THE DESIGN AND CONSTRUCTION OF A SPARK GAP ASSEMBLY
AND ASSOCIATED CIRCUITS

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ABSTRACT

The electronic circuit and performance of a spark gap assembly are described. This assembly gave 150 nsec pulses up to 10 kV into a 6 Ω load at a repetition time of 12 msec and was used for driving a number of large-area spark chambers.

Mechanical details are given of a modified version of the spark gap that was actually used.

A fast trigger circuit delivering 10-15 kV pulses with a delay of about 60 nsec is also described.

For protection of the spark chambers and other equipment, a monitoring device switches off the high-voltage power supplies should one of the gaps break down.
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1. INTRODUCTION

For an experiment\textsuperscript{1}) using a large number of wire spark chambers\textsuperscript{2}) a total of 20 spark
gaps were required.

As the dimensions of the chambers varied greatly, the output voltage of the spark gaps
had to be variable from \(\sim 6 \text{ kV}\) to \(10 \text{ kV}\), depending on the type of chamber to be powered.
The spark gaps had to be fully interchangeable in order to reduce the number of spares.
Further requirements were: pulse width \(\sim 150 \text{ nsec}\) with an overshoot of the leading edge in
order to compensate for the capacitive load that the spark chambers represent; recovery of
the spark gap voltage to 99\% within 12 \text{ msec}; and the possibility of firing the gaps at a
peak rate of 70 Hz (average 20 Hz). Delay and time jitter between triggering and the firing
of the gaps should be kept at a minimum.

2. THE SPARK GAP AND ITS MECHANISM

2.1 Construction

For the experiment, use was made of an already existing type of spark gap (Model A,
Fig. 1). A modified version (Model B, Fig. 1) of this spark gap is drawn in Fig. 2. Their
construction is symmetrical and consists of two equal gaps, each carrying half the voltage.
The spark gap is filled with pure nitrogen. Tungsten inserts on the electrodes serve to
reduce the wear during sparking. In Model B the mechanical adjustment was made easy by
soldering the inserts of the end electrodes onto partially slit nuts.

![Model A and Model B](image_url)

Fig. 1 : Photograph of spark gaps Model A and B
Fig. 2: Spark gap prototype (scale 2:1)

For reasons mentioned in Section 2.2, two needles were mounted in the centre of the central (trigger) electrode by means of nylon screws.

2.2 Firing

The central electrode is kept at half the voltage across the gap by means of external resistors. The spark gap fires when the breakdown voltage of one of the gap halves is exceeded. For this purpose a negative pulse is applied at the trigger electrode, causing one half of the gap to break down, after which the other half follows.

Rapid initiation of breakdown is achieved by a corona discharge between the two needles in the central electrode. The needles are connected via large resistors (R₁ and R₄ in Fig. 3) to the high-voltage and the low-voltage sides of the spark gap.

If the gap is balanced and just holds a voltage $V₀$ across it, it will operate (at constant pressure) over a voltage range $V₀/2$ to $V₀$ if a triggering voltage $> V₀/4$ is applied. This is verified in practice.
3. CIRCUIT OF THE SPARK GAP ASSEMBLY

Figure 3 shows the circuit diagram.

3.1 Delay line

A lumped delay line with a characteristic impedance approximately equal to the load impedance (6 Ω) is charged to twice the voltage of the output pulse via a charging resistor \( R_C \). When the spark gap fires, this delay line is discharged into the load.

The inductances between the 1000 pF condensers consist of 1/2 turn, diameter 40 mm of 1.5 mm copper wire.

In order to achieve the desired overshoot of the leading edge, two additional condensers of 2200 pF have been incorporated in the delay line on the side nearest to the spark gap.

The total capacity \( C \) of the delay line is 13.400 pF. Considering that recharging of the delay line to 99% takes \( t = 4.6 \frac{R_C}{C} \), and that this time \( t \) should be less than 12 msec,

\[
R_C < \frac{t}{4.6 \frac{R_C}{C}} = 195 \text{ kΩ}.
\]

In practice the situation was less favourable, since the supply voltage had a 300 Hz ripple of \( \sim 3.5\% \) (being a three-phase, full wave, 50 Hz power supply), which necessitated a decrease of \( R_C \) to about 135 kΩ.

For several reasons it is not advisable to decrease this resistor too much; one is that decreasing the resistor value increases the peak load on the power supply; the other reasons are discussed in Sections 3.2 and 3.4.

3.2 Trigger time constants

The spark gap is balanced by means of resistive divider \( R_1 + R_2 \) (Fig. 3). The trigger pulse is applied via a capacitor \( C_T \) of 50 pF.

The stray capacity of the central electrode is estimated to be about 10 pF; thus the recharging time constant is

\[
\frac{R_1 \times R_2}{R_1 + R_2} (C_T + 10 \text{ pF}) = 1.2 \text{ msec}.
\]

Figure 4 shows the recharging curves of a spark gap as a function of time.
The breakdown voltage of the entire spark gap is assumed to be 22 kV (11 kV for each half), while the actual working voltage is 20 kV. Line A is the anode potential during recharge of the delay line.

The vertical distance between curves A and C is equal to the breakdown voltage of the upper half of the spark gap (11 kV), while the distance between line B and the horizontal axis equals the breakdown voltage of the lower half of the spark gap.

The hatched area indicates the region where the trigger electrode operates safely. Curves D and E indicate the potential of the trigger electrode during recharge for two different values of the recharge time constants: curve D, for a time constant of 1.3 msec, stays well within the safe limits; curve E, for a time constant of 3 msec, goes outside the limits, which results in spurious firing of the spark gap.

A reduction of the charge time constant of the delay line implies an equal reduction of the trigger time constant. In the existing circuit, this would either mean choosing a smaller trigger condenser, or reducing $R_1$ and $R_2$.

A smaller trigger condenser $C_T$ reduces the trigger amplitude and increases the trigger delay, while a smaller value of the resistive divider increases the power drain and causes dissipation problems for the resistors.

3.3 Jitter

In order to ensure reliable triggering of the spark gap, and to avoid excessive variation in the delay time (jitter), two corona needles are used as mentioned in Section 2.1. It is of the utmost importance that the needles are sharp and clean, otherwise the frequency of the corona discharge becomes too low, which leads to jitter of the output impulses.

Our design used ordinary sewing needles, mounted in nylon screws in order to isolate them from the trigger electrode. With clean needles the jitter was less than 5 nsec. During use, dirt accumulated on the needles, causing jitter, which necessitated removal and cleaning of the needles after every four or five million pulses.
3.4 De-ionization

Efforts have been made to reduce the charge time constant of the delay line. This was only partly successful, since with further reduction of the charge time, occasional multiple firing occurs. As care had been taken to comply with the requirements on the trigger time constant, this could only be explained by the fact that the de-ionization of the nitrogen used in the gaps was the limiting factor.

4. CONSTRUCTION DETAILS

4.1 Choice of materials

In the original design the isolating body of the spark gap was made of plexiglas. Although a shield was mounted to protect the plexiglas from direct UV radiation, the decomposition of the plexiglas caused problems, mainly because the needles got dirty with the decomposition products and corroded fairly quickly. Nevertheless these spark gaps served well for the whole length of the experiment.

In order to reduce these troubles, another prototype was designed with the isolating body made of pyrex glass. Here the problems were less, although it was still necessary to wipe the needles after about $10^7$ pulses because of a deposit of tungsten evaporating from the electrodes under influence of the sparks.

The other metal parts are made of brass, with the exception of four tungsten "pills" for the actual spots where the sparking occurs. These tungsten pills are brazed onto the brass pieces and machined afterwards.

Care should be taken to avoid sharp edges, especially around the hole in the central electrode, as this causes not only instability but also a fairly rapid change of the breakdown voltage during the first few million pulses owing to burn-off of the electrodes. In our prototype the change of the breakdown voltage amounted to +2.5% after the first $15 \times 10^5$ pulses.

4.2 Gas

The gaps were filled with 99.9% pure nitrogen at 1.4 atm pressure.

Continuous flushing of the spark gap with nitrogen was avoided, since the 0.1% impurities in the gas seemed to corrode the corona needles and leave a deposit on them rather rapidly.

4.3 Resistors

Originally, carbon film resistors were used for the resistive divider and the series resistors of the corona needles. These resistors failed frequently under normal operation, giving an open circuit. Presumably, migration of the carbon under influence of the high voltage was the cause of the trouble. For this reason, the carbon film resistors were replaced by a chain of composite resistors moulded in an epoxy-resin compound. After replacement, no more open circuits were recorded. For the divider, $2 \times 6$ resistors of 6.8 MΩ/1 W were used, whilst the series resistors of the corona needles consisted of $6 \times 15$ MΩ/1 W.
4.4 Condensers

The high-voltage condensers used were LCC 20 kV HTX ceramic type. Although this type has its drawbacks, namely high temperature coefficient and relative poor resistance against the mechanical shock that accompanies the discharge, they were chosen because of their ready availability and relatively low price.

4.5 Mechanical adjustment

In view of the interchangeability, the breakdown voltage of all the spark gaps had to be adjusted slightly above the maximum supply voltage used (20 kV). Both halves of the gap were adjusted to 1.70 ± 0.02 mm distance, which, at a nitrogen pressure of 1.4 atm, gave a breakdown voltage of 21-22 kV.

The distance between the tips of the corona needles was not very critical; it was set at approximately 1 mm.

5. FAST TRIGGER CIRCUIT

One master spark gap was used to trigger all the 20 gaps used for powering the spark chambers. The complete circuit of the fast trigger unit is given in Fig. 5. An NIM pulse (~800 mV on 50 Ω) was applied, via an inverting transformer, to the base of an avalanche transistor. The transformer also stepped up the signal amplitude and served to isolate the input of the avalanche generator.

For minimum rise-time of the input signal it is necessary to wind the primary turns between the secondary turns. In order to reduce feedback to the input due to capacitive coupling of the primary and the secondary windings, the leads were passed through two ferrite beads.

![Circuit diagram of the master spark gap](image)

Fig. 5 : Circuit diagram of the master spark gap
The output pulse of the avalanche generator (approx. 500 V) drives the EL 360, a power pentode, from cut-off to saturation. The resulting anode current unbalanced and fired the spark gap. The series resistor of 330 Ω limits the control grid current of the EL 360 in order to prevent damage to the avalanche transistors caused by overload.

The maximum anode voltage of the EL 360 is 7.5 kV, which limits the spark gap voltage to about 15 kV.

If higher spark gap voltages are required, the circuit of Fig. 6 can be used. Here the anode circuit of the EL 360 is modified. The resistors $R_2 + R_3 (= R_1$, which is the condition to balance the gap) are chosen such that the anode voltage of the EL 360 does not exceed 7 kV.

![Fig. 6: Details of a master spark gap for higher voltages](image)

6. **RISE-TIME, DELAY, AND TIME-JITTER OF THE OUTPUT PULSES**

Since the delay and time jitter between triggering of the master gap and triggering of the slave gaps depends to a large extent upon the rise-time of the master output pulse, it was important to make the master gap as fast as possible. The rise-time of the output pulses from the master gap is roughly proportional to $L/R$, where $L$ is the stray inductance and $R$ the load resistance. As, for a given load, $R$ has a fixed value, it is clear that $L$ should be kept at a minimum.

Since about 20 slave gaps had to be triggered from one master gap, it would have represented a very heavy load on the master gap to drive each gap separately via a 50 Ω cable. For this reason the slave gaps were divided into groups of three, each group being driven by one trigger cable (RG 213 U). In this way the master gap is loaded with seven 50 Ω cables (~ 7 Ω). The input resistance of the slave gaps is about 1 kΩ. The resulting mismatch of the trigger cable has a favourable effect on the trigger amplitude, and there are no drawbacks.

Delay and time-jitter of the master gap, measured from half-height of the input trigger to 90% of the output pulse height, are given in the following table.

The breakdown voltage of the spark gap was adjusted at 17.5 kV.

Nitrogen pressure was 1.4 atm.
<table>
<thead>
<tr>
<th>Supply volts</th>
<th>Delay</th>
<th>Jitter</th>
<th>Rise-time</th>
</tr>
</thead>
<tbody>
<tr>
<td>kV</td>
<td>nsec</td>
<td>nsec</td>
<td>nsec</td>
</tr>
<tr>
<td>16</td>
<td>60</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>14</td>
<td>65</td>
<td>5</td>
<td>20</td>
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<td>12</td>
<td>80</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>11</td>
<td>95</td>
<td>100</td>
<td>20</td>
</tr>
</tbody>
</table>

(See Fig. 7.)

Fig. 7 : Input and output signals of the master spark gap:
Hor. 50 nsec/div.
Vert. input 1 V/div.
output 10 kV/div.

The over-all delay for the spark gap assembly, measured from half-height of the NIM input to 90% of slave output volts, amounted to 105 nsec with a jitter of 10 nsec (see Fig. 8). The delays given by interconnecting cables have already been subtracted from this value.

The supply voltage of the master gap was 14 kV.

7. PROTECTION

The equipment had to be protected against two possible hazards. One is that a delay-line condenser fails, going short-circuit. This happened for 6 condensers out of some 220 over a year's operation. The other hazard is that a spark gap breaks down continuously (say owing to loss of nitrogen pressure or failure of the balancing resistors).
In both cases the circuit draws excessive current, thereby heavily overloading the charging resistors, which means a serious fire hazard. In the second case there also exists the risk of damage to the spark chambers because of continuous high-rate pulsing. Therefore a protective circuit was built which cut the mains supply to the high-voltage packs if one of the failures occurred.

The circuits work on the principle that there should be no appreciable current consumption in the interval between the time that the delay lines are fully recharged (≈ 12 msec after a trigger) and the time that the next trigger occurs.

![Waveform diagrams](image)

**Fig. 8**: Input signal master spark gap relative to output signal slave gaps:
- Hor. 100 nsec/div.
- Vert. input 1 V/div.
- output 10 kV/div.

By monitoring the current it is easy to distinguish the large current drain caused by a component failure from the drain due to occasional spurious firing.

Each power supply has a built-in monitor (Fig. 9), the output of which is connected to one of the eight control inputs of the protective circuit (Fig. 10). Each of the control inputs has its own integrating network, the integration time constant being chosen so as not to react on single spurious firing. Every time that the master spark gap is triggered, a trigger signal is applied at the trigger input of the protective circuit as well.

Via a timing multivibrator, the trigger signal paralyses the control inputs for about 20 msec, after each trigger, which is ample time for the delay lines to recharge. In the case of current consumption that is unaccounted for, the output of the control circuits sets a flip-flop which eventually cuts the mains supply via a relay. The flip-flop has to be
Fig. 9 : Circuit diagram of the current monitor

Fig. 10 : Circuit diagram of the protective circuit
reset by hand. This reset serves also to override the protective circuit during switching-on of the equipment.

8. PERFORMANCE

The system as a whole consisted of 20 slave spark gaps + 3 spares, 1 master spark gap + 1 spare, and 8 high-voltage power supplies + 2 spares. It has been in operation for 4000 hours over a period of about one year giving some $14 \times 10^6$ pulses. During this period there were six failures of the high-voltage condensers (short circuit), no failures of the moulded resistor chains or other relevant parts.

The needles had to be cleaned and resharpended twice. In addition to this, all the spark gaps received a general overhaul once (cleaning, polishing, and readjustment of the electrodes).

As the jitter of the output pulses depended mainly upon the condition of the corona needles in the master spark gap, these were cleaned after every $2 \times 10^6$ pulses.

There were several breakdowns of the master spark gap. Some were due to the wrong choice of avalanche transistors, but this was cured by installing one of a better type (RT 3333 A). Other causes of breakdown were one high-voltage condenser short circuit, one broken nitrogen connection, one high-voltage connector arcing across, and one EL 360 failure (bad vacuum).

Acknowledgements

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