PARTIAL DISCHARGES—A BRIEF REVIEW AND A BIBLIOGRAPHY

R. S. NEMA AND V. PRABHASHANKER

(*Department of High Voltage Engineering, Indian Institute of Science, Bangalore–560012*)

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ABSTRACT

A short review of partial discharges, mainly from literature in English along with a bibliography of about 500 references has been presented for the benefit of Indian workers in the field.

Key words : Partial Discharges; Insulation Systems; High Voltage Engineering; Discharge Locations.

INTRODUCTION

With the economic necessity of higher stresses, the subsequent need for better quality control tests and with the advent of new types of insulants, the study of partial discharges in electrical apparatus and insulation systems is of considerable current interest. A review of the existing state of knowledge, mainly from published literature in English along with a bibliography of about 500 references has been presented for the benefit of Indian workers in the field.

This paper consists of a short review and a bibliography. The review is mainly from literature published in English. The numbers referred to in the review pertain to those in column—' review reference numbers ' in the Subject Index of the Bibliography.

The references in the bibliography have been identified as standards (S), reviews and books (R) and by the year of publication (e.g., 59/3). The bibliography is of papers published mainly in English. In the other languages it is by no means complete. However, several important papers in other languages have appeared later in English.

THE REVIEW

Electrical breakdown, due to a ' disruptive ' discharge, of electrical insulation can be complete bridging between two electrodes when it is called 'puncture'. It could also be a partial breakdown of a portion of the insulation. When the breakdown propagation is limited by the inability of the electrical field to sustain it further, the discharges may be called 'corona'. When the propagation is limited by the presence of a better grade of insulation in the path of the discharge, the discharges could be termed 'partial discharges'. American practice, however, prefers the term 'corona' to include all types of partial discharges meaning, thereby, partial breakdown of insulation [1]. The authors would prefer to distinguish between 'corona' and 'partial discharges'. 'Corona' has been studied since several decades as a basic process in the breakdown of gases. Detailed reviews by Loeb [2] are available on the subject. Later work has been reported in literature [3]. Corona will be discussed further, here, only to the extent it is relevant to the understanding of partial discharges.

Study of corona was reported by Karapatoff as early as 1929, followed by Baker in England. Considerable impetus was provided by Whitehead and his group, followed by Mason, Garton, Mole and others. In America, much work has been done by Dakin, Liao and others. The earlier work [4] has been discussed in some of the earlier books [5]. A few reviews have been published over the years [6]. The field configuration with different electrode systems, study of the ionisation, conduction and breakdown phenomenon in liquids and the behaviour of charging of electrets are all pertinent to an understanding of the effects of partial discharges [7].

BREAKDOWN BY INTERNAL DISCHARGES

The inception (Vi) and extinction (Ve) voltages.—In insulation systems, stress concentrations occur in regions of lower permittivities. Partial discharges are initiated when the breakdown stress of any part of the insulation system has been exceeded. At the inception voltage (Vi) for that insulation system, when air filled voids are present, breakdown occurs in the voids when the sparking stress as given by the Paschen's curve for breakdown in air is exceeded [8]. Thus a critical dimension of the cavity corresponding to the minimum inception level for that insulation system exists depending on the relative void/insulation thickness and the thickness/permittivity ratios. This minimum voltage could be so low that discharges could occur around even 500 volts [9]. The stress in an air void would be a maximum ($= \epsilon E$) in a thin wide cavity perpendicular to the direction of the field, but the shapes of the voids have a great effect both on the maximum field in a void and its variation within the voids. As the area to depth ratio increases, the ratio of the average stress in the void to that in the solid would decrease [10].

Sometimes, sealed cavities in plastic insulation can be stressed to high levels. However, once discharges begin, the inception levels fall to the usual values.

Both the inception and extinction voltages depend on the pressure and temperature of the gas in the voids. In cases where the temperature affects the permittivity of the solid insulation, Vi would be lowered to the extent to which the relative stress is increased in the voids [11]. The inception and extinction voltages depend on the earlier stress history to which the discharging voids have been subjected [12].

Because of gas formation in oil impregnated systems, inception to extinction voltage ratios could be higher than in air systems [13].

The discharge magnitude, q.—This is proportional to the capacitance which is discharged and the voltage across it. The pulse rise time is of the order of nanoseconds and inception level and discharge magnitudes can be estimated by a capacitor (*a*, *b*, *c*) network [14]. The magnitude depends on the pressure, temperature and type of gas in the cavity, the ratio of the cavity to the series insulation thickness, resistivity of void surfaces [15] and the time for which the discharges have lasted [16]. The discharge magnitude against overvoltage curves are of different types depending on the insulation systems. These curves exhibit a hysterisis as the voltage is first raised and then lowered. The shapes and areas of these curves vary in different ways with experimental procedure and ageing. Indeed, generalisations are difficult from a study of these curves [17]. A single discharge, noted on the oscillograms, could be the record of the cumulative effect of a quick succession of discharges occurring at different sites [18].

The distribution of the magnitudes are, in general, random in nature. The distributions vary with the mode of experimentation, ageing and overvoltages [19]. In some experimental set-ups an exponential decrease is noted in the pulse number with increasing pulse magnitudes. From this and the inception levels at which the pulses occur, an estimate of the cavity depth can be derived and hence a rough estimate of the void distribution can be obtained. However, only small areas of a cavity would be involved, rarely more than 0·1 mm in diameter [20].

Recurrence of discharges.—The recurrence of discharges depends on the inception and extinction levels, the discharge sites and upon the charges transferred across the cavity walls during the discharges. With dc voltages the discharge recurrence rate is governed by the permittivity-resistivity product and can range from one per second or less to one in several days. In the case of a.c. voltages discharges occur in successive halves. Superposition of dc and impulse voltages on a.c. also affects the discharge rates [21].

Study of data obtained with multichannel pulse height analysers has shown that the number of pulses *versus* overvoltage gives rise to hysteresis curves which change with the overvoltage and age. This is found both with experimental samples and cables in service [22]. Pulse interval *versus* time charts do seem to give some indications of the condition of the insulation during ageing though much more study is indicated [23]. With overvoltages not only do the number of pulses increase but also the magnitudes. However, under certain circumstances the rise time increases, the magnitudes decrease and oscillatory signals are obtained necessitating different measuring techniques [24].

Anomalous breakdown—In many experimental set-ups and in practical insulation systems, partial discharges occur in the direction of the field and often perpendicular to the direction of the field. The final puncture, due to internal discharges, mostly, does not take place where one expects it, namely, at the points where apparently the stress should be high. Retention of charges on the surface or below has a profound effect on the development of intense local stresses. A comprehensive model of the mechanisms involved are far from being defined [25]. Similar anomalous breakdowns have been described with discharges in oil and air over insulating surfaces [26]. Though explanations have been offered, better controlled experiments and suitable models have yet to be described to explain the anomalous behaviour with internal and surface discharges.

BREAKDOWN BY SURFACE DISCHARGES

A capacitor model similar to the abc model used with internal discharges along with the Paschen's curve is valid. However, the gaps at which the minimum discharge levels are noted differ from those for internal discharges [27]. Empirically, Vi varies approximately as (Insulation thickness/Permittivity)$^{.5}$ to a limited extent. Evidence indicates that inception levels are reduced and the number of pulses are increased as the nonuniformity of the field increases. The number of discharges varies with the area of the effective electrodes. With overvoltages, the pulse magnitudes increase, the magnitude distribution is modified and a stage may be reached when puncture occurs [28]. Unlike internal discharges, surface discharges can occur further away from the electrode and are not limited by cavity dimension. The effects of temperature and pressure are very much similar to those of internal discharges, though the magnitudes would be different. In some organic materials (polythene, synthetic resin bonded paper, oil impregnated pressboard) discharge channels spread first below the surface followed by puncture [29].

Earlier discharges on the surface affect the subsequent progress of the discharge paths and circular discharges have been explained on this basis [30]. The scatter of the magnitudes about the mean depends on the field configuration and area of the electrodes. Square edged electrodes show a greater scatter than either rounded rods or flat rods while the least scatter is obtained with truncated needle electrodes with very small active area [31].

Mechanism of Breakdown

The fundamental mechanisms of breakdown due to partial discharges are almost same whether they are internal or surface discharges. Formation of pits, track formation, tracking when a carbonized track is left, otherwise erosion on the surfaces, penetration into the material in random directions which may or may not include carbonisation (treeing), loss of mechanical strength, chemical degradation and formation of surface films, moisture, thermal instability due to increased dielectric losses, local heating and or cumulative heating (at higher frequencies) are involved in both the cases [32]. The differences arise due to the larger magnitude pulses possible with surface discharges and the greater possibility of the continued removal of the product of discharges [33]. Any understanding of the mechanism of the breakdown will have to explain the phenomenon of treeing with erosion and with carbonisation, the branching angles and sequence of the tree development, the rate of growth of channels and the final criteria for defining ultimate puncture [34]. The growth of surface tracks, the selective developent of a track prior to breakdown, the branching angles and their sequence, the effect of surface resistivity and bulk resistivities and the growth of the discharge tracks below the surface layers have to be explained. Electron bombardment, irradiation ion bombardment all seem to play a part [35]. But the instantaneous charge retention and its spread with time at different sites seems to play a major role in these phenomenon and in thin film insulation breakdown [36]. A study of electret formation could perhaps throw some light. Studies have been conducted by measuring the charge distribution pattern analysing the discharge products and studying the energy requirements by studying material resistance or life when subject to internal and surface discharges with and without mechanical strain [37].

The surface discharge patterns depend on the roles played by electrons and ions. Due to their higher mobility electrons can respond to faster changes in voltage (of the order of 10^9 V/Sec) and lead to different patterns [38]. Analysis of discharge products show that more than electrons or ions are involved [38]. Much more work has to be done before exact models can be offered to explain all aspects of the phenomenon.

ASSESSMENT OF MATERIALS

Test Procedures.—Of immediate interest is the optimum utilisation of materials. Much attention is being paid to the development of test procedures whose results can be correlated with service performance. An attempt is made to assess (*a*) the relative merits of different materials and (*b*) the merits of different combinations or systems of materials. These studies therefore, reduce to estimating the probable life (or resistance of materials) when subject to discharges. With desirable lives ranging from 10 to 20 years, methods of accelerating tests and associated extrapolation techniques assume importance. Test frequency, overvoltage or voltage stress, electrode geometry, specimen thickness and preparation, ambient conditions (atmospheric humidity, temperature, ventilation, etc.) and mechanical stress form the major parameters. Four general classes of electrode systems may be identified depending on whether the discharges arise at the electrode surface or the insulator surface and whether the discharge products can be swept from the discharge region or not [39]. Resistance to internal discharges have been tested by embedded electrodes, electrodes enclosed in oil as an ambient medium, electrodes surrounded in an epoxy covering to prevent surface discharges. Resistance to surface discharges has been tested with hemisphere—plane, cylinder-plane, sphere-plane or needle-plane electrodes [40]. Crossed cylindrical electrodes have been found useful when testing film under mechanical tension [41]. Variations of stress at different parts of a few normally used electrode systems in homogeneous media and computer programmes for calculating more complex fields with dielectrics have been published [42]. The fact that extremely sharp electrodes do not give discharges at very low voltages has led to the empirical concept that the critical gradients should be exceeded for some distance for breakdown in gas or oil which may be the ambient or the void medium [43]. Perhaps, highly sensitive methods of measurement may be useful and lead to a better understanding of the partial breakdown phenomenon.

Samples have been prepared by moulding, machining, extruding, with and without fillers. In almost all cases the sample preparation and mechanical stresses and heat cycling during tests have considerable effect on the life [44].

Two distinct procedures of tests for surface discharge resistance are used. In one the maximum gradients are along the surface and discharges are initiated to run along the surface, generally, to simulate the conditions which arise due to surface pollution. The insulation surface is subject to high stress and high temperature of the discharges on the surface tracking tests [45]. Only a few studies of comparative evaluation of these tests are available. Empirical relationship between ratio of energy of formation of the carbon bonds ($\triangle$HC) and the energy to form all the bonds ($\triangle$Hcpd), the life and tracking and erosion failures have been obtained [47].

In the other test procedure, the main field is perpendicular to insulation surface and these tests are generally indentified as discharge resistance tests. Usually, the life with a.c. voltages can be given in terms of number of cycles to breakdown making possible frequency accelerated tests. However, it is always advisible to check these tests by establishing the frequency limits within which correlation of results are permissible. Though as high as 10 KHz can be used, even 1·4 KHz can in some cases lead to erroneous estimates of life at 50 Hz [48]. At very high frequencies the heating effect and the formation of conducting surfaces on the voids can distort the life results due to differences in the mechanisms of breakdown [49].

Life also gets reduced with increased stress and overvoltages may be used to accelerate the tests. In the case of surface discharges, enhanced overvoltages increase pulse magnitudes and at very high stresses discharges may penetrate without erosion and lead directly to puncture. With internal discharges, fresh sites may be exposed, sites which would never be active at lower operating stresses. Hence, acceleration by enhanced overvoltage should be done with care and rarely is the voltage raised beyond 2 to 3 times the allowable inception level. For internal voids, the shape of the overvoltage-pulse magnitude curves could indicate the void distribution and several attempts have been made to use these curves for assessing cable insulation and transformer insulation systems.

Generally, deeper voids (in the direction of the field) are more dangerous than smaller ones, though the converse is also reported to be true. Studies with a scanning electron microscope of polythene cable insulation showed voids less than 0·01 mm along the axis. Upto 11 KV/mm stress these do not seem to have any effect on a.c. life [50].

In oil-paper systems moisture content is an important parameter to be considered. The partial discharge inception voltage in oil-oil impregnated systems is not covered by a simple law. Discharges due to formation of gas in moist insulation does not occur with less than 3% moisture as dielectric breakdown occurs earlier. With moisture greater than 3% partial, discharges occur with a time delay which increases with increasing water content [51]. SF_6 impregnation with polythene foam cable has also been suggested for improving the discharge inception levels [52].

Though voids are taken to be normal sites for discharges, more often, discharges occur at the edges of inclusions leading to puncture. A study with needle inclusions of glass, wood and steel conducted on polythene cable indicate that glass causes lower life. Air cavities give a Life, $L = K/F^n$ where F is the field strength and n is about 9 for polythene. Apparently, inclusions embedded during the process of manufacture are different to those embedded after manufacture which can be studied by use of air voids alone [53]. The susceptibility of oils to discharges is tested with gassing tests. The ability to evolve or absorb gases arising due to bombarment of the oil surface by discharges in air, nitrogen, oxygen, and hydrogen have been studied. The relative quality of the oil depends not only on the composition and additives but also on the presence of paper barriers [54].

Significance of the measured quantities.—Intuitively, the energy dissipated in a discharge should be the governing feature in determining the extent of deterioration. In view of the small areas involved [20], the area or volume of insulation in which the discharge is dissipated should be of particular significance. Thus, at any particular test voltage, correlation of life with the sum of the squares of the charge magnitudes (Σq^2) the sum of the charge magnitude (Σq), either the maximum charge or the charge amplitude distribution have been attempted [55]. Though, some success is achieved in well designed samples, in most practical cases it has been difficult to identify the dangerous pulse magnitudes characteristic of the materials. This is partly because direct correlation between the actual discharge at the site and the measured value is not usually possible. It is also partly because the energy concentration or the actual discharge site area cannot be defined.

The overvoltage life curves show decreased life with increased overvoltage, more due to the increase in the number of discharges per cycle than due to substantial increase in pulse magnitudes in artificial voids. Whereas, with surface discharges though increase in magnitude does reduce life, puncture is not always at the end of the maximum discharge site. In general, corona intensity and breakdown times are not correlated [56]. Perhaps, the quadratic rate or even the total pulse magnitude, characteristic of the material, related to the inception level should be of significance. Studies on simulated transformer insulation have appeared where the overvoltage, pulse magnitude (q or μV) or quadratic (Σq^2) rate curves have been presented.

With few exceptions all measurements show hysterisis. With repeated measurements the RIV values for voltage decrease show less variation than for voltage increase. In most cases, sound insulation shows recuperation after 15 hours. Generally, but not always, deteriorated insulation shows no recovery. Free oil circulation helps recovery. There is a critical voltage Uc. Pulse magnitudes below Uc are slight and do not cause damage. At Uc or more, discharges are very intense and cause damage to insulation without causing breakdown. The voltage Uc, is temporarily or permanently diminished by the critical discharges left behind. Critical discharges are 'auto-extensive', that is, their intensity increases more or less rapidly in time, under constant voltage, before becoming stable. The quadratic rate along with the maximum pulse magnitudes and the position at which it occurs on the a.c. cycle seems to be useful [57]. Discussion presented at the CIGRE 1968 meeting presents valuable insight into the experience of several workers.

Considerable data has been collected by manufacturers using radio influence voltage meters (RIV meters) both in America and Europe. Now-a-days charge measurements are preferred. This is mainly because, both the discharge amplitudes and the position of the cycle at which they occur are of significance. A general correlation cannot be established between RIV (μ V) and charge (p C) measurements though for each test specimen and apparatus set-up correlations are possible [58]. Recommendations, therefore, prefer charge measurements in future, though for local comparisons RIV meters may be used.

Schering bridges are often used. A rapid increase in the value of tan δ with increase in the stress is taken to indicate the discharge inception voltages. This method is less reliable than those using charge measurements [59].

It is extremely costly and difficult to ensure the ideal requirement of discharge free equipment. Considerable difficulty is experienced in categorically defining safe permissible levels. These could be specified only with the growth of considerable practical experience. A few papers giving such experience and the basis for arriving at the levels are available [60].

Location of Discharge Sites

Several methods for locating discharge sites in cables have been described, mostly with unshielded cables. Most methods use the travel time of the pulses to the two ends while some use scanning methods [61]. One interesting method uses the fact that x-rays reduce the discharge levels as a scanning device for locating discharge sites in busbar insulation. The signals picked up by a high frequency magnetic pick-up where the magnetic path is completed by the stator core has been used as a scanning device in high voltage generators for locating insulation defects within the slots [62].

For transformers the problem is more complicated. A discharge in a transformer winding generates three kinds of voltage pulses at the terminals (1) a pulse transferred by the capacitances, (2) a pulse caused by a travelling wave, (3) a low frequency oscillation governed mainly by the inductance. Location can be obtained by finding the time delay at the two terminals, either directly or by delay networks and coincidence circuits. The particular method which is most sensitive depends on α or the series to shunt capacitance ratios of the windings. By noting the pulse polarity with 4 detectors, the limb in which the discharge occurs and whether it is a turn to turn or turn to ground fault can be located. By a process of finding the discharge inception levels when grounding the delta points separately with the help of voltage vectors, knowing the voltage distribution along the transformer winding, location is also possible. Knowing the detector response of the pulse injected at different locations by repetitive surge generators and comparing the patterns obtained in service, location has also been attempted. Simple methods, suitable for use in the site are yet to be developed fully [63].

Analysis of gases and the ratio of the different gases have been suggested as means for identifying the nature and site of discharges in oil filled transformers [64].

DETECTION TECHNIQUES

Detection and measuring techniques have been discussed and detailed analysis presented by several authors. Great care has to be taken in the layout of the measuring circuits, the elimination of spurious discharges, use of discharge free components, careful shielding, placement of the leads and specimen at suitable distances away from heavy earthed objects in the use of proper calibration methods and in the interpretation of results. The choice of the detector bandwidth and gain characteristics for high sensitivity measurements are governed to a large degree, by the specimen capacitance, inductance and the LCR values of the measuring impedance. Though important, due to lack of space, further discussion will not be presented and the reader should do well to read the cited references [65].

Laboratory Techniques

These have included the use of Lichtenberg figures, heat-set discharge patterns, use of colouring powders which mark the positively and negatively charged regions in different colours (colourograms), use of capacitance probes, photography of light pulses with or without photomultipliers, drum camera, current measurements, multichannel discharge level analysers and gas analysis have been used. All these methods are useful in following the ageing process and in understanding the tracking, treeing and discharge sequence mechanism [66].

Conclusions

Though much work has been done in the field of partial discharges, several aspects remain to be studied. Some of these aspects are:

(1) The development of models which explains the tracking, erosion and treeing mechanisms, branch formation and anamolous breakdowns.

(2) The effect of degradation products on the above-mentioned phenomena.

(3) The relationship between the pulse magnitudes and material structure parameters along with the proper definition of critical levels for the pulse amplitudes beyond which destruction can occur.

(4) The evolution of elegant and conventional fault location methods of particular use in the field.

(5) Collection of more data regarding the relationships between the critical discharge magnitudes, mechanical stress history, the environmental parameters of both individual materials and systems and ageing.

(6) The detailed study of practical and simulated insulation systems for the purpose of standardising test procedures suitable for evaluating complete insulation systems.

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