High Voltage Engineering

Lecture # 6
Kanal Discharge
(Townsend's Secondary Coefficient)
& Paschen's Law

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Electron Avalanche
Electron Avalanche Triggering More Avalanches

When Space Charge Concentration increase beyond $10^7$ or $10^8$ i.e. noe

$n_0e^{ax}$ exceeds $\sim10^7$ to $10^8$
Streamer Breakdown or Kanal Discharge

Development of streamer in nitrogen at 200 Torr
Breakdown in Uniform Fields
(Small Gap Distances, d in mm)

When Gap Distance d between electrodes in a uniform field is very small (in mm range), α is still a very small value even at Breakdown Field Intensity

For the above conditions, the space concentration could not acquire its critical amplification (the number of electrons ~ $10^8$)

The charge carriers (electrons) are also released in these conditions from the electrode surface (secondary or γ Process)
Secondary or $\gamma$ Process

- The secondary processes are ionization of the gas caused by the positive ions, photons and the excited molecules, basically ejection of Electrons from the cathode surface:

  ✓ Positive Ion Effect ($\gamma_{\text{ion}}$)
  ✓ Photon Effect ($\gamma_p$)
  ✓ Metastable Effect ($\gamma_m$)

The three processes of cathode effect are described quantitatively by a coefficient $\gamma$ as follows

$$\gamma = \gamma_{\text{ion}} + \gamma_p + \gamma_m$$
Townsend’s Second Ionization Coefficient

“The number of secondary electrons on an average produced at the cathode per electron generated by the primary process, that is per ionizing collision in the gap”

\[ \gamma \] strongly depends upon the cathode material and it is a function of field intensity and pressure of the gas

\[ \gamma = f(\frac{E}{p}) \]

Like \( \alpha \), \( \gamma \) also represents a probability process
Townsend’s Second Ionization Coefficient

If the mean number of secondary electrons per avalanche produced are $\mu$, then

$$\mu = \gamma (e^{\alpha d} - 1)$$

If the primary electron generation process begins with $n_o$ number of electrons, the second generation begins with $\mu n_o$ number of electrons.
Development of Conduction Current Uptil Breakdown

\[ I = I_0 e^{\alpha U} \]

\( \alpha \) or Primary Process Current

Photo Electric Current

\( \gamma \) or Secondary Process Current
Development of Conduction Current

In the event of positive ion space charge distorting the field, the amplification of $\alpha$ which increases with distance and time is given as

$$I = I_0 e^{\alpha d}$$

$\mu(t)$ can be written as then

$$\mu(t) = \gamma \left\{ \exp \left[ \int_0^d \alpha(x, t) \, dx \right] - 1 \right\}$$
Development of Conduction Current

The movement of charge carriers (electrons and positive ions) in the gap is responsible for the growth of circuit current.

The saturation level of the curve in (region II) is also called the steady state region.

The number of positive ions diffusing per second at the cathode are just equal to the number of newly-formed electrons arriving at the anode, the steady state growth of electronic current in this region can be given by

\[ I = I_0 e^{\alpha d} \]
Development of Conduction Current (III Region)

\( n_0 = \) the number of electrons emitted by primary process from the cathode (at \( x = 0 \)) per second. In other words, \( n_0 \) avalanche develop in uniform field at the cathode with initial electrons

\( n_0' = \) the number of secondary electrons produced at the cathode per second.

\( n_0'' = \) the total number of electrons leaving the cathode per second.

\[ n_0'' = n_0 + n_0' \]
Development of Conduction Current (III Region)

Each electron leaving the cathode makes on an average \((e^{ad} - 1)\) collisions in the gap \(d\)

the total number of ionizing collisions per second in the gap will be

\[n_0'' (e^{ad} - 1)\]

\[\gamma = \frac{n_0'}{n_0'' (e^{ad} - 1)}\]

\[n_0' = \gamma \cdot n_0'' (e^{ad} - 1)\]

\[n_0'' = n_0 + n_0'\]

\[n_0'' = n_0 + \gamma n_0'' (e^{ad} - 1)\]

\[n_0'' = \frac{n_0}{1 - \gamma (e^{ad} - 1)}\]
Development of Conduction Current (III Region)

\[ n''_0 = \frac{n_0}{1 - \gamma(e^{\alpha d} - 1)} \]

The number of Electrons arriving at the anode is given by

\[ n_d = n''_0 e^{\alpha d} \]

\[ n_d = \frac{n_0 e^{\alpha d}}{1 - \gamma(e^{\alpha d} - 1)} \]

\[ I = \frac{I_0 e^{\alpha d}}{1 - \gamma(e^{\alpha d} - 1)} \]
Development of Conduction Current (III Region)

\[ I = \frac{I_0 e^{\alpha d}}{1 - \gamma (e^{\alpha d} - 1)} \]

The denominator has \( \gamma (e^{\alpha d} - 1) = \mu \) i.e. mean number of secondary electrons per avalanche produced

For \( \mu \ll 1 \), the secondary ionization or \( \gamma \) process is insignificant i.e. above relation reduces to

\[ I \approx I_0 e^{\alpha d}. \]
Condition of Breakdown

So condition of Breakdown would be

\[ \mu = \gamma (e^{\alpha d} - 1) = 1 \]

Or if \( e^{\alpha d} \gg 1 \)

\[ \gamma e^{\alpha d} = 1 \]

Townsend’s Criteria for Spark Breakdown in Electropositive Gases

If \( \alpha \) is constant throughout the gap length
The discrepancy in Townsend’s Mechanism was the calculation of time required for breakdown which took drift velocity of electrons into consideration. The time was too long, contrary to the actual time measured experimentally for large gap lengths.

The missing link was the effect of Space charge called as Eigen Space Charge due to avalanche created that produces the instability

\[ n_0 e^\alpha x_c \approx 10^8 \]

\[ \alpha x_c = \alpha d_c = \ln 10^8 = 18.4 \]
Breakdown with Streamer
(Streamer or Kanal Mechanism) Large gap Length

Equation by Raether keeping in view the Space Charge Electric Field

\[
\alpha x_c = 17.7 + \ln x_c + \ln \frac{E_a}{E_0}
\]

The condition for transition from series of avalanche to streamer breakdown assumes that this eigen space charge field approaches nearly equal to the externally applied field \((E_a \approx E_0)\)

For \(\alpha x_c = \ln 10^8\), \(x_c\) works out to be equal to 2.01 cm
Paschen’s Law

• “The Break down Voltage $U_b$ of a gaseous Dielectric is a unique function of the product of Pressure $p$ and Distance $d$ over a large range of Pressure
Today’s Text Covered from Chapter 3 of IEEE Press Book  (Ravindra Book)  
Uptil Article 3.2.5