Several factors may cause the breakdown voltage to be lower than predicted from Figure 1.8: The walls of the cavity may be covered by static charges, either produced when the cavity was formed or left after previous discharges; it may cause up to 20 per cent variation. Semi-conducting layers may occur on the walls of the cavity, more or less short-circuiting the cavity. This may cause a considerable increase of the stress at which the cavity breaks down [C4]. The effect of these semiconducting layers will be discussed later.

INCLUSIONS. In extruded plastics or cast resin insulation various inclusions can occur. Such inclusions may consist of dirt, paper or textile fibres, and other foreign particles. Depending on the kind of plastics used the foreign bodies are more or less impregnated by the plastics and inclusions of reduced strength are formed. After breakdown of the inclusion, gas is formed and gas discharges occur. The breakdown voltage is presumably lower after the first breakdown. Gooding and Slade [I1] observed that metal splinters may cause discharges even if they are well imbedded in the dielectric. It is assumed that at the sharp edges of the splinter a local field concentration takes place so that the breakdown strength of the dielectric is attained. A small amount of insulating material breaks down and a gas-filled cavity is formed.

OIL-FILLED CAVITIES. Cavities filled with oil occur between layers and in butt gaps of oil-impregnated paper insulation such as in transformer windings and in cables. The stress in an oil-filled cavity can be calculated in a way similar to that of the gas-filled cavity. The most frequently occurring case is a cavity which is flat in a direction perpendicular to the direction of the electric field. Then the stress in the cavity is $\epsilon_2/\epsilon_1$ times as large as in the dielectric, where $\epsilon_1$ is the dielectric constant of the oil and $\epsilon_2$ that of the solid dielectric. If the cavity is spherical the ratio is $(3\epsilon_2)/(\epsilon_1+2\epsilon_2)$, and if the gap is long and flat parallel to the electric field the ratio is 1. The breakdown stress of oil is not so well known as that of gas. It is strongly dependent on contamination and the amount of dissolved gas. It also depends on the kind of oil. Some information can be found in the CIGRÉ report of de Vos and Vermeer [A10], who studied the breakdown of oil between dielectric walls. If the oil breaks down gas bubbles are produced and gas discharges occur in these bubbles. As a liquid is able to absorb gases, balance is reached between the formation of gas by discharges and the absorption of gas by the liquid. As a consequence the discharges either extinguish, increase, or become stable.



### 2.2. *Internal discharges at a.c. voltage*

ANALOGUE CIRCUIT. The behaviour of internal discharges at a.c. voltage can be described conveniently with the analogue circuit of Figure 1.9 [A1, B1, B2, C1]. The capacity of the cavity is represented by capacitor c, the capacity of the dielectric in series with c by b. The rest of the sample is represented by a.

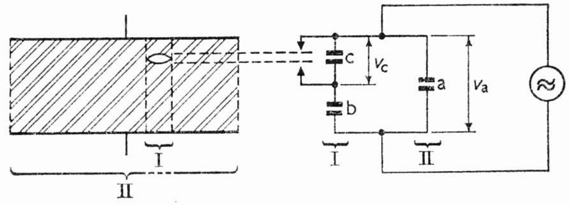



Figure 1.9. *Representation of a cavity in a dielectric: I corresponds to the faulty part of the dielectric; II corresponds to the sound part of the dielectric*

RECURRENCE OF DISCHARGES. In Figure 1.10 the high voltage across the dielectric is denoted $v_a$, the voltage across the cavity is $v_c$. When this voltage $v_c$ reaches the breakdown voltage $U^+$ a discharge occurs in the cavity; $U^+$ is given by the Paschen curve. The voltage then drops to $V^+$ (usually less than 100 V) when the discharge extinguishes. This voltage drop takes place in less than $10^{-7}$ sec [A1, A3]; this is extremely short compared with the duration of a 50 c/s sine-wave so that the voltage drop

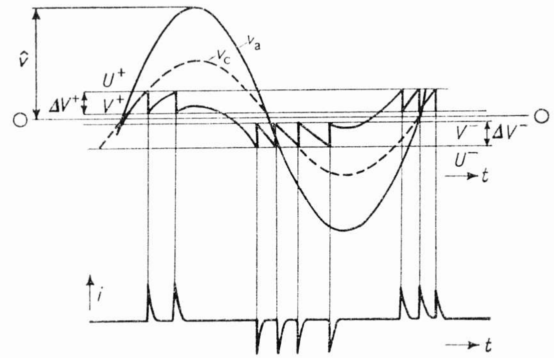



Figure 1.10. *Recurrence of internal discharges*

It depends on small effects such as sharpness of the electrode, moisture, surface conditions, etc.

(6) Discharges recur quite regularly during each half-cycle of an a.c. voltage. If the discharge impulses are displayed on an oscilloscope with appropriate time-base they are seen as fairly stationary groups of discharges. In some cases the discharge pattern is characteristic for the kind of discharge, such as discharges adjacent to an electrode, surface or corona discharges.

(7) The magnitude of a discharge is defined by the amount of charge transferred in the leads of the sample. The discharge magnitude $q$ is related in a simple way to discharge energy $w$ and inception voltage $V_i$: $w \simeq 0{\cdot}7qV_i$. The magnitude of internal discharges increases with increasing cavity dimensions.

(8) According to Mason the deterioration of dielectrics generally takes place in three stages. At first the attacked surface is uniformly eroded; then pits are formed (in case of internal discharges at the periphery of the cavity); after that sharp channels are formed which lead to breakdown (treeing). The rate of deterioration is proportional to frequency, increases strongly with stress, and depends on the kind of dielectric.

(9) In order to determine the discharge resistance of insulating materials several test methods have been devised. With most methods surface discharges are used. The tests are accelerated with higher stresses or higher frequencies. Tables have been drawn up in which the insulating materials are placed in order of succession of their discharge resistance. However, these Tables do not prove to be valid under all circumstances, and differences exist between the results of different methods.

(10) It is believed that discharges below a certain magnitude are harmless to the dielectric. This limit is called the permissible discharge magnitude; it is strongly dependent on the stress at which the dielectric is operated. Some estimations of this permissible discharge magnitude are found in literature; they amount to about 2 pC at 3 kV/mm and correspond to speculations made by the author in Section 6. In these speculations it is assumed that there is a maximum cavity depth which is permissible. The smallest discharge which may occur in a cavity of that depth is calculated and taken as the permissible discharge magnitude. From this point of view not every discharge larger than 2 pC is dangerous but only those occurring in cavities of the critical depth.

CHAPTER 2

# Detection of Discharges

## 1. PRINCIPLES

Discharges give rise to many phenomena which may be used for detection. These phenomena are illustrated as follows:

$$\text{Partial discharges} \rightarrow \begin{cases} \text{Electric phenomena} \begin{cases} \text{Dielectric losses} \\ \text{Electric impulses} \end{cases} \\ \text{Electro magnetic radiation} \\ \text{Light} \\ \text{Heat} \\ \text{Noise} \\ \text{Gas pressure} \\ \text{Chemical transformations} \end{cases}$$

The detection of electric phenomena is most frequently performed, viz., measurement of dielectric losses and detection of electric impulses. The non-electric detection methods are not used so often because they are in many cases less sensitive than the electric ones. Any of these phenomena might be used for detection of discharges at a.c. voltage, d.c. voltage, or voltage surges. This study will, in general, be limited to detection at a.c. voltage only. In all cases attention must be paid to the following aspects.

DETECTION. Detection comprises the determination of the absence or presence of discharges. The voltage at which the discharges appear is determined. All sorts of methods may be used.

MEASUREMENT. The magnitude of the discharges may be measured by means of several electrical methods.

LOCATION. Location comprises the establishment of the place of the discharges. The choice of the method depends strongly on the nature of the investigated object. Noise or light produced by discharges may sometimes be used. With cable cores electrical scanning methods are available.

EVALUATION. Evaluation comprises the assessment of danger involved by discharges. This is a difficult task; even if the magnitude and location of the discharges and characteristics such as field strength and frequency are known, it is difficult to predict the voltage life of the dielectric.

## 2. NON-ELECTRICAL DETECTION

### *2.1. Light detection*

TRANSLUCENT DIELECTRICS. Internal discharges are visible only in translucent dielectrics. The radiation is feeble but may be increased by increasing the frequency of the applied voltage. Whitehead [A1] mentions investigations of Gosden with cores of polythene-insulated cables at frequencies of 0·1 and 2 Mc/s. Light detection has also been used for scanning of polythene-insulated cores. The core under test is passed through water and radiation due to discharges is observed by means of photomultiplier tubes. The set-up is reliable and simple; the sensitivity, however, is limited. Mildner [I4] estimates that the sensitivity is not more than 50 pC. Rogers and Skipper [B8] used photomultipliers for the detection of discharges in polythene samples at d.c. voltage. In this case, where discharges occurred only a few times per hour, the method was particularly useful because the detector was unaffected by spurious discharges at the electrode edges, or by mains interference.

SURFACE DISCHARGES AND CORONA. Surface discharges may very well be detected by means of photography. The sample is placed in the dark-room, and the shutter of the camera is opened for some time during which high voltage is applied to the sample. In addition the sample is illuminated for a short time so that a photograph is obtained on which the picture of the discharges is superimposed on that of the sample. Examples are given in Plate I(a) and (b). The sample is an experimental terminal of a 10 kV PVC-insulated cable tested at a frequency of 50 c/s. The first surface discharges appear at 13 kV; their magnitude is smaller than 3 pC. At higher voltages the discharges increase.

It follows from these tests [A3] that small discharges of the order of 1 pC may be detected. The required exposure time varies with the discharge magnitude. For small discharges below 10 pC an exposure time of the order of 10 hr is required, for discharges between 10 and 100 pC about 3 hr, whereas for larger discharges 1 hr or less is sufficient. The exposure time depends also on the concentration of the discharges. For example, corona discharges concentrated around the point of a needle of the order of 20 pC could be recorded in a few minutes. Furthermore, the sensitivity may be increased and consequently the exposure time decreased by increasing the frequency of the applied a.c. voltage.



A relation between discharge magnitude and brightness or size of the pictures is difficult to establish. The concentration of the discharges, their repetition frequency, and possible motion affect this relation.

### *2.2. Heat detection*

The temperature rise caused by discharges, or more likely caused by a bad dielectric deteriorated by discharges, may be measured. Scanning by hand of a cable or bushing after an overvoltage test is a well-known method. Robinson [A2], for his study of mass-impregnated cables, used thermocouples placed at intervals along the cable sheath. The place and instant of a breakdown could be predicted by the temperature rise preceding breakdown. The method, however, is not sensitive and the magnitude of discharges cannot be measured.

### *2.3. Noise detection*

AURAL. The aural detection of discharges is an old and established method. The 'hissing test' for cables and bushings has long been in use. Austen and Hackett [B2] have investigated the sensitivity of this method. In a certain case where a discharge at 50 c/s was known to be external they obtained a sensitivity of about 40 pC. Stark [F9] found values between 20 and 80 pC for discharges at the surface of bushings.

OIL-IMMERSED MICROPHONE. Anderson [K1] and Beldi made use of an ultrasonic transducer immersed in the oil of a high voltage transformer. The main object of the study has been the detection of discharges at impulse voltage, but discharges at power frequency may be detected as well. Even some location is possible. The sensitivity is restricted by ultrasonic noise caused by magnetostriction in the iron core of the transformer. Moreover, the noise from faults imbedded in the dielectric structure is attenuated. The method does not seem to be sensitive, but unfortunately Anderson does not give an estimation of sensitivity. However, it has the advantage that the measurement is not disturbed by corona or discharges outside the test object. Equipment according to Beldi is commercially available (see also Chapter 4, Section 4).

CONTACT MICROPHONE. When cables are tested good use can be made of the relatively small distance between discharge and surface of the cable. If a contact microphone is placed at the cable surface, attenuated oscillations are found at the location of a discharge. This is explained by the fact that the microphone and the dielectric form an elastic system which responds to the pressure impulse caused by a discharge. The frequency spectrum of the noise shows a maximum at the characteristic frequency of the elastic system. This frequency is approximately

$$f = \frac{1}{2\pi\sqrt{(m/s)}} \qquad \ldots (2.1)$$

where $m$ is the mass of the microphone and $1/s$ is the elasticity of the column of insulating material under the microphone. In practice the

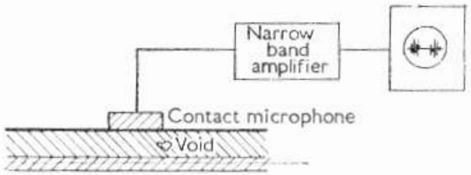



Figure 2.1. *Noise-detection circuit. Narrow band amplifier with variable midband frequency*

characteristic frequency is of the order of 2 kc/s. In order to test the validity of equation (2.1) the author has varied the weight of a microphone [A3]. At four times its original weight the microphone vibrates at a frequency which is about two times lower than the original frequency. This is in accordance with equation (2.1).

In Figure 2.1 a circuit is shown which has been used for conducting experiments on plastic-insulated cables [A3]. A contact microphone is coupled to a narrow-band amplifier which is tuned to the characteristic frequency of the system. The damped oscillations caused by discharges are displayed on the screen of an oscilloscope.

When the contact microphone is moved along the cable the height of the signal on the oscilloscope shows a sharp maximum at the place of the discharge. In Figure 2.2 this is shown. In Figure 2.3 the same is shown when the microphone is moved around the cable. It follows that a sharp location is possible.



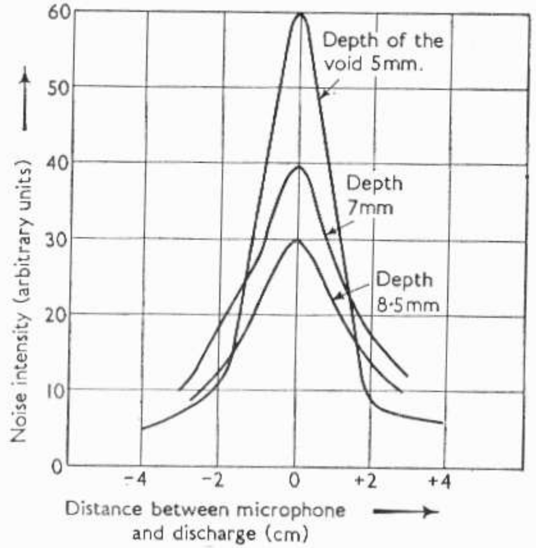



Figure 2.2. *Noise detection: variation of noise signal along a cable*

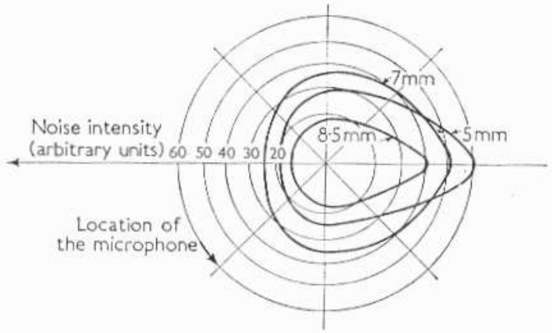



Figure 2.3. *Noise detection: variation of noise signal around a cable*

From these Figures it can also be seen that the signal decreases if the discharge is situated deeper in the dielectric; simultaneously the location becomes less sharp. In different dielectrics such as PVC, polythene, and paper, similar curves have been obtained.

The sensitivity which can be obtained with this set-up has been determined. If the microphone is placed directly upon the core, the minimum detectable discharge may be as low as 5 pC. However, layers of conducting material usually wrapped around the core attenuate the signal heavily. For instance, one layer of carbon-black paper attenuates the signal twofold, while a sheath of lead of about 1 mm thickness may attenuate the signal tenfold. Consequently, a sensitivity of about 100 pC in a finished cable seems to be the best that can be obtained. Alatalo [A9], who mentions a Russian specification for noise detection, comes to the same conclusion and states that the sensitivity is unsatisfactory. A further disadvantage is formed by the disturbances created by the movement of the microphone over the cable surface. This disturbance makes the method impracticable as a routine test.

### 2.4. *Gas pressure*

Kitchen and Pratt [K2] have detected discharges in the air gaps between a cable conductor and the insulation by measuring the air pressure in this gap. Due to the chemical reaction of the activated oxygen with the insulation, the gas pressure decreases as soon as discharges occur. A refined method is obtained by measuring the internal gas pressure of two samples by means of a differential manometer. One sample is stressed the other is not. No indication is given about the sensitivity; the application of the method is very restricted.

### 2.5. *Chemical transformations*

The occurrence of chemical products, partial breakdowns, burned traces, etc., caused by discharges may be used for detection and location. Robinson [A2] determined the presence of wax in mass-impregnated cables, formed by discharges, by means of dying the paper tapes. He used magenta dye, which gives the tapes a bright colour except for the places where wax has been formed. In this way good location of discharges is possible. Robinson shows several examples of wax in butt-gaps between strands, etc. As the sample must be demolished for inspection the application of the method is restricted.

### 2.6. *Survey of non-electrical methods*

In Table 2.1 the principal characteristics of the non-electrical methods have been collected. The symbol (+) means that the referred method is suitable for the purpose; the symbol (−) indicates that the method is unsuitable.



TABLE 2.1. NON-ELECTRICAL DETECTION METHODS

| *Technique* | *Application* | *Sensitivity* | *Measurement* | *Location* |
|---|---|---|---|---|
| Visual, photo-electric, or photographic detection of light | Surface discharges | Of the order of 1 pC, or less if higher frequencies are used | In some cases a rough estimation of discharge magnitude may be made | + |
| | Internal discharges in translucent dielectrics | Of the order of 50 pC | | |
| Manual or thermoelectric detection of heat | Very large internal discharges which have deteriorated the dielectric | Very insensitive | — | + |
| Aural or microphonic detection of noise | Internal and surface discharges | In favourable cases 5–50 pC, usually more | — | + |
| Manometric detection of gas pressure | Internal discharges in accessible air spaces only | Unknown | — | − |
| Visual or chemical detection of chemical transformations | Discharges in objects which may be demolished; surface discharges | Insensitive | — | + |

## 3. ELECTRICAL DETECTION: PRINCIPLES

### 3.1. *Basic diagram*

As has been indicated in Figure 1.10, discharges in a sample cause current impulses in the leads of the sample. A great variety of circuits is in use to detect these impulses, but all these circuits can be reduced to one basic diagram. In Figure 2.4 this diagram is shown. The elements are

High voltage source,
Sample *a* affected by discharges,
Impedance *Z* across which voltage impulses occur caused by the current impulses in the sample,
Coupling capacitor *k*, which facilitates the passage of the high frequency current impulses,
Amplifier 'A',
Observation unit 'O', which may be, for instance, a loudspeaker, a voltmeter, or an oscilloscope.

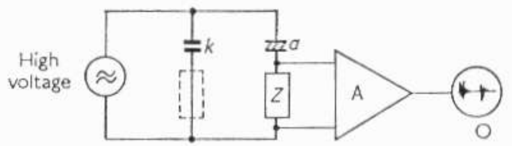



Figure 2.4. *Basic diagram for electrical discharge detection*

Some of these elements are discussed in more detail in the following sections.

### 3.2. *The detection impedance*

The impedance *Z* may be connected to the sample in two ways: either *Z* is placed in series with the sample (see Figure 2.4) or *Z* is placed in series with the coupling capacitor which is indicated in Figure 2.4 by a dotted line. Both ways are electrically equal: the same voltage occurs across the impedance *Z*.† In practice the connection of *Z* may be of importance. For instance, if the sample is large, *Z* is often placed in series with *k* so that the large charging current of *a* does not pass through the impedance *Z*. Two impedances commonly used are a resistor R shunted by a parasitic capacity *C*, or an oscillatory circuit, LCR. The voltage impulses which occur across these impedances may be calculated with the aid of Laplace transformations.

† Assuming that the impedance of the h.v. source is large.



RC CIRCUIT. In the RC circuit the impulse appears to be unidirectional of a shape as shown in Figure 2.5. The impulse is given by

$$V = \frac{q}{(1+C/k)\,a+C} \cdot \exp(-t/Rm) \qquad \ldots(2.2)$$

where $q$ is the magnitude of the discharge causing the impulse, $q = b.\Delta V$; $a$, $C$, and $k$ are shown in Figure 2.5. Furthermore,

$$m = \frac{ak}{a+k} + C \qquad \ldots(2.3)$$

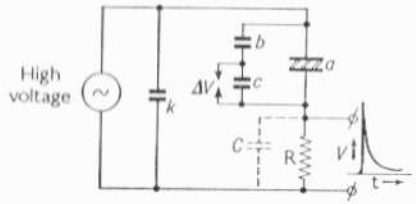



Figure 2.5. *Response with RC circuit*

LCR CIRCUIT. In case of the oscillatory LCR circuit (see Figure 2.6) the impulse is an attenuated oscillation with the *same crest voltage* as with an RC circuit,

$$V = \frac{q}{(1+C/k)\,a+C} \cdot \exp(-t/2Rm).\cos\omega t \qquad \ldots(2.4)$$

where

$$\omega = \sqrt{\left(\frac{1}{Lm} - \frac{1}{4R^2m^2}\right)}$$

and $m$ satisfies equation (2.3).

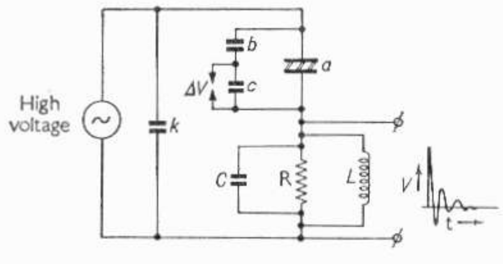



Figure 2.6. *Response with LCR circuit*

*Remarks*

(1) It follows from equations (2.2) and (2.4) that the height of the impulse is proportional to the magnitude $q$ of the discharge.

(2) It follows further that the height of the impulse is independent of $R$. However, if $R$ is small the time constant $Rm$ is small and thus the impulse is sharp. In most amplifiers this sharp impulse will not fully be amplified and the resulting impulse, as shown for instance on an oscilloscope, becomes smaller if $R$ is decreased.

(3) If $a$ is large the height of the impulse is determined by $a$ only, as

$$v' \simeq \frac{q}{a}, \quad \text{for } a \gg C \text{ and } k$$

(4) It also follows from equation (2.2) that a coupling capacitor $k$ is necessary, as otherwise $C/k$ in the denominator is large and the impulse becomes small. In some circuits described in the literature a separate capacitor for $k$ is not provided and $k$ is equal to the capacitance of the high voltage source. It is clear from the above considerations that this may lead to uncertain results.

### *3.3. Frequency spectrum—choice of amplifier*

AFTER RC CIRCUIT. The unipolar impulses produced over the RC detection impedance have a frequency spectrum which is nearly constant in height up to a frequency $f_1 = 1/(2\pi Rm)$, as shown in Figure 2.7. As

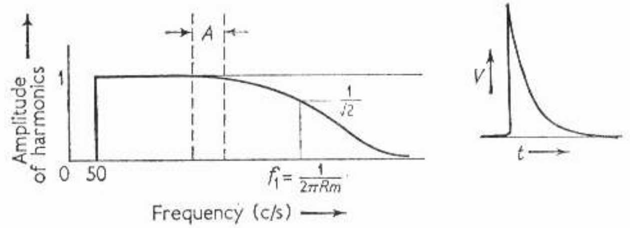



Figure 2.7. *Frequency spectrum of unidirectional impulses (RC circuit)*

$m$ depends on the circuit constants ($m = [a.k]/[a+k]+C$) the extension of the frequency spectrum depends on the circuit and the magnitude of the resistor $R$.



The amplifier used for the amplification of these impulses should obviously have a bandwidth which extends to or beyond $f_1$. In some cases a narrow-band amplifier with a midband frequency below $f_1$ is used, as shown under $A$ in Figure 2.7. The height of the signal obtained is proportional to that of the original signal.

AFTER LCR CIRCUIT. The oscillatory impulses which occur over an LCR network have a frequency spectrum as shown in Figure 2.8. The midband frequency $\omega$ is given by formula (2.4); it follows from this

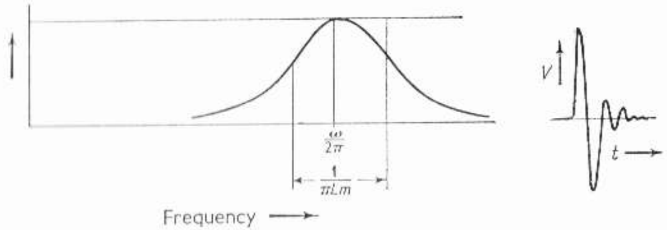



Figure 2.8. *Frequency spectrum of oscillatory impulses (LCR circuit)*

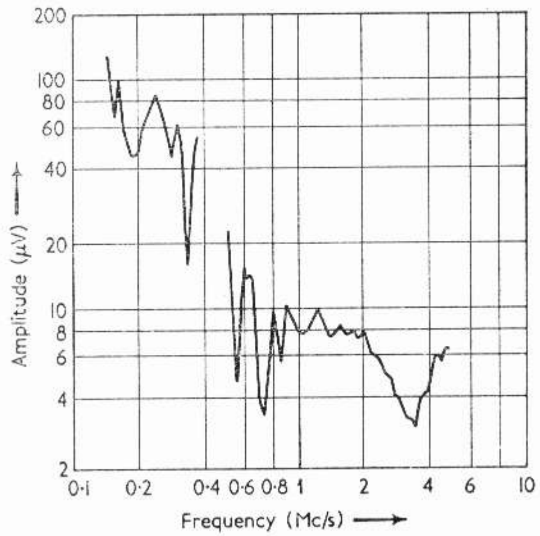



Figure 2.9. *Frequency spectrum of an impulse caused by discharges in a transformer* [A11]

formula that $\omega$ is determined both by the LCR impedance and the circuit constants.

The amplifier behind an LCR network should have a bandwidth which is equal to or broader than that of the signal. According to Mole [F2], sufficient sensitivity is obtained if this bandwidth is more than thirty times the bandwidth of the signal. If the sample comprises self-induction, as is the case, for instance, in a transformer, the frequency spectrum is not as smooth as in Figures 2.7 or 2.8. Widman [A11] has shown that the frequency spectrum of discharge impulses from a high voltage transformer may follow a complicated pattern, as shown in Figure 2.9. In such a case RC detection with a broad-band amplifier is preferred.

### *3.4. Observation*

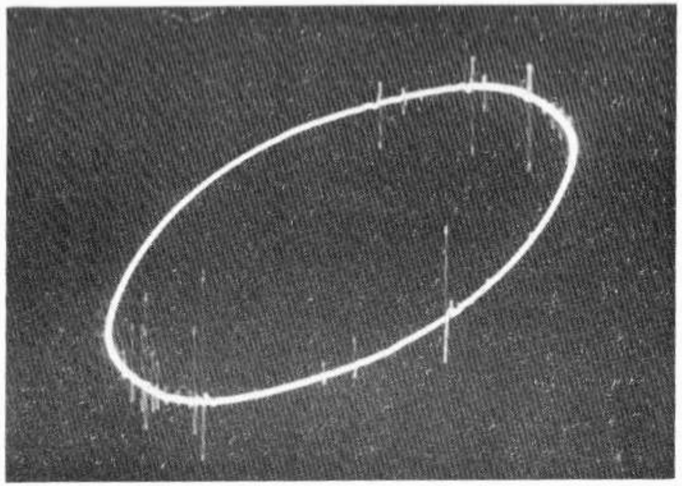
The impulses caused by discharges can be observed in different ways, either separate or integrated.

LOUDSPEAKER. Observation of discharge impulses by means of earphones or a loudspeaker is simple; but no more information than the presence or absence of discharges and a rough estimation of their intensity is obtained.

VOLTMETER. A better means is formed by the voltmeter, the reading of which can be recorded. Several types of voltmeters are in use. However, a voltmeter has its disadvantages, the principal being that the reading is as much affected by few large as by many small discharges.

OSCILLOSCOPE. One of the best choices is the oscilloscope. The discharge impulses usually are displayed on a time base of the same frequency as the applied high voltage. Recurrent discharges in successive cycles cover each other and a stationary picture is obtained. With the aid of an oscilloscope the magnitude of the individual discharges can be measured, this magnitude being proportional to the height of the impulses on the screen. From the character of the picture on the screen it can sometimes be decided if the observed impulses are caused by disturbances from the mains, by corona discharges at the high voltage leads, or by discharges in the object under test. In Figure 2.10 examples of such oscillograms are shown, these oscillograms are superimposed on a 50 c/s elliptical time base.

Sometimes triggering of the time base is preferred, i.e. the time base is started every time a signal appears. The impulses which recur every cycle of the 50 c/s sine wave are superimposed to form one impulse.



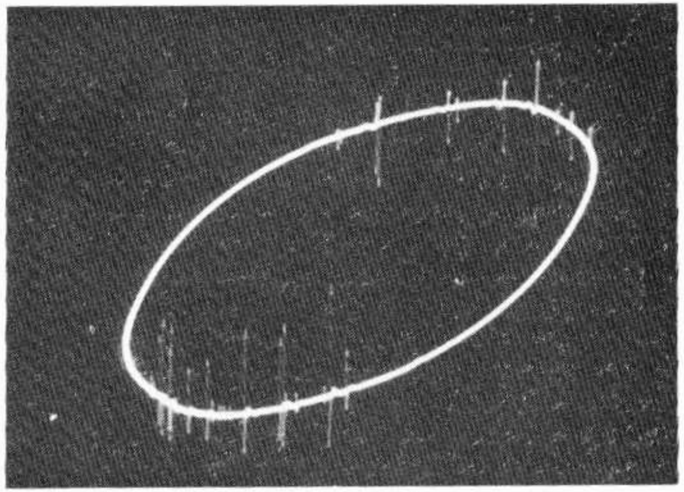


Figure 2.10. *Examples of oscillograms of discharges, displayed on a 50 c/s time base*

*facing page 58*

TABLE 2.2. ELECTRICAL DETECTION METHODS

| | | | | | | |
|---|---|---|---|---|---|---|
| Straight detection | RC impedance | | Narrow-band amplifier | Voltmeter and loudspeaker | Renaudin<br>Knosp | [F6]<br>[N12] |
| | | | Broad-band amplifier | Oscilloscope | Blanchardie and Aftalion | [F7] |
| | | | | Impulse counter | Laverlochere | [A6] |
| | | | | Observation of travelling waves | Kreuger | [A3] |
| | LCR impedance | | Narrow-band amplifier | Oscilloscope | Mole<br>Viale | [F1]<br>[F3] |
| | | | Broad-band amplifier | Oscilloscope | Quinn<br>Graham c.s. | [F5]<br>[A12] |
| | | | | Crest-voltmeter | Damstra | [F8] |
| | | | | Oscilloscope (ERA model III) | Mole | [F9] |
| Balanced detection | RC impedance | H.F. Schering bridge | Narrow-band amplifier | Oscilloscope | Graham c.s. | [A12] |
| | | | Broad-band amplifier | Oscilloscope | Austen and Hackett | [B2] |
| | | | | | Greenfield | [G4] |
| | | | | Voltmeter | Arman and Starr | [G1] |
| | | Differential method | Broad-band amplifier | Oscilloscope and crest-voltmeter | Kreuger | [A3] |
| | | Discriminator | | Oscilloscope | Hashimoto | [G3] |
| | LCR impedance | | Bridge circuit | Voltmeter | Arman and Starr | [G1] |
| Loss detection | Schering bridge | | Vibration galvanometer or electronic detector | | Common practice | |
| | Doubly balanced bridge | | Vibration galvanometer and oscilloscope | | Gelez | [H1] |
| | Electronic wattmeter | | Wattmeter | | Veverka and Cháldek | [H2] |



## 5. CHARACTERISTICS OF ELECTRICAL DETECTION CIRCUITS

The principal characteristics of electrical detection circuits are the *sensitivity*, *resolution*, and *balance*; these are analysed below.

### *5.1. Sensitivity of RC circuits*

SIZE AND SHAPE OF IMPULSES AT THE DETECTION RESISTOR. The height of the impulse across the detection resistor $R$ in Figure 2.25 and the shape of this impulse has been given in formula (2.2), viz.,

$$v = \frac{q}{(1+C/k)\,a+C}\cdot\exp(-t/Rm)$$

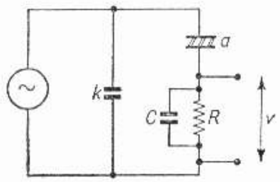


Figure 2.25

This formula may be transformed to

$$v = \frac{q}{C_{\text{tot}}}\cdot\exp(-t/\tau) \qquad \ldots(2.5)$$

where $C_{\text{tot}}$ is the total capacity over which the charge transfer $q$ is divided, or

$$C_{\text{tot}} = \left(1+\frac{C}{k}\right)a+C \qquad \ldots(2.6)$$

and $\tau$ is the time constant of the impulse,

$$\tau = Rm = R\left(\frac{a.k}{a+k}+C\right) \qquad \ldots(2.7)$$

The author has shown elsewhere [A3] that for a Schering bridge or differential circuit (as shown in Figure 2.26) this voltage impulse is also equal to

$$v = \frac{q}{C_{\text{tot}}}\cdot\exp(-t/\tau) \qquad \ldots(2.8)$$

*Results*

(9) The discharge voltage diagram yields, together with the pattern on the oscilloscope, some information on the origin of the discharges. Examples are shown in Figures 6.15–6.20. The conclusions drawn from these diagrams, however, are not certain and should be checked.

(10) The defects which may be found with discharge detection are manifold. Some examples are

Space between conductor and insulation.
Cavities in the dielectric, e.g. cracks, voids due to shrinkage, air pockets.
Inclusion in the dielectric, dirt, foreign particles, splinters, etc.
Insufficiently dried paper in paper–oil dielectrics.

Some of these defects are shown in Figures 6.21–6.23.

(11) The measures which should be taken to prevent discharges generally follow from the character of these defects; in sub-section 3.2 these measures have been considered.

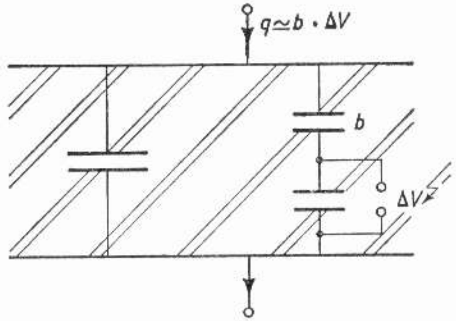
(12) The relation between discharge measurement and voltage life is still vaguely known, partly because reliable measurements have been made in the last decennium only and partly because other factors, such as field strength, pressure, etc., have not always been taken into account.

(13) With regard to voltage life one statement can be made with certainty. The magnitude of the electric field is of prime interest; the magnitude of the discharges affects the voltage life to a lesser extent.

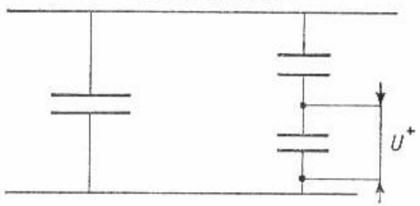
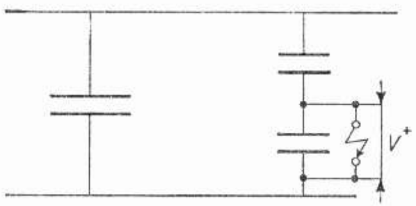
(14) In a few cases only experience of the voltage life exists. In sub-section 3.3 some figures have been reported.

# Appendix A. Terminology

## Terms Related to Discharges

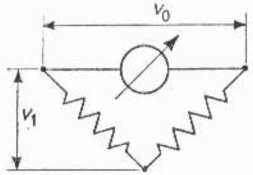
| *Term* | *Symbol* | *Explanation* |
|---|---|---|
| DISCHARGE (short for PARTIAL DISCHARGE) | | Electric discharge which does not bridge the electrodes; examples are *internal* discharges in cavities in a dielectric, *surface* discharges along an insulator, and *corona* discharges around a sharp edge. |
| DISCHARGE MAGNITUDE | $q$ | The charge transfer in a sample caused by a discharge in this sample. This magnitude can be measured with most discharge detectors and is therefore of practical value.   |
| PERMISSIBLE DISCHARGE MAGNITUDE | | Maximum discharge magnitude which is considered to be harmless in a certain construction. This measure is strongly dependent on factors such as field strength, frequency, required voltage life, etc. |
| DISCHARGE ENERGY | $w$ | The energy which is dissipated by the discharge. This energy may be calculated from the discharge magnitude $q$ and the inception voltage $V_i$ by the relation $w \simeq 0{\cdot}7q\,.\,V_i$. |

## Terms Related to Discharges—*continued*

| *Term* | *Symbol* | *Explanation* |
|---|---|---|
| INCEPTION VOLTAGE | $V_i$ | Voltage over the sample at which the first discharges are observed if the voltage is *increased*. The magnitude of the discharges which can be observed is determined by the sensitivity of the detector used. A statement of an inception voltage without reporting the sensitivity is therefore incomplete. |
| EXTINCTION VOLTAGE | $V_e$ | Voltage over the sample at which the discharges disappear if the voltage is *decreased*. Same remarks as with inception voltage. |
| INCEPTION STRESS<br>EXTINCTION STRESS | $F_i$<br>$F_e$ | Stress *in* the dielectric in the region of a discharge site at which the discharges appear or disappear. |
| IGNITION VOLTAGE | $U^+$ or $U^-$ | Voltage over the cavity (or in general over the discharge path) at which the cavity breaks down.<br>Before Discharge<br> |
| REMANENT VOLTAGE | $V^+$ or $V^-$ | Voltage which remains over the cavity after breakdown.<br>After Discharge<br> |
| DISCHARGE RESISTANCE OF INSULATING MATERIALS | | The resistance of a material to deterioration when exposed to discharges. The discharge resistance is sometimes stated as the 'time to breakdown' caused by discharges under standard conditions. |



## Terms Related to Detectors

| *Term* | *Symbol* | *Explanation* |
|---|---|---|
| MINIMUM DETECTABLE DISCHARGE OR SENSITIVITY | $q_{min}$ | Magnitude of the smallest discharge which can be observed with a certain detection circuit. |
| RESOLUTION | $r$ | Number of discharge impulses per unit of time which may be resolved, either by the detection circuit or by the detector (or minimum time between discharge impulses which can be separated by the detector). |
| REJECTION RATIO | $m$ | In a balanced detector: the ratio between the unwanted signal over the lower arms and the signal over the detector.<br><br>$m = \frac{V_1}{V_0}$ |
| CALIBRATION IMPULSE | $q_{ca}$ | Artificially generated charge transfer, which is used for the determination of the magnitude of an observed discharge. |
| DISCHARGE STANDARD OR DISCHARGE REFERENCE | | Device for the generation of discharges of constant magnitude. This device is preferably of very small capacity. |