Modelling and Analysis of High Pressure Peaking Switch

Bindu S ¹, Mrunal Parekh ², H A Mangalvedkar ², Archana Sharma ³, D P Chakravarthy ³
¹,² Department of Electrical Engineering, Veermata Jijabai Technological Institute, Matunga, ³APPD, BARC; Trombay, Mumbai-400085

E-mail: bindubalu@rediffmail.com

Abstract. This paper presents modelling and analysis of peaking switch used in Marx generator, such that the rise time of the pulse produced by the Marx generator is reduced substantially. Towards this FEMM (Finite Element Methods Magnetics) software is used for the field modelling of the switch and MATLAB for circuit modelling to observe the rise time. The switch has to produce pulse with sub-nanosecond rise time, hence the electrode distance has to be minimum. This switch can withstand high voltage only under high pressure. A mathematical model is simulated in MATLAB to see the performance under high pressure.

1 Introduction

The high power pulses are used in many industrial, societal and defense applications. Marx generator is one of the source used to generate the short time high energy pulse. The output of the Marx generator is coupled to a peaking capacitor and peaking switch to decrease the rise time of the generated pulse. The short rise time plays an important role in the pulsed systems. This short rise time, high power pulse is fed to various loads like plasma gun, ion gun, electron gun, vircator / antenna etc. The applications include high power radar, plasma ion implantation, diamond cutting, food irradiation, surface coating, waste water processing, medical electronics, Ultra Wide Band(UWB) systems, defence etc.[1-5]. The goal of an Ultra Wide Band(UWB) system is to interact with the increasing combination of soft and hardware functions in electronics.

This paper deals with the design and modeling of peaking switch to modify the output pulse of a Marx generator to achieve the required rise time to develop UWB signals. The pulse from the Marx generator forms the input to an antenna which will generate and radiate the UWB signal. The radiated signal from the antenna depends upon the pulse and the rise time of the pulse generated by the peaking switch. The output pulse depends on the gap inductance of the switch, the fast discharge capacity of the peaking capacitor, the dielectric medium in the switch and the gas pressure [6-13]. This paper discusses the circuit model of the switch with a detailed analysis carried out using the software FEMM and MATLAB [14]. The inter-electrode distance in the switch is very small and high voltage pulse is applied under very high pressure to the switch. The high pressure is needed in the switch to withstand the high voltage of the pulse. Therefore an attempt has been made in this paper to formulate a mathematical model for the switch under pressure.
2. Aspects of ultra fast switching

The Peaking switch is a major component of an UWB system. A fast pulse rise time decides the high frequency components of the resulting spectrum. To sharpen the rise time of a pulse, a spark gap configuration, called a peaking switch is used. The crux of the peaking switch is the establishment of very high electric fields in the inter electrode spacing. A uniform electric field is generally achieved using a Rogowski electrode profile [12], hence this profile is used for modelling the switch. The uniform field is characterised by constant electric field through out the inter electrode region associated with linear voltage profile. The uniform field between the electrodes is produced by applying high voltage between the electrodes, under high pressure. The electric fields produced in the inter electrode region is in the range of MV/cm. The velocity of propagation of the electron avalanche is proportional to the electric field applied to electrodes.

The peaking switch is said to have closed when the potential difference between the electrodes is sharply reduced and current becomes circuit limited. The development of the pre breakdown phase of the spark is related to the minimum closure time of the spark gap, which in turn determines the rise time [7]. This rise time depends on electric field intensity, gas pressure and type of gas medium. This could be modelled as an R-L-C network.

3. Development of Equivalent circuit model of the switch

Figure 1 shows a peaking switch with Rogowski electrode profile. The input to the switch is given to the electrode-I and load is connected to the electrode-II, $r_{\text{arc}}$ is the radius of the arc , $r_{\text{inner}}$ is the radius of the electrode, $r_{\text{outer}}$ is the radius of the outer enclosure of the switch and ‘d’ is the inter electrode distance. In this section we develop an equivalent R-L-C circuit model of the switch during the arcing phenomena.

![Switch model with Rogowski profile electrode](image)

![Switch equivalent circuit](image)

**Figure 1. Switch model with Rogowski profile electrode**

**Figure 2. Switch equivalent circuit**

3.1 Switch Inductance under arcing condition

The inductor, ‘$L_s$’ of the switch can be considered as a co-axial transmission line with $r_o$ and $r_{\text{arc}}$ as the outer and inner radius of the transmission line[6].

$$ L_s = \frac{\mu_0 \mu_r \ln \left( \frac{r_o}{r_{\text{arc}}} \right)}{2\pi} $$

(1)

Where ‘d’ is the channel length in cm,$\mu_0$ is the permeability and $\mu_r$ is the relative permeability.

The inductance per unit length $L_s'$ of the spark gap is then given by
The inductance of the channel can also be written as:

\[ L_s = \frac{\mu_0 \mu_a \ln \left( \frac{r_0}{r_{arc}} \right)}{2\pi} \]  

The inductance can be also written as:

\[ L_s = 2s * d * \ln \left( \frac{r_0}{r_{arc}} \right) \]  

Since \( r_o >> r_i \), the rise time of few nano second the log term is about seven. Hence

\[ L_s \approx 14 * d \]  

The channel inductance limits the achievable rise time of the switch by inhibiting the rate of rise of voltage. Hence to achieve minimum rise time the channel length should be as small as possible.

### 3.2 Switch Capacitance under arcing condition:

The switch capacitance can be evaluated by

\[ C = \frac{2\pi \varepsilon_0 \varepsilon_r}{ln \left( \frac{r_0}{r_{arc}} \right)} \]  

where \( \varepsilon_0 \) is the absolute permittivity of the medium and ‘\( \varepsilon_r \)’ is the relative permittivity of the medium.

### 3.3 Switch resistance under arcing condition

The switch resistance can be evaluated by

\[ R_{channel} = d \cdot \frac{p}{2a \int i(t)^2 dt} \]  

where \( d \) is the gap length, \( p \) is the gas pressure, \( i(t) \) is the current flowing through the channel, and \( a \) is a coefficient characterizing the nature of the gas. It was obtained that \( a = 0.8-1 \) (atm-cm²)/(s-V²) for air and nitrogen and 30 (atm-cm²)/(s-V²) for argon[10].

### 3.4 Peaking Capacitor

The entire experiment consists of the pulse generator which is a Marx generator to which a peaking capacitor and peaking switch is connected as in ‘figure.3’. The rise time of the output pulse can be improved by using peaking capacitor. The peaking capacitor will hold the energy for a short time and discharge much faster than the erected Marx generator. The value of the peaking capacitor is evaluated by considering the load impedance \( R_{load} \) and the source impedances \( L_{\text{marx}} \) and \( C_{\text{marx}} \) of Marx generator.

\[ C_p = \frac{L_{\text{marx}}}{R_{\text{marx}}} \left( \frac{1}{R_{\text{marx}}} \right)^{\frac{L_{\text{marx}}}{C_{\text{marx}}}} \]
The peaking capacitor is selected to achieve exponential decay through the load. It is placed after all the Marx spark gap switches and before the peaking switch as in ‘figure 3’

![Figure 3. Marx generator and peaking capacitor connected to the load](image)

4. Electrostatic modelling

The ‘figure 4’ shows the coaxial spark gap model of the peaking switch with electrodes having Rogowski profile modeled using FEMM. One of the conductors is charged to a high voltage (300 kV) and other one is at ground potential. The switch geometry taken for simulation is having electrode diameter 2.63cm and gap distance 2mm. The diameter of the whole cylindrical structure of the switch is 8.1cm and its volume is 289.46 cubic cm. This analysis gives the electric field distribution, field density, energy stored in the switch and total switch capacitance. ‘figure 5’ shows the field intensity plot and it is uniform throughout the distance. A comparative study of different electrode geometries like plane-plane, point-plane, partially uniform electrode and Rogowski profile are carried out using this software. The modelling helps to detect non-uniformities in the field intensity. The energy stored in the switch and its capacitance is given in Table 1. The table shows that plane-plane and Rogowski electrode profiles, which have uniform field intensity have higher energy storage. Therefore the selection of Rogowski profile for the shape of the electrodes in the switch is perfectly justified.

![Figure 4. FEMM switch model shows density plot Of a Rogowski profile electrode](image)

![Figure 5. Electric field intensity plot for a Rogowski profile](image)
### Table 1 Energy stored and capacitance for different geometries

| Electrode configuration | Energy stored (Joules) | Capacitance of the gap (pico farads) |
|-------------------------|------------------------|-------------------------------------|
| Plane-Plane             | 0.00538726             | 0.1197                              |
| Point plane             | 0.00362011             | 0.0804                              |
| Partly uniform          | 0.00353064             | 0.0784                              |
| Rogowski                | 0.00404199             | 0.0898                              |

5. **Circuit simulation**

The circuit simulations are helpful for investigating the principle of operation of the overall system performance. The accuracy of this method depends on the value of the equivalent circuit parameters evaluated from the geometry. The simulations are carried out with and without pressure.

#### 5.1 Simulation without pressure

Switch is modelled as a series combination of inductor and resistor, in parallel with a capacitor [8]. This switch is connected to the peaking capacitor and load resistance. The inductance of the switch calculated using equation(2) is 25nH. At the time of switching the value of resistance is kept constant and its value is 0.13Ω [11]. The switch capacitance is 0.0898pF and peaking capacitor is 40pF. The circuit simulation is done with MATLAB Simulink. The peaking capacitor is initially charged to 300kV; which discharges through the switch and the load. The rise time obtained is 1ns and peak voltage is 220kV as shown in 'figure.6'. This simulation is not taking care of gas inside the switch and its pressure. It only gives the effect of gap distance and geometry on the output pulse.

![Figure 6. Output pulse for a switch with 2mm gap distance and air as the medium without pressure](image-url)
5.2 Simulation under pressure

The switch is expected to withstand the voltage of 300kV for a gap distance of 2mm under pressurized conditions. The gas pressure under various inter electrode distances could be calculated from Paschen’s law. The breakdown voltage under uniform field in air is given by equation (8) [12].

\[ V = 6.72\sqrt{Pd} + 24.36Pd \]  \hfill (8)

Voltage \( V \) as a function of \( Pd \) value is given by

\[ V = \frac{B+Pd}{\ln Pd+C} \]  \hfill (9)

where \( B \) and \( C \) are constants given in reference [13]. ‘Figure 7’ Shows the breakdown voltage vs gap distance for air and SF\(_6\) gas under 5bar and 10 bar pressure.

**Figure 7.** Graph showing the gap distance Vs breakdown voltage under different pressure for air and SF\(_6\).

**Figure 8.** Output pulse for a switch with 2mm gap distance and air as the medium under high pressure.

The objective of this paper being the reduction in rise time, it is essential to minimize the channel inductance. The inductance reduces when the electrode gap distance is small. Once the gap distance
reduces the operating pressure has to increase to withstand high voltage. The lumped element model of
the switch is developed using Rompe and Weizel arc resistance model. The non linear differential
equation is solved by finite difference method to find the rise time and peak voltage of the output pulse
generated by the switch under different pressure.

Now the fixed arc resistance as shown in ‘figure.2’ could be made variable by incorporating the
resistance as a function of pressure as in equation (6). This gives the model of the switch under pressured conditions. The result obtained from such incorporation is shown in ‘figure. 8’ which gives the
typical output pulse from a peaking switch with air as the medium under various pressures. For 1 bar
pressure the voltage is 40kV and rise time is 0.06ns. As the pressure increases the peak voltage also
increases. When the pressure is 15 bar the peak voltage is 450kV. The result show that as the
pressure is increased the breakdown voltage increase, which means that switch gets closed for higher
voltage. This modelling show that the rise time can be reduced by reducing the switch inductance and
the peak applied voltage can be increased by increasing the pressure in the switch.

6. Conclusion
The paper has modelled a peaking switch and brought out the salient points towards reducing the rise
time of the switch. It has been shown that reduction in switch inductance reduces the rise time of the
pulse output. The switch needs to be applied high voltage under high pressure. It has been shown that
the high voltage could be achieved by increasing the pressure in the switch.

The switch model for the desired rise time has been made and analyzed in FEMM software. Switch
equivalent circuit model is simulated using MATLAB to observe the pulse rise time. The
generation of sub-nanosecond pulse is possible only under high pressure. High pressure switch model
is made by considering the arc resistance as a pressure dependent variable. These modelling
techniques will be useful in implementing the high pressure peaking switch for UWB application

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