

A Study of Electric Breakdown Theory to Model Dielectric Surface Flashover

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Abstract— Electric flashover on power system apparatus and safety equipment can result in destruction to equipment and injury to workers, as well as pose a danger to anyone in the vicinity of this occurring. This phenomenon still continues to be an issue today despite over 100 years of research into the problem. It was determined that an exhaustive literature review should be performed to investigate mathematical models proposed thus far, evaluate them, and deduce if errors or weaknesses exist due to lack of knowledge at the time of development. We desire to find a model, assemble one out of others, or create one out of insight gained to more accurately represent dielectric surface flashover. A review was performed of static, dynamic, avalanche-streamer-leader, and surface interaction models. Employing electro-hydrodynamic models to model the avalanche-streamer system is typical in the physics literature. However, the incorporation of the Elenbaas-Heller analytical model for a leader was examined. A proposal to use Elenbaas-Heller with the surface electron emission avalanche model is presented, possible weaknesses of both streamer-leader models are discussed, and future research to remedy these weaknesses is proposed.

I. INTRODUCTION

Although the modeling of electric insulation breakdown has been investigated since the beginning of the last century and thousands of papers have been published, an all-encompassing understanding of breakdown over an insulating surface has still not been produced to this day. The published knowledge has been incorporated into the design of apparatus and equipment in the power industry to prevent flashover. However, flashovers are still encountered on apparatus, and have dangerously occurred on line maintenance personnel safety equipment [1]. Hence, a model is desired to fully describe dielectric surface flashover to gain a complete understanding of the phenomenon in order to design for the elimination of its occurrence. An exhaustive review was performed on static, dynamic, avalanche-streamer-leader, and surface interaction models with the goal of finding an adequate existing model. Although many questions still have to be answered and new questions have come out of the current research, a streamer-leader model combined with surface interaction concepts is proposed with the hope that it will offer more de-

scriptive and predictive strength to a dielectric surface breakdown model as suggested by experimental evidence out of static research.

II. STATIC MODELS

Mathematical models have been developed since 1958 that describe insulation breakdown over a dielectric surface where critical values are calculated by solving a single function of related independent values. These “static” modeling efforts also produced criteria for events such as discharge propagation and flashover. Most papers and reports in flashover research often begin with the ubiquitous 1958 paper of Fritz Obenaus modeling an arc flashing over a portion of a polluted surface, with the unbridged portion in series with the arc [2]. This is essentially the physical scenario of most pollution flashover models. Kirchoff’s voltage rule is applied around the closed series circuit comprised of the source, arc, and pollution layer. This gives a “static” equation incorporating the arc voltage, length, and current employing $V_{arc} = Ax\bar{i}^n$ (hereafter called the Obenaus equation) to represent the electrical characteristics of the arc

$$V_s = Ax\bar{i}^{-n} + iR_p \quad (1)$$

where V_s is the source voltage, x is the arc length, i is the current, R_p is the pollution layer resistance, and A , n are empirical constants. Neumarker functionalized the pollution layer as a function of arc length $R_p(x) = r_p(L-x)$ with L total insulator length, to allow for change in arc length, resistance, and current [3]. This allows one to calculate derivatives of (1) resulting in expressions for critical current i_c (for which discharge would extinguish if the current falls below), critical source voltage V_c that must be applied in order to sustain an arc of length x , critical arc length x_c that the arc can’t grow beyond for a given voltage and current, critical field $E_c = V_c/L$ over the insulation length, etc. The author gave these as arc extinction conditions for which flashover was impossible (i.e. $E < E_c$ or $r > r_c$).

Static investigation of propagation criteria began with Hampton in 1964 [4]. In conducted experiments measuring voltage along the pollution layer via probes underneath the pollution strip, he suggested the propagation condition $E_{arc} < E_p$, with $E_{arc} = V_{arc}/x$, calculated as an average field over the arc length. Wilkins and Al-Bahgdadi followed with a progressive ionization or successive root formation explanation rather than a single arc foot propagating across the surface [5]. The authors experimentally detected currents flowing in the pollution layer after the arc foot had passed, confirming multiple arc roots.

Static models also attempted to quantify arc propagation speed. Boylett and McLean experimentally found that the arc speed increased with magnitude of current, indicative that discharge growth occurred by ionization avalanches [6]. They also found discharges along the arc channel to the surface, confirming Wilkins and Al-Bahgdadi in disproving the notion of a single arc foot at each end of the breakdown. In an attempt to answer the propagation mechanism question, Mercure and Drouet used ring probes embedded in the electrolyte to measure the surface currents [7]. They also burned an arc between two plates sloping towards one another, and found propagation in the direction of decreasing

gap where field strength and resulting arc current density increased, suggesting propagation by thermal ionization.

A good review of the static concepts prior to Mercure and Drouet can also be found in Rizk's 1981 CIGRE review paper [8].

III. SURFACE INTERACTION EFFECTS

Although research on surface interaction effects in air had really begun in the 1960s, progress in the field has accelerated with publication of Virouroux et al in the 1980s [9]. The field of research has ultimately converged on two possible surface flashover involvement mechanisms: secondary electron emission avalanche (SEEA), and electron cascade.

SEEA involves the high electric field stresses felt at the cathode causing field emission of electrons from the "triple junction" between the insulator, cathode, and air (gas) surroundings. Some electrons travel outwards into the gas, but some travel along the surface colliding with it. By an elastic collision with atoms in the surface, impact ionizations occur that release additional "secondary" electrons along with the primary electrons out from the surface layer. Some of these primary and secondary electrons may produce tertiary electrons from surface impact ionizations, and so on. The space above the surface is filled with negative charge undergoing charge amplification, and the surface is positively charged. The insulator surface being positively charged adjacent to the electrode enhances the electric field stress at the triple junction causing more electron ejection by field emission until avalanche occurs in the ionized gas layer above the surface, and breakdown occurs.

Another surface interaction mechanism proposed for surface flashover is electron cascade whereby electron propagation occurs within the insulator surface. This is explained by energetic electrons (or photons given off from impact ionizations above the surface) colliding with the surface and exciting surface electrons from the valence into the conduction band via electron impact or photonic excitation. This excitation can also occur from injection of electrons into the insulator via quantum tunneling at the cathode/insulator junction. The conduction band electrons are propagated through the insulator by the electric field across it. This mechanism also leads to the expulsion of electrons from the surface due to ionizing collisions within the surface, and production of positive "holes" in the valence band.

To include one of these methods in a flashover model, we need to quantify our qualitative description. With regard to ejecting electrons from the surface in SEEA, it seems logical to just apply the material work function to assess how much energy an incoming electron or photon needs in order to eject another electron from the surface. However, conductors have electrons in a conduction band energy level, whereas dielectric insulators have their electrons in the valence band. To eject electrons from the insulating surface the incoming electron or photon's energy must exceed that which is needed to raise the electron first from the valence band to the conduction band, and then supply the work function with enough energy to expel the electron from the surface [10].

Another mathematical relationship to link the surface effect with whatever arcing/breakdown model we are using above the surface (i.e. streamer-leader model) is the

ratio of the yield of ejected to primary electrons, existing in the form of an equation called the secondary-electron yield curve

$$\delta = \left(\frac{B}{\zeta} \right) \left(\frac{An}{\alpha} \right)^{\frac{1}{n}} (\alpha d)^{(1/n-1)} (1 - \varepsilon^{-\alpha d}) \quad (2)$$

where δ is the yield, B is the escape probability, ζ is the secondary electron excitation energy, α is the secondary electron absorption constant, A is the primary electron absorption constant, d is the maximum penetration depth of the material, and n is the power law exponent [11]. For reasons not developed here, further concepts around δ are used to show the range of primary electron energies that will produce a secondary electron yield $\delta \geq 1$, and this may prove that the electron cascade model is "highly suspect". For a discussion on this, the reader is directed to [12]. Thus, we will concentrate on using SEEA.

IV. AVALANCHE-STREAMER-LEADER MODELING

The first models used to represent streamers, leaders, and arcs were fluid approximations and rigorous analytical models. The fluid approximation is a mathematical formulation of charge growth, diffusion, and drift analogous to a fluid growing and distorting in space from field forces pushing and stretching it. It is represented by an electrohydrodynamic mathematical model, and is often used to model avalanche and streamer progression at the head of a leader.

The analytical method involves a different approach, and is usually used for arcs, but can be employed for the leader. The arc or leader channel is modeled as a mathematical cylinder encompassing a plasma (expressed by its conductivity), an electric field, and a temperature. This mathematical structure is called the Elenbass-Heller energy balance equation and was designed to model a channel of equilibrium plasma. As the leader is an equilibrium plasma, it can be represented by

$$-\frac{1}{r} \frac{d}{dr} rJ + \sigma(T)E^2 = 0, J = -\lambda \frac{dT}{dr} \quad (3)$$

where r is the radial distance outwards from the axis of the cylindrical channel, E is the electric field, $\sigma(T)$ is conductivity of the plasma, and $\lambda(T)$ is diffusion constant of the gas (both functions of $T =$ temperature) [13]. Boundary conditions at $r=0$ are $T=T_{m(max)}$ and $dT/dr = 0$, and $T=T_w$ at $r=R$ which is the "wall" of the cylinder. E is known in the equation, but is usually expressed in terms of its relation to current in Ohm's law

$$i = E \int_0^R 2\pi r \sigma dr \quad (4)$$

Equations 3 and 4 are a nonlinear system. Steenbeck's 1932 method of solution is employed to solve the system, whereby $\sigma(T)$ and $\lambda(T)$ are both replaced with $\sigma(\Theta)$ with Θ being a heat flux potential function

$$\Theta = \int_0^T \lambda(T) dT = \frac{W}{2\pi} \ln \frac{R}{r_0}, W = \frac{i^2}{\pi r^2 \sigma_m}, i = \pi r_0 \sigma_m E \quad (5)$$

with W the power released per cm of the column. Elenbaas-Heller does not allow for radiation losses from the cylinder, so a thin tube of radius r_0 is set up as the conductive channel and the region from r_0 to R functions as a region of zero charge allowing radiation through the r_0 boundary. Thus, for the thin tube of radius $r_0 \ll R$, $T = T_m$, and $\sigma = \sigma_m$ in the tube, and $\sigma = 0$ outside the tube. Creating these equations required Steenbeck to use the principle of minimum power where the temperature in the tube must end up at a value such that the power W is minimized. This validity of this assumption has been debated up to today. With this formulation, three unknowns exist: T_m , r_0 , and E . An integration of (3) with an assumption of uniform energy σE^2 in the channel allows for an expression describing the heat flow through the tube walls due to radiation and diffusion of energetic particles as $4\pi\lambda_m(T_m - T_0) = i^2/\pi r^2 \sigma_m$ but this gives us T_0 , which is another unknown. Defining the outer radius as the point where the conductivity drops by a factor of e , Steenbeck formulated an expression relating T_m to W

$$T_m = \left(\frac{I}{8\pi\lambda_m k} W \right)^{1/2} \quad (6)$$

where I is the current from Saha's equation formulation

$$I = N_e e b E (\pi r_0^2) \quad (7)$$

with N_e the electron density and b the electron mobility under the field E [14].

V. DISCUSSION AND RECOMMENDATIONS FOR FUTURE RESEARCH

Modeling a flashover on a dielectric surface would seem to require interaction between the streamer-leader mechanism and the surface mechanisms. Hence, linking the supplying of electrons from the dielectric surface in the surface models (i.e. the electron yield δ and the work function/valence to conduction band energy requirements) to the model representing the leader above the surface would be necessary. The Elenbaas-Heller/Steenbeck analytical model with its component of "energy" in the form of temperature $T_m - T_0$ leaving the side of the inner cylinder would be a starting point towards this calculation, and a completely valid one given the experimental observations of Boylett and McLean. This temperature difference is from energy leaving the cylinder uniformly around the circumference in the form of photons and electrons. With the leader or arc channel horizontally parallel to the surface and above it, one could calculate the equivalent amount of electrons leaving the cylinder downwards and interacting with the surface by deducing the percent of the circumference facing downwards from which electrons and photons could collide with the surface. From the yield ratio and the numbers of elec-

trons and photons colliding with the surface, the increment to the electron/ion concentration at the height of the leader due to the surface interaction could be calculated. This additional electron/ion base would then enter the cylinder as current from the streamer head, increasing the conductivity σ within the cylindrical leader model.

Some authors have indicated that for understanding of the flashover mechanism to progress, a method of measurement of the electric field E within the streamer and leader must be developed [13] and [14] as there is a lack of data on channel field distributions, and calculations are due to indirect evaluations and assumptions [14]. Advantages of actual experimental knowledge would allow for the verification of Hampton's criteria for arc propagation, and an evaluation of the average value of E_{arc} often calculated from V_{arc}/x in static models. Criticisms exist of the Elenbaas-Heller model (as well as other approaches) being rife with assumptions that may be giving a deceptive understanding of the mechanisms at work. Observations exist that are not explainable by electrohydrodynamic models, such as electron runaway from the positively charged tip of a streamer exhibiting a strong field [13]. In employing Elenbaas-Heller for leader modeling, debate continues as to the validity of Steenbeck's use of the minimum power principle [15], [16], and [17]. The authors find that "error incurred by the use of Steenbeck's principle is uncontrollable and may be unacceptably high" [15].

In theory, obtaining the electric field of a streamer or leader can be done by obtaining the charge distribution, and then analytically calculating the electric field using the charge distribution as a source. One suggested method would be to use multiple antennas in triangulation to read the signal from the discharge and then use interpolation with signals from known controlled benchmark distributions to deduce the unknown distribution. Another suggestion for investigation is the incorporation of mathematical inverse methods to assist in this approach. Based on consultation and feedback, we hope to pursue investigating the experimental determination of the electric field in the streamer/leader and building a channel model incorporating surface interaction in the future in an effort to advance dielectric flashover theory.

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