Steep Voltage Triggering of a Simple Two Electrode Crowbar Gap

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Abstract:

The principle of triggering a simple two electrode crowbar-gap working under atmospheric pressure is discussed. By means of a low impedance 100 kV trigger-generator reliable triggering in a testcircuit has been achieved, giving a 44 kV, 20 nsec Rise, Pulse at the crowbargap. The inherent jitter of the crowbargap was found to be only 0.5 nsec, though the overall jitter of the triggersystem was 20 nsec. The gap passed a current of 60 kA when the capacitorunit has been charged to 30 kV.
Contents:

Abstract

1.0 Introduction

2.0 Triggering of a two electrode crowbargap by a steep voltage

3.0 Experimental arrangement and testresults

4.0 Conclusions

5.0 Acknoledgements

6.0 References

7.0 Figures
1.0 Introduction.

In many experiments in thermonuclear research condenserbanks have to be built up in a crowbar(clamp-)circuit, either to generate a current of a shape similar to a squarewave or in general to obtain a unipolar pulse. Switches used in the crowbarbranch of the bank have to ful fill certain requirements which are different to those of a startswitch:

- "Triggering"of a crowbarswitch has to be possible in a wide range independently of value and sign of the voltage appearing across the switch. In most cases the crowbarswitch will be triggered at currentmaximum thus the working voltage will be very small or even zero.
- The " Hold-off voltage" is either DC or impulse this depending wether the crowbarswitch is at the capacitor- or loadside of the startgap.
- Inductance and Resistance of a crowbarswitch should be as small as possible as this will define the smootheness and decay of the current in the loadcircuit.

In last years many different constructions have been in use and each particular type of switch has shown where it is best placed. Ignitrons are usefull in banks up to 20 - 30 kV and where fast switchingis not required, and Dielectric Switches have been worked up to MA. Following a common trend towards higher voltages spark gaps offer simple construction and reliability in triggering. The problem appearing with spark gaps used as crowbargs is the absence of a sufficient high working voltage, if the triggermoment is the currentmaximum. Different systems of crowbargaps working at normal airpressure have been reported. Koch (1) used two Trigatrons in serie, Fig. 1 , and an auxiliary voltage supplied to the middle - electrode system made it possible to spark both gaps independently. Similar arrangements (2,3) using three-electrodesystem had been successful.
Wilhelm and Zwicker (4) operated a two-electrode crowbargap with one electrode decoupled by a saturable inductance, a further discussion of this principle is given in a separate paper. Our main effort dealt with the problem to spark a simple two-electrode-airgap to be used in crowbarapplication in a 40 kV condenserbank. The requirements for the triggergenerator have been worked out for the condition if a low inductive gap (30 to 50 nH) is connected directly to the transmissionline-system in the bank. The generation of a suitable high trigger-pulse at the crowbargap will be mainly affected by the internal impedance of the triggergenerator and the risetime of its pulse. Experimental results of a 40 nH two-electrode-crowbargap in a test-circuit showed that it is possible to trigger a 30 kV gap by means of a 100 kV triggergenerator. Reproducibility of currentwaveshape and low jitter were obtained and it can be deduced that this principle of triggering might be useful particular in low inductive and closely arranged bank circuits.

2.0 Triggering of a two-electrode crowbargap by a steep voltage wave.

Most of the passive crowbarsystems used in condenserbanks can be converted to the equivalent diagram shown in Fig.2. Storage elements consisting of one or several condensers in parallel are connected by transmissionlines I to the startswitches $S_1$ and crowbarswitches $S_2$ and transmissionlines II run to the common point, called collector, to which the load (in many cases being a magnetic field coil) is connected too. The usual working condition of the crowbarsystem will be that the startswitches will be triggered and the current in the load will proceed to its peak value according the equivalent R,L and C components in load and startcircuit. When the current has reached its maximum triggering of the crowbarswitches starts,
thus the voltage across the latter will be negligible small as it is only the resistive voltage drop which remains in the current maximum. The triggergenerator therefore has to generate between the points A and B an additional voltage which causes the breakdown of the crowbar gap. Fig. 3 shows the simplified equivalent circuit with its impedances which will be only the transmission line impedances for the first time interval (t smaller than two transittimes in the transmission lines) considered in this case. It shall be noted that the whole process of triggering, i.e. the rise of trigger pulse to the breakdown point should proceed within a time of about 20 nsec (a value which has been achieved in the experiment) which is far below usual transittimes from the switch to the load and back (in banks with many parallel elements) therefore the use of $Z_2$ is justified. As far as the storage side is concerned transittimes in the line I will be only a few nsec, thus after two transittimes the effective impedance is determined by the inductance in the condenser unit and the line I. Calculation shows that these impedances will be very similar to $Z_1$ or even higher therefore we shall consider $Z_1$ only.

The equivalent circuit shows also the inherent inductances of the start switch $L_{HS}$ and crowbar switch $L_{Cr}$ and the inductances of the connections $L_{A1}$ (Switches), $L_{A2}$ (trigger generator). Ohmic resistances, usually in the order of some Milliohms can be neglected in comparison to the impedances already discussed.

Our interest shall be directed to find the factors governing the generation of a voltage $U_{AB}$ which will be the working voltage for the crowbar gap, if a trigger generator is connected to the Points A and B and the internal impedance of the trigger generator beeing $Z_G$. Equation 1 gives the equivalent parallel impedance which is a complex function of $\omega$ and $A(\omega)$ beeing the equivalent ohmic component (Equ. 2) and $B(\omega)$ beeing the equivalent inductive component (Equ. 3)

$$Z_{AB} = \frac{(Z_1 + j\omega L_{HS})(Z_2 + j\omega L_{A1})}{Z_1 + Z_2 + j\omega (L_{A1} + L_{HS})} = A(\omega) + jB(\omega)$$

Equ. 1
\[ A(\omega) = \frac{(\frac{\omega}{L_H S L_A} + \frac{\omega}{L_H S L_A}) (\frac{\omega}{L_H S L_A} + \frac{\omega}{L_H S L_A}) + \omega^2 (L_H S L_A) (L_H S L_A)}{(\frac{\omega}{L_H S L_A})^2 + \omega^2 (L_H S L_A)^2} \quad \text{Equ. 2} \]

\[ B(\omega) = \frac{(L_H S L_A + L_A) (\frac{\omega}{L_H S L_A} + \frac{\omega}{L_H S L_A}) - (\frac{\omega}{L_H S L_A} - \omega^2 L_H S L_A)(L_H S L_A)}{(\frac{\omega}{L_H S L_A})^2 + \omega^2 (L_H S L_A)^2} \quad \text{Equ. 3} \]

To obtain the voltage output of the generator we can reduce the circuit to the equivalent diagram Fig. 3b. Further we will assume the trigger generator to consist of a cable with a characteristic impedance \( Z_0 \), as in most cases the trigger generator is a pulse generating unit connected through a sufficient long cable to the switch.

As known, for the acting voltage in the equivalent circuit the voltage \( V_G(t) \) has to be taken, \( V_G(t) \) is the generator voltage and a function of the time \( t \). At the points A and B a voltage \( U_{AB}(t) \) is then generated:

\[ U_{AB}(t) = i(t)A + \frac{d}{dt}B \quad \text{Equ. 4} \]

\[ i(t) = \frac{2V_G(t)}{Z_0 + A} \left( 1 - e^{-\frac{t}{T}} \right) \quad \text{Equ. 5} \]

\[ T = \frac{L_A + B}{Z_0 + A} \quad \text{Equ. 6} \]

and the general solution for the working voltage \( U_{AB}(t) \) is given by

\[ U_{AB}(t) = \left[ \frac{A}{Z_0 + A} \left( 1 - e^{-\frac{t}{T}} \right) + \frac{B}{L_A + B} e^{-\frac{t}{T}} \right] 2V_G(t) + \frac{B}{Z_0 + A} \left( 1 - e^{-\frac{t}{T}} \right) 2 \frac{dV_G(t)}{dt} \quad \text{Equ. 7} \]

Now we have to make a further assumption on the waveshape of the generator voltage. The ideal case would be a voltage step–function, but in practice the voltage will rise only
by a certain rate and it will have more a sinusoidal shape. Both cases shall be discussed for comparison:

1) Generator voltage $U_G(t) = 0$ for $t < 0$

   $U_G(t) = U_G$ .... const. for $t \geq 0$

   as $\omega \to \infty$

   The equivalent impedance has to be written then:

   $A = \frac{(L_{HS}Z_2 + L_{A1}Z_1)(L_{A1} + L_{HS}) - L_{HS}L_{A1}(Z_1 + Z_2)}{(L_{A1} + L_{HS})^2}$ .... Equ. 8

   $B = \frac{L_{A1}L_{HS}}{L_{A1} + L_{HS}}$ ... Equ. 9

   and using Equ. 8 the working voltage in the first moment is then

   $V_{AB}(t=0) = \frac{L_{U_G}}{L_{A2} + B} B$ ... Equ. 10

   This meaning that in the first moment the voltage will be distributed according to the inductances. By use of practical values derived from an existing 40 kV condenser bank:

   $Z_G = 50$ Ohm

   $L_{HS} = L_{A1} = 80$ nH (air spark gap)

   $L_{A2} = 40$ nH

   $Z_1 = 3$ Ohm (parallel transmission line)

   $Z_2 = 8$ Ohm (2 cable each 16 Ohm in parallel)

   follows:

   $A = 5.5$ Ohm \hspace{1cm} $B = 40$ nH

   and $U_{AB}(t=0) = U_G$

   $T = 1.44$ nsec

   The generator voltage is distributed equally between the parallel inductance $B$ and the inductance of the trigger cable connection $L_{A2}$ generating at the crowbargap a voltage equal to the generator voltage. But within a few nsec a final value

   $U_{AB} = \frac{2U_G}{Z_G + A} = 0.2 \ U_G$ will be established.
2) The generator voltage shall have a sinusoidal shape

\[ U_G(t) = U_G \cdot \sin(\omega t) \]  

**Equ. 11**

and the transient voltage at the crowbar gap is then described by the equation:

\[ V_{AB}(t) = \frac{2U_G}{\sqrt{(\frac{Z_G}{A})^2 + \omega^2(L_{A2} + B)^2}} \left( A \cdot \sin(\omega t - \varphi) + \omega B \cos(\omega t - \varphi) \right) + \ldots \]

\[ + \frac{A \cdot \omega (L_{A2} + B) - \omega B(Z_G + A)}{\sqrt{(\frac{Z_G}{A})^2 + \omega^2(L_{A2} + B)^2}} \left( -e^{-\frac{t}{T}} \right) \]

**Equ. 12**

By using the previous values for the impedances and inductances and assuming the generator voltage rising in 25 nsec to its peak value (AC 10 Mcs) the diagram Fig. 4 has been derived showing the crowbar gap voltage and the trigger current.

The maximum voltage again in this case will be \( U_{AB} = 0.14 \ U_G \)

The working voltage for the gap will be determined in its value and shape by the distribution of the inductances and impedances and by the original risetime of the trigger pulse. The most important factor reigning the value of the voltage, apart from the very first few Nanosec, is the internal impedance of the trigger generator. Usual impedances given by the characteristic impedance of trigger cables will cut down the voltage output to a insufficient low value considering risetimes of 2o to 30 nsec. In application for a 4o kV condenser bank the value of the DC breakdown voltage is predetermined for the crowbar gap and by fixing the approximate breakdown time it is possible to predict the required voltage using published data on formative time lags in air gaps (5, 6). After this the following table shows the required overvoltage for some breakdown times:

<table>
<thead>
<tr>
<th>% Overvoltage</th>
<th>20</th>
<th>40</th>
<th>60</th>
<th>80</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>nsec Breakd. time</td>
<td>52</td>
<td>20</td>
<td>12</td>
<td>9</td>
<td>6</td>
</tr>
</tbody>
</table>

A more than 100% overvoltage would be necessary for the previous discussed case of a square shaped trigger pulse as the working voltage will decay within a few nsec and the trigger generator
would have to be worked at 150 to 200 kV, a rather high value. For the case 2 in which a sin-wave had been considered we found that the working voltage will be only 14 % of the generator voltage and taking only a 40 % overvoltage we will have to run the trigger-generator at 400 to 500 kV to fire a 40 kV crowbar-gap.

The measures to improve the voltage gain may be summarized:

a) The internal impedance of the trigger-generator has to be decreased.

b) The trigger-pulse has to rise within a few nsec, (steep voltage wave).

c) The inductance of the connection from trigger-cable to crowbar-gap has to be kept as small as possible.

The principle of steep voltage - low impedance triggering as it has been achieved in a simple way, is shown in the diagram fig. 5. The trigger-system consists of a common pulse-generator and a pulse-forming part. The capacitor $C_A$ is charged by a comparative slow rising pulse to a suitable voltage which in the reported case was 80 to 100 kV. An auxiliary gap, which fires at a preset value, connects the capacitor $C_A$ to the crowbar-gap and a fast rising pulse is generated between the points A and B i.e. at the crowbar-gap. In Fig. 6 the equivalent circuit for the steep voltage circuit is shown, $L_A^2$ representing the inductances of the pulse-forming capacitor and the auxiliary gap, and $C_{Cr}$ being the crowbar-gap capacity.

The rise of voltage at the crowbar-gap is now given by $L_A^2$ and $C_{Cr}$ and the voltagedecay in the auxiliarygap. The voltage-gain depends mainly on the ratio $\frac{L_A^2}{L_{A2}+B}$ neglecting the over-swing due to $C_{Cr}$ which will be damped by the relative slow decreasing gap resistance $R_{Aux}$. In Fig. 7 the theoretical and expected voltages wave shape show the importance of a fast break-down in the auxiliary gap. As it is known, the ionisation in
a spark gap is dependent on the gas pressure and improvements with concern to faster breakdown can be obtained by working the auxiliary gap under higher gas pressures.

3.0 Experimental arrangement and test results.

In a test circuit a 40 kV, 5 μF capacitor was connected through a 0.8 m long parallel transmission line to the start- and crowbar gap assembly and a further transmission line about 1 m long gave connection to the load. The start- and crowbar gap were assembled to a unit as shown in Fig.8, the start gap was a Trigatron type spark-gap whose one electrode was also used as one electrode of the crowbar gap and the second crowbar electrode was arranged just underneath the common electrode, thus UV illumination of the crowbar gap was given by the discharge in the main gap. As a result of the close arrangement of both gaps the crowbar gap fired also without obtaining a trigger pulse usually after two to three half cycles due to the lowered breakdown voltage (because of the very intensive illumination and also drifted particles from the main discharge). The measured circuit parameters are given in table 1:

Table 1 Circuit parameters of test circuit

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitor</td>
<td>$C = 4.9 , \mu F$</td>
</tr>
<tr>
<td></td>
<td>$L_C = 150 , nH$</td>
</tr>
<tr>
<td></td>
<td>$R_C = 20 , mOhm$</td>
</tr>
<tr>
<td>Load:</td>
<td>$L_{SP} + L_{II} = 760 , nH , (\text{transmission line 2 included})$</td>
</tr>
<tr>
<td></td>
<td>$R_{SP} + R_{II} = 3 , mOhm , (\text{transmission line 2 incl.})$</td>
</tr>
<tr>
<td>Start switch and transmission line 1:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$L_{HS} + L + L_{A1} = 270 , nH$</td>
</tr>
<tr>
<td></td>
<td>$R_{HS} + R_I = 5 , mOhm$</td>
</tr>
<tr>
<td>Crowbar switch:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$L_{Cr} = 40 , nH$</td>
</tr>
<tr>
<td></td>
<td>$R_{Cr} = 5 , mOhm , (\text{estimated})$</td>
</tr>
</tbody>
</table>
Table 1 contd.

Main discharge frequency: 66 kC/s
Current maximum: 60 kAmp
(30 kV charging voltage)
Start switch: 0.06 Coulomb
Crowbar switch: ~6 Coulomb
Crowbar time constant: 100 usec
Start gap electrode I: 50 mm Diameter Copper
Start gap electrode II: 50 mm Diameter Copper
Crowbar electrode: 40 mm Diameter Copper

For the tests which had been carried out at 30 kV the gap distances had been adjusted to the given values: Start gap: 14 mm, DC breakdown voltage 38.5 kV measured; Crowbar gap: 9.5 mm, DC breakdown voltage 33 kV measured; Auxiliary gap: 30 mm, DC breakdown voltage 80 kV measured.

The complete circuit arrangement is shown in Fig. 9, including maintest circuit, start- and crowbar trigger circuit and jitter-measuring circuit. Triggering of the start circuit has been provided by 30 kV pulse generator, whose negative going pulse is supplied through a decoupling resistor (1 kOhm) to the trigger electrode in the trigatron. The overall jitter in the start circuit was measured by looking for the timespread in the coil voltage and a typical value of 40 nsec was observed.

The trigger circuit for the crowbar switch consisted of the previous discussed two stage generator. The first stage generated a 100 kV pulse by means of cable - doubling as shown in Fig. 9. This system proved to work very reliably with concern to reproducibility of the obtained waveshape, because only one switch is needed. The second or "fast" stage was formed by a low inductance ceramic capacitor (700 pF) closely connected to the crowbar switch by the auxiliary air gap.

A resistive voltage divider for 100 kV allowed the registration of the crowbar gap voltage and together with a surge scope (Tektronix 507) a timeresponse of about 10 nsec was achieved.
The obtained waveshape of the 100 kV triggercircuit is given in Diagram 10 and 11. The triggerpulse, after breakdown of the auxiliary gap, rises in 20 nsec to 44 kV at the crowbarelectrode and breakdown of the crowbargap is achieved with a jitter of 20 nsec, this value is again the overall jitter of triggercircuit and crowbargap. As far as the jitter of the crowbargap alone is concerned, this value can be derived from Fig.11 and it is the ratio of spread in breakdown voltage divided by the rate of voltagerise and this gives a jitter of 0.5 nsec only. Thus the main portion of jitter is to be shared between the auxiliary gap and the sparkgap in the 25 kV pulsegenerator.

Usefulness of a crowbarswitch is judged also by the range in which a reproducible waveshape of current is obtained i.e. whether it is possible to trigger the switch in a certain range before and after current maximum. With positive charging of the main discharge capacitor and supply of a negative trigger pulse for the crowbargap it was possible to trigger the crowbargap from 1 μsec before to 0.5 μsec after current maximum.

Registration of load-current as well as triggervoltage, as shown in Fig.11, has been carried out for 10 consecutive discharges for each setting of trigger time at the delay-trigger unit.

Measurement of the current in the load has been done by means of a Rogovskicoil in the loadcircuit and integration of the obtained signal. The load current is shown in Fig.12. For reason of comparison it is convenient to define the amount of ripples in the crowbar waveshape by the ratio of the mean deviation of two consecutive currentmaxima divided by the mean current maximum:

\[ W = \frac{|I_1 - I_2|}{|I_1 + I_2|} \cdot 100 \]

according to Fig. 13. Taking the values of Fig.12 we obtain W=7.7%.

4.0 Conclusions

From consideration of the general circuit of a crowbarbank consisting of many elements the main factors governing the
generation of a suitable high working voltage for the crowbar gap have been found to be the internal impedance of the trigger generator, the rise of the trigger pulse and the inductance of the connection between trigger generator and crowbar gap. In a test arrangement reliable operation of a two electrode air gap of simple construction was achieved, the current maximum was 60 kA and the switch carried 6 Coulombs per discharge. To trigger the gap (set for 33 kV static breakdown voltage) a 100 kV trigger generator delivered a 44 kV pulse with a risetime of 20 nsec at the crowbar gap. The overall jitter was measured with ± 20 nsec, though a 0.5 nsec jitter for the crowbar gap itself could be deduced from the spread in breakdown voltage. Therefore further improvement of the system could be obtained in development of low impedance generators for 100 to 150 kV and low (nsec) jitter.

5.0 Acknowledgements.

The authors wish to thank Dipl. Ing. G. H. Schmitter for the given assistance in performing this work, carried out in the Institut für Plasmaphysik GmbH, Garching, Dr. R. Zwicker and R. Wilhelm who made us available their gap assembly and all our colleagues for many helpful discussions.

6.0 References.

2) V. Mark, Kunze R. C., Crowbarfunkenstrecke, Jahresarbeitsbericht 1964, Institut für Plasmaphysik, Garching.
5) Fletcher, R.C. Impulse breakdown in the $10^{-9}$ sec range of air at atmospheric pressure. Phys. Rev. 76 (1949), pp. 1501


7.0 **Figures.**

List of Figures:

- **Fig. 1** Cascadecrobargap after KOCH (Ref. 1)
- **Fig. 2** General circuit of a Capacitorbank with passive crowbar.
- **Fig. 3** Triggering of a crowbargap by overvoltage.
- **Fig. 4** Working voltage $U_{AB}$ for sinusoidal generatorvoltage
- **Fig. 5** Principle of steep voltage - low impedance triggering.
- **Fig. 6** Equivalent diagram, steep voltage triggering.
- **Fig. 7** Triggervoltage at crowbargap, calculated.
- **Fig. 8** Start-and Crowbargapassembly in testcircuit.
- **Fig. 9** Testcircuit.
- **Fig. 10** 100 kV Triggerpulse
- **Fig. 11** Crowbargapvoltage when triggered with 100 kV pulse.
- **Fig. 12** Current in loadcoil
- **Fig. 13** Definition of rippels in crowbarcurrent.
Fig. 1 Cascade crowbar (Koch, Ref. 1)

Fig. 2 Capacitor bank with passive Crowbar

Figure 1 and 2
Fig. 3a Triggering of a crowbargap by overvoltage

Fig. 3b Triggering of crowbargap, equivalent circuit

Figure 3a and 3b
Fig 4 Working voltage $U_{AB}$ at crowbargap
Generator: Z 50 Ohm, 10 MCs, 100 kV $U_{max}$

Principle of Steep voltage—low impedance Triggering

Figure 4 and 5
Fig. 6  Steep voltage triggering equiv. circuit

Fig. 7  Trigger voltage at crowbargap

Fig. 8  Start- and crowbargap assembly in testcircuit

Figure 6, 7 and 8
Fig. 6  Steep voltage triggering equiv. circuit

Fig. 7  Trigger voltage at crowbargap

Fig. 8  Start- and crowbargap assembly in testcircuit

Figure 6, 7 and 8
Figure 9 Testcircuit
Fig. 10  100 kV Triggerpulse
100 nsec/div
25 kV/div
measured at open cable-end

Fig. 11  Crowbargap voltage
(Trigger voltage 100 kV)
50 nsec/div
12.5 kV/div
10 pulses
Timeresponse 10 nsec

Fig. 12  Current in load-coil
10 μsec/div
23 kA/div

\[ W = \frac{I_1 - I_2}{I_1 + I_2} \times 100 \% \]

Fig. 13  Definition of ripples in crowbar current

Figure 10, 11, 12 and 13