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(Course Coordinator: W. Sarjeant)

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HIGH VOLTAGE/PULSE POWER TECHNOLOGY

GRADUATE COURSE EECS596

University of New Mexico

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Lecture 3
PULSE VOLTAGE CIRCUITS
by
W. L. Williams

PREFACE

With the recent increase in technological needs and the interest in the power conditioning arena, one of the problems facing workers in the field is the lack of texts or notes describing recent progress, particularly in the area of repetitive power conditioning. For this reason and because of expanding internal requirements, the University of New Mexico (UNM) and the Los Alamos Scientific Laboratory (LASL) have created a set of lecture notes based upon the graduate course taught recently at UNM. The objective of these notes is to create a record of many of the advances in the field since the last text in the field was published just after World War II. In this context, the lectures presented are oriented toward an introduction of the reader to each of the areas described and present sufficient background information to explain many of these advances. They are not intended to serve as design engineering notes, and thus the reader is referred to the references at the end of each lecture for detailed technical information in specific areas.

The preparation of these writings is a result of a considerable teamwork effort on the part of LASL and Sandia staff. In particular, Cathy Correll, in conjunction with Jo Ann Barnes and the rest of her efficient word processing staff, carried the major responsibility for preparation of the lectures while the lecturers did the proofreading and revisions. As course coordinator, it is a pleasure to acknowledge the strong support of Ray Gore, our E-Division Leader, and Shyam Gurbaxani who is the UNM Graduate Center Director, Los Alamos Campus.

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October 3, 1980

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Lecture 3
PULSE VOLTAGE CIRCUITS
by
W. Willis

I. SCOPE

The problems associated with very high voltages may be avoided in part by a variety of pulse-multiplication techniques. These methods are quite varied but share two features, the use of modest dc voltages and the use of switching techniques, to produce in some manner a vectorial transient addition of voltages.

Many such methods exist, but only the Marx bank, spiral generator, inversion generator, and Blumlein will be addressed here in detail. Two other methods will be given a brief discussion as matters of interest. An important system, the pulse transformer, is the subject of a separate discussion. Also, some aspects of transmission lines will be taken for granted in this lecture and justified elsewhere.

II. MARX BANK

A. History

The history of this generator is interesting, particularly to those who are actually struggling to build a Marx bank, and also because the terminology describes circuits as an Erwin C_2 or Erwin R_3 , which recognizes Erwin Marx who described these generators in 1923. At about that time quantum mechanics also began to appear in publication.

Rather good performance was obtained even in those days. In 1926 Burov, of Russia, described a 100-kV pulse with a 10-ns duration. He did not describe the measurement technique. However, a 10-ns duration pulse, even if it is triangular in waveform, yields a 5-ns risetime. One hundred kilovolts in five nanoseconds is still respectable.

Burov used, incidently, a Hertzian shortwave peaking gap and is one of the earliest references for use of a peaking gap to sharpen the output of a Marx bank.

By 1938, Schering and Raske of Germany reported a 400-kV pulse with a 10-ns risetime. This is 40 kV/ns, which is also satisfactory. They described the five stage Marx bank as using CO₂-pressurized spark gaps, and there was no mention of sharpening gaps to obtain that performance. The first reference in American literature seems to be R. C. Fletcher, in 1949, who used a gaseous peaking gap and reached 20-kV output, which is not particularly high voltage but 0.4-ns risetime yields 50 kV/ns rate of rise. Again, there was no mention of how the output was measured. Other information reveals that he built his own special spectroscope for doing so, but it was never described in print.

Figures 1 and 2, from J. C. Martin, Nanosecond Techniques, show the state of the art in recent years. The note on Figure 1 indicates where Los Alamos Scientific Laboratory (LASL) was in 1975, about 8 years behind the state of the art.

There are two points that should be mentioned here. First, these systems are not commercially available but show that somebody worked extremely hard for a special application. Second, when you start looking at numbers, this can be misleading. Megavolt systems are required to get this kind of performance, not 100-kV or 50-kV systems, for reasons that will show up very quickly.

Fig. 1. Marx Bank State of the Art

Fig. 2. Marx Bank Erection Time

Figure 2 shows the erection time per megavolt for the best design and the accent is on best. LASL is not noted on this particular one. Erection time involves the manner in which Marx banks are fired, a critical parameter of Marx banks that has a lot to do with the mechanical layout and design. Erection time is not given by formulas very handily, but is a good measure of how well a bank will work. Again, in Fig. 2 it is not stated whether the erection time includes a sharpening gap or not. As an example, consider a megavolt bank in terms of 100 kJ. Using the relationship for energy storage, and a simple calculation:

$$U = \frac{1}{2} C V^2$$

so that

$$C = \frac{2 U}{V^2}$$

which, at 1 MV, leads to

$$C = \frac{2 \times 10^5}{10^{12}} = 0.2 \mu\text{F}$$

The Marx bank, which means quite a few capacitors in a series, then requires 100 nH in this system at 1970 performance levels shown in Fig. 1. That is impressive for a 10-stage Marx with 2- μF capacitors, only 10 nH per stage, including the inductance of the capacitor, the hook-up, the spark gap, etc. Now if this is operated as a 100-kV system, the same relationship only allows 1 nH per Marx bank stage. That is why at this point the performance curve does not describe physically practical systems. Very high voltage Marx banks are required to yield this kind of performance.

B. Basic Configurations

The fundamental concept of the Marx bank is quite simple--charge capacitors in parallel and discharge them in series. Figure 3 shows three basic arrangements. Figure 3a is perhaps the most economical of parts, since the output switch may be optional in some cases, where a modest level of dc on the output is acceptable. If the load happens to be a gas discharge, and will operate with some dc on it, the designer can save a switch. It is not a usual case, but it is possible. The circuit gives the same voltage polarity out as is put in if polarity is of interest. Normally, this need is avoided by reversing the power supply, but sometimes this is difficult for one reason or another. It has a drawback with respect to triggering, which will be discussed later. We are more interested in charging at this point. However, the first gap in the string goes high upon firing, producing a high-voltage transient phase in the trigger system.

Figure 3b inverts the supply voltage sign and, in this case, the output is at ground potential except during the charging transient. One advantage lies in the fact that one terminal of S1 is at ground potential. This may be an advantage in the triggering design because high-voltage isolation is not a problem. The Ion Physics MiniMarx line is of this design and employs a trigatron-type gap as the first switch. It generates a 100-kV pulse with a 2-ns risetime. The trigatron is a type of spark gap that is usually triggered with respect to ground. Figures 3a and 3b are drawn in the ladder system. Figure 3c is somewhat different. This is an even further step away from high-voltage dc supplies. It uses both a positive and a negative supply to charge and there are only half as many switches as there are in the single polarity case. Switching is not necessarily simpler. If the same voltage output is required as before, then the switch has to hold off twice as much voltage as in the other Marx banks, so it uses fewer switches but it is a more difficult switch to build. Do not be misled by apparently concealed advantages. A drawback on the output point is that the full erected

Fig. 3. Marx Bank Circuit Configurations

voltage appears across the output resistor. It is difficult to find a megohm resistor that will withstand a megavolt, even for a short time. One reason why these circuits are typically built ladder style is because when they erect, the voltage across any one resistor is the stage voltage rather than the bank voltage. The resistor to ground on each stage does have advantages for charging speed. Visualize the charging components as inductors rather than resistors. There is an obvious charging time problem for banks of 10 or 12 stages. Marx banks typically are not a high-repetition rate device. The old timers were after very high voltages for things like E-beam systems that tend to melt down, if operated at a high-repetition rate. If a fast Marx bank is desired, do not use resistors. Serious inefficiency problems appear, for one thing. Another is just getting the charge on the capacitors. Go to a set of inductors with another set of constraints. It is still possible to charge with a dc supply. In that case the first inductor normally becomes very large with respect to the rest of the system components, so that when the bank is fired, it does not dump back into the power supply. It makes the calculation of how long it takes to charge much simpler than for the RC case. Also, there is no real reason why, given inductors and capacitors, the Marx bank could not be designed as a high-voltage pulse-forming network (PFN).

C. Charging Methods

Figure 4a is an n-stage Marx bank with a step input U_t/n , where U_t is the desired output. From a charging analysis standpoint it does not really matter whether the resistors are given as $R_0/2$ or are replaced by R_0 with the lower elements eliminated. The output voltage available at any instant is, theoretically, the sum of the individual stage voltages. Thus, we have an RC line in which, except for the first stage, all forcing functions are time and position dependent. Two solutions are conveniently available. One relationship, according to Fitch, is

Fig. 4. Marx Bank Charging Performance

$$V_S(t) = \sum_{i=1}^n V_i(t) \cong 1 - \frac{\theta}{\pi^2} \exp \left\{ -\left(\frac{\pi}{2} \right)^2 t \right\}$$

Fig 4 B

$$T_{CH} = R_O C_O n^2$$

where T_{CH} is the lag of the n th stage with respect to the input stage.

G. W. Swift presents a power series analysis that he takes to the limit as n goes to infinity. This is the relationship shown on Fig. 4b with a few finite cases shown. The $R_t C_t$ time constant is the total R and total C of the circuit shown. The fact that five or more stages are effectively infinite makes this useful for calculation of banks of many stages. Note that the time t is given in terms of the $R_t C_t$ time constant. For a simple case, take $1\text{ M}\Omega$ and $1\text{ }\mu\text{F}$ for R_O and C_O , which are typical numbers, and 10 stages. A 10-stage Marx of that type takes about 100 s after the first stage is charged before the last stage charges, almost 2 min. Now is that consistent? In Swift's analysis in the same case, R_O is 10^7 because there are ten $1\text{-M}\Omega$ resistors and 10 of C_O in parallel, for a total of 10^{-5} F . Thus, $t = R_t C_t$ and that still comes out to about 100 s on the normalized scale of Fig. 4b. Swift's analysis shows that the bank would be 93% charged at the end of that time constant. The agreement between the two methods is good--only a few per cent difference. In either analysis, something better than 100 s is required to get the bank charged. The expression given in Fig. 4b is useful. Express time in terms of the RC time constants and solve for the time required to charge to 98%, 94%, or whatever is desired. The analysis does not describe the final stage. It says what the output would be if all these capacitors are in series with switches as shown and fired at a given time. In that curve, if the Marx is fired at 100 s, 93% is the total output because the input capacitors are charged but the ones behind it, although nearly charged, are slightly lower. It really describes the output voltage of the Marx bank, not the final stage voltage. However, a designer probably would not use an RC bank at a very high repetition rate, but would use an inductive system.

In the case of an LC circuit, recourse may be taken to the PFN characteristics that will be covered in a subsequent lecture. Ideally, such a network has a characteristic time given by

$$\tau_{\text{CHG}} = \sqrt{L_{\text{MARX}} C_{\text{MARX}}}$$

and discharging into a matched impedance requires a time 2τ . In mismatched cases, oscillations occur that extend this time. More commonly, some command charge system is employed in which an external inductor, large with respect to the Marx inductors, is resonated against the total network capacitance. Charging is usually accomplished in a half cycle of the resonant frequency, leading to

$$\tau_{\text{CHG}} = \pi \sqrt{L_{\text{TOTAL}} C_{\text{MARX}}}$$

The point here, neglecting the switches, is that normally the pulse out is much, much faster, even at a kilohertz. There is perhaps 1-ns charge the bank. The output falls typically in a microsecond or in that order, so that there are orders of magnitude time differential between the discharge period and the charging period, which means the input inductance can be huge compared to the one in the Marx bank, and is used for isolation. So, effectively, the Marx inductances almost are not there. Simply look at the bank as a total capacitor and a charging inductance. Put a voltage step on it and it starts to ring in the classic resonating circuit fashion. It charges up in half a cycle at most--in a period that can be made fast compared to an RC time constant.

D. Discharging of the Marx

The inefficiencies of charging have a matching set of inefficiencies that have to do with the discharge. Figure 5 reveals that, in general,

Fig. 5. Marx Bank Discharge Relationships

$$\tau_0 = \frac{R_0 C_0}{2}$$

$$L = \frac{2 Z_0 \tau}{n \left[\frac{I_{LC \text{ MAX}}}{I_L} \right]}$$

a stage capacitor is paralleled by two charging impedances Z_0 in the resistive case, the self-time constant is just

$$\tau_{\text{DISCH}} = \frac{Z_0 C_0}{2}$$

and must be long compared to the output pulse for good efficiency. The two end cases are best, since each has only one resistor and therefore has twice the impedance. With many stages, that factor disappears in overall analysis. The point is the existence of a discharge time constant. The Marx discharges very quickly into the load with a much slower competing process because the impedances are large compared to the load impedance. Nonetheless the discharge is in there, drawing energy during the pulse and drawing current out of the capacitor back through the charging resistors, at the same time the bank is delivering current to the load. The competing process is an inefficiency. It has more than one repercussion and it can involve heating problems in the system.

When inductances have been used as charging impedances, the behavior is similar except for the appearance of resonance in place of the simpler RC case. The analysis in Glasoe and Lebacqz is straightforward and summarized here.

A given mesh will attempt to resonate with a current given by

$$i_{LC} = V_N \sqrt{\frac{C}{L}} \sin \frac{t}{LC}$$

where L and C are the mesh values of the Marx and V_N is the stage voltage. For good efficiency, the self-ring period T is chosen much greater than the discharge period τ . Thus, the sine of the angle may be replaced with the angle and

$$i_{LC} \approx V_N \frac{C}{L} \frac{t}{\sqrt{LC}} = \frac{V_N t}{L}$$

and t has a maximum value of τ , since the process terminates when the bank is discharged.

If the Marx discharges into a matched impedance (PFN-like behavior), the Marx current is

$$I_1 = \frac{n V_N}{2 Z_N}$$

and one can relate the efficiency by the ratio of i_{LC}/I_1 .

This case is more apt to be discharge inefficient than the resistive case. The resistive case normally has the loop currents swamped, almost nothing goes into the resistors.

E. Marx Triggering and Erection

Up to this point, the Marx circuit has seemed quite simple and straightforward. The subtleties appear in the relationships between triggering, mechanical assembly, and erection. Very little has been mentioned previously about how the necessary switch closures are accomplished. Although other switches have been used, spark gaps will be assumed for this discussion.

(Two papers, Marx and Marx-like High-Voltage Generators by R. A. Fitch, and Overvoltage and Breakdown Patterns of Fast Marx Generators by R. W. Morrison and A. M. Smith, have been drawn upon for the following material.)

This gets into the part of the Marx bank that is both nonquantitative and frustrating. Discussion will start with the backbone circuit, Fig. 6. It is the relationships among the mechanical assembly, triggering

Fig. 6 Backbone Circuit

C_{g1} Δ gap electrode capacitance

C_o Δ stage energy storage capacitance

BACKBONE CIRCUIT

FIGURE 6

and erection (closing of all of the switches) of the Marx bank to number of stages times the stage voltage, hopefully, of output voltage. Other switches have been used but spark gaps are assumed all the way through. Very few Marx banks are not made with spark gaps as a matter of fact, so there are not many exceptions to worry about. Assume now that somehow we trigger the first gap. Thus far there has been little discussion about the triggering. All the gaps here are two-element gaps, and the voltage can be increased until something collapses or the first one can have an overvoltage, or somehow be designed to be overvolted. It is possible to build a husky trigger system, pulse the first capacitor, overvolt that stage, and launch the bank that way. Argue that only the first gap is triggered on purpose.

When the first gap fires, all voltages around the loop must add up as before, to zero, by Kirchhoff's Law. (Gaps are opposite in sense to capacitors.)

$$\begin{aligned} N V_o &= N V_{\text{gap}} && \text{initial} \\ N V_o &= (N - 1) V_{\text{gap}} && \text{one gap fired} \\ N V_o &= (N - 2) V_{\text{gap}} && \text{two gaps fired} \end{aligned}$$

or, alternatively, the voltage across an unfired gap should be

$$V_{\text{gap}} = \frac{N V_o}{N - n}$$

where n is the number of fired gaps.

This model is, fortunately, too simple. It predicts an accelerating rate of overvoltage firing, which is not always observed, does not predict order of firing, and is pessimistic for many-stage Marxes. The latter is due to the small overvoltage per stage produced by triggering one gap.

Figure 7 shows the physical layout and equivalent circuit of a simple stacked Marx. (In Fitch's notation, a C1 Marx, that is, capacitively coupled, single column.) Some simplification is still present. C_g is the gap capacitance, C_c the capacitance between stage capacitors, and C_s the stray capacitance to ground.

Because of voltage holdoff and assembly considerations, C_s is usually very small, only a few picofarads. C_c can be quite different. In order to reduce height and inductance, the capacitors C_g may be quite close. Two Maxwell pulse capacitors may exhibit up to 50 pF or so for C_c , and 1.25 μ F, 4-kV CSI metal case units can have up to several hundred picofarads between the electrodes of adjacent units.

A trigger is shown in this particular case. That trigger is commonly brought in through a small capacitor for voltage isolation, and 250 pF is a typical number for the trigger. Assume a trigger is applied. In that case the lower electrode of C_{g2} is driven with respect to ground to +V. Consequently, the upper electrode of C_{g2} jumps to 2 V. It appears that this will overvolt gap C_{g2} because the charging string has the top of C_{g2} at dc ground before triggering. Unfortunately, the 2-V pulse sees divider C_c and C_{s3} to ground. The equation says that

$$V_{cg2} = V \left(1 + \frac{C_{s3}}{C_c} \right)$$

If the stray capacitance is small and the coupling capacitor is large, what happens is obvious. At first V_{cg2} is small and the divider action takes it off. The step voltage will get there. The charging resistors are still present and eventually, since the charging resistor returns to ground, C_{s3} will discharge and the voltage will appear across C_c and C_{cg2} . Sooner or later the gap will go, but it goes with an RC delay and the capacitive divider slows it down. Fitch comments that if the bank erects at 60% of the self-break on the gap it is

Fig. 7. Layout and Circuit Relationships

FIG. 7

a healthy bank. It should run dependably at 70% of self-break and up. But if the divider is bad enough, it may not even erect. The transients may all filter off on RC time constants down the line to where the bank ends up on the backbone circuit with the overvoltage distributed equally across all the gaps and none of them fired. The solution for this is to go to what Fitch would call a C2 Erwin Marx, as shown in Fig. 8a. A zigzag pattern, mechanically, leaves the strays to ground from the capacitor the same as they always were. The stray coupling capacitor jumps stages, bridging two gaps in an alternating pattern. This can be done in a spiral of three and get a C3 Marx, etc. In practice, three is about as high as people normally go. We will come later to the use of resistors instead of capacitors and with physical components start calling these R1, R2 and R3 Marxes.

The behavior is a bit different in the C_2 case. Now when the first gap is triggered, the lower electrode of C_{g2} jumps to 2 V, C_c is no longer a divider with respect to the next gap up. It does see C_s and has to charge it through the impedance of the stage. Basically, the voltage appears across C_{g2} , the capacitive divider has gone away and the next gap fires quite nicely. In a Russian paper describing an Arcadex/Marx, quite large strays are inserted on purpose to hold the upper electrode of C_{g2} at ac ground and virtually the entire voltage appears across the second gap to fire it. This looks very elegant; it is going to go right up the line, firing 1, 2, 3, 4, and 5. Again life is not that simple. To preview coming attractions, look what happens when lower C_{g2} has been driven to 2 V, fired C_{g2} , and now lower C_{g2} tries to jump to 3 V. Unfortunately, C_c has coupled the 2 V point around to the top of C_{g3} and partially unloaded the gap intended to fire next. The interactions start to chase themselves up the ladder.

This problem has been analyzed in detail by Morrison and Smith. The complexity of the problem can be seen by examining their analysis of a 10-stage Marx in which the first gap is triggered and the interactions of the capacitive dividers are carefully studied (Fig. 8b). They have

Fig. 8. Marx Triggering Sequence

FIG. 8A

FIG 8B

10-STAGE MARX
 OVERVOLTAGE PATTERN AS SUCCESSIVE GAPS FIRE

Ref. 4

Fig. 9. R3 Martin Marx

*R3 MARTIN***FIG. 9**

assumed ratios, by putting in a coupling capacitor large enough to give a ratio to the gap capacitor of 10 and a stray capacitance that is twice the gap capacitance. The stray is fairly easy to keep small, because normally the capacitors are well away from the ground plane. The coupling capacitor normally is not small because in fighting inductance the capacitors are close. These are given as $C_c/C_g = 10$ and $C_s/C_g = 2$. The analysis assumes firing the first gap and following the transients up a 10-stage Marx through all the capacitive dividers. After triggering gap 1, gap 2 is the most extremely overvolted of all gaps, so it will fire. When 2 breaks down, the voltages in the capacitive divider vary. At some points, for example, gap 4, they are inverted and at some they are not. But 3 is still normal and most overvolted. This, then, keeps on going to 3 then 4. When the fourth gap breaks down, the problem comes "What Happens?" Gap 5 is high and it goes. When 5 goes, 6 is high, 8 is high, 10 is high, and the question is "What goes next?" The outcome is that for different ratios in these dividers, the Marx bank may start erecting from the bottom, turn around and erect back down from the top and meet in the middle, or other kinds of unexpected patterns can occur. Now that is not a trivial consideration. Take any two capacitors with a little space left between them. A charging current flows and there is some inductance associated with that current. The bank has large capacitors with respect to the coupling values. This can result in a version of what we will hit later, in resonant charging. The behavior depends on whether the capacitor has a metal can or dielectric can. But the circuit can swing up to something like four times the stage voltage across that stray coupling capacitor. If it is closely spaced, arcs in the air or oil dielectric can occur. There will be arcs from stage to stage and firing patterns that are very hard to predict, in terms of voltages that are going to appear.

One consequence of this behavior is the use of mid-plane gaps in Marx banks. For triggering purposes, a nonsymmetric gap is desirable. However, this presupposes knowledge of the electrode voltages, a condition that is not, in general, met in banks of many stages. If the bank

uses dielectric case capacitors, and they often do, this may punch right through the dielectric case. The Maxwells, for example, have a preferred side up from the ground. But if the preferred side up is in the overvolted stray side, and four times rated voltage occurs, punch-through may destroy it. So, how is a bank made to operate dependably? This brings up the point of triggering.

The use of more than one triggered gap is common in many Marx banks in order to reduce jitter. This, combined with back coupling, yields a more predictable system. Figure 9 is an R3 Martin Marx (named for J. C. Martin, who pioneered the use of three-electrode gaps in Marx banks) in which the first three gaps are externally triggered. This circuit depends upon triggering by maintaining the trigger electrode potential while the electrodes change voltage.

Up until now these have been called Erwin Marx, because the Erwin Marx is a two-electrode system. The Martin Marx is characterized by spark gaps with trigger electrodes. In one of these a trigger system fires the first three stages so that at the top of C_4 the voltage rises to 4 V for overvolting on subsequent stages. The gaps have trigger electrodes and the circuit design reveals what is going on. The fourth gap trigger electrode is held down to the voltage of the bottom stage, which is going to be V, and the lower main electrode will jump to 4 V. What actually happens in this type of circuit is that the trigger voltage changes very little while the main electrode swings. In the first stages swing the trigger electrode to fire the bank, from there on up hold the trigger down to the potential of preceding stages with discrete components while the electrode itself swings away for triggering. These are quite dependable in jitter and triggering. There are a couple of penalties to pay. For example, shown is a very simple triggering with three input capacitors. When the plasma forms in the gap arc, the trigger electrodes are tied to stage voltages and are fed back down into the triggering system. It makes the triggering system a bit nasty. Also, voltages of 3 V, 2 V, and 1 V are summed, yielding miscellaneous

sloshing in the trigger system. Typically, there is some resistance in series with each of the trigger capacitors to limit the surge currents that flow in the coupling capacitor. Only $50\ \Omega$ or so do not affect the system (because they do not draw current until the arc is actually formed, at which point the triggering is over). Do not, however, put the trigger resistor back at the other end of the cable because then the cable capacitance and resistor produce an RC circuit that will slow the trigger pulse. Part of the precision of these systems is related to the risetime of the trigger generator. There is yet another approach for which no figure is included. A high-energy Marx runs to large capacitors and large strays are associated with them. It is not unusual to build another small Marx bank, which has the same basic characteristics and cross couple all the way up between stages. This small, very low energy Marx bank is very, very fast. It runs in parallel and you trigger the entire Marx bank with another Marx bank. That is an expensive and difficult way to go, but can be the ultimate in precision, because the risetime for erection is set by a very small fast Marx rather than a large sluggish Marx.

F. Output Considerations

G. A. Mesyats, in a translation of "Formation of Nanosecond Pulses of High Voltage," presents an interesting analysis of the effect of the spark gaps on the Marx output waveform. This circuit model (Fig. 10) replaces the bank with C_0 , an equivalent capacitor, which is the stage capacitance divided by the number of stages. An inductance associated with the Marx circuit is given. There are two resistors in the model. R_L is an equivalent fixed resistance. Sometimes a little resistance is added to the Marx bank for damping purposes to prevent ringing. There is always some fixed resistance in the connections. R_{sp} is a spark gap resistance and there is an output load resistance paralleled with a load capacitance, probably a stray. When the gap resistance is pertinent, he approaches the problem with

Fig. 10. Mesyats Circuit Model of Marx Bank

$$C_0 = C/n$$

$$U_0 = nU$$

R_L = Equivalent Fixed Resistance

FIG. 10

$$R_{sp}^2(t) = \frac{pd^2}{2a \int_0^t i^2 dt}$$

where $R_{sp}(t)$ is the gap resistance as a function of time,

p is gap pressure in atmospheres

d is gap spacing, in centimeters

i is current in amperes

a is a gas constant, ≈ 0.8 to $1 \frac{\text{atm cm}^2}{\text{V}^2 \text{ sec}}$

for air or nitrogen.

For a given breakdown voltage, as pressure goes up, R_{sp} goes down. (Paschen's Law)

If the spark resistance is considered, the output pulse amplitude becomes

$$U = U_0 \left[1 - \left(\frac{1}{\sqrt{1 + 2B}} \right)^2 \right] \sqrt{\frac{1 + 2B}{2B}}$$

where

$$B = \frac{R_{sp} C}{\tau}$$

and

$$\theta = \frac{2 \rho d^2}{a U^2}$$

The pulse front width is defined as the ratio of pulse amplitude to maximum front curvature and is given by

$$t_f = \frac{128}{27} \frac{\left(\frac{1 - (2B)^{-1/3}}{1 - \phi(A)} \right)^{3/2}}{\quad} \quad \text{for } B > 5$$

where

$$A = \frac{L}{\theta R_H}$$

$$\phi(A) = 0.157A - 0.0108 A^2 + 0.00017 A^3$$

A small θ (called the spark time constant) yields a larger, faster rising pulse. Examples are:

$d \approx 1$ cm at atmospheric pressure
 $t_f \geq 10$ ns, even with no circuit inductance

When the gap pressure is high enough, the output is determined by the remaining parameters. If C_H , the load capacitance, is neglected

$$t_f = 2.2 \frac{L}{R_H} \quad 10 \text{ to } 90\%$$

Further, if R_H is $\gg 2\sqrt{L/C_0}$, the half-width pulse height is $0.7 R_H C_0$. This defines L in the sense that a 1-ns risetime requires an L of $10^{-9}R_H$. For P it is the spark resistance that he has calculated. C is the total bank capacitance for parameter θ , and θ , in turn, is derived out of PP_2 .

Mesyats discusses the curvature of the front, where we would be more inclined to speak of the risetime. He calls θ the spark time constant, and it is the key parameter of this discussion. The smaller θ is, the faster the Marx bank is going to be. It does more or less agree with other relationships used to describe gap behavior. There is a relationship between geometry, pressure, and the voltage a gap will hold off. Going up in pressure increases θ , but the down-quadratically-with-voltage relationship agrees with other relationships that show a preference for small spacings and high pressures. Mesyats worked out a couple of examples in his paper. He took a case where d was a centimeter and p was an atmosphere. This is about a 30-kV spark gap so it is not an unreasonable design. He goes through all these equations and comes out with 10 ns using that kind of a gap for the Marx risetime. This is the minimum time, even if the inductance for his model is zero. If the pressure is set high enough, the time can be reduced to 1 ns. If you take this model, when the gap pressure is high enough, other parameters in the circuit determine risetime, which is the usual result in any of these spark gap switch systems. Increasing pressure and voltage with the spacing reduced generally yields a better system. If you are in a position to design your own spark gaps, you are better off to increase pressures and voltages, and decrease spacing. The key relationship defines L and says that a nanosecond risetime requires inductance of 10^{-9} times the load impedance. If the load impedance is very low, then a fast risetime is difficult. Another point -- can you neglect the stray capacitor C_H ? Current flow is given by $C(dv/dt)$. This current drops some voltage back in the Marx impedance and in the case of very,

very fast Marx banks, dv/dt can be a large number. Even small capacitors will start loading back in the system. There is an important comment related to that. One can very easily, in these pulse systems, come up with the situation where output voltage and output current wave forms do not remotely resemble one another. Sharpening gaps and so forth can produce a voltage pulse with virtually zero risetime. Then comes the discovery that the current pulse is performing differently because it is determined by the inductance of the system and the impedances scattered around. Power delivered to a load may be well out in time.

One way around this is to pulse charge a low impedance intermediate storage element with an output switch. If the bank is going to erect to 100 kV, try to set the output switch to break down at, say 95 kV. The Marx pulse is rising in some fashion for 100 kV. At 95 kV, the sharpening switch closes and what the outside world sees is something that looks extremely sharp. This is very common practice in E-beam systems where there is usually some kind of transmission line that the Marx charges in 2 or 3 ms. On the output there is a spark gap that fires very quickly. When that breaks down, looking back into the system, you do not see the Marx bank, but the transition section, which has a very low impedance. This is capable of delivering a current pulse, similar to the voltage pulse, for many purposes. It is one way of getting around all of the inductance associated with the Marx bank and of stiffening up the risetime of the system.

1.1. INVERSION GENERATOR

Let us now consider the inversion generator shown in Fig. 11. It is related to the Marx bank and what Fitch calls a vector addition system. It has several advantages and disadvantages. It resembles a Marx bank but the switches are not in series. The charging circuit is not shown, but the capacitors are charged in alternating sequence, minus or

Fig. 11. Inversion Generator Circuit

plus, plus to minus, etc. One disadvantage is that there is no way to trigger one switch from the next and there is no capacitive coupling between the stages. They do not see one another from a triggering standpoint, which means on this sort of circuit, triggering every switch must be accomplished somehow. There is no convenient way of triggering only one switch. Let us look at the advantages first. Erection of the inversion generator is quite straightforward. Closing a switch starts a capacitor-inductor circuit ringing according to

$$I = V \sqrt{\frac{C}{L}} \sin \frac{t}{\sqrt{LC}}$$

This L is fairly large relative to the value in the discharge circuit, and it is usually put in deliberately for timing purposes. Each circuit should ring with the same period. After a half period, $T = \pi \sqrt{LC}$, the capacitor has reversed polarity, adding to the unswitched units. Since some losses are incurred in the switch and connections, the output is

$$V_o(t) = \frac{nV}{2} \left(1 - e^{-\alpha t} \cos \frac{2t}{T} \right) *$$

where

$$\alpha = \frac{R}{2L}$$

One thing is immediately apparent. The output voltage begins to appear at once with a risetime set by the ringing portion of the circuit. This is usually fairly long with respect to the desired output time in order to minimize losses in the switches. As a result, an output switch, commonly an overvolted gap, is normally a part of the circuit.

Unlike the Marx bank, load currents do not have anything to do with the switches. So all the switch loss, switch inductance, resistance, etc., are out of the way. The output is from a string of capacitors in series. A low-inductance fast-current pulse can be produced by this generator. The generator has advantages and, buried away, a couple of big disadvantages. The triggering problem has been mentioned. The trigger must stand off the entire bank voltage on the upper stage. The really interesting fault occurs if one of the switches fails to go, for example, S_3 , then C_2 and C_4 invert and suddenly there is +5 V looking at a capacitance charged -1 V. If the switch tries to hold, the capacitor is going to be highly stressed. High-voltage capacitors just do not like to be reversed. Even if an excessive overvoltage did not occur, damage could result from excessive ringing. Another difficulty occurs if the bank is charged up and dumping becomes necessary. There is no really convenient way, in case of malfunctions, to save this circuit by dumping it in a hurry. Also, a prefire will ring one stage, probably without firing the other switches. The complexities of preventing these failures reduce the initial attractiveness of the LC inversion generator.

IV. BLUMLEIN

The Blumlein rates about one page in Glasoe and Lebacqz, as a special case of a Darlington discharge circuit. In this case, the description is in terms of a PFN. In very fast discharge networks, the Blumlein is more nearly a single-stage LC inversion generator. Since the PFN mode is the normal one, the discussion will begin there. Figure 12 is a somewhat redrawn version of Fig. 11.16 from Glasoe and Lebacqz.

Initially, all capacitors, C_1 - C_8 , are charged to the same sign and potential. It should be noted that C_5 - C_8 must charge through the load. If the load is normally open, for example, a gas discharge, a parallel path must be provided. In many cases, the load is a pulse transformer primary for impedance conversion.

Fig. 12. PFN Blumlein

PFN BLUMLEIN

FIG. 12

Something similar to this is used with some laser loads. The pulse transformer is handy for klystrons, magnetrons, and similar devices to provide an impedance match. This type of a PFN is used in rather broad pulse applications because it is difficult to get very low inductances and very low inductance capacitors. One side is charged to ground and the other side through the load. If the load happens to be a gas discharge, a bypass must be provided for charging C5-C8. It can be an inductor or a resistor. When the switch is closed, the left stage, as a ringing stage, can ring until it has reversed the charge on C1. C1 is now plus on the bottom and minus on the top at which point C2 can ring and reverse. This ringing will progress down the line until eventually the charging capacitor C4 is charged inversely, and the whole line is effectively inverted. This reversal concept will be used several times in the rest of the discussion. The main point is that a short across the end of a transmission line causes the line to invert in polarity. At this point, the model of Fig. 13 shows a circuit in which effectively a battery that is inverse in sign to the original charge of transmission line impedance, the line impedances, and a battery of original polarity are across the load. It is now obvious that the plus to minus, plus to minus sequence yields 2 V across the load.

The lines commonly built have all of the capacitors of the same size for procurement reasons and the inductors are different because they are easier to tailor. There is a characteristic time given by $\sqrt{L_{\text{tot}} C_{\text{tot}}}$ that is the time it takes for a switching function to move one way down the line. It will turn out in most of these cases that the time of interest is down the line and back interval. With voltage doubling and $2Z$ in the source, if the load impedance is $2Z$ the output voltage equals the charge voltage. The circuit doubles the voltage and then divides it again, a necessarily characteristic operation on these. If it turns out that the load is not resistive but, in the case we are commonly interested, some kind of a gaseous discharge, then this has a feature of ringing up to 2 V to break down the gaseous discharge and then discharging current. If the overvoltage is needed for a sharpening gap or something of that sort the system doubles the charge voltage and in that sense acts like an inversion generator.

Fig. 13. Blumlein Transient Equivalent

TRANSIENT EQUIVALENT

FIG. 13

The switch requirements are never greater than V charge, an advantage in many applications, such as with thyratrons. On the other hand, the switch shorts the left PFN so that the current is nominally V/Z or twice the matched load current.

In faster circuits a PFN may not be practical. Then a distributed network, either cable or stripline, may be used. It is at this point that ambiguity begins. It was pointed out in the work by Mesyats that the switching time of a spark gap can affect the leading edge of a waveform in the several nanoseconds time scale. Also, the switch and connections will have an associated inductance. In the case of a lumped PFN, this may be included in the PFN calculation. Here it leads instead to an

$$e^{-\frac{R}{L}t}$$

type of behavior with R function of time. The effect is to launch a wave down the Blumlein with a finite risetime. Since propagation velocities in lines tend to be 1.5 ns/ft, a cable of, say 10 ft, will depart from a transmission line behavior and begin to behave more like a simple LC circuit with a ringing waveform. The analogy to an LC inversion generator then becomes apparent.

In Blumlein systems, operation ranges all the way from real transmission-line behavior to real LC inversion circuit technique, depending on the trade-off in time constants of the system. The Tachisto laser is touted as a Blumlein system. In point of fact, the switch closure and gas breakdown occurs about half way through the inversion and it does not look like a transmission line at all. It looks like lumped L's and C's. When people talk about a Blumlein, look carefully at the closing time of the switch to see whether it is really a Blumlein or an LC inversion circuit.

A number of clever configurations that involve folding of the line have been developed. Figure 14 is a case in point. Initially the intermediate coaxial cylinder is charged as usual. (Upper half) When the switch is closed, the outer coaxial line undergoes the sign reversal from left to right previously described. At time τ the reversal reaches the right end so that the situation is as shown on the lower half, with both lines adding across the load. The two lines then discharge in series according to the usual procedure. One necessary condition in this is that the intermediate conductor is thick compared to the skin depth of the current that flows in the line. If that is not true, one side affects the other. One can also do this with stripline geometries and there are many, many geometries. Tom Burkes of Texas Tech has a number of these he uses for transformers and stepups.

V. SPIRAL GENERATORS

Spiral generators are a little hard to understand. This material is directly from a paper by Fitch. It does not follow his notation because it is difficult to carry his notation here. This is an approach to understanding two or three types of pulse generators other than Marx banks. In Fig. 15, if a set of striplines is charged in the fashion shown, alternating sign vectors zero to plus, as shown below $t = 0$ are established and the net output voltage is zero. The equations are for stripline. The inductance and the capacitance are in terms of spacing and width. From these arise the same impedance and transmission time relationships already mentioned. When the switches short the active lines in this system, at time τ reflections occur on the right, the vectors are reversed on each line, and a $2nV$ output voltage results of $2nV$. The impedance is $2nZ$ since the lines appear to be in series electrically. The result is voltage multiplication from a, relatively speaking, high-impedance source. Also, there is a delay after closing the switch of one transmission time. The circuit will stay inverted for two transmission times, so it is fairly easy to decide how long the

Fig. 14. Folded Co-Ax Blumlein

Upper Half-as Charged
Lower Half- After Inversion

FOLDED CO-AX BLUMLEIN

FIGURE 14

Fig. 15. Stripline Inversion Circuit

$$L = 4\pi \cdot 10^{-7} \frac{a}{b} \text{ HY/M}$$

a = SPACING

b = WIDTH

$$C = \frac{\epsilon_R}{36\pi \cdot 10^9} \frac{a}{b} \text{ FD/M}$$

$$Z = \sqrt{\frac{L}{C}}$$

$$\tau = \frac{2 \times \sqrt{\epsilon_R} \times \text{LENGTH}}{C}$$

$$Z_0 = 2NZ = \frac{240\pi Na}{\sqrt{\epsilon_R} b}$$

$$V_0 = 2NV$$

FIG. 15

lines have to be for a desired pulse width. What has been done in Fig. 16 is to go one step further and wrap the lines around a central core. Initially, these lines are charged from ground to positive. When the switches close, counter-clockwise waves come around and invert in the same manner. We are approaching a spiral generator by wrapping the lines around a common core. The principle is the same. Note that there are multiple switches. That is a complexity we are going to eliminate.

In Fig. 17 the active lines, the ones to be switched, are on the left. The passive lines are on the right. In a sense, this is Fig. 15 unfolded. We want to see what occurs and why these are not ideal. The switch shorts points A and C, launching an inverted vector down the line. This occurs on the other narrow lines so that there are six vectors stacked up. Unfortunately, there is another set of lines A-B and these are shorted also. These vectors try to invert the passive vectors in the wrong sense. The impedance formula shows that the impedance depends upon the spacing. If the A-B spacing is large and the passive one small, A-B is a high-impedance line, the passive line is a low-impedance line, and when the vectors arrive, you have a voltage divider that only cancels a portion of the vector. The formulas are worked out in terms of geometry.

A single-switch arrangement yields a loss mechanism that relates a number of parameters and it comes out in a coerror function. Figure 18 shows this loss in the form of β . There is a different β for the spiral generator. This one is in terms of dielectric constant and length divided by spacing for copper. If the line is fairly long, the β will be quite decent. If the need is for a very fast line, then β will tend to be small. This expression will appear again in the spiral generator equations, but it is more complex. This is still the simple case of switching a set of parallel plate lines in parallel. In the spiral generator, the transmission line is wrapped on itself and another layer of dielectric added so it does not short against itself. The result is a pair of lines back to back, or one line for all intents and purposes.

Fig. 16. Wrapped Line Generator

FIG. 16: WRAPPED LINE GENERATOR

Fig. 17. Single Switch Inversion Circuit

Use of single switch

Fig 17

Fig. 18. Inversion Loss Mechanisms

$$V_0 = 2NV \operatorname{ERFC} \left[\frac{\text{LENGTH}}{480 \sqrt{A}} \left(\frac{\rho \epsilon \mu_0}{t} \right)^{1/2} \right]$$

PLOTS OF $\frac{\sqrt{\epsilon} \text{ LENGTH}}{A}$

$$\rho = 1.7 \times 10^{-6} \text{ OHM-CM}$$

FIG. 18

One line is grounded and one charged as shown in Fig. 19. The case of a switch in the middle is a little easier to understand. Initially, there are alternating opposed vectors. The switch is closed and a vector is launched both ways from the switch. When these lines are shorted, the energy transfers from a voltage on a capacitor in an electrostatic field to a current in the inductor, a magnetic field. When the line reverses, the energy transfers back to the electrostatic field and progresses back down the line. In effect, the short launched by the switch runs around unwinding the coils in both directions at first and cancels the upward-directed vector, and as it goes around generates a ramp. Eventually, the waves reach the two ends of the line, reflect, and start back inward. As they start back down, they begin to invert the cancelled vectors and the voltage continues to climb. Finally, the transmission reflection arrives at the switch, reflects off the switches, starts in the other direction and the generator starts to wind down again in the same fashion, generating a saw-tooth output. These are not normally high-energy systems. They are used in trigger systems. The risetime is relatively slow, particularly if large multiplication is desired. Many turns with a lot of voltage multiplication generates a long ramp in time. A sharpening gap is common in the output. Normally, the switch is not in the center because that is physically inconvenient, but at one end of the line and you launch only one vector. The commercial variety of these uses a cryotron, the PT55. The cryotron is a great device that runs anywhere from one time to a couple of thousand and fails. The sharpening gap is electrically extremely noisy. The spiral generator does not produce a 2-nV output due to three loss mechanisms, switch impedance, resistive losses, and coupling effects.

Figure 20 treats the first case. If the switch closes exponentially with a response time τ , the voltage along the line at a given time t is described by $V_1(t)$ as shown. By manipulation, the voltage as a function of time at a position is then $V_t(l)$. Since the ideal switch charges the line to V , the area under the ideal voltage trace is just $V L$. Thus, the first loss is described by the area ratio defined as β_1 and plotted.

Fig. 19. Spiral Generator

$$0 < t < \tau, \quad V_0(t) = 2 \frac{t}{\tau_T} V$$

WHERE τ_T = ONE TURN TIME

τ_L = STRIPLINE ONE-WAY TIME

$$\tau = 2 \tau_L$$

$$\tau < t < 2\tau$$

$$V_0(t) = 2 \left(n - \frac{t - \tau}{\tau_T} \right) V$$

FIG. 19

Ref. 7

Fig. 20. Spiral Generator Switch Loss

1. SWITCH EFFECTS

$$V_z(t) = V_z \left[1 - e^{-t/\tau_s} \right]$$

SO THAT

$$V_t(z) = V_t \left\{ 1 - e^{-\frac{(L-z)\sqrt{E}}{c \tau_s}} \right\}, \quad L = \text{TOTAL LENGTH}$$

$$B_1 = \frac{1}{VL} \int_0^L V_t(z) dz \quad \text{OR}$$

$$B_1 = 1 - \frac{\tau_s}{\tau} \left[1 - e^{-\tau/\tau_s} \right]$$

Resistive losses appear much as in the simple case treated before, except that the expression has been rearranged in Fig. 21. Again, area ratios with the ideal case lead to β_2 , plotted for the cases of copper and aluminum. The axis is times a thousand. If the line is 6000 cm (200 ft, ~200-ns risetime); this term alone is about 10%. This is worked out in terms of a spacing that is fairly realistic, 10 mils. Kaptan has an ultimate failure of about 6 to 7 kV per mil and the failure point is 60 kV in that case.

There is a third β term difficult to describe mathematically. For example, the system behaves as a pulse transformer whose natural frequency depends upon the leakage inductance between the first turn and its closest neighbor. Secondly, the active and passive lines are always coupled by the inductance of one turn. The passive lines can discharge through the switch by the inductance of the midturn, and, to an extent, the waves in the active lines enter the passive lines by inductance of inner and outer turn. This complex situation is not readily amenable to analysis. It should be possible to write an empirical formula. What Fitch concludes is that the overall data for the spiral generator are the product of the two for which there is an analysis plus a loss that is not readily analyzed. Numbers of around 1/2 for the product of the three terms are typical. People have done better than that. A β of 0.9 has been built in specific cases. Maxwell has a paper on high-voltage spiral generators. They built a couple of them and have a couple of basic relationships on output capacitance, etc. They discuss the problems they have had. The problems typically are related to the fact that the generator is wound with a stripline. That means there is a nasty tendency to go around the edge or, more dramatically, right through because there is a high field stress right at the edge of the foil. Much work was done grading edges with resistive paper or conducting paints, water, and copper sulfate solutions. There are a number of techniques to keep the field concentrations down. The stripline, particularly narrowly spaced striplines, are subject to edge effects because of the high-field stress at the edge of the metal. Flashover is a serious

Fig. 21. Spiral Generator Resistive Losses-Ideal Switch

$$V_T'(z) = V_{0RFC} \left[\frac{1}{120\pi} (\epsilon \epsilon^{1/2} \mu_0 c)^{1/2} \frac{z}{4d(L-z)^{1/2}} \right]$$

$$B_2 = \frac{1}{VL} \int_0^L V_T'(z) dz$$

$$\text{For } V_0 = 2\eta B_2 V$$

$$d = 0.25 \text{ MM} \quad (10 \text{ MILS})$$

$$\epsilon = 2.2$$

Ref. 7

problem. They quoted β 's of about 0.6 or 0.7 on some units. They have generators 1-1/2 ft in diameter and 3 ft overall length with two 10-mil conductors and 10-mil Mylar, vacuum impregnated and capable of repeated operation at about 700 kV. The 1-MW goal was obtained. However, edge failure prevented subsequent charge.

VI. COAXIAL GENERATOR :

Figure 22 has sketches of two coaxial generators. The first is connected so that the center conductors are bridged at the right end and at the left end, a switch. This is not much different than the lines already discussed. Fitch reports an analysis that states that if $2N$ is more than 9, performance degrades. That means about four cables are all you can stack. The limit arises because of the stray capacitance between the lines. The impedance of a coaxial cable compared to stripline is so high that the generator impedance increases rapidly with n . If this is 50- Ω cable, a 200- Ω source impedance results, with only four of them. It does not take much stray capacitance at 200 to load the generator. These are typically relatively low-energy pulses. They might be used for trigger generators and applications of that sort. The second circuit is electrically connected differently. It is called a time-isolation transformer. Instead of tying all the grounds together as in the first system, a center conductor to ground, center-conductor-to-ground pattern is used all the way up. All of the centers and all of the braids tie together at the left. Instead of charging the cable in this case a fast pulse is launched down the cable. A 700-kV generator built this way had a very fast risetime. Again, it is a high-impedance source, but it goes along with Fitch's paper on the vector inversion concept. You are only limited by your ingenuity on how you can stack up elements and switch some of them to get the vectors all turned over and lined up for whatever period of time you need. The author of this paper quotes performance that is impressive. The paper consists almost entirely of the mathematical analysis on how to fit all the various stray

Fig. 22. Co-Ax Pulse Generators

.. 20.69 DUE TO Z_s CAPACITANCE _____ F Ref. 7

A. Chodorow, Proc IEEE, July 75

Figure 22

Ref. 8

elements in order to optimize the system. Mathematically beautiful but there is not one word on how to physically implement the analysis.

1. J. C. Martin, "Nanosecond Pulse Techniques," Circuit and Electromagnetic System Design Notes (AWRE), Note 4, April 1970.
2. G. B. Swift, Marx Banks, Van Nostrand.
3. G. N. Glasoe and J. V. Lebacqz, "Pulse Generators," Dover, New York, 1965.
4. R. W. Morrison and A. M. Smith, "Overvoltage and Breakdown Patterns of Fast Marx Generators," IEEE Trans. Nucl. Sci., August 1972, pp. 20-31.
5. R. A. Fitch, "Marx and Marx-like High Voltage Generators," Proc. IEE, April 1972.
6. G. A. Mesyats, "Techniques of Shaping High-Voltage Nanosecond Pulses," March 1971, Foreign Technology Division, WPAFB, report FTD-HC-23-643-70.
7. R. A. Fitch and V. T. S. Howell, Proc. IEE, Vol. IV, No. 4, April 1964, "Novel Principles of Transient High-Voltage Generation."
8. A. M. Chodorow, Proc. IEEE, July 1975, "The Time Isolation High-Voltage Impulse Generator," pp. 1082-1084.