# Analysis of the triggering behaviour of Marx generators using Spice simulations

B. Lassalle, F. Bayol, R. Degnon
*ITHPP, Thégra, France*

*Abstract*

The basic operation of a Marx generator is well known and simple: capacitors are charged in parallel through high impedances and discharged in series, thus multiplying the output voltage compared to the charging voltage. As a basic explanation, in a Marx generator using spark gap switches, triggering the first stage is sufficient to double the voltage on the second stage's switch and so on. All the switches are then switched on in an avalanche mode. However, the behavior is often more complex. The parasitic impedances of the geometry play an important role for the creation of overvoltages. This can make the design and the development of Marx generators quite challenging, especially when aiming for good reproducibility and precise timing. The simulation method presented here has been developed to easily compare the effects and performances of different parameters on the Marx erection. Thus, the designers can readily optimize and compare different triggering schemes or other parameters influencing the erection process. Secondly, by coupling LTspice and Python, a statistical approach is presented to also study the effect of the triggering circuit and other parameters on the overall jitter of the machine.

# I. INTRODUCTION

To achieve the best performances in the Marx erection delay and jitter, various triggering techniques have been developed, but unfortunately, there is no "best practice" technique that can be applied systematically. For every new design, the engineers must choose the best way to obtain the required performances. If the initial choice of the triggering scheme does not achieve the expected performances, a lot of time can be spent experimenting to optimize the triggering scheme.

The Figure 1 (ref.[1]) illustrates reasonably well the complexity that a triggering scheme can reach. In the same Marx, multiple triggering techniques can be mixed. In this example there is surrounded in (1) "multiple stage triggering". The triggering generator is connected to the first stages' trigger electrodes to trig them simultaneously and thus increase the overvoltage on the other switches. The resistors surrounded in (2) are called "inter-stage triggering". These resistors pick-up the voltage on the previous stages to increase the field enhancement in the switches during the erection time by preserving the voltage of the trigger electrode to a lower voltage compared to the respective stage level. Finally, the "ground resistors" surrounded in (3) have the same function as those in (2). A complex scheme like this, coupled with the number of non-negligible stray impedances in the Marx is impossible to analyse or optimize without the use of simulations.

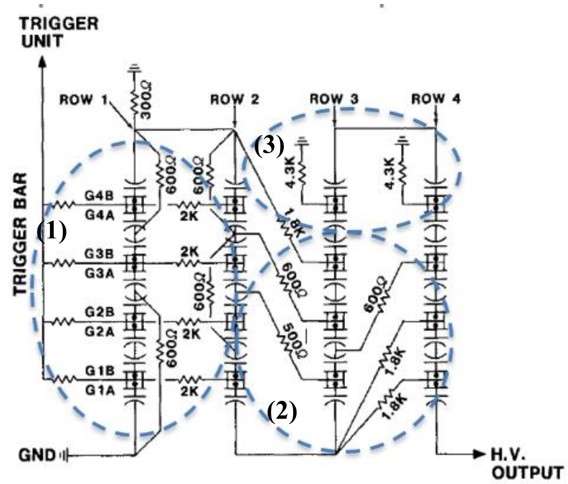


*Figure 1: PBFA triggering scheme*

The purpose of this study is not to give a thorough understanding of the benefits and drawbacks of the various available triggering techniques but it is to expose a general simulation method that designers can use to find the most adapted triggering circuit (or optimize an existing one) depending on the Marx parameters and constraints.

To simulate the erection behaviour with a SPICE simulator, in addition to the basic elements of the circuit, it is necessary to take into account at least these two things: the stray capacitances of the full machine and a spark gap model. These two elements are developed below.

# II. STRAY CAPACITANCES

On all kinds of Marx using spark gaps, the stray capacitances are preponderant in the erection behaviour. This is even more true on large generators using mostly capacitors with metallic bodies and/or when the Marx is designed in a very compact form to optimize the rise time. The estimation of the stray capacitances using simple analytic formulas tend to underestimate them and it is time consuming and/or too complex. Thus, the best way is to use a 3D field solver to obtain the Maxwell capacitance matrix of the full system.

$$\begin{bmatrix} C_{11}+C_{12}+ \\ +\cdots+C_{1n} & -C_{12} & \cdots & -C_{1n} \\ -C_{21} & C_{21}+C_{22}+ \\ & +\cdots+C_{2n} & \cdots & -C_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ -C_{n1} & -C_{n2} & \cdots & C_{n1}+C_{n2}+ \\ & & & +\cdots+C_{nn} \end{bmatrix}$$

*Figure 2: Capacitance matrix for a n conductors' system (ref. [2])*

Of course, the matrix size increases quickly with the number of stages in the Marx. A threshold can be fixed below which the stray capacitances are neglected. This is helpful to decrease simulation time and increase the stability of the simulation.

## III. SPARK GAP MODEL

To accurately simulate the Marx erection process, the spark gap should be modelled by taking into account at least the following two phenomena: the breakdown delay and the dynamic resistance of the arc. A spark gap model for LTSPICE was shared in ref.[3]. It proposes different formulas for the breakdown delay and the dynamic arc resistance. It is up to each engineer to choose the formulas adapted to his design depending on different parameters, such as the pressure in the switches, the overvoltage time range and so on. In the example presented here, to estimate the breakdown delay, we use the formula from ref.[4].

$$\rho\tau = 97800\left(E/_{\rho}\right)^{-3.44} \tag{1}$$

Where $\rho$ is the gas density in g/cm$^3$, $\tau$ is the breakdown delay in seconds, and E is the average electric field in kV/cm. Without going in the details of ref.[4], the theory is that the breakdown delay is mostly dependent of the heating phase of the channel in the gas.

It is possible to find in the bibliography various formulas to calculate the arc resistance dynamic. In most cases, they use the theory of the development of a spark channel defined by Braginskii (ref.[5]). To calculate the spark resistance, we use a formula defined in ref.[6].

$$R = \frac{d}{4600}\left(\frac{p\xi}{\sigma^2}\right)^{0.33}\frac{1}{\int I^{0.67}dt} \tag{2}$$

Where $d$ is the length of the air gap in cm, R is the resistance in ohms, $p$ is the absolute pressure in *ata*, $\xi$ is 4.5, $\sigma$ is the conductivity in ohm.cm$^{-1}$ and I the current in the spark gap channel in A.

The spark gap model in ref.[3] also defines a dynamic inductance depending on the arc diameter. In common Marx generators, the inductance of the overall system is much more than the arc inductances. Therefore, it is possible to neglect this dynamic calculation to lighten the simulation.

## IV. MARX ERECTION BEHAVIOR

In the real life, most of the time, it is impossible to improve the Marx erection behaviour by playing with the stray impedance values. Indeed, the stray impedances are indirectly imposed by the respect of the other design constraints like the size, the capacitor design, the rise time, the dielectric strength, … Thus, the main way to improve the erection behaviour is the design of the trigger circuit. By using the recommendation above, some simulations were done to simulate the behaviour of a 20 stage balanced Marx for different triggering circuits. It is possible to compare the output performances, or other voltage/current in the circuit. One of the most interesting results is the closure delay of the switches presented in Figure 3. As we can see, we achieved a decrease of the overall erection delay by approximately 25%. The triggering schematic *sch1 (with the longer triggering delay)* consists of the triggering of the five first switches, the other switches firing in avalanche mode. The best delay performances are achieved with the *sch4* which use a mix of triggering methods like in the Figure 1.

As the simulation concern a balanced Marx using three electrodes spark gap switches, each switch is modelled using two spark gap models. One for the negative side and one for the positive side of the switch (respectively represented by "o" and "+" in the Figure 3). It is possible to guess that the five first switches are triggered by a negative pulse since all the first five positive gaps are triggering first and relatively simultaneously. We also see that when the third electrode of a switch is not referenced (*sch1*), the positive and the negative side close at the same time. The "inter-stage triggering" method allows us to reference the trigger electrode of the switches at a lower voltage than the voltage reached by the respective stage during the erection time. So, the electric field in the switch is strongly enhanced and unbalanced. Thus, a side of the switch breakdown first and the second in an avalanche mode. In this way, the total closure delay of the switch is decreased.

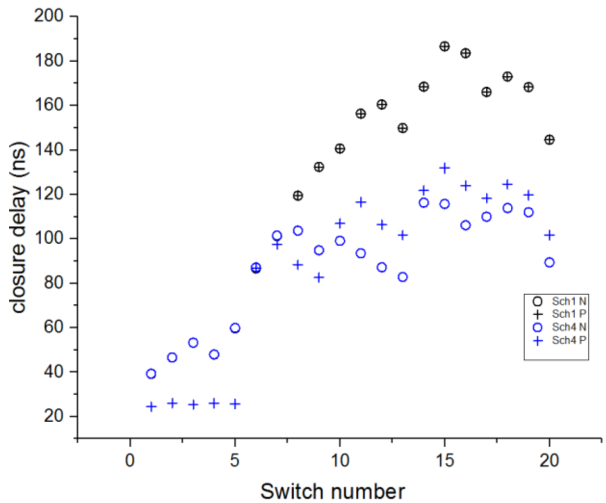


*Figure 3: Switches closure delay (N and P side of the switch)*

Decrease to the overall closure delay also has a positive effect on the output performances of the Marx. Firstly, it slightly decreases the rise time. Secondly, it permits a decrease to the oscillations at the beginning of the output pulse (see Figure 6). Nevertheless, decreasing the delay and smoothing the output voltage is not the only target of the trigger optimization. It is also essential to check the impact on the jitter and this is the purpose of the rest of the study.

## V. EFFECT ON JITTER

It is commonly known that the self-break voltage of a spark gap switch has a statistical behaviour. The behaviour of the switches is probably the main source of the jitter in the Marx as the other elements of the Marx should be stable from shot to shot. To minimize the jitter introduced by the switches, it is so necessary to limit the effect of this self-break voltage spread on the closure delay by trying to increase the rise time of the electric field during the erection process. This is the role of the trigger scheme.

To check the benefits and drawbacks of different triggering schemes, it is necessary to introduce this statistical behaviour in to the simulation. If a switch specimen is available, it is possible to characterize it experimentally. To do that, it is usual to plot its self-break voltage depending on the pressure. To be able to exploit these experimental results, at least for the expected nominal pressure value, it is recommended to do a lot of self-break experiments. The reason for that is that we need to fit the statistical behaviour with a probability distribution. When doing these experiments, some extreme low self-break values should appear (see orange triangle on Figure 4). It is thus common to use a generalized extreme value distribution to fit the results. The Gumbel min. distribution (or Gumbel left) is well adapted both because it fits the experimental results and because it is easy to define, with only two parameters: the mean and the standard deviation (like a normal distribution).

*Nota: The behaviour of the switch depends on the pressure level vs. the surface condition of the switch's electrodes (ref[1]) and this should evolve with the electrodes ageing depending on the commuted coulombs at each shots. With the Gumbel law, it is possible to test the effect of this ageing by simply increasing the standard deviation parameter.*

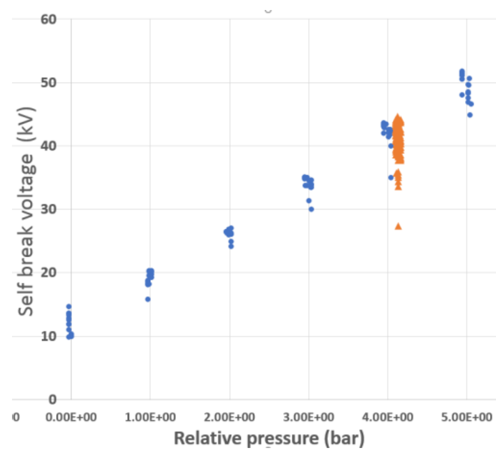


*Figure 4: Self-break curve of a spark gap switch*

To integrate this statistic behaviour in the SPICE simulation, Python is used to generate random values according to the statistical law defined experimentally. Then, Python is used again to randomly modify the self-break voltages of each switch in the SPICE netlist and then launch the simulation. Batch of simulations are launched up to 1000 for each triggering scheme to obtain a stable value of jitter. As a remark, if you have experimental results on individual switches or if it is chosen to have different switch configurations in the Marx, it is of course possible to generate "personalized" random values for each switch.

In the Figure 5 below, the closure delay for each switch is plotted for two different triggering circuits. This time, it is possible to add error bars representing the jitter of each switch. The graph is thus useful to see which spark gap generates the bigger jitter and therefore, where it is necessary to add some effort to the triggering circuit. The Figure 6 illustrates how the triggering circuit can influence the Marx output. The rise time decreases slightly and the output is smoothed due to the small differences between the switches' closure delays. The impact on the overall jitter is clearly visible and moreover, very late shots are suppressed.

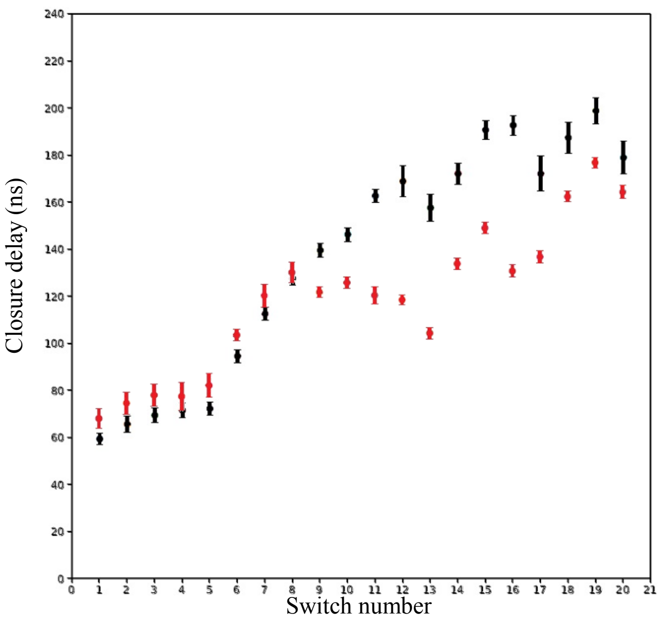


*Figure 5: Closure delays of the negative gaps for two different trigger schemes*

## VI. CONCLUSION

Triggering behaviour of Marx generators can be difficult to analyse due to the large effect of the interconnecting impedances. The present method has been developed to provide Marx designers with a useful tool to understand the erection behaviour and optimize the triggering circuit.

More than the triggering circuit can be analysed with this method. The effect of gas pressure in the switches, resistance values, rise time and polarity of the trigger generator, electrodes roughness, statistical behaviour of the Marx in case of self-break of a switch… are also in the scope of this simulation method. However, although it is based on some experimental results, this method is mainly a comparative method and it is not intended to obtain the absolute jitter of the real generator.

During this optimization process, the delay and jitter are not the only constraints that the designer has to take into account. It is always necessary to think about the feasibility and the eventual constraints added by the modifications of the triggering scheme. Finally, the best triggering schematic should be a compromise between the best performances and the realization constraints.

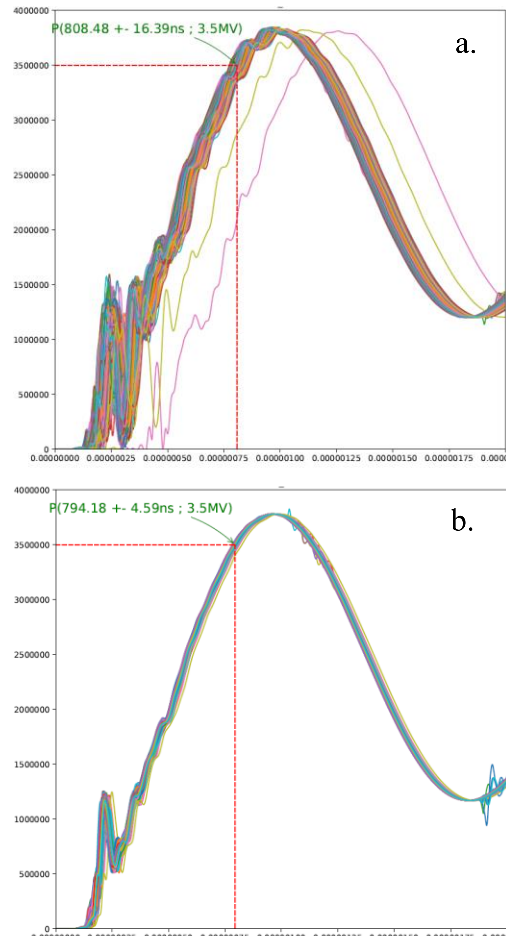


*Figure 6: Output voltage comparison for two different triggering schematics. 500 simulations in each case. (a. Sch1, b. Sch4)*

## VII. REFERENCES


[1] L.X. Schneider "Engineering high reliability, low jitter Marx generators", 1985, Sandia National Labs, NM 87185, 5th IEEE PPC

[2] E. DI Lorenzo "The Maxwell capacitance matrix", 2011, Fast Field solvers, WP 110301

[3] J.C. Pouncey "A spark gap model for LTspice and similar circuit simulation software", 2015, Univ. of New Mexico, IEEE PPC

[4] T.H. Martin "An empirical formula for gas switch breakdown delay", 1989, Sandia National Labs, IEEE 7th PPC

[5] S.I. Braginskii "Theory of the development of a spark channel", dec 1958, J. Exp. Theor. Phys., vol 34, pp 1068-1074

[6] A.A. Kim "Gas switch performance depending on current in the circuit", 2006, HCEI Tomsk, Proc 14 Symp. High Current Electronics.