Thoughts on the Possibility of Damage of High-Voltage Electrical Insulation below the so-called Inception Voltage: The Historical Background – Part I

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Abstract

Partial discharges (PD) may cause damage to high-voltage (h.-v.) electrical insulation and eventually breakdown. It is known, however, that sudden breakdowns occurred in industrial insulations after only a few months in service, although they had passed the suggested international specifications tests. In this paper, we investigate the possibility of damage of an h.-v. insulation even below the inception voltage, giving the historical background which led to certain thoughts. References to previous work are given and a differential equation is proposed regarding the possibility of having charging phenomena below the inception voltage.

Keywords

Partial discharges, high voltage insulation, cavities, inception voltage, leakage currents

Introduction

PD may cause significant damage to the h.-v. insulation [1], [2]. PD may start from asperities on the electrodes, from enclosed voids, from fissures and/or from enclosed foreign particles [3]. Numerous publications tackled the question of the relation between PD parameters and insulation damage [4]–[7].

Although a voluminous amount of research has been performed on the questions of insulation damage and PD, no particular attention was given to possible charging events below inception voltage. However, such events were held responsible (at least partly) for the failure of insulation equipment back in the fifties and the sixties of the last century [8]-[11]. Such incidents were reported, regarding big electrical machines as well as high voltage switches that failed abruptly, although they passed all tests the international technical committees were suggesting [8]. Which were these incidents? In the 1950's one major US manufacturer produced and sold large rotating machines with cast polymer insulation. At that time all available diagnostic techniques suggested that there should be no problem at all from low leakage currents. Surprisingly enough, these rotating machines failed while in service in a few months. Another occasion of impressive failure was registered when another US manufacturer producing 15 kV class vacuum switches, reported that, although all normal tests at that time were done, unexplained erosion of cast epoxy insulation occurred in these switches, only after a few years in service. Such were the incidents that led to the exploration of the below inception regime of charging phenomena [12]. Scientific evidence of "something" happening below inception was provided by Filippini [13], who suggested that treeing propagation followed growth along current paths. Furthermore, Brancato [14] indicated the possibility of relating current below inception with temperature rise. In his own words, "perhaps the most exciting but speculative project is the development of techniques to determine temperature rise of void surfaces due to partial discharge. ... electrical aging may in reality be a chemical reaction in voids induced by the deposition of energy. This deposition is expended in the raising of the temperature of the walls of the void, in creation of ozone and possibly nascent oxygen which tend to oxidize the surface chemical reactions which in the presence of water components form nitric or nitrous acids which deteriorate the void surfaces and finally mechanical erosion by the resulting ion stream impinging on the void". In the same publication, Brancato also pointed out that measuring or sensing techniques may not be adequate for all classes of dielectric materials or to all aging environments and/or the inadequate sensitivity of some instruments to detect changes. Recent papers point out to the slow decline of inception voltage with time [15]. Is this also an indication of charging phenomena below the so-called inception? Would such phenomena play a role regarding the decrease/decline of inception voltage?

Hints about possible damaging events below inception voltage were discussed in a brief report by E. Brancato back in 1991 [16]. Previous work on air gaps with a non-uniform electrode arrangement suggested that such charging events were possible [17]-[20]. To the best of our knowledge, until now there are indications of possible charging effects below inception voltage but a definite proof is missing.

It is the purpose of the present paper to offer the historical background of the approach regarding charging events below the inception voltage and to explore a bit further the events below inception. An equation, which was proposed many years ago by Bruning, is discussed.

On the Problem of Inception Voltage – Historical Background

Inception voltage is called the lowest voltage under a.c. conditions, at which repetitive PD of a specified magnitude in successive cycles are observed, as the applied voltage increases [21]. Above the inception level, an insulation may deteriorate depending on the magnitude of the imposed voltage. Things become more blurred when an insulation is subjected to an applied voltage which is lower than the extinction voltage (according to the seminal publication by Kelen [21], the extinction voltage is the voltage at which discharges of a specified magnitude will recur when an alternating voltage, which exceeds the discharge-inception voltage, is reduced).

In his important paper, Bruning and colleagues [9], pointed out that unexpected insulation failures occurred despite the fact that the insulation was operating below the inception voltage. In this doctoral thesis, Bruning [8] pointed out that there were problems in tackling and understanding the basics of current-voltage relationships for new insulating materials and/or new devices. For example, the design failure of epoxy insulators, which used the application of criteria for porcelain discharge onset, did not sufficiently characterized low current performance with contamination. On another occasion, there was a lack of fundamental current vs. voltage analytical model for the design of a new type of transformer windings. In many cases of transformer failures, discharge testing did not indicate low level pre-discharge activities with operation. Problems also arose with underground cables, where aging effects, exacerbated by the presence of water, may give higher discharge currents which are below the level which can be satisfactorily measured. Bruning speculated that low level discharge currents cause a destructive local temperature effect. Problems related to the above questions were revealed in the USA with electrical machines, cables and high-voltage switches, which failed unexpectedly although all of them passed the required tests prescribed by the international technical committees.

All the above point to the fact that there is a need for a fresh approach for this problem, an approach which may give a possible solution to charging effects below inception. Efforts have been undertaken in Bruning's seminal publications [8], [9], where questions such as the following were put:

a) what is the insulation leakage current-voltage characteristic?

b) what is the effect of such a leakage current?

Efforts were also undertaken in some publications, albeit with a different insulating material and a much simpler electrode arrangement [17]-[20]. In those papers, indications were presented that effects below the so-called inception level may exist. Moreover, experiments performed in polyethylene samples with enclosed cavities, indicated that at relatively low voltages sharp current waveforms were detected. This indicates sudden streamer PD mechanism in enclosed cavities. In previous years, comments regarding the relation between such sudden PD waveforms and events at or below the inception level were offered. It was speculated that there may be sudden bursts related to local rising of temperature in a cavity [22]-[26].

Possible Relation Between PD Events at Inception Voltage and Charging Events below Inception

Bruning and colleagues [8], [9], [27] proposed an equation describing the quasi-steady state for current flow

$$\nabla^2 V + \nabla V \cdot \nabla s / s = 0 \qquad (1)$$

where, ∇ is the gradient and ∇^2 is the Laplace operator expressed as a function of the location, V is the local voltage and s the local conductivity of the fluid (in our case air). They also proposed that it would be plausible to state that the local air temperature is related to the local power dissipation which is leakage current times the local voltage gradient. This being true, the local electrical conductivity is related to the local temperature. The question was as to whether such an equation was leading to a burst or sudden PD pulse even below inception. Would this be possible?

In fact the above equation was characterized as the "thermal model" in Bruning's Ph. D. Thesis [8]. It suggests a thermal model of gaseous conduction which under certain conditions of limited diffusion rate of ionized species, low radiant energy loss, and low thermal conductance, a diffuse current flow may generate a diffuse conduction process. Similar pulseless regimes were suggested in [28]. Furthermore, the same direction of research, without however being so specific, was pointed out in [29], [30], where pseudoglow regimes were observed. It may well be that the current not indicated on a conventional PD detector is a current below the detection level.

More in detail, if one assumes that in the gas there is a dissipative current flow, using classical notation,

$$\nabla V \bullet J = 0 \tag{2}$$

$$J = sE \tag{3}$$

$$\nabla \bullet sE = 0,\ \text{but}\ E = \nabla V \tag{4}$$

and consequently,

$$\nabla^2 V + \nabla V \bullet \nabla s / s = 0 \tag{5}$$

The above equation, in the case of a constant conductivity s, reduces to the well known Laplace/Poisson equation. However, for a gaseous conduction process, where the there is a partial variable ionization as J varies with time and position, we have finally Eq. (5).

As was noted in a previous paper [27], solution of the distributed – perhaps pulseless current flow – then proceeds from ionization determined from both Saha's equation and the heat balance determining the local temperature. The complexity of the transport processes have not permitted ab initio calculations. However, approximations indicate a variation of current density and field strengths, which indicate the possibility of current below the detection level. Whether the continuous thermal conduction model arises from true continuous conduction or from pulses too short to be detectable by conventional PD detectors, it is a question in need of an answer. It is interesting to note, however, that sudden bursts of pulses at or below the so-called inception voltage were observed recently, not only in conventional polymers but also – albeit less frequently – in nanocomposites [31], [32].

Research by Bruning and colleagues [9], [10] indicated that damage observed below inception was very similar to the damage above inception. In these papers, indications were offered that chemical changes below inception were similar to those noted above inception. Such indications gave strong ground for suggesting that "something" goes on below the inception voltage. Chemical changes that indicate chemical deterioration below inception imply the existence of charging phenomena that may render shorter the lifetime of the insulation. Charging effects below the inception voltage may imply that there is no voltage below which no deterioration takes place. More precisely, it is known that the lifetime L (time to failure) is given by the formula

$$L = c(V - V_0)^{-k} \quad (6)$$

where, V is the applied voltage, V_0 is the voltage below which no deterioration takes place and k is a constant. k, V_0, and c are constants depending on the insulation material (it should be noted that original form of Eq. (6), referred to in [33], was

$$L = (A - \alpha)^{k}(V - \alpha A)^{-k}$$

where, L is life in minutes, A is the 1 min strength, α is a material constant, k is another material constant and V is the applied voltage). However, if one assumes that there is damage below the inception voltage, then

$$V_0 = 0 \quad (7)$$

and Eq. (6) becomes

$$L = cV^{-k} \quad (8)$$

As was noted in [9], "most equipment designers use this empirical relation without having settled the fundamental question as to whether $V_0 = 0$ or not, since empirical experiments in reasonable time periods cannot distinguish between the two forms", i.e. that of Eq. (6) from that of Eq. (8). Ambiguities regarding Eq. (6) still remain to this day, especially if one looks at insulation lifetime models [34]. The question of whether V0 = 0 is also relevant to the sensitivity of PD detector as well as to the thickness of the examined insulation, deserves to be further explored. It was reported before, that scaling laws exist, i.e. a thicker insulation requires a more sensitive PD detector [35], [36]. Needless to say that the sensitivity of a PD detector determines the inception voltage of either an insulating material or a full insulation system, or in the words of one of the most distinguished researchers of the good old generation, E. Brancato, "... electric stresses in the absence of internal discharges can cause changes in material properties. Some ascribe the changes to electrochemical reactions, while others express the suspicion that the observed changes are really caused by partial discharges but the corona detecting system is too insensitive" [37].

From the above it is indicated that, although there is not yet a universal name to it, "something" must occur below the inception voltage. Whether this "something" can be referred to as "charging phenomenon" or can be manifested as "signal", is not yet clear. Moreover, if one sees the more practical questions and if one tackles the problems of the role of antioxidants in cable insulation, one may say that antioxidants are incorporated to prevent premature degradation during extrusion, but the role of the residual antioxidant on insulation response to aging stresses has not yet been quantified, especially in voltages below the inception level [38].

Conclusion

The present paper is an introduction to the problem of possible charging effects below the so-called inception voltage. The historical background of an approach – different from the usual approaches – is given as well as the indications that charging phenomena below inception may exist. Below inception sudden pulses were observed with an electrode arrangement of point-plane with air as insulating material. It is speculated that minute abnormalities on the cavity surface may act as emission sites and thus provoke small charging phenomena not easily detected by normal conventional PD detectors. An equation regarding the current flow in a cavity was given and commented upon. In a future publication, a solution of the said differential equation will be given together with appropriate comments.

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