Switching Notes

Note 35

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Electron Drift Velocity and Ultrafast Gaseous Switching

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Abstract

Ultrafast switching (100 ps domain) depends on extremely fast electrical pulses generated by mm spark gaps at high gas pressure (typically H_2). The electron drift velocity under such breakdown conditions is too slow to explain the observed switching times. A type of experiment is suggested.

1 Introduction

As we push the limits of ultrafast switching we are concerned with switching hundreds of kilovolts (kV) in picosecond (ps) times. Practical results have been obtained for high-power impulse-radiating antennas (IRAs) [1, 2]. In the first case 120 kV was switched in less than 100 ps into an impedance of roughly 200 Ω using a gaseous hydrogen switch with a mm gap operated at 100 atm. pressure. In the second case almost 1 MV was switched in less than 200 ps with a switch gap of a few mm in flowing oil, feeding an 85 Ω load.

Some simple models for this ultrafast switching are presented in [3]. Three processes are considered:

1. Growth rate of an electron avalanche
2. Velocity of electromagnetic propagation in the switch region
3. Inductance of the arc

For 100 Ω loads this gave an estimate for the maximum rate of voltage rise as roughly $6(10^{15})$ V/s.

The resistive phase formulas in [4] give various times ranging from 2 ps to 0.4 ns. Clearly experimental results with IRAs (0.1 ns) are considerably out of the domain of previous measurements. This leads one to prefer the faster formulae. Also the observed rise times are possibly larger than the switching time due to electromagnetic propagation in the switch/lens region (non-ideal geometry for wave launching into the lens).

As we move to faster and faster high-voltage switching, it is important to have better physical models for the switching process. The present paper explores another physical process, the speed of electron drift across the switch gap in gas.

2 Electron Drift

The point here is that it takes time for an electron to cross the switch gap. This time may also be a limiting factor in switching speed. Consider Fig. 2.1. As we shall see, the speed of electron drift is much less than c.

Electron drift at a speed v_e is given by (SI units)

$$v_e = \mu_e E \tag{2.1}$$
$$\mu_e \equiv \text{electron mobility}(\mathrm{m}^2\mathrm{V}^{-1}\mathrm{s}^{-1}).$$

So now we need to appeal to measurements. Back in the 1960s we were very concerned with this in the context of air conductivity for the nuclear electromagnetic pulse (EMP) [5, 6, 7]. For this purpose A. V. Phelps gave the first author his original detailed plots of electron drift speed as well as other parameters for dry and moist air. See also [8, 9]. Other measurements of these parameters were also sponsored under the EMP program [10, 11, 12]. Yet other measurements were made under other sponsorship, e.g., [13, 14].

Now we are concerned with various gases such as might be used as switching media. Hydrogen is often used for this purpose due to its fast recombination time for repetitive pulsing, and its reducing

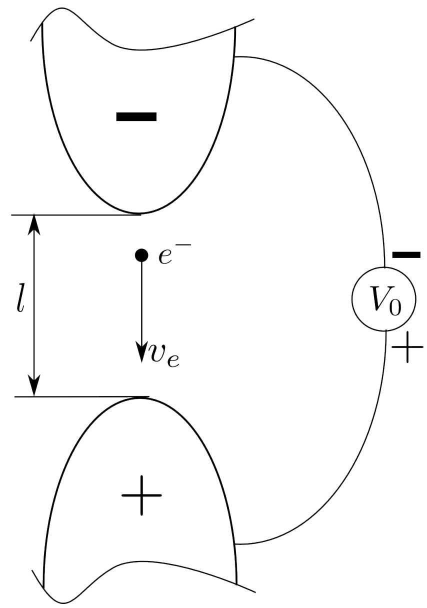


Figure 2.1: Electron drift across switch gap

character (non-oxidizing) for the switch electrodes (typically copper tungsten). Measurements of electron drift in hydrogen are reported in [14].

Consider first air. As in [7] we see that for large electric fields (EN_0/N) the electron mobility is not significantly dependent on the water vapor content. As we approach electrical breakdown at a few MV/m we see that the electron mobility has dropped to about 5×10^{-2} m^2/(Vs) from its much larger values at low fields. Near breakdown then, we have a drift velocity of (from [7])

$$v_e = \mu_e E = [5 \times 10^{-2}][3 \times 10^6] \simeq 1.5 \times 10^5 \text{ m/s} \tag{2.2}$$

Note that while μ_e scales as $\mu_e N/N_0$, it is a function of EN_0/N. Thus this speed near breakdown is independent of N (molecular density of air). As one goes to higher pressures and allows smaller switch gaps for a given voltage, the above speed remains about the same. We might call this an electron breakdown speed. As one exceeds DC breakdown field ($\simeq$3 MV/m at STP) the number in (2.2) can become a little larger, but one is in avalanche conditions.

Additional measurements for air are found in [14]. They find for

$$\begin{aligned} \frac{E}{N} &= 4 \times 10^{-19} \text{ V m}^2 \\ v_e &= 3.96 \times 10^5 \text{ m/s} \end{aligned} \tag{2.3}$$

This corresponds at STP to

$$\frac{EN_0}{N} = [4 \times 10^{-19}][2.68 \times 10^{25}] = 10.7 \text{ MV/m} \tag{2.4}$$

which is significantly in an avalanche region (above breakdown). Going down to about 3 MV/m we have

$$\begin{aligned} \frac{E}{N} &\simeq 1.3 \times 10^{-19} \text{ V m}^2 \\ v_e &\simeq 1.4 \times 10^5 \text{ m/s} \end{aligned} \tag{2.5}$$

which is in approximate agreement with (2.2). Note that in this and some other papers E/N is given in units of Td where

$$\begin{aligned} \mathrm{Td} &\equiv \text{Townsend (after John Sealy Townsend)} \\ 1\mathrm{Td} &= 10^{-21}\mathrm{Vm}^2 = 1\ \mathrm{zVm}^2 \\ \mathrm{z} &\equiv \text{zepto} = 10^{-21} \end{aligned} \tag{2.6}$$

Some measurements [14] have also been made in hydrogen. They find for

$$\begin{aligned} \frac{E}{N} &= 2.5 \times 10^{-19}\ \mathrm{V\ m}^2 \\ v_e &= 4 \times 10^5\ \mathrm{m/s} \end{aligned} \tag{2.7}$$

This corresponds at STP to

$$\frac{EN_0}{N} = [2.5 \times 10^{-19}][2.68 \times 10^{25}] = 6.7\ \mathrm{MV/m} \tag{2.8}$$

This is above breakdown, which is about half that of air or 1.5 MV/m at STP [15]. This gives [14]

$$v_e \simeq 6 \times 10^4\ \mathrm{m/s} \tag{2.9}$$

or about 40% that of air. So it would seem that about 10^5 m/s is an appropriate drift velocity for electrons at breakdown conditions. This applies to both air and hydrogen (albeit with a lower breakdown field in the latter case). In avalanche, the speed can be a little larger.

3 Electron Drift Time Across mm Gap

Consider a 1mm gap. This is appropriate for 100 kV and 100 atm. of H_2. Then we have

$$\begin{aligned} l &= 1\ \mathrm{mm} \\ v_e &= 6 \times 10^4\ \mathrm{m/s} \\ t_d &= \frac{l}{v_e} \equiv \text{ drift time } \simeq 17\ \mathrm{ns} \end{aligned} \tag{3.1}$$

This is much larger than the observed rise times cited previously. So this time cannot explain the observed rise times.

Returning to Fig. 2.1, there must be another mechanism to explain the fast rise times. As electrons enter the gap there will be very large electric fields at the tip of the resulting streamer. These can ionize the gas in front of the streamer, creating a higher speed for the streamer tip. In this model it is the streamer closure which initiates the strong electromagnetic pulse, this occurring some significant time after streamer initiation. We can also have streamers coming from the positive electrode due to the above-breakdown fields. It is only after closure that the conditions in [3] come into play.

4 Gap Closure Time

As the streamer(s) are closing the gap there will be some small current flowing due to the increasing capacitance at the gap associated with the smaller (than $2d$) distances between positive and negative charges in the gap region. It would be good to have some data concerning what might be called closure time in this extreme domain.

As illustrated in Fig. 4.1, let us make a simple model based on change in switch capacitance as the streamer(s) close the gap. Consider a bicone with conductors at an angle θ_0 from the axis. From [16] and Fig. 4.1(a) the characteristic impedance is

$$Z_c = \frac{Z_0}{\pi} \ln\left(\cot\left(\frac{\theta_0}{2}\right)\right) \simeq 120 \ln\left(\cot\left(\frac{\theta_0}{2}\right)\right) \tag{4.1}$$

For a convenient number assume

$$Z_c = 100\ \Omega\ , \qquad \theta_0 \simeq 47^\circ \tag{4.2}$$

The capacitance of a region near the apex is

$$C = \frac{t_r}{Z_c} = \frac{\text{transit time}}{\text{impedance}} = \frac{d \sec\theta_0}{c Z_c} \tag{4.3}$$

out to some distance $d \sec\theta_0$ as in Fig. 4.1(b).

If now we remove the portion of the bicone near the apex as in Fig. 4.1(b), we can use C as an estimate of the capacitance change in going from the configuration in Fig. 4.1(b) to Fig. 4.1(c) which roughly models the closure of the switch. This change in capacitance gives a displacement current across the gap as it is closing. The current during closure (the prepulse) is then roughly

$$\begin{aligned} I_c &\simeq V_{ch} \frac{C}{t_c} \qquad (4.4) \\ t_c &\equiv \text{ closure time} \\ V_{ch} &\equiv \text{ voltage across gap} \end{aligned}$$

as illustrated in Fig. 4.1(d).

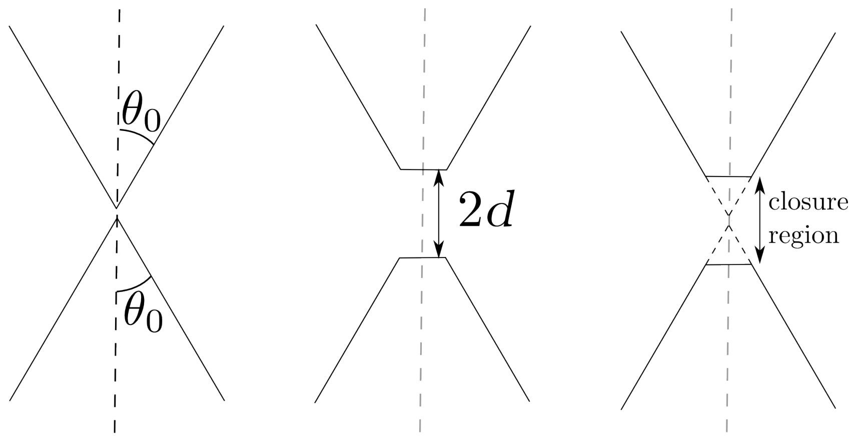
Here we see that, while we may not know t_c or I_c very well, the product is limited as

$$\int_0^{t_c} I_c(t)dt \simeq I_c t_c \simeq V_{ch} C \tag{4.5}$$

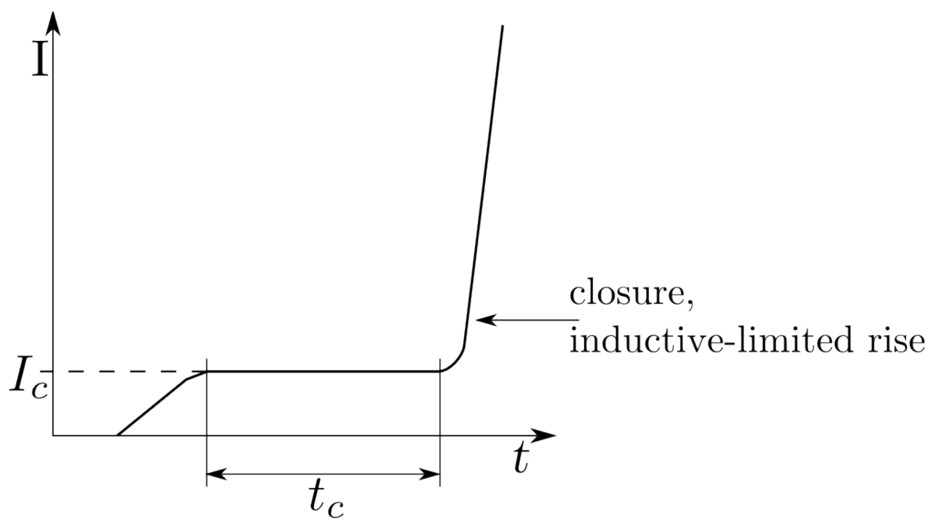
with the remaining uncertainty being in the value of C. The value from (4.3) is very approximate, since it does not include the detailed electric field distribution in Fig. 4.1(b), which depends on the detailed geometry of the gap.

As an example, let us choose

$$\begin{aligned} t_c &= 10 \text{ ns} \\ V_{ch} &= 200 \text{ kV} \qquad (4.6) \\ d &= 1 \text{ mm} \end{aligned}$$



(a) Ideal bicone (b) Pre-breakdown gap (c) Post-breakdown gap



(d) Pre-closure signal

Figure 4.1: Simple model of breakdown signal

Then we have

$$\begin{aligned} C &\simeq 0.05 \text{ pF} = 50 \text{ fF} \\ I_c &\simeq 1 \text{ A} \\ V_c = Z_c I_c &\simeq 100 \text{ V} \end{aligned} \tag{4.7}$$

This is quite measurable, say by a B-dot or D-dot sensor, say on the surface of one of the cones (with signal cable inside the cone), or even on a symmetry plane perpendicular to the bicone axis. Using the usual formulae [16], fields are relatable to voltage and current.

Note, however, that the signal immediately following the prepulse is *much larger*. This will have to be considered in the design of the instrumentation.

Another possible problem is the repeatability of t_c. For a triggered switch, even if we accurately know the time that the trigger signal is applied, variation of t_c (switching spread) might limit the use of such switching in arrays (where accurate synchronization is required).

5 Concluding Remarks

For high-pressure-gas switch gaps there appears to be a significant switching delay due to streamer propagation. This is, in part, associated with the slow electron drift velocity at electrical-breakdown electric fields. Of course, one can consider vacuum gaps for which electrons can reach relativistic speeds (and generate X-rays).

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