HIGH VOLTAGE ENGINEERING - UNIT 2

1. Electrical Breakdown of Gases in Quasi-Uniform Fields

Quasi-Uniform Fields

By this meant an electrode gap where the ratio of the maximum and minimum fields is less than about 10. Common examples are electrode systems where one electrode is a rod and the other is a tube and both are coaxial.

The avalanche size is given by

$$n(x) \;=\; exp(\int \acute{\alpha}(E).dx)$$

(See page 1.4). If $\acute{\alpha}$ is known as a function of E ,and E is known as a function of x, the avalanche size can be determined. If analytical expressions are not known for these functions, or cannot be integrated, numerical integration can be used.

See ‘Example – quasi-uniform fields.pdf’.

2. Electrical Breakdown of Compressed Gases in Uniform Fields

Introduction

The electrical breakdown strength of gases increases with pressure, as may be seen from the Paschen's Law graph (page 1.6). Why? As the pressure increases the mfp *decreases* and so a higher electric field is required in order that the electrons may gain sufficient kinetic energy (k.e.) between collisions to cause ionisation. However, it is found that Paschen's Law no longer applies for pressures above about 5 bar, *unless* great care is taken

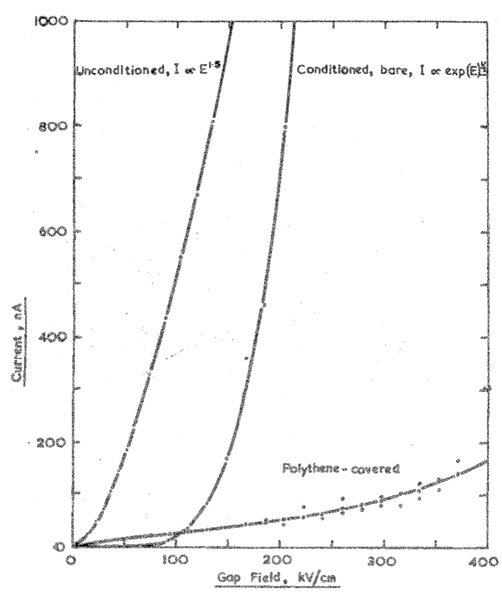
- to limit the emission current from the cathode and
- to avoid the presence of dust, particularly conducting particles.

The higher the pressure the harder it becomes to avoid the effects of cathode emission currents and dust.

Electron Emission Currents

The graph at the right shows the very high currents caused by field-enhanced electron emission. The 3 graphs refer to plane-parallel electrodes:

- the electrodes just after being manufactured and polished (top graph),
- the same after several breakdowns (middle graph), and
- the same with a thin (0.1mm) layer of polythene stuck to the surfaces (lowest graph).



There are two mechanisms by which such emission can occur: (a) Schottky and (b) Fowler-Nordheim emission.

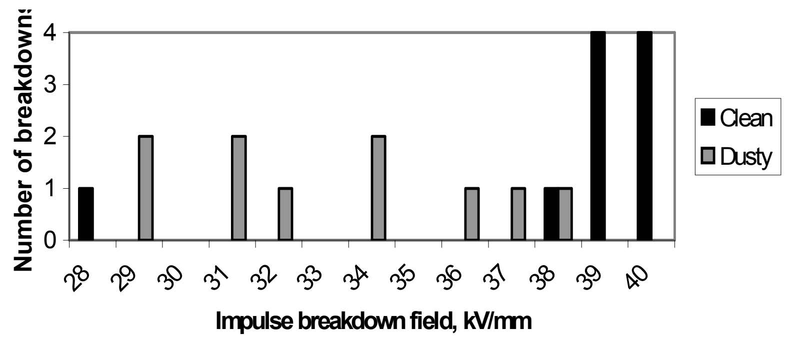
Simply explained, Schottky emission is the effect of a high field in reducing the work function, that is, the energy which electrons need in order to leave the metal; and Fowler-Nordheim emission is a quantum mechanical effect by which electrons can 'tunnel' through a thin potential wall.

The latter requires virtually perfectly clean surfaces and is therefore only possible in near vacuum conditions. In all practical cases, therefore, only Schottky emission or 'field-enhanced thermal emission' occurs.

$$\text{Current density, } J = AT^2 . \exp(-B\sqrt{E}/T)$$

where E is the electric field at the surface, T is the temperature in degrees Kelvin and A & B are constants. It requires relatively high electric fields at the surface, before significant emission occurs, and so does not greatly affect breakdown at atmospheric pressure.

The breakdown of nitrogen at 15 bar and a 2mm electrode separation

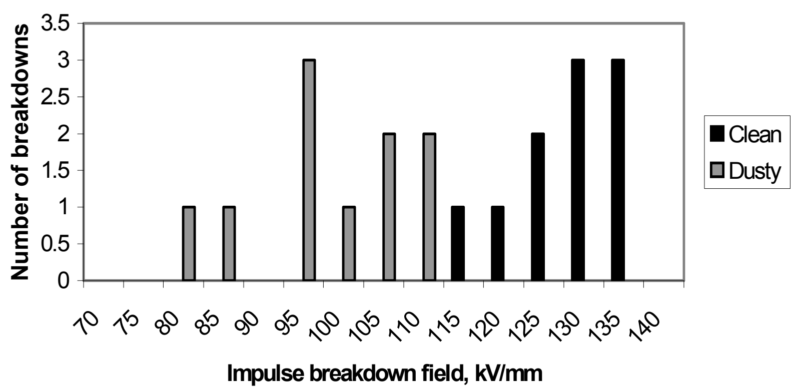


The two histogram figures demonstrate the effect of dust on the impulse strength of nitrogen (above) and SF_6 (next page) at 15 atm - a lowering of the breakdown strength by some 30 to 50%, even with polythene-covered electrodes stopping electron emission.

Clearly imperfections such as emission currents and dust are the cause of the breakdown voltages for high pressure gases being lower than expected from Paschen's Law.

Why does dust cause problems, and increasingly so as the pressure increases? Why do emission currents cause problems, and what causes them?

The breakdown of SF_6 at 15 bar and a 2mm electrode separation



Why does dust cause a problem?

This illustration is merely for interest and for those of a mathematical bent.

The answer lies in the exponential relationship between α and E, as the following example will show.

Consider a conducting particle of 10-μm size attached to one electrode: suppose, for simplicity, it enhances the field by a factor of 5 for the first 5 μm, 3 for the next 5 μm and 2 for a further 5 μm. First, the breakdown field for the case without a particle is calculated, using simple equations for α(E) and assuming breakdown occurs for αd=18.4 – since this is the criteria for streamer formation across the gap.

Then, for 4 different pressures and some value of E, the values of α.Δx for these 3 regions and the rest of the gap are calculated. **By trial and error the value of E is found which makes Σ(α.Δx) = 18.4 (I used Excel).**

The results are tabulated below. The value of E with a particle present is compared with the value for a clean gap – without any particles present – and it is seen that the effect of particles is very small at atmospheric pressure but rapidly becomes very significant.

Air pressure (in bar)	**1**	**5**	**10**	**15**
α/p = 18.4/(p*10*1100) =	1.84	0.368	0.184	0.1227
ln(α/p1100) = -27.4*p/E =	-6.393	-8.003	-8.696	-9.101
∴without particle, E (in kV/mm) =	4.29	17.12	31.51	45.16
By trial and error: main gap field, with particle =	4.20	16.15	28.61	39.54
∴First 5 μm: α.Δx =	1.49	5.04	8.100	10.32
∴Second 5 μm: α.Δx =	0.62	1.63	2.26	2.58
∴Third 5 μm: α.Δx =	0.21	0.40	0.46	0.46
∴Rest of gap, α.10 =	16.07	11.37	7.61	5.04
Sum across gap of all these α.Δx =	18.40	18.43	18.43	18.40
∴E(with particle)/E(without) =	0.980	0.943	0.908	0.876
Percentage strength reduction =	**2.1**	**5.7**	**9.2**	**12.4**

In case this is not clear, the full calculation is given overleaf for the 5 bar case. (N.B., as usual, all quantities are in units of kV, mm, bar and their combinations.

For the uniform-field case (**no particle**), at 5 bar,

$$\exp(\alpha d) = 10^8, \quad \text{i.e.,} \quad \alpha d = 18.4, \quad \text{so} \quad \alpha = 1.84\ /\text{mm}$$

$$\text{But} \quad \alpha/p = 1100 \exp(-27.4\ p/E)$$

$$\text{So} \quad 1.84/5 = 1100 \exp(-27.4 * 5/E)$$

$$\therefore \quad E = 17.12\ \text{kV/mm}$$

For the uniform-field case **with** a particle, at 5 bar, using E = 16.15 kV/mm,

$$\exp(\int \alpha.dx) = 10^8, \quad \text{i.e.,} \quad \int \alpha d = 18.4 \approx \Sigma\, \alpha.\Delta x$$

$$\text{Since} \quad \alpha = 5*1100*\exp(-27.4\ p/E)$$

$$\therefore \quad \alpha_1.\Delta x = 5*1100*\exp(-27.4\ p/5E) *5*10^{-3} = 5.04$$

$$\therefore \quad \alpha_2.\Delta x = 5*1100*\exp(-27.4\ p/3E) *5*10^{-3} = 1.63$$

$$\therefore \quad \alpha_3.\Delta x = 5*1100*\exp(-27.4\ p/2E) *5*10^{-3} = 0.40$$

$$\therefore \quad \alpha_4.\Delta x = 5*1100*\exp(-27.4\ p/E) *9.975 = 11.37$$

$$\text{Sum,} \qquad \boldsymbol{\Sigma\, \alpha.\Delta x = 18.4}$$

Repeat calculation – but for SF_6

Consider the same conducting particle of 10-μm size attached to one electrode and again enhancing the field by a factor of 5 for the first 5 μm, 3 for the next 5 μm and 2 for a further 5 μm. The breakdown field for the cases with and without a particle are calculated in the same way, but assuming breakdown occurs for αd=16.1, this being the criteria for streamer formation across the gap for SF_6.

Again it is seen that the effect of particles is very small at atmospheric pressure but rapidly becomes very significant, indeed disastrous, for SF_6.

SF_6 pressure (in bar)	**1**	**5**	**10**	**15**
∴without particle, E (in kV/mm) = (230*p +1.61) / 26 =	8.91	44.29	88.52	132.75
By trial and error: main gap field, with particle =	8.88	25.66	37.60	48.65
∴First 5 μm: α.Δx =	4.62	10.93	12.94	14.37
∴Second 5 μm: α.Δx =	2.31	4.26	3.16	1.72
∴Third 5 μm: α.Δx =	1.16	0.92	(-1.72)	(-4.60)
∴Rest of gap, α.10 =	8.01	(-4821)	(-13204)	(-21818)
Sum of positive α.Δx values =	16.10	16.11	16.10	16.10
∴E(with particle) / E(without) =	0.996	0.579363	0.425	0.366
Percentage strength reduction =	**0.4**	**42.1**	**57.5**	**63.4**

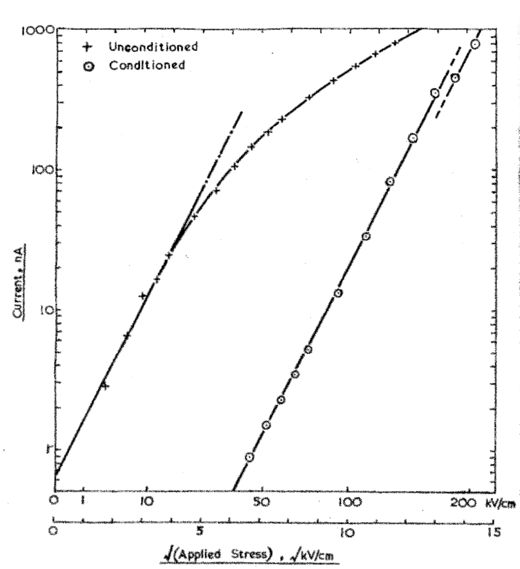
Note: for most cases in SF_6 the value of α is negative for the main gap, so K is determined for the enhanced area only.

The 'Jumping Particle' Mechanism

Another possible breakdown mechanism involving dust particles is the 'jumping particle' mechanism: dust particles on the electrodes will become charged to the same potential and therefore be attracted to the opposite electrode. If light enough, they will accelerate towards the other electrode and, it is suspected, discharge by a minute spark when a few micrometres away, just before contact is made. It has been shown that at high pressures electrical breakdown can easily be 'triggered' by small injections of plasma – ionised gas – into the gap.

Electron Emission

When the bare-electrode graphs of the emission figure on page 2.1 are re-plotted for the Shottky relationship, as log(emission current) versus √(electric field), a good straight line was obtained – as seen on the right. This shows that the emission was indeed the Shottky 'field-enhanced thermal emission' process and not the Fowler-Nordheim quantum-mechanical barrier-tunnelling one.



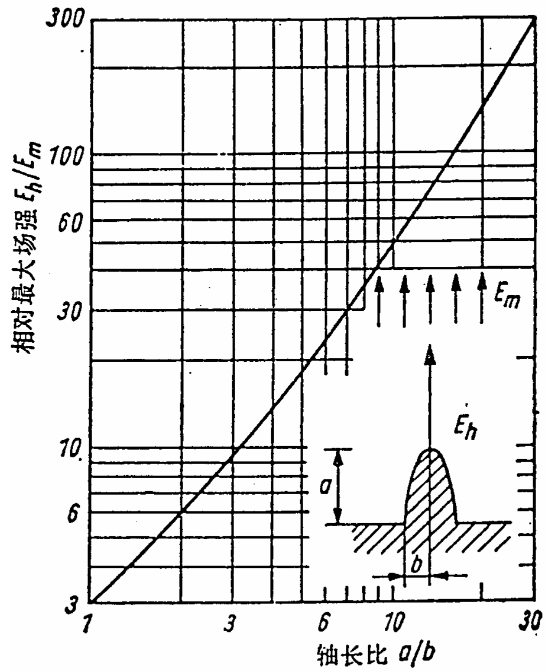
As stated above, in a good vacuum it is likely that the mechanism for electron emission is the Fowler-Nordheim one, but for compressed gases the necessary thin energy barrier could not exist as the surfaces of metals are covered in thin layers of tarnish such as moisture, oxides and surface-adhering gas molecules – there is no such thing as a clean surface at sub-microscopic levels. Consequently Schottky emission has to be assumed.

Virtually all the electron emission takes places at tiny protuberances – little 'hills' of micron dimensions – on the surface of conductors where the field there may be magnified several times.

These can cause the electron emission to increase by several orders of magnitude. Typically 90% of the emission from a surface will come from a few of these 'hot spots'. The figure shows the field enhancement caused at the tip of a 'hill' shaped as half an ellipsoid of revolution.

Note that even a hemispherical 'hill' has a field enhancement by a factor of 3 at its top.

The very high number of electrons emitted from the top of the 'hill' are more likely to form avalanches which can transform into streamers in the high-field area near the emission point.



In addition, the avalanches do not need to become so large, in order to transform into streamers, as there are many developing in parallel, all adding to the field distortion – which is what causes streamer development.

Conditioning of Electrodes

The lowering of breakdown strengths by the very high electron emission currents from bare electrodes at the high electric fields which can be reached at high pressures also need explaining. The electron emission tends to be from very small areas where a pointed protuberance (=a microscopic 'hill') enhances the field. However the very high current densities further distort the field locally leading to streamer-type breakdown mechanisms. Consequently gas gaps between bare electrodes will break down at very low voltages initially.

After several breakdowns the breakdown voltage will stabilise at a higher level: it is believed that this reflects the 'burning off', of areas of high emission and of particles of dust on the electrodes. The energy released by the spark burns, vaporises or melts the surface protuberances and dust particles. The electrodes are then said to be 'conditioned'.

This agrees well with the graphs on page 2.1 and 2.4 where it is seen that the emission from the 'unconditioned' electrodes greatly exceeds that of the 'conditioned' electrodes. Also near the top of the conditioned-electrodes graph there seem to be a break where the emission decreases by what at first sight may appear a small amount, but is in fact a decrease by a factor of two. A reasonable explanation would be that the emitter of the highest current was melted by the current and ceased emitting.

Consequences and cautions

The effect of dust and electron emission in reducing the breakdown strength of gases from the values calculated using the streamer criterion has been demonstrated, but we cannot estimate the actual breakdown voltage. The field above the irregularity (dust or 'micro-hill') IS increased, so avalanches can form there easily. Electrons ARE emitted, so multiple avalanches can form simultaneously – presumably 100 avalanches of 106 electrons distort the field much as an avalanche of 108 electrons would. But we obviously cannot know what irregularities are present – their sizes and numbers.

Furthermore, even if we could know that the conditions are such as to cause a streamer to form in the enhanced-field region above a particular irregularity – this does not mean breakdown will occur.

For example, in SF6, the field away from the enhanced-field region will probably be below the critical field and therefore the streamer will only develop in the high-field region. This localised streamer will act as a conducting extension of the irregularity - causing a new enhanced-field region at the streamer's tip. But whether this will be sufficient to cause a further streamer, and thus be a self-propagating phenomena, leading to complete bridging of the gap and complete breakdown, is obviously unknown.

In general, practical applications of compressed gases are in general restricted to a maximum of about 5 bar, as a result of the many uncertainties and problems with the use of highly compressed gases, that is, the difficulties in achieving both a dust-free system and low electron emission rates.

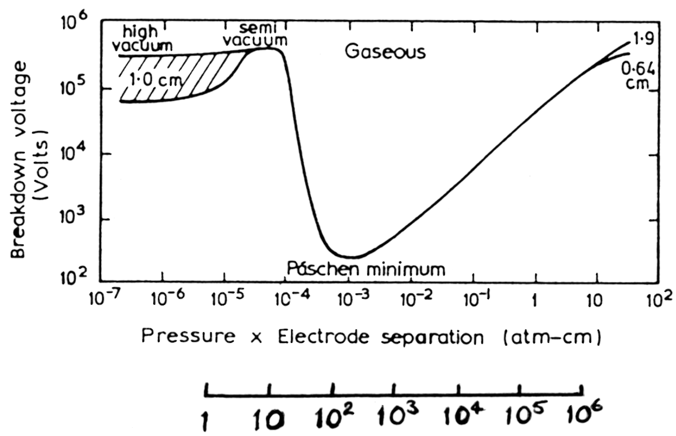
3. Electrical Breakdown in Vacuum

Surprisingly, vacuum breakdown is a topic which has much in common with breakdown in compressed gases in that it is largely controlled by the imperfections. These are of two kinds: small areas of very high electron emission from small protuberances (very small pointed 'hills') on the electrode surfaces; and the presence of free particles.

In a vacuum of 1 μbar (=10^{-3} torr) the average distance between collisions is about 50 mm so no avalanche or streamer breakdown can take place.

Small conducting particles will increase the field at their own surface and there may then be high levels of electron emission from their surface.

However, high-field emission of electrons from small sites ('hills' or conducting particles) on the cathode surface causes local heating of the *anode* surface opposite, where the 'jet' of electrons impacts. This impact area will be very small since there is no spreading out of the beam of electrons since there are no collisions with gas molecules. Furthermore the current density at the emission source may be sufficient to cause melting or even explosion of the cathode protuberances, if it is pointed enough.



The extra scale shows the number of mean free paths in the gap width,
i.e., the number of times an electron will – on average – collide
(elastically or inelastically) with molecules in crossing the gap

The heating at the point where the electrons impact causes the release of metal vapour and absorbed gases from the metal surface. It is this resulting vapour which breaks down.

Thus, in a vacuum of better than 1 μbar, the breakdown strength is related to the electric field and to the condition and material of the electrodes, and not to the actual level of vacuum. There is therefore no difference between a l-μbar, or a 0.0l-μbar, vacuum as far as breakdown strength is concerned.

The small protuberances causing the high-density electron emission can be removed by medium-energy 'conditioning' of the electrodes, again, as is the case with compressed gases.