude that they were not clearly identifiable as partial discharges. The significance of these results is discussed in the next section.

CHAPTER VI

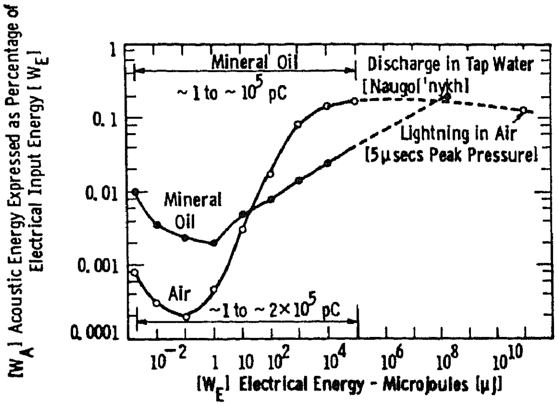
SIGNIFICANCE OF EXPERIMENTAL RESULTS

As discussed previously, partial discharges in transformer oil have several forms of energy associated with them. Figure 13 shows graphically the acoustic energy of a partial discharge as a function of the total energy of the discharge in mineral oil. The acoustic energy can be seen to vary from .1% to 4% of the total energy from .01 μJ (10^{-8} joules), which corresponds to a 1 pC point discharge in mineral oil, to 10^4 μJ, which is a 10^5 pC discharge. Thus, the amount of energy capable of being measured by acoustic means is at most a few percent of the electrical energy. After attenuation in the oil and reflection at the tank wall, the acoustic signal is reduced even more. Harrold (3-79) had estimated that this attenuation reduces the signal to about one-tenth of its initial value. However, he also has shown that at a distance of 1 meter from a 1 pC discharge in mineral oil, the measured acoustic signal is 6 μVQP, which compares favorably with an average value of .5 μVQP from electrical pulse measurements of discharges in transformers. It can still be seen that the acoustic technique is adequate for the detection of fairly large discharges in transformers.

As reported in the previous section, the current transformer setup can only detect the much higher discharge levels that occur at voltages very near to breakdown than those that can be detected by the capacitive corona detectors. The other detection technique, that uses the pickup coil, has two major disadvantages when compared with the capacitive detectors : it requires two or more energy

Figure 13

Acoustic Energy as a Function of Total Discharge Energy



(3-79)

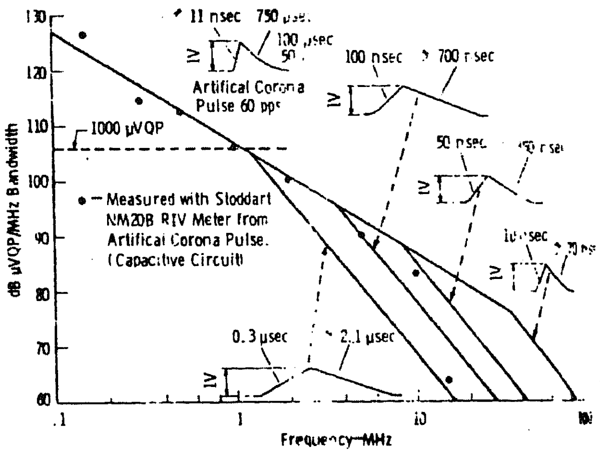
conversions, and it detects different frequency components of the emitted energy of the discharge.

Energy conversion. The first major disadvantage involves energy conversion. For radio frequency (rf) emission to take place, the electronic energy must be first converted to electromagnetic energy. The electromagnetic energy must then be detected by the coil antenna, but this requires the conversion of the electromagnetic energy back to electronic energy in the coil. Since energy conversion is not 100% efficient over the whole frequency range, there is less energy available for detection than if there were no energy transformations, as in the case of the capacitively coupled circuits. These circuits are connected directly to the test cell and, therefore, detect the partial discharge currents whithout any energy transformations. It is not surprising then that the sensitivity is greater for the latter than for the pickup coil antenna.

Frequency component sensitivity. The second major disadvantage of the pickup coil is that of detecting different frequency components of the emitted energy of the discharge. The calculated frequency spectra for several partial discharge pulses having different rise and decay times, but of constant pulse height, are shown in figure 14. For all the pulses shown, the magnitude of the components in the frequency range covered by the Hipotronics corona detector, 1 kHz to 500 kHz, are significantly larger than those in the frequency range covered by the pickup coil system, which is

Figure 14

Calculated Frequency Spectra of Partial Discharges of Various Pulse Shapes



in the 1 MHz to 500 MHz range. Only a pulse of larger peak amplitude has the necessary energy required to have components in the frequency range that the pickup coil system is sensitive that have magnitude equal to the components in the lower range of pulses having smaller peak amplitude. Thus, the pickup coil detection system was much less sensitive to the smaller discharges than the corona detector.was.

CHAPTER VII

CONCLUSIONS

As shown in chapters five and six, the capacitively coupled detector has some advantages over both the pickup coil and the current transformer detectors, with the former having a much greater sensitivity than the latter two. The reasons fore this are essentially twofold : first, the capacitor coupling allowed for more direct measurement and second, it measures energy components of the discharge that are of greater magnitude than either the coil or the current transformer. Thus, it appears that the capacitively-coupled device is more suited for detection of partial discharges for the evaluation of the electrical quality of transformer oils than the other two methods.

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