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THE WAVEFORM ANALYSIS FOR ZAREM TYPE HIGH VOLTAGE PULSE GENERATOR

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Abstract

A 30 - 40 kV pulse generator using Zarem type was developed. A pulse distortion showing a deficiency on the rear top was frequently encountered. This note describe the detail of the pulse forming principle. The encountered distortion was analyzed. Simulations demonstrate the same result. The feature of the spark gap was also addressed. A solution of this problem is given.

Introduction

The project of the cluster klystron requires a 30 to 40 kV pulse generator to drive the mod-anode. Since it requires a pulse with positive polarity and the voltage is modest within the capability of a spark gap without transformer, Zarem type pulse generator^[1,2] was thus selected^[3]. However, the high voltage experiment always shows a pulse distortion. The cause was recognized to be due to the spark gap, because this phenomenon doesn't appear under low voltage experiment where a mechanical switch is employed. In order to solve this problem, a thorough understanding of the pulse forming process is necessary. This note is dedicated to describe the analyses, simulation along with an imperfect switch, followed by a study of the spark gap, leading to a final solution.

Experimental phenomena

An experimental set up of Zarem type¹ high voltage pulse generator is shown in Fig. 1. The PFN (Pulse Forming Network) is formed by a spiral line, namely a solenoid wound on the copper

1. To our knowledge, the earliest circuitry of this type fit for mismatched load was designed by A. M. Zarem and his colleagues[1] in 1958. A Russian scientist Vvedenskii[2] also published a similar circuitry in 1959.

Fig. 1 An experimental set up of high voltage pulse generator.

Fig. 2 Experimental pulses showing the "skirt" and the "deficiency"
CH1 -- trigger pulse, CH2 -- main output pulse

pipes with kapton film in between as insulation. The real solenoid is split into two pieces but electrically connected in series in order to shorten the length. The total delay time of the spiral line is about 320 ns, which determines the pulse duration time. The spark gap is used as the switch. The modules used in the experiments are EG&G GP-41B and GP-32B.

It was found that the output pulse is always behind the breakdown of the trigger pulse with a random delay time. Before the front edge of the main pulse there appears a "skirt", which we believe is due to a partial discharge. Fig. 2 shows some typical experimental results.^[4] It can be seen that the "skirt" shape is random. Sometimes it lasts 200 nS. Besides the "ringing" and the noise on the top of the pulse, the "skirt" is always accompanied by a "deficiency" on the rear part of the top. Interesting enough, no matter what the skirt shape is, if one cuts the "skirt" and amends it to the "deficiency", it will just fit, as the shaded areas shown on the Figure.

The random "skirt" feature is considered to be due to the performance of the spark-gap. Since the breakdown in the main gap occurs gradually, the spark gap requires a finite amount of time to close the circuit. The cause of the "deficiency" is recognized as a feature of the Zarem circuit and will be addressed in the next sections.

Analysis of the discharge process of the Zarem circuit

The principle circuit of the Zarem circuit is shown in Fig. 3, where a transmission line

Fig. 3 The principle circuit of a Zarem pulse generator

ACB is employed to form a pulse. In principle, the transmission line can be substituted by any kind of PFN. In our case the PFN is the spiral line as mentioned above.^[3] For simplicity, we start the analysis with a simple transmission line.

The essential feature of a Zarem type pulse generator is that a charged transmission line discharges simultaneously at both ends, to which an open (or capacitive) load and a matched load are connected respectively. The later will absorb any reflected wave from the other end, but also produce a discharge wave toward the other end.

Let's take a close look at the discharge process. In Fig. 3, Points A and B are two ends of the PFN. Z_0 is its characteristic impedance and τ_0 its delay time. Point L is the load location. Between point A and point L is a piece of transmission line with characteristic impedance Z_1 and delay time τ_1 . (This represents a general case. In the normal Zarem circuit there is no transmission line A-L, or $\tau_1 = 0$.) Point C is the mid-point of the PFN. In our case, A and B represent

the two terminals of the solenoid. L is the mod-anode. The transmission line A-L is a coaxial line, of which the length (in time unit τ_1) is exaggerated in comparison with the PFN in this figure to make illustration clear.

We assume the coaxial line is matched with the PFN, i.e. $Z_1 = Z_0$. Furthermore, we replace the matched termination R_T by an infinite transmission line, as shown in Fig. 4(a), that doesn't change the process but is helpful to illustrate the wave movement.

Fig. 4. illustrates the process in detail. Before the switch is closed, $t < 0$, the bottom line is at high voltage $-V_0$, while the upper line is at ground potential (Fig. (b)). Once the switch is closed, $t = 0+$, the potential on the upper line is suddenly raised to $+V_0$ as shown on Fig. (c) because the charge between the two lines can't discharge instantly. The discharging through point A to the coaxial line is in a rate determined by the impedance of the lines. Since $Z_1 = Z_0$, the discharge current is:

$$I = V_0 / (Z_0 + Z_1) = V_0 / 2Z_0. \quad (1)$$

Correspondingly, the incident wave entering the coaxial line is:

$$V_i = \frac{Z_1}{Z_1 + Z_0} V_0 = \frac{V_0}{2} \quad (2)$$

as shown in Fig. (d). The dashed lines on Fig. (d) to (p) represents the current distribution. We define a positive current flow to be toward the right, and negative to the left. The solid lines are the potential distributions. Once the discharging occurs, there will be an incident wave with magnitude of $V_0/2$ toward the load (left-hand in the figure). Meanwhile, the potential on the transmission line (PFN) reduces to $V_0/2$ also. This potential will propagate towards the right at the speed of light¹, equivalent to a "reflected" (opposite direction) wave with a negative magnitude.

As mentioned above, the load in our case is an open circuit. At time $t = \tau_1$ the wave arrives to the load point "L", and then reflects immediately and completely making the load voltage twice as much as the incident wave. (see Fig. (f)). Then, the voltage at L remains constant until $t = \tau_0 + \tau_1$.

The similar discharging process occurs at the point B, but the incident wave entering the infinite transmission line will never be reflected. Meanwhile a negative "reflected" wave moves toward the left and arrives at the load at $t = \tau_0 + \tau_1$. Then it reflects again and eventually is

1. Should the transmission line is filled by a dielectric, the speed is, of course, that of light in dielectric.

Fig. 4 The voltage & current profiles along the PFN at different times.
Solid line-- voltage
Dash line -- current (positive to the right)

absorbed by the termination R_T (gets into the infinite transmission line).

Using the concept of wave propagation, the voltage and current distribution along the PFN at some particular moments are obtained and shown in Fig. 4. The arrows show the direction of the wavefront.

Fig. 4 shows "snap shots" of the distributions (location dependent waveform) at variant time. At some fixed points one can find the time dependant waveforms. We then found they are quite different at different locations, as shown in Fig. 5, which is deduced from Fig. 4. At the load point, L, the waveform has full voltage V_0 with the same magnitude as that of the DC supply and the duration is exactly the delay time of the PFN, τ_0 , but has a time delay τ_1 . However, at the other end of the PFN, point B, there are two pulses in sequence with magnitude of only a half voltage $V_0/2$ and duration time of τ_0 for each. At the middle of the PFN, point C, there are also two pulses in sequence, but the first one has full voltage with a half duration time, $\tau_0/2$, the second is half voltage with duration τ_0 .

Actually, the experiments shown in Fig. 6.^[5] demonstrate the above arguments. The waveforms at points L, B, C agree well with Fig. 5, except for the ringing and noise. The waveform at point A, however, is not obvious because $\tau_1 \ll \tau_0$. Note τ_1 is exaggerated in Fig. 5, while in practice the step on Fig. 5(A) is immersed in the rise and fall time. In our experiment, τ_0 is 320 nS, while τ_1 is only about 3 nS.

Fig. 5 The pulse waveform at different points

Fig. 6 The pulses at different locations

Discharging from a real spark gap

In above section we assumed the switch is an ideal one that closes instantly. However, experiments show the breakdown of the main gap of the spark gap has a significant delay following the trigger breakdown. This suggests that the breakdown occurs gradually along with the processes of ionization and avalanche formation. Therefore, instead of a step function simulating an ideal switch, a real spark gap can be replaced by a random function.

In order to clarify the process, Fig. 7 shows the equivalent discharge circuit. For an ideal

Fig.7 The equivalent discharge circuit

switch, the voltage source $V_s(t)$ corresponds to a step function:

$$V_s(t) = V_0 S(t) \quad (3)$$

where the step function $S(t)$ is:

$$S(t) = \begin{cases} 0 & t < 0 \\ 1 & t \geq 0 \end{cases} \quad (4)$$

The resultant discharge waves were shown in Fig. 4. To express these waves analytically, let's check the polarity first. Fig. 8 shows the discharge loop at point A when discharge begins. The

PFN and the coaxial line can be replaced by impedances Z_0 and Z_1 respectively. This loop clearly indicates the polarities, so the voltages across these impedances should be:

$$V_{ai} = \frac{Z_1}{Z_1 + Z_0} V_s(t) \quad (5)$$

and
$$V_{ar} = -\frac{Z_0}{Z_1 + Z_0} V_s(t) \quad (6)$$

At point B, a similar discharge process occurs where

$$V_{bi} = \frac{R_T}{R_T + Z_0} V_s(t) \quad (7)$$

and
$$V_{br} = -\frac{Z_0}{R_T + Z_0} V_s(t) \quad (8)$$

Fig. 8 The discharge loop at initiation

The right-bound waves, V_{ar} and V_{bi} , will be absorbed by the matched load R_T . The left-bound waves, V_{ai} and V_{br} , will arrive at the load with different time delays. Therefore, the pulse seen at the load terminal is:

$$V_L(t) = 2[V_{ai}(t - \tau_1) + V_{br}(t - \tau_0 - \tau_1)] \quad (9)$$

The appearance of the coefficient 2 is due to complete reflection from the open end that causes the voltage to double. Assuming $Z_1 = Z_0$, $R_T = Z_0$ and substituting the above equations, we obtain:

$$V_L(t) = V_s(t - \tau_1) - V_s(t - \tau_0 - \tau_1) \quad (10)$$

Clearly the total voltage is the sum of two waves, as was illustrated in Fig. 4. However, this equation is valid for any discharging function. Fig. 9 illustrates the summation of the waves. Comparing with the experimental result shown in Fig. 2, we see that the deficiency on the pulse top is due to the discharge wave coming from the other end of the PFN.

Simulation

The above analysis has been further verified by simulations using the code Micro-Cap IV. Fig. 11 shows the simulation circuit. It is the same as Fig. 3 with $Z_1 = Z_0 = R_T = 200$ ohm. Evidently, the simulating results Fig. 10 and Fig. 5 are consistent with each other. The lack of the pulse at point C is because there is no test point at the middle of the transmission line of the simulating circuit.¹

1. It is possible to simulate the waveform at Point C by splitting the transmission line into two halves, thus the node in between is the Point C.

Fig. 9 The output pulse summed by the two waves

In the case that the switch is imperfect as suspected in a spark gap, three switches in parallel are employed. Each one is closed at a different time and with a different resistance in series. The circuit is shown in Fig. 11 and the switches are defined as:

- K1: turn on at 100 nS with 1.5 k Ω in series, turn off at 150 nS
- K2: turn on at 150 nS with 1.0 k Ω in series, turn off at 160 nS
- K3: turn on at 170 nS with 0.01 Ω in series, turn off at 1.5 μ S

The result, shown in Fig. 12, is reasonably consistent with the analysis shown in Fig. 9 and the experimental data in Fig. 2.

Features of the spark gap and an improvement of the pulse waveform

It is recognized that a key point is the imperfection of the spark gap. In order to speed up the breakdown process, we tried to connect a capacitance in parallel with the spark gap. The reasons are as follows.

Fig. 10 The simulated pulse waveform at different points
(a) Point L, (b) Point A, (c) Point B

Fig. 11 Simulating circuit

Fig. 12 Pulse waveform with switches
simulating the spark-gap
upper curve -- $V_L(t)$
bottom curve -- $V_s(t)$

Fig. 13 The pulse obtained using the
negative trigger pulse mode

It is known that the breakdown is faster when the applied voltage is close to its upper limit. The lower the voltage, the longer the breakdown delay time. Certainly the breakdown is dependant on the voltage. The related discharge current is limited by the impedance of the PFN. The discharge current will drop the voltage across the gap. A parallel capacitance, which is charged with high voltage, will sustain a higher current and provide more energy early in the breakdown so as to speed up the process. Therefore a faster breakdown is expected.

Too large a discharge energy (current) may shorten the life time of the spark gap. However, Our circuit uses a charge and current much less than the design specification of the GP-41B spark gap. So it should be safe to use a capacitor.

We have used 40 kV capacitor with value up to 100 pF. The delay time has indeed been improved. The "skirt" phenomenon still exists though it is better.

We contacted EG&G, the manufacturer of the spark gap, concerning the appearance of "skirt" in the pulse. They claimed that this phenomenon would not be unusual, and was possibly due to the cross interaction between the trigger and the opposite electrode, that the trigger pulse may leak into the main pulse. In considering the mode of operation, which is recommended by the manufactory, the trigger is exerted with positive pulse, while the opposite electrode is at negative high voltage, it gives more chance to have the "cross interaction" before the main gap really breaks down.

The process is like this. At first, the gap between trigger electrode and the adjacent electrode breaks down after the trigger pulse is applied. Second, the gap between trigger electrode and the opposite electrode breaks down. At this stage, because the area of the trigger electrode is small, the discharging current is limited. There is a partial discharge between the trigger and opposite electrodes. This is so called "cross interaction". In other words, the opposite electrode is not fully closed to the ground, but closed with a certain amount of resistance, or a "partial close-up", similar as what we did in the simulation. This partial close-up causes a "skirt", which is undesirable. Eventually, after the discharging expanding to the whole area, the gap between opposite electrode and the adjacent electrode breaks down, i.e. the main breakdown occurs. This is the third breakdown, and only at this moment, the spark gap can be regarded as really closed.

Based on this understanding, we investigated an alternative mode, where the trigger is exerted with a negative pulse, the same polarity as the opposite electrode, so that the voltage between them is less than the voltage between the opposite electrode and the adjacent electrode. Therefore, above mentioned second breakdown, between the trigger and opposite electrodes, will not happen. Namely, one can get rid of the "cross interaction" or "partial close-up".

However, this mode is not recommended by the manufacturer according to its specification sheet. The reasons are two fold. First, it may shorten the life time. Second, it requires a higher trigger voltage. Nevertheless, these disadvantages are not serious in our case. Since the designed pulser will work only at very low repetition rate, life time should not be a big issue. The

higher trigger voltage is readily available in the trigger driver TM-11A.

The negative trigger mode has been applied and much better improved results were obtained. Fig. 13^[6] shows the pulse obtained in the experiment. From Fig. 13 one can still see the noise and some distortions. The noise is due to the oscilloscope itself. Because the measurement is on the single shot, the waveform can not be smoothed by averaging. Also, there are some error due to the high voltage probes, they pick up the spray field and make the pulse form a little distortion.

Mismatched load analysis

We were also concerned with what will happen if the coaxial line is not matched with the main transmission line (PFN), i.e. $Z_1 \neq Z_0$. Obviously, a reflection occurs whenever a wave reaches an unmatched point. The reflection coefficient is:

$$\rho = \frac{Z_0 - Z_1}{Z_0 + Z_1} \quad (11)$$

Therefore, instead of a sharp pulse front edge, as shown in Fig. 5(a), a step wave occurs

Fig. 14 Front edge of the pulse at the load, Point L, with coaxial line unmatched
(a) $Z_1 < Z_0$, (b) $Z_1 > Z_0$

when $Z_1 < Z_0$, or an oscillating wave when $Z_1 > Z_0$. Fig. 14 shows the resultant wave at the load for some particular values. A similar reflection happens at the back edge.

Although the distortion of the waveform is not desirable, it is not a big concern in practice due to the following reasons.

1. The values chosen in the figure are for serious mismatches (impedance ratio is 2 to 3), in order to make the distortion evident. In practice it is usually much better.

2. The coaxial line length of 3 nS is pretty short in comparison with the PFN, (more than 300nS.) so the transient process due to mismatch is less important.

3. The waveform is smoothened due to the capacitance at the load and other parasitic capacitance.

On the other hand, other distortions like ringing due to parasitic parameters may be more serious than that due to mismatch.

It is also conceivable that when the coaxial line is short enough, it can be regarded simply as an extra capacitance adding to the load capacitance with a value of $C = \tau_1/Z_0$. On the other hand, the line inductance can be ignored due to the short transient time.

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