Chapter - 6

Generation of Sub-nanosecond Pulses

6.1 Introduction – principle of peaking circuit

In certain applications like high power microwaves (HPM), pulsed laser drivers, etc., very fast rise times - in the sub-nanoseconds range - are required. It is not possible for generation of such ultra-fast pulses by directly using a Marx generator even after reduction of the internal inductance to the practically realizable limits. Therefore, in addition to a Marx generator, a peaking circuit arrangement has been used [15-16], [20-21] & [29-30]. In the present work, attempts were made to design the peaking circuit for a Marx generator comprising of ten stages, each stage capacitor being 10nF, 20kV. After analysis & simulation work, a peaking circuit including a peaking capacitor has been designed. A high pressure (70 kg/cm$^2$) chamber to accommodate the peaking capacitor, peaking switch, the matching load resistor and a Pearson current monitor has been designed & fabricated.

The peaking circuit comprises of a very low inductance capacitor having a suitably low capacitance value, a peaking switch & a load circuit. Together, the peaking circuit inductance will be much lower than that of a Marx.

The schematic of the peaking circuit is shown in fig.6.1. $C_P$ is known as the peaking capacitor. The peaking-switch is a spark-gap and $Z_o$ is the load impedance usually equal to the characteristic impedance of the peaking circuit.

![Fig 6.1.Schematic of Marx with peaking circuit](image)

Initially the peaking switch is open. The Marx is charged to the desired voltage and discharged (by spark-over of the Marx output switch) into the very low inductance peaking
capacitor $C_P$. The voltage across the peaking capacitor is twice the no-load output voltage of the Marx due to transient behavior of RLC circuit having low R. Here, L is the inductance of the Marx. When the voltage across the peaking capacitor reaches the maximum (i.e. peak value), the peaking switch (which is a sparkgap) sparks over and the peaking capacitor discharges into the load. A very fast current pulse of short duration is generated due to the low capacitance of the peaking capacitor & low inductance of peaking circuit as a whole (comprising of the peaking capacitor, peaking switch and load).

6.2 Design of peaking circuit

As discussed above, peaking circuit comprises of the peaking capacitor, a peaking switch and the load.

6.2.1 Design of peaking capacitor

The basic component of the peaking circuit is a low capacitance value, high voltage rated capacitor with an extremely low inductance. The common practice is to have a cylindrical capacitor [15] & [20] with inner & outer electrodes in the form of hollow stainless steel cylinders of suitable diameters & length to realize required capacitance and having adequate dielectric strength to withstand the maximum voltage.

The capacitance of a cylindrical capacitor of length $l$, diameters of inner and outer electrodes $a$ & $b$ respectively, is given by equation (6.1):

$$C = \frac{2\pi \varepsilon_o \varepsilon_r l}{\ln \left(\frac{b}{a}\right)}$$

Where $C$ is the capacitance in farads,

$\varepsilon_o$ is absolute permittivity of free space $=8.854 \times 10^{-12}$ F/m,

$\varepsilon_r$ is the relative permittivity of the dielectric medium of capacitor,

$l$ is the length of the cylindrical capacitor,

$b$ is the diameter of the outer electrode, &

$a$ is the diameter of the inner electrode.
The capacitance of the peaking capacitor is usually very small – ten to less than 100pF to enable achieving desired very fast rise times. In the present case a value of 10 pF is considered.

Importantly, the maximum electric field intensity should be considerably lower than the breakdown strength of the dielectric. In the present work, Perspex with $\varepsilon_r = 3.3$ and breakdown strength of about 16kV/mm (rms) under 50 Hz voltages has been chosen as the dielectric for the capacitor. The breakdown strength under very fast (sub-nanosecond) pulses will be much higher, possibly 25kV/mm to 30kV/mm [38].

Considering all the above, the following dimensions have been worked out:

- $C = 10$ pF,
- $a = 49$ mm,
- $b = 122$ mm, and
- $l = 50$ mm.

The maximum electric field is given by equation (6.2):

$$E_{\text{max}} = \frac{2V}{a \cdot \ln\left(\frac{b}{a}\right)} \frac{V}{m}$$

Here, $a$ is in meters and $V$ is the nominal no-load output voltage of the Marx and for the present case, $V=200kV$ giving $E_{\text{max}} \approx 18$ kV/mm which is quite safe compared to reported breakdown strength of 25kV/mm [38].

### 6.2.1.1 Estimation of inductance of the peaking capacitor

The inductance of the peaking capacitor is given by equation (6.3):

$$L_p = \frac{\mu_0}{2\pi} \cdot \ln\left(\frac{b}{a}\right) \cdot \text{length (in m)} \quad \text{Henry's}$$

Substituting the values

- $\mu_0 = 4\pi \times 10^{-7}$ H/m,
- $a=49$ mm,
b=122 mm and
l= 59 mm = 0.059m

We get \( L_p \approx 10\text{nH} \).

### 6.2.2 Design of peaking switch

The peaking switch is most commonly a sparkgap. Before breakdown (sparking), the sparkgap can be represented simply by its capacitance \( C_{sg} \). From Fig 6.1, as the voltage \( V_o \) across \( C_p \) rises, this voltage is shared between the gap capacitance \( C_{sg} \) & the load impedance \( Z_o \).

As the value of spark-gap capacitance is low, its impedance is very high compared to load impedance \( Z_o \). Therefore before spark-over of peaking switch, a very large share of the voltage appears across the gap capacitance.

The current flowing in the peaking loop before spark-over takes place is given by

\[
I_{ZO} = \left( C_{sg} \times \frac{dV_o}{dt} \right)
\]  

(6.4a)

The voltage appearing across \( Z_o \) is given very closely by

\[
V_{ZO} = \left( C_{sg} \times \frac{dV_o}{dt} \right) \times Z_o
\]  

(6.4b)

This voltage pulse appearing across \( Z_o \) before breakdown of the spark-gap is known as ‘pre-pulse’. The pre-pulse should be as low as possible which is possible only by reducing \( C_{sg} \) to the extent possible. \( C_{sg} \) can be made minimal by using needle-needle configuration of electrodes for the spark-gap. Therefore, this is the most common spark-gap configuration in use. However, such a needle-needle configuration has a poor breakdown voltage. To achieve higher breakdown voltage, a high pressure gas (possibly air) is used as the medium which necessitates an insulating chamber (to house the spark-gap) which can withstand very high pressures of the order of tens to hundreds of kg/cm\(^2\).

Once the peaking switch i.e. the high pressure switch breaks down, the electrodes, including the shanks and the spark path constitute an inductance which should be as low as possible. This has been emphasized many times. This again implies a closely spaced return path,
keeping in view requirements of electrical insulation between the peaking switch components & the return path.

6.2.2.1 Inductance of peaking switch

The schematic of the peaking circuit along with load is shown in fig 6.2.

![Schematic of peaking circuit along with load](image)

6.2.2.2 Inductance of electrodes

As there is no direct formula for estimating the inductance of the conical electrodes shown in fig 6.3, an approximate estimation of inductance is carried out by segmenting the electrodes into five segments A, B, C, D & E, each 5mm in length, as shown in fig 6.3. The segments A, B, C & D have diameters of 20mm, 15mm, 10mm and 5mm respectively and segment E is further divided into five segments of 1mm length each. The segments are treated as rods of the above diameters.
Fig 6.3 Schematic of sparkgap electrodes

The inductance of the above configuration is given approximately by equation (6.5). Here, for all the segments, the outer (return) electrode diameter remains constant at 122 mm and inner electrode diameters of the segments vary, the values being as given above (20mm, 5mm, 4mm…, 1mm).

Inductance of one electrode is given by equation (6.5):

\[
L_e = 2 \times 10^{-7} \left\{ \ln \left( \frac{122}{20} \right) + \ln \left( \frac{122}{15} \right) + \ln \left( \frac{122}{10} \right) + \ln \left( \frac{122}{5} \right) \right\} \times 0.005 + \left[ \ln \left( \frac{122}{4} \right) + \ln \left( \frac{122}{3} \right) + \ln \left( \frac{122}{2} \right) + \ln \left( \frac{122}{1} \right) \right] \times 0.001
\]

\[
L_e = 13.8 \text{nH}
\]

For two electrodes \( L_e = 13.8 \text{ nH} \times 2 \approx 28 \text{nH} \)

The bottom plate of the cone is 2.5mm thick and dia 60mm. This link connects the peaking capacitor and sparkgap electrode. The inductance of this is given by equation (6.6):

\[
L_{\text{link}} = \left( \frac{\mu_0}{2\pi} \times \ln \left( \frac{122}{60} \right) \right) \times 2.5 \times 10^{-3} = 0.4 \text{nH}
\]
6.2.2.3 Inductance of spark path between the electrodes

The inductance of the spark path $L_{sp}$ with respect to return path is given by equation (6.7). The arc may be assumed to be a conductor of diameter 0.1mm. Length of the spark channel is the gap length of 1mm. The metallic cylindrical shell of diameter 122mm is the return path. Therefore the inductance of the spark path is:

$$L_{sp} = \left( \frac{\mu_0}{2\pi} \ast \ln \left( \frac{122}{0.1} \right) \ast 10^{-3} \right) \approx 1.5 \text{ nH}$$

(6.7)

6.2.2.4 Inductance of load Resistor

The load resistor is a Perspex tube of 45mm outer dia and 50mm length filled with copper sulphate solution of required resistivity. The inductance of the load circuit is due to the connecting leads and inductance of copper sulphate load with respect to return path.

The connecting links on both sides of copper sulphate tube are of 2.5mm length and 50mm dia. The inductance of one connecting link is given by equation (6.8):

$$L_{q2} = \left( \frac{\mu_0}{2\pi} \ast \ln \left( \frac{122}{50} \right) \ast 2.5 \ast 10^{-3} \right) \approx 0.5 \text{ nH}$$

(6.8)

For two connecting links, the inductance is given by 1 nH (=0.5nH *2)

The inner dia of the CuSo$_4$ tube is 40mm and this is the diameter of inner conductor, with the outer electrode of 122 mm dia as the return conductor. The Inductance of the copper sulphate resistor with respect to return path is given by equation (6.9):

$$L_{cu} = \left( \frac{\mu_0}{2\pi} \ast \ln \left( \frac{122}{40} \right) \ast 50 \ast 10^{-3} \right) = 11.2 \text{ nH}$$

(6.9)

Therefore total inductance of the load resistor = 1 nH + 11.2 nH = 12.2 nH

6.2.2.5 Inductance of forward path of load circuit with respect to return path

In the present case, provision is made to measure the output current by passing the LV terminal of the copper sulphate resistor through the Pearson current monitor. The LV terminal is a conductor of dia 22mm and length 75mm. The return path for this LV terminal is a conductor and is placed 70mm above the LV terminal. The inductance of this is given by equation (6.10)
6.3 Total inductance of the peaking circuit

From the above, the total inductance of the peaking circuit $L_P$ is the sum of inductances of (peaking capacitor, electrodes, spark-path, load resistor and path for mounting Pearson coil).

Thus,

$$L_P = 10 \text{nH} + 28 \text{nH} + 0.4 \text{nH} + 1.5 \text{nH} + 1 \text{nH} + 11.2 \text{nH} + 19.1 \text{nH} \approx 72 \text{nH}.$$  

It is evident that this is very small but not insignificant.

6.4 Simulation of Marx with peaking circuit

For the schematic shown in fig 6.1, the equivalent circuit of the Marx with peaking circuit is developed in PSPICE and is shown in fig.6.4. The Marx comprises of ten stages, each stage capacitor of rating 10nf, 20kV. During erection of the Marx, the equivalent capacitance is 1nf and the no load output voltage of the Marx is 200kV. This output voltage is fed to the peaking capacitor and the voltage across the peaking capacitor becomes nearly double of 200kV i.e. close to 400kV. The peaking switch is set to spark-over when the voltage across this peaking capacitor reaches this maximum value.

$$L_{1f} = \frac{1}{2} \left( \frac{\mu_0}{2\pi} \ln \frac{2h}{r} \right) \cdot \text{length}$$

$$L_{1f} = \frac{1}{2} \left( \frac{4\pi \cdot 10^{-7}}{2\pi} \cdot \ln \frac{2 \cdot 70}{11} \cdot 75 \cdot 10^{-3} \right) \approx 19.1 \text{nH}$$

Fig 6.4. Equivalent circuit of Marx with peaking circuit
Thus, the equivalent circuit consists of two loops, Marx loop ABCD and peaking loop BEFC. Marx loop consists of equivalent capacitance of Marx, total inductance of Marx, equivalent series resistance of Marx and capacitance & inductance of peaking capacitor. The peaking loop consists of capacitance & inductance of peaking capacitor, inductance of spark-gap electrodes and load.

6.4.1 Characterization of 200kV Marx generator

Short circuit discharge experiments were conducted on the 10nF/stage, 20kV/stage, ten stage Marx generator with nominal output voltage rating of 200 kV, 20J. The experimental output current discharge waveform of the Marx into a short circuit is shown in fig 6.5(a) and the simulation discharge waveform is shown in fig 6.5 (b). Period & frequency of discharge wave are 300ns and 3.3MHz. From the known value of $C_T \approx 1\text{nF}$, using equation (4-1) of Chapter-4, the value of $L_T$ is 2.3$\mu$H

Fig 6.5 (a) Experimental current waveform for discharge of the Marx into a short circuit
Fig 6.5 (b) PSPICE current waveform for discharge of the Marx into a short circuit

As discussed in Chapter 3, the value of ESR has been estimated for the Marx by PSPICE simulation. The values of resistances so obtained for the Marx generator are shown in Table-6.1. The values of resistance are plotted as a function of the current magnitudes and shown in fig.6.6

Table-6.1 Experimental positive peak currents and corresponding resistances of 200kV Marx generator

<table>
<thead>
<tr>
<th>L=2.3µH</th>
<th>1st peak</th>
<th>2nd peak</th>
<th>3rd peak</th>
<th>4th peak</th>
<th>5th peak</th>
<th>6th peak</th>
<th>7th peak</th>
<th>8th peak</th>
<th>9th peak</th>
<th>10th peak</th>
<th>11th peak</th>
<th>12th peak</th>
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<tbody>
<tr>
<td>Experiment</td>
<td>925</td>
<td>790</td>
<td>680</td>
<td>590</td>
<td>500</td>
<td>430</td>
<td>360</td>
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<td>Simulation</td>
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<td>ESR=2Ω</td>
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<td>ESR=2.1Ω</td>
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<td>ESR=2.4Ω</td>
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<td>ESR=2.5Ω</td>
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<td>ESR=2.6Ω</td>
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<td>ESR=2.9Ω</td>
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<td>ESR=3.1Ω</td>
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Fig 6.6 Current versus ESR for 200kV Marx generator

From table- 6.1 for current of nearly 1 kA the ESR is 2 Ω. Also, from chapter-3, the estimated ESR for a single capacitor of this Marx is 0.2Ω for higher currents of the range 2kA and for ten stages the resistance comes to 2Ω. Therefore, the ESR of Marx is taken as 2 Ω.

6.4.2 Characterization of peaking circuit

The total capacitance and inductance of the peaking circuit are 10 pF and 72 nH respectively. Therefore, the characteristic impedance $Z_O$ of the peaking circuit is given by equation (6.11):

$$Z_O = \sqrt{\frac{L_T}{C_T}} = \sqrt{\frac{72 \text{ nH}}{10pF}} = 85 \text{ ohms}$$

For proper matching, the load impedance of the peaking circuit is made equal to characteristic impedance. The ESR of the peaking capacitor will be approximately of the order of 0.1Ω. This is very much less than $Z_O$ (85 Ω) and hence neglected in the peaking loop. Therefore, in the simulation circuit, the total resistance is considered to be 85 Ω.

6.5 Analysis of Marx generator with peaking circuit

As explained above, the whole Marx with peaking circuit consists of two loops, Marx loop ABCD and peaking loop BEFC. The analysis for the two loops is carried out sequentially.
6.5.1 Analysis of Marx loop (ABCD)

The equivalent circuit of the Marx loop is shown in fig 6.7.

Fig 6.7 Equivalent circuit of Marx loop

C_m represents the equivalent capacitance of Marx during erection and is equal to 1nF,

L_m represents the total inductance of Marx and is equal to 2.3µH,

ESR is the equivalent series resistance of the Marx and is equal to 2Ω,

L_P represents the inductance of the peaking capacitor and estimated to be 10 nH,

C_P represents the capacitance of peaking capacitor and is taken as 10 pF

V_i is the no-load nominal output voltage of the Marx appearing across C_m and is equal to 200kV (20kV/stage * 10 stages=200kV),

V_P represents the voltage across the peaking capacitor &

I_1(s) represents the current in the Marx loop (ABCD).

By using Laplace transform, the loop equation is given by

\[
\frac{V_i}{s} = I_1(s) \left[ \left( \frac{1}{C_m s} + \frac{1}{C_p s} \right) + (L_m + L_p)s + R \right] \ldots (6.12)
\]

For simplifying the analysis the internal inductance of the peaking capacitor (10 nH) is neglected as this value is very much lower than the inductance of the Marx circuit (2.3 µH). Thus equation (6.12) becomes (6.13):
The voltage across the peaking capacitor is given by

\[ V_p(s) = \frac{V_i}{s} \left( \frac{1}{C_p s} \right) \]  
\[ \text{--- --- --- --- --- --- --- (6.14)} \]

\( V_p \) is obtained by dividing equation (6.14) with equation (6.13) and the simplified equation is given by

\[ V_p(s) = \frac{V_i}{s} \frac{1}{\left\{ \frac{C_m + \frac{C_p}{C_m} + L_m C_p s^2 + R C_p}{s} \right\}} \]  
\[ \text{--- --- --- --- --- --- --- (6.15)} \]

Substituting the values

\( V_i = 2 \times 10^5 \text{ V}, \ C_m = 1\text{nF}, \ C_p = 10\text{pF}, \ L_m = 2.3\mu\text{H} \quad \& \quad R = 2\Omega \)

in equation (6.15), the equation is simplified as (6.16)

\[ V_p(s) = \left( \frac{2 \times 10^5}{s} \right) \left( \frac{1}{1.01 + (2.3 \times 10^{-17} s^2) + (2 \times 10^{-11} s)} \right) \]  
\[ \text{--- --- --- --- --- --- (6.16)} \]

Detailed solution for the above equation (6.16) is given in Appendix-2.

The solution for equation (6.16) from Matlab is given by

\[ V_p(t) = 1.98 \times 10^3 - \frac{1.98 \times 10^3 \times (cos(0.2110^3 t) + 2 \times 10^{-3} \times sin(0.2110^3 t))}{e^{4.3 \times 10^5 t}} \]  
\[ \text{--- --- --- --- --- --- --- (6.17)} \]

From this equation (6.17), as shown in Appendix-2, the time to peak is 15ns. By substituting this value of t=15ns in equation (6.17), we get a peak output voltage of 394.6 kV.

The above is by analysis.

Now, simulation is carried out in PSPSICE for the Marx loop (ABCD) shown in fig.6.7 and the voltage waveform across the peaking capacitor is shown in fig.6.8.
Fig 6.8 Voltage across the peaking capacitor (before spark-over of peaking switch)

From the waveform, it is observed that the time taken for the voltage to reach its peak value is 15ns and the peak value is 394.6 kV. These values match fully with the results from circuit analysis.

6.5.2 Pre-pulse current in the load circuit

As explained above in section 6.2.2, pre-pulse current flows through the load even before the spark-gap fires. The magnitude of the pre-pulse current depends on the spark-gap capacitance $C_{sg}$. Therefore, this capacitance $C_{sg}$ should be as low as possible, needle–needle configuration is commonly used [40]. In the present work also, same configuration is assumed.

PSPICE simulation has been carried out to observe the effect of value of spark-gap capacitance $C_{sg}$ on magnitude of pre-pulse current. By placing the $C_{sg}$ across the peaking switch and from simulation the pre-pulse current for two different values of $C_{sg}$ (i.e. 0.5 pF and 0.2 pF) are 20A & 8A respectively. If $C_{sg}$ is taken as 2 pF, as for a plane parallel gap of same spacing of 1mm, pre-pulse current would be 75A giving a voltage pre-pulse of 6.4 kV ($75A \times 85\Omega$).

Higher the value of $C_{sg}$, higher will be the pre-pulse current. Also, the time taken for the voltage to reach its peak value increases slightly and voltage across the peaking capacitor slightly reduces. For instance, for the very high value of $C_{sg} = 2$ pF, the time taken for the voltage to reach its peak value, shifts from 15ns to 16.4 ns and the peak voltage comes down
from 394.6 kV to 392.15 kV. For a value of 0.2 pF for $C_{sg}$, time to peak is 15.17 ns and peak voltage is 394.5 kV. The variation in voltage magnitudes & times to peak are only nominal.

6.5.3 Analysis of peaking Loop (BEFC)

The equivalent circuit of the peaking loop is shown in fig 6.9

![Equivalent Circuit of the Peaking Loop](image)

Fig 6.9 Equivalent circuit of the peaking loop circuit

$V_P$ is the voltage to which the peaking capacitor has got charged by the Marx and is equal to 394.6kV

$L_P$ represents the inductance of the peaking capacitor and the estimated value is 10 nH,

$C_P$ represents the capacitance of peaking capacitor which is 10 pF,

$L_{PS}$ represents the inductance of the peaking switch & load circuit and the estimated value is 62 nH,

$Z_o$ represents the load and is equal to characteristic impedance and equal to 85 Ω,

$I(s)$ represents the current in the peaking loop (BEFC).

The current in the loop, in Laplace form, is given by

$$I(s) = \left( \frac{V_P}{s} \right) \frac{1 + \frac{s^2 C_P L_{PS}}{s^2 C_P L_{PS} + s Z_o C_P}}{1 + \frac{s^2 C_P L_{PS} + s Z_o C_P}{s C_P}}$$

By substituting the values (mentioned above) in equation (6.18) and simplifying, we get
Detailed solution for the above equation (6.19) is given in Appendix-2.

The solution for equation (6.19) from Matlab is given by

\[ I(t) = \frac{5.37 \times 10^3 \times \sin(1.02 \times 10^9 \times t)}{(e^{0.59 \times 10^9 \times t})} \]  \hspace{1cm} (6.20)

The above is by analysis.

Further, simulation was carried out using PSPICE for the peaking loop (BEFC) shown in fig.6.9 and the output current waveform is shown in fig.6.10. From the waveform, it is observed that the time taken for the current to reach its peak value from zero is 1 ns and the peak value is 2.53 kA. The 10% to 90% time interval, which is usually taken as the rise time, is 0.62 ns. Thus, this configuration achieves sub-nanosecond rise time. With the analysis, it is evident what is needed for further reduction!

By substituting the above value of \( t = 1 \) ns in equation (6.20), we get an output current of 2.53 kA which is the same as the value obtained from simulation. The output voltage across \( Z_o = 85 \Omega \) is 214.8 kV.

![Simulated output current waveform across the load](image-url)
Fig 6.11 Simulated output current waveform across the load for reduced load circuit inductance

However, in practice, Pearson current monitors are not used and the inductance of the load circuit will be lesser by 19.1 nH. For this configuration, the simulated waveform is given in fig.6.11. The current has a peak value of 2.95 kA with a zero to peak rise time of 0.88 ns. The conventional 10% to 90% rise time is 0.53 ns. This establishes the possibility of achievement of sub-nanosecond rise time output current voltages by this technique.

6.6 Fabrication of Peaking circuit

As discussed in section 6.2.1, the peaking capacitor is placed just after the output stage of Marx. The schematic arrangement of Marx with output switch and peaking circuit is shown in 6.12. The primary source for charging the Marx comprises of single phase auto transformer, a 230V/7800V high voltage transformer (output current rating 25mA) and a voltage doubler rectifier circuit. Upon closing the switch S, the maximum voltage available at the output of voltage doubler rectifier circuit is 22 kV (7800 V * 2*√2). After considering efficiency of charging, each stage capacitor gets charged to a voltage of 20kV and upon erection of Marx, the total no load voltage across the output of Marx is nearly 200 kV (20 kV per stage * 10 stages). Peaking capacitor gets charged to nearly double the voltage of Marx i.e. 400 kV and this voltage is discharged into load thereby generating a very fast pulse. The dimensional diagram of the peaking circuit is shown in fig.6.13.
Fig 6.12 Schematic of 200kV Marx with output switch and peaking circuit
Fig 6.13  Dimensional diagram of peaking circuit
The peaking circuit and the Marx output switch have to be accommodated within a height of 58cm (total Marx height). The output switch is made up of spark-gap electrodes of 49mm diameter, these electrodes permit an adjustable gap distance. These electrodes are housed in a long hollow Perspex cylindrical chamber arrangement to avoid external surface flashover.

The peaking capacitor of rating 10pF, 400kV is designed and fabricated according to the dimensions presented earlier. The peaking capacitor is made up of a hollow cylinder of 50 mm length with inner and outer electrode diameters of 49mm and 122mm respectively. Perspex is the dielectric medium between inner & outer electrodes. In the present case, O-rings are placed on either side of the electrode to hold the electrode tightly. Also in addition to O-rings, a stopper can be placed to prevent the electrode-2 from moving up due to pressure in the peaking-switch chamber. On either side of the peaking switch electrode, the Perspex (of the peaking capacitor) is corrugated to avoid surface flashover.

The tip of the conical electrodes of the peaking switch are made to have very small radius to minimize the area of the peaking electrodes, thereby having very low peaking switch capacitance. One of the electrodes is mounted on top of the copper sulphate solution tube with a locknut. The gap distance between the spark-gap electrodes is adjusted with this locknut. The wall thickness of the Perspex chamber and all the joints are designed to withstand high pressures and tested upto pressure of 70 kg/cm² without any measurable leakage.

The load resistor is copper sulphate solution inside a hollow Perspex tube of internal diameter of 40 mm & outer diameter of 45 mm diameter and 50mm long. The concentration of copper sulphate is 14.25 gm/liter of copper sulphate [39], to give the desired value of resistance 85Ω.

6.7 Possible methods of output pulse measurement

In principle, the rise time and peak output current can be measured in two ways. In the first method, the output current & rise time can be measured by using Pearson current monitor model. In the second method the voltage across the load can be measured by using a high voltage potential divider with DSO. The DSO is connected across the LV arm of the potential divider to capture the voltage waveform. Rise time can be directly obtained from the captured waveform. The voltage across the load \( V_{ZO} \) is estimated by multiplying LV arm voltage with the potential divider ratio. The peak output current is estimated from this voltage \( V_{ZO} \) and load resistance \( (85\Omega) \). One problem associated with the second method is to bring the
HV lead from the pressurized peaking switch chamber to the exterior and also providing insulation.

In the present case, provision is made to include Pearson coil after the load resistor. The LV terminal of dia 22mm is extended by 75 mm to incorporate Pearson current monitor. The end point of the LV terminal is connected to the return path, which is connected to Marx earth point.

However, the rise times of the available Pearson current monitor & Attenuator probe of the DSO were several nanoseconds. Therefore no efforts were made to measure the rise times. In practice, output pulse is characterized by spectra of radiated energy from the output. As no facilities were available, this could not be tried out.

6.8 Design of trip pulse generator

In high voltage Marx generators, almost invariably, the first stage spark-gap is provided with an external triggering circuit. Once the first stage spark-gap fires, twice the voltage appears across the second spark-gap and breakdown occurs in that gap. Similarly increasing voltages appear across the subsequent stages and Marx erection take place. Therefore, external triggering is required for the first stage spark-gap. The methods for controlling triggering of the first stage spark-gap electrodes of Marx generator are using a three electrode gap or using a trigatron gap. Some of the earlier researchers [41-45] have developed triggering circuits for their research work. In the present work, a compact trip pulse generator has been developed for triggering the first stage spark-gap electrode of the 200 kV Marx generator. The schematic & experimental set up of the trip pulse generator are shown in fig.6.14 & fig.6.15 respectively.

The single phase 230V ac supply is fed to the primary of an isolation transformer (230V/110V). The output (secondary) voltage of the isolation transformer is rectified and a capacitor C_1 is charged to peak voltage 156 V (110* √2). By pressing the push button PB, the above capacitor discharges into the primary winding of an ignition coil and a high voltage pulse is generated at its secondary terminals. This high voltage pulse is applied to one end of the flexible conductor as shown in fig 6.14 and the other end of this conductor is placed very near to one of the first stage spark gap electrodes. Due to application of this pulsed voltage, first stage spark gap fires and remaining gaps fire subsequently as explained above.
Fig 6.14 Schematic of trip pulse generator

Fig 6.15 Experimental setup of Marx generator with trip pulse generator
6.9 Summary and conclusions

In Chapter-4, it has been shown that generation of very fast pulses (sub-nanosecond rise time) is not possible with a Marx generator due to the unacceptably high internal inductance. A very fast pulse can be generated if the whole circuit has low capacitance and low inductance. This can be achieved by discharging the Marx output into the peaking capacitor and the peaking capacitor into the load generating a very fast pulse due to its very low capacitance and very low inductance. Therefore, in this chapter, generation of sub-nanosecond pulses using peaking circuit in addition to 200 kV Marx generator has been studied by both simulation and analysis.

Design, analysis and simulation of the peaking circuit have been presented in detail in this Chapter. A low value 10 pF peaking capacitor with low inductance 10 nH and peaking switch with conical spark-gap electrodes have been built. This configuration lowers the capacitance of the gap. The capacitance will be very small – possibly much less than a pF. The inductances of the electrodes & spark-path have been estimated to be 28.4 nH & 1.5 nH respectively. The low capacitance greatly reduces pre-pulse currents into the load even before the spark-gap fires and improves the output current rise time. Simulation is carried out to study the effect of peaking switch capacitance. Higher the value of this capacitance, higher will be the pre-pulse current. Provision has been made to pressurize the peaking switch chamber with gas, to achieve high withstand & breakdown voltages also enabling fast recovery of the gap. Provision to measure the rise time of the peak output current waveform has been made using a Pearson current monitor. For proper matching, the load, i.e. copper sulphate resistor is filled with suitable concentration of copper sulphate to give desired resistance. Controlled triggering for the first stage spark-gap of Marx is realized by external means using a trip pulse generator. This has proved quite reliable.

The total functioning of the circuit has been analyzed as two sequential discharges. Firstly, the Marx (overall capacitance, inductance & ESR being 1 nF, 2.3µH & 2 Ω respectively) charges the peaking capacitor (10 pF & 10 nH). This has been studied by both analysis & simulation. The peak voltage across peaking capacitor is 394.6 kV & time to peak is 15 ns. The peaking switch is expected to spark-over at this time of 15 ns. Thus, in the second stage, the peaking capacitor discharges through the peaking switch (<< 1 pF, 30 nH) and load has a resistance (85Ω, 32 nH). The output across the load has a zero to peak rise time of 1 ns and the conventional rise time (10% to 90%) is 0.62 ns. The current on discharge has a peak value
of 2.53 kA. In practice, the mounting arrangement for Pearson current monitor will not be required thus reducing the inductance of peaking circuit to 53 nH from 72 nH. By simulation, this gives a zero to peak rise time of 0.88 ns and a 10% to 90% rise time of 0.53 ns.

Thus, it has been demonstrated, by analysis & simulation that, by using peaking circuit, sub-nanosecond rise time output current & voltage pulses may be realized. As facilities for these measurements were not available, experiments were not carried out.