# Solid State Pulsed Power Systems

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*Abstract*

A Pulsed Power System is characterized by its energy storage system, the energy can be released in the form of a high power pulse to the load, by means of a switching device. The energy storage is usually either of an inductive or a capacitive nature. The limiting device in a Pulsed Power System is often the switch, which limits the pulse peak power and the repetition rate. The conventional approach in Pulsed Power designs is to use a gas switch such as a thyratron, ignitron or spark gap. However these devices have limited lifetime, high cost, low repetition rate and high losses. Thanks to the continued improvement of the high power semiconductors in switching speed, voltage and current rating, solid-state semiconductors have become the device of choice for pulsed power systems.

In the last decade *Physique & industrie* has successfully developed a variety of Pulse Power Systems based on solid-state switches to cover the vast range of application requiring high voltage pulses.

This paper describes the architecture of several pulse power systems and their typical characteristics.

## I - High Power Solid-state Switches

The first semi-conductors used as high power switches were the Thyristors and GTOs, they can handle several kilovolts and kilo-amps, however their low switching speed is a serious limitation.

Today, the semiconductor devices of choice5 for high power switching are the MOSFETs (Metal Oxide Field Effect Transistor) and the IGBTs (Insulated Gate Bipolar Transistor). The MOSFETs are substantially faster than IGBTs (typical switching time: 200ns for an IGBT, 20ns for a MOSFET), but IGBTs are more efficient at high voltage (less losses), cheaper per kW switched, and are being manufactured at higher voltage ratings (up to 6500V), where the MOSFETs are limited to 1200V. So generally, MOSFETs are used only when a high switching speed is required. However sometimes MOSFETs are preferred even for lower speed switching because they are more easy to stack in a series/parallel assembly than IGBTs.

Another type of solid-state high power switch is the saturable core inductor. This switch can perform nanosecond switching times of almost unlimited power. It is by nature extremely robust, yet it is not a gated switch. It is used in conjunction with a semiconductor switch to obtain faster switching time. The switching time of a saturable core inductor is defined by the time it takes to saturate. In the close state the impedance of the switch is the one of the saturated inductor (the relative permeability drops to 1, i.e. as if there was no core). In the open state the impedance of the switch is the one of the unsaturated inductor, which is typically about 10000 times the saturated impedance. Saturable inductor switches are usually used in series with a semiconductor switch to sharpen the pulse shape, or in magnetic compression designs, to obtain pulse power in the hundreds of GW range. The use of saturable core switches leads to generators with fixed pulse width.

The choice of the modulator switch is closely tied to the one of the modulator topology, to achieve the requirements

## II - Pulsed Power System Topologies

### 1. Capacitor Discharge

This section describes different topologies of pulse generators with direct transfer from a capacitive energy storage to the load.

The major benefit of these kinds of systems is that they deliver square output pulses synchronous with the switch gate control. However, for the pulse to be quasi-square the energy stored in the capacitor has to be one or two order of magnitude higher than the energy delivered to the load.

The most basic Power Pulse Generator requires a simple energy storage bank (capacitor or line) charged with a DC high-voltage power supply, in series with a switch. When the switch is closed, the voltage is directly applied to the load.

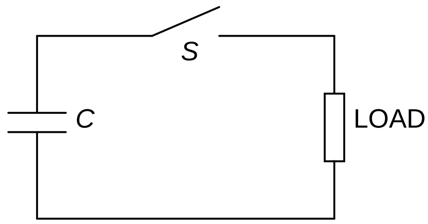


*Figure 1.1: basic pulse generator topology*

Unfortunately, the voltage rating of the available semiconductor switching devices rarely matches the voltage requirements of the power supply. For this reason it is usually necessary to use more complex topologies involving numerous lower voltage/current switches.

*1.1 Series Switch Topology*

A common approach to build high voltage pulse generators switch, is stack in series and parallel multiple lower voltage / current semi-conductors. If it is relatively easy to put in parallel MOSFETs and NPT IGBTs due to their positive temperature coefficient, their series assembly is much more difficult. Because of differences in semiconductor characteristics and their gate drive circuits, a complex monitoring and synchronization of each switch gate is required, in order to maintain a good dynamic voltage sharing of the switches and prevent their damage. Furthermore, the system has to be able to handle the failure of one of the switches without destroying the whole assembly as well as an over-current emergency turn-off.

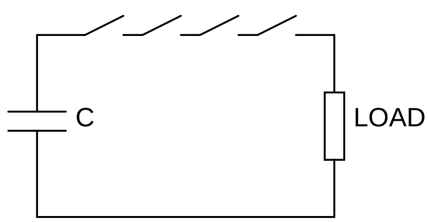


*Figure 1.2: Series Switch Topology*

Despite the apparent simplicity of the series switch topology, this approach requires a complex dynamic voltage balancing, which often results in a slower switching time. In addition, in order to charge the tank capacitor, an expensive high voltage DC source is needed.

*1.2 Pulse transformer Topology*

One solution to avoid the need of high voltage switches is to use a step up pulse transformer to transform a voltage that doesn't exceed the voltage rating of the semiconductor switch (typically from 1kV to 6kV) to the desired output voltage. To reduce the leakage inductance a high number of primaries are preferred. Either, a single switch can be used to control all the primaries, or several switches, each controlling on or a group of primaries as shown in the figure 3. When several switches are used, the current is shared between them. The fact that they drive different primaries insures a better current sharing.

The advantages of this design are the following:

- Fairly low DC voltage source, easy to achieve with a Boost converter.
- Galvanic isolation of the output.
- Positive or negative pulse polarity
- Simple Gate drive, because it is referenced to ground

The drawbacks of this design are:

- The necessity to demagnetize the transformer limits the duty cycle to a maximum of 10%.
- Maximum Pulse duration limited by the available volt-seconds of the transformer core (and thus its size).
- Pulse rising time limited by the transformer leakage inductance.
- Need for good synchronization of the gate drive to avoid one switch being over-loaded.
- Losses in the transformer (about 5%)

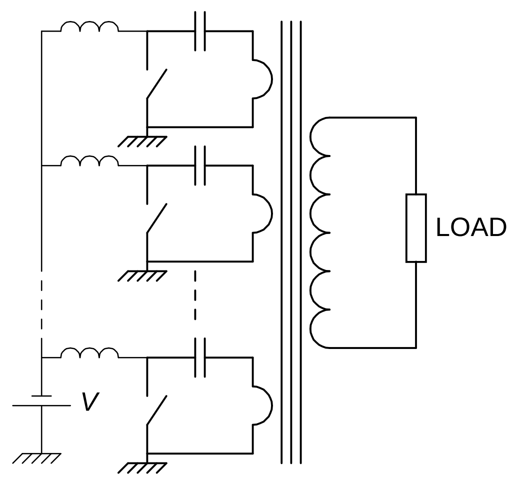


*Figure 1.3: Pulse transformer Topology*

*Physique & industrie* has developed a range of Pulse generators, based on the Pulse Transformer Topology and using its state-of-the-art low leakage inductance transformers. These compact pulse generators can deliver up to 100kV and 100A pulses, with rising time less than 1 µs and pulses length from 2µs to 30µs.

### *1.3 Series Pulse transformers Topology*

A different approach to using transformers is to cascade them, i.e. to use a series of pulse transformers rather than one large.

Since each core is independent, the currents will naturally be shared equally between all the switches. A nice feature of this topology is that by adding a diode in parallel of the primaries, the gate control synchronization between each switch is no more critical; each switch can be turned on or off independently. The output voltage will just be the sum of the contribution from the closed switches; so one could use this opportunity to adjust the output voltage of the pulse generator by just closing the right number of switches.

The leakage inductance is lower when a transformer ratio of 1:1 is chosen, and is comparable to the one of a well-designed single transformer topology with multiple primaries described earlier.

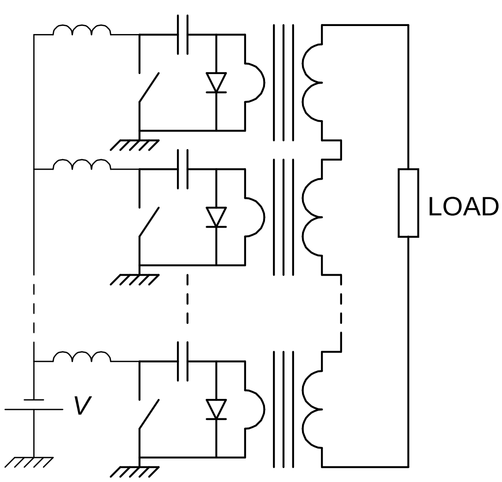


*Figure 1.4: Series Pulse Transformers Topology*

The advantages of this design are the following:

- Fairly low DC voltage source, easy to achieve with a Boost converter.
- Galvanic isolation of the output.
- Positive or negative pulse polarity
- Simple Gate drive, since it is referenced to ground
- Excellent current sharing
- No need for good synchronization of the switches
- Possibility of selecting different output voltage by turning on only a reduced number of switches.

The drawbacks of this design are:

- The necessity to demagnetize the transformer limits the duty cycle to a maximum of 10%.
- Maximum Pulse duration limited by the saturation of the transformer core (and thus its size).
- Pulse rising time limited by the transformer leakage inductance.
- Losses in the transformer (about 5%)
- Assembly design more complex than single pulse transformer design

### *1.4 Adder Topologies*

In this kind of pulse generator there is no transformer between the tank capacitor and the load, the system is simply composed of basic pulse generator cells, formed by a capacitor and a switch, stacked in series. The challenge in this type of generator is due to the floating nature of each basic cell, and the high d$V$/d$t$ with respect to the ground occurring during the rising and falling time of the pulse. Each cell must have a way to supply its floating capacitor, and a way to trigger its floating referenced switch.

The triggering system is usually done by means of a pulse transformer or better yet, a fiber optics system.

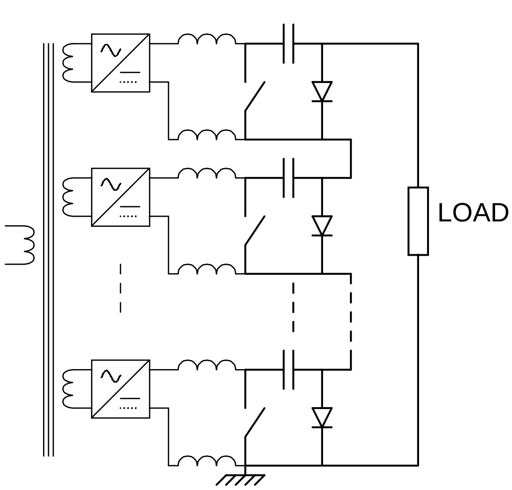


*Figure 1.5: Adder Topology*

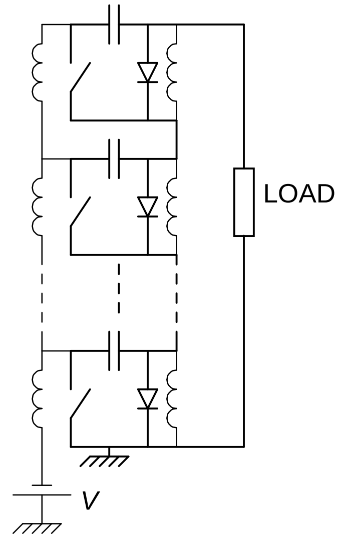


*Figure 1.6: 'Solid-State Marx' Adder Topology*

The capacitors are charged either by using DC converters like shown in figure 1.5, or via inductors as shown in figure 1.6. This topology is also called Solid-State Marx because of its similitude to the Marx generators architecture. The classic Marx generator uses spark gaps as switching devices. The shown version is modified in order to use semiconductor switches.

Like the series pulse transformer topology, the current through each switch is inherently identical, and the voltages of the individual cells are added up. Thanks to the diode, each switch can be turned on or off independently of the other ones, which makes the system particularly robust and offers the possibility of adjusting the output voltage.

Great care must be taken to limit capacitance between each cell and the ground.

The advantages of this design are the following:

- Fairly low DC voltage source, easy to achieve with an inverter.
- Excellent current sharing
- No need for good synchronization of the switches
- Possibility of selecting different output voltage by turning on only a reduced number of switches.
- No transformer demagnetization circuits
- High Duty Cycle
- Unlimited pulse length
- Very fast rising time
- Low losses

The drawbacks of this design are:

- No galvanic isolation of the output.
- Negative pulse polarity only
- Relatively complex floating gate drive (not referenced to ground)
- Parasitic capacitance

## 2. LC Resonant charge transfer

This section describes different topologies of pulse generators where the energy is transferred by resonance between capacitive and inductive forms, before to be transferred to the load. By nature, a resonant charge transfer pulse generator is well suited to supply capacitive loads, and is current limited which protects the switch against short circuits of the load. The pulse generated is not square, and has a relatively slow rise time compared to the switch turn-on time, but can be decreased by means of saturable inductors.

The drawback of these kind of systems is that they have to be designed specifically to match the load impedance. If the load doesn't match the impedance of the generator, the pulse waveform will be altered and some of the energy will be reflected back into the system.

*2.1 Basic resonant charge transfer*

The figures below show several basic circuits based on resonant charge transfer.

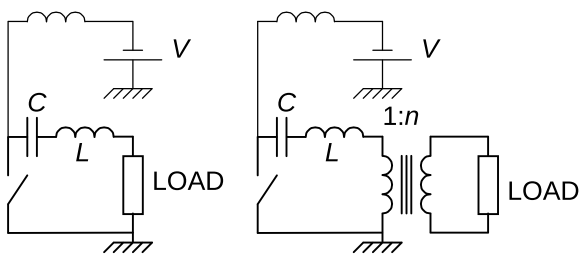


*Figure 2.1: basic resonant charge circuit with and without step-up transformer*

The resonant transfer, using a transformer, can actually use the transformer's own leakage inductance as inductor.

Those systems must be designed to match the load, in order to get a complete energy transfer and the desired pulse waveform to the load. A challenge is to manage the cases were the load does not match the generator (in case of breakdown for example).

***Pulse shape waveform*.**

In case the load is purely resistive, the differential equations describing the basic series RLC circuit is:

$$v'' + \frac{R}{L}v' + \frac{1}{LC}v = 0$$

where $v$ is the voltage across the load.

In critically damped conditions, the solution of the differential equations is :

$$\text{if} \quad R = 2\sqrt{\frac{L}{C}} \quad \text{(critically damped)}$$

$$V_{\text{load}}(t) = \frac{2V}{\sqrt{LC}} t.\exp\left(\frac{-R}{2L}t\right)$$

Where $V$ is the initial capacitor voltage.

The peak voltage occurs at $t = \sqrt{LC}$ and its amplitude is :

$$V_{\max} = \frac{2V}{e} = 0.736\,V$$

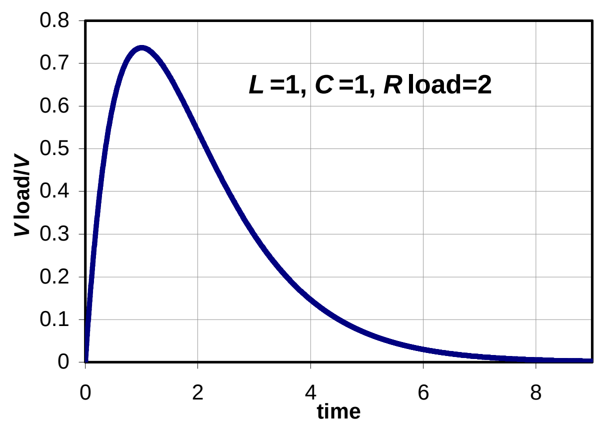


*Figure 2.2: pulse waveform on a resistive load in critically damped condition*

If the resistor is less than the critically damped value (under-damped), the system will oscillate, and if it is greater (over-damped) the pulse tail will be longer.

The critically damped value is thus the ideal value for the load, however using a slightly under-damped resistor $R$=0.85$R_{\text{critical}}$ allows reducing the pulse tail without having any significant oscillation, but reduces the max voltage to 0.7 $V$.

Figure 2.3 shows the pulse waveform for a load in the critically damped condition ($R$=2 in this case) and in a slightly under-damped condition ($R$=1.7).

To further reduce the pulse width and symmetrize its waveform, a capacitor can be added in parallel to the load (or may be naturally part of the load). Figure 2.3 shows the effect of a capacitive load on the pulse shape. With a capacitive load of about $C$/4, the shape of the waveform is almost symmetrical and its width is reduced by a factor 2 compared to a purely resistive load in critically damped condition.

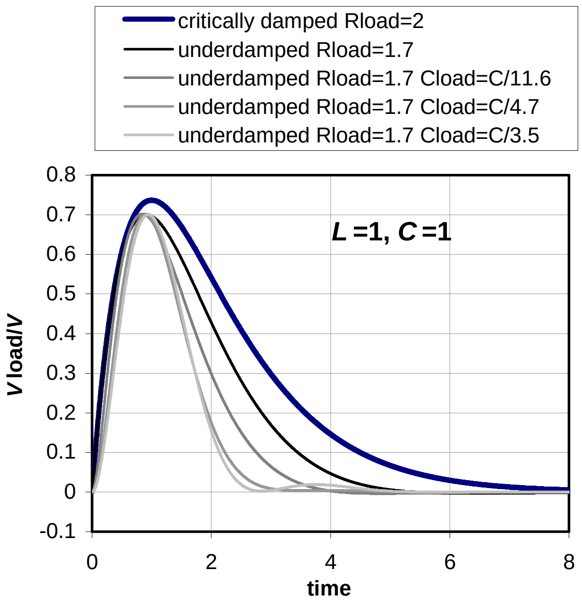


*Figure 2.3: pulse waveform optimization to shorten the pulse length*

***Power Switch*.**

In a resonant charge transfer design, the switch needs to be able to withstand direct voltage $V$ and the reverse voltage $V$. In addition, the current flowing into the switch should stay in the 'on' state until the current stops flowing. These are exactly the working conditions of a symmetrical thyristor, which is ideal for resonant charge transfer where its low switching time is not an issue. To use an IGBT as a switch requires the addition of a series diode in order to withstand the reverse voltage $V$.

*2.2 Magnetic Pulse Compression Systems*

For systems requiring high pulse generators with peak power greater than 100MW and up to several Terawatts, an alternative to a massive assembly of semiconductor switches is the use of magnetic pulse compression. The idea is to generate a relatively long pulse with semiconductors, and to compress it in the time domain using resonant charge transfer through saturable inductors.

Figure 7 shows an example of a pulse generator using 3 stages of magnetic compression, including a resonant transformer to step up the pulse voltage. The capacitor $C_1$ is resonantly charged with the tank capacitor $C$.

In general, the intermediate capacitors are chosen to be equal in order to have complete charge transfer, and $C$ is chosen very large, so that $C_1$ is charged at $2V$, where $V$ is the voltage on the tank capacitor $C$. In the particular case of figure 7, because of the 1:$n$ transformer, the capacitors $C_1$, $C_2$ and $C_3$ must verify $C_1=n^2\ C_2 = n^2\ C_3$ for the energy transfer to be complete.

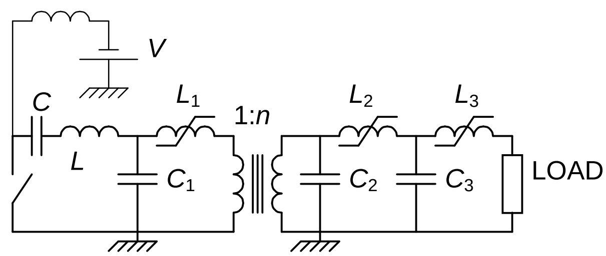


*Figure 2.4: Magnetic Pulse Compression Topology*

Figure 8 shows the voltage pulses on capacitors $C_1$, $C_2$, $C_3$ and on the load. One sees the pulse width compression as the charge is transferred through the pulse compression stages. Since the energy in the pulse remains the same, the pulse becomes shorter while the pulse power is increased.

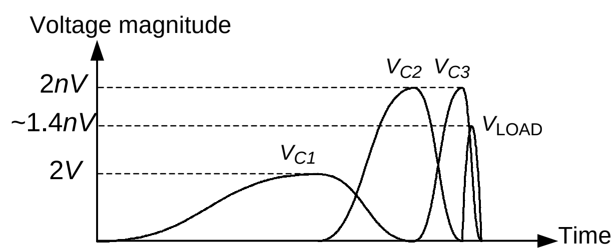


*Figure 2.5: pulse propagation in the compression stages*

Let's define the compression rate ratio $\kappa$ of stage $n$, as being the ratio of the pulse rise time of one stage over the one of the next stage, one can write:

$$\kappa = \tau_n / \tau_{n+1} = \sqrt{L_n / L_{n\_saturated}}$$

If we assume that the saturated and unsaturated inductances vary by a factor $\mu/\mu_0$, the compression factor can be written:

$\kappa < \sqrt{\mu_r}$ where $\mu_r$ is the relative permeability of the magnetic core.

Practically, the compression factor is limited by the space between the coil and the core and the core packing factor for Metglass cores, leading to a compression factor from 3 to 10.

The last stage of magnetic compression is similar to the basic charge transfer system described in section 2.1, so the same consideration applies for its pulse shape. The pulse symmetry and width can be improved if the load resistance and capacitance are chosen as follows:

$$R_{load} = 0.85 R_{critical} = 1.7\sqrt{\frac{L}{C}}$$

and

$$\mathrm{C}_{\mathrm{load}} \approx C_3 / 4$$

The advantages of this design are the following:

- Simple and robust design.
- Very high power capability (up to terawatts)
- Short pulse length (down to several nanoseconds
- Positive or negative pulse polarity if a transformer is used.
- Simple Gate drive, since it is referenced to ground
- Load can be resistive and capacitive.
- The switch is intrinsically protected against over-current even in problematic load conditions (short or open).

The drawbacks of this design are:

- No ‘off the shelf’ saturable inductor, a careful design is required for each of them.
- A core demagnetization is needed
- The system must be designed to match the load. In case the load is open or shorted (and does not match the generator anymore), the design must handle the reflected pulse energy going back into the system.
- The pulse width is not adjustable.
- The pulse shape is not rectangular

*2.3 Resonant doubler*

In the following circuit, the capacitors are charged in parallel, and a resonant circuit is used to inverse the voltage across one capacitor, thus applying twice the charge voltage 2*V* to the transformer.

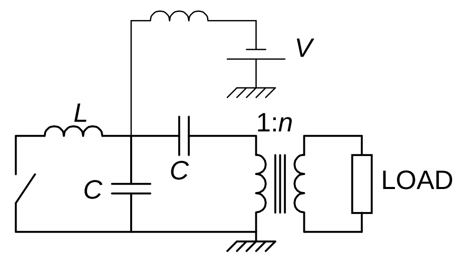


*Figure 2.6: resonant charge circuit with and without step-up transformer*

Even in case the load is purely resistive, the differential equations describing this basic circuit is a 3rd order differential equation.

*2.4 Fitch pulse generator or resonant charge transfer Marx*

This topology, called Fitch Impulse Generator, is, like the Marx topology, made of several cells that are charged in parallel, and discharged in series. In this case the basic cell is the LC resonant doubler described in the previous section. During the charging phase, each capacitor is charged with the voltage *V*, but since each couple of capacitors is in opposition, the total voltage on the capacitor column is zero.

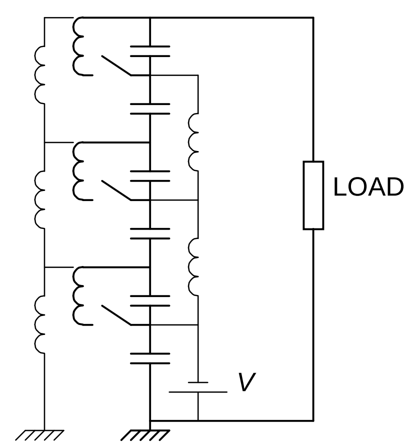


*Figure 2.7:3 stages ’Fitch’ pulse generator*

Half of the capacitors are connected to external switched circuits with a series inductance. When the switches are closed, after one half-cycle of resonant charge transfer, the voltage on those capacitors are now reversed and at that time all the capacitors voltages are adding, so that the total voltage on the capacitor column is now 2*nV* (where *n* is the number of stages of the Marx and *V* the charging voltage).

### 3. Line Discharge

A transmission line is a distributed capacitor, it can be used as an energy storage instead of a capacitor. The line is charged slowly and the energy is released by means of a switch in a matched load. One of the properties of the transmission lines is their ability to produce a constant-voltage output pulse when discharged into a resistive load that matches the line characteristic impedance.

Compared to a square pulse generator based on a capacitor discharge (described in section 1), the energy stored in a matched system is just equal to the energy delivered to the load because the energy transfer is complete.

Another advantage is that the output current is limited, no matter what the load impedance is, which inherently protects the switch against over-current.

*3.1 Basic transmission line discharge*

The following figure shows a transmission line charged by a voltage source *V*, and discharge into the load by mean of a power switch.

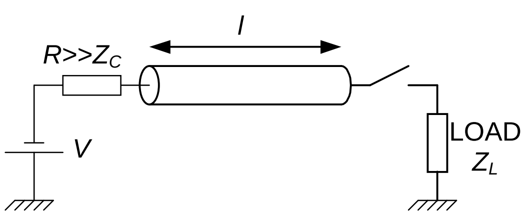


*Figure 3.1: basic transmission line discharge*

To get a complete transfer of energy from the line to the load, the impedance of the load $Z_L$ has to match the characteristic impedance of the line $Z_C$. The output voltage is a square with a voltage which is half of the charging voltage supply, and its width is equal to 2 times the transit time in the line.

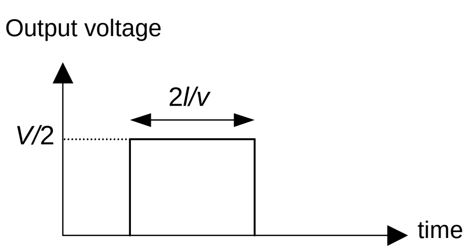


*Figure 3.2: transmission line pulse waveform*

One disadvantage of the topology depicted in figure 3.1 is that the power transfer switch must be located between the high-voltage center conductor and the load. The following alternative topology has the switch reference to the ground, but outputs negative pulses. It is the distributed equivalent of the LC resonant charge transfer generator depicted in figure 2.1 (a).

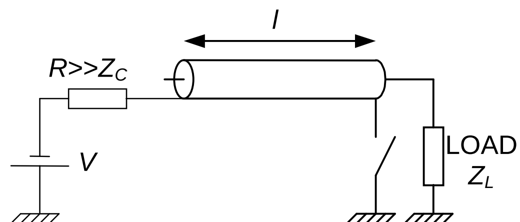


*Figure 3.3: alternative transmission line discharge($Z_L$=$Z_C$)*

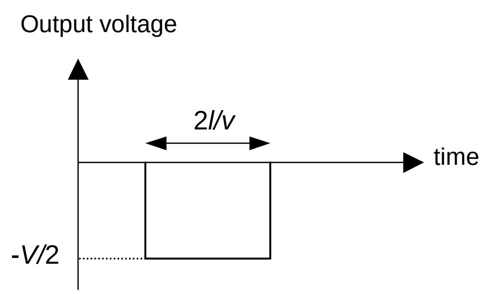


*Figure 3.4: transmission line pulse waveform*

This configuration although simple because of the ground referenced switch, does have the drawback that in co-axial geometry the outer conductor of the cable has a floating voltage.

*3.2 Self-Matched line discharge*

One of the inconveniences of a line discharge is that the load has to match the impedance of the line, which is not always possible in case of complex or variable load impedance. The Self-Matched line topology overcomes this inconvenience. An added load matched to the line's characteristic impedance $Z_C$ absorbs all the energy reflected by the unmatched impedance. The downside is a loss, of at least 50 % of the energy stored in the line, by dissipation in the added resistive load.

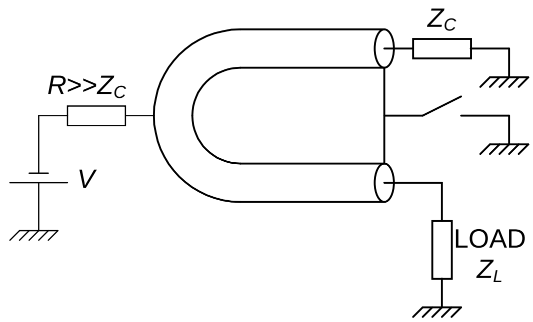


*Figure 3.5:Self-Matched line*

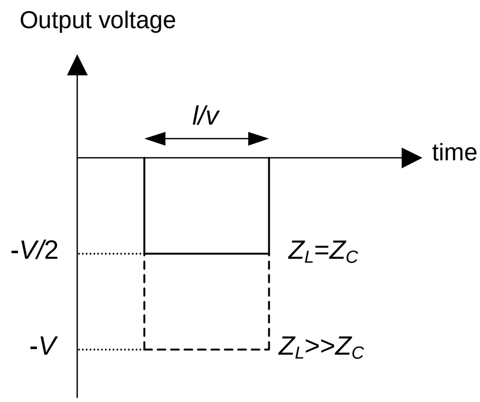


*Figure 3.6: Self-Matched line pulse waveform*

As in the topology described in figure 3.3, this configuration also has the drawback that in co-axial geometry the outer conductor of the cable has a floating voltage. Also the two ends of the cable and the terminating resistor have to be in a very low inductance configuration to obtain a good rise time. The switch has to discharge not only the cable capacitance but also the stray capacitance of the cable's outer conductor to ground. However, it can produce very good results if built carefully.

*3.3 transmission line adder*

In general, it is possible to replace the capacitive energy storage in all the topologies described in section 1 by a transmission line. The output voltage is only a half of what it is with a capacitor, but the energy stored is much lower and the pulse shape square-like.

Let's transform the Marx pulse adder using capacitive energy storage, described in section 1.4, by its equivalent using transmission lines.

The figure 3.7 below shows the transmission line Marx. If $n$ is its number of stages, the load impedance must be $nZ_C$ to match the line impedances. The pulse length is equal to two times the line transit time, and the amplitude is $nV/2$, where $V$ is the charging voltage.

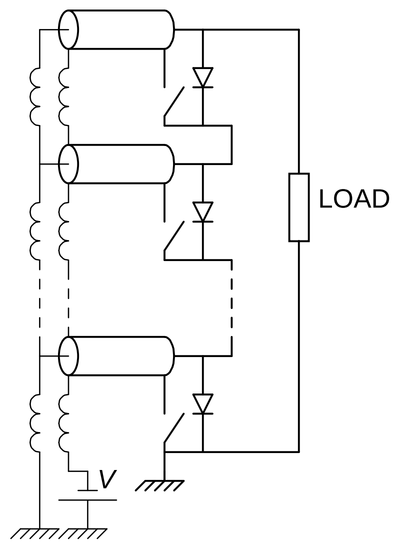


*Figure 3.7: Transmission line 'Marx'*

*3.4 Blumlein line discharge*

There are features of the transmission line pulse modulator that are often inconvenient for high-voltage work. First, the matched pulse has an amplitude only half that of the charge voltage. Second, either the pulse is positive but the power transfer switch must be located between the high-voltage center conductor and the load, which makes its triggering difficult, or the switch is referenced to ground, but the pulse polarity is negative.

These problems are solved by the Blumlein transmission line configuration [A. D. Blumlein, U.S. Patent No. 2,465,840 (1948)]. The circuit consists of two (or more) coupled transmission lines. Fast-shorting switches cause voltage reversal in half the lines for a time equal to the double transit time of the line. The output pulse produced has the same amplitude as the DC charge voltage.

The Blumlein line circuit is the distributed equivalent to the LC resonant doubler described in section 2.3

There are two basic Blumlein configurations: one with 2 distinct transmission lines (figure 3.7

(a)) and the nested coaxial transmission lines (figure 3.7 (b))

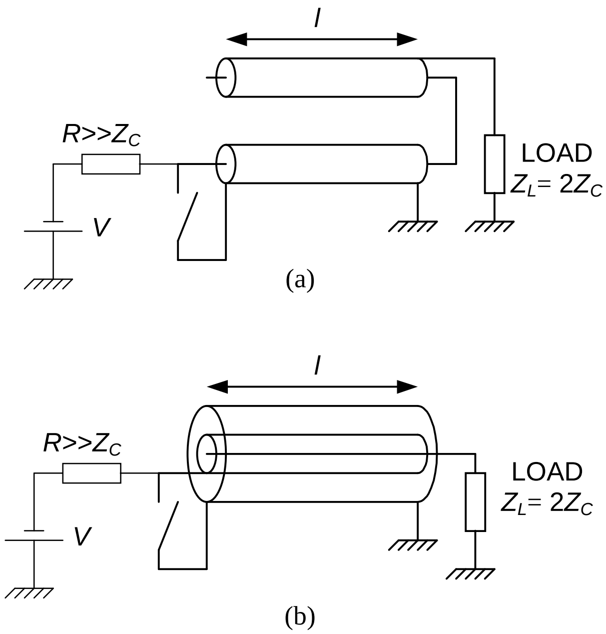


*Figure 3.7: Blumlein line configurations*

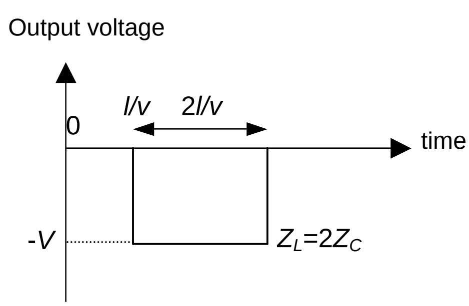


*Figure 3.8: Blumlein pulse waveform*

The output pulse voltage is equal to the charging voltage and its width is twice the line transit time. The rising edge pulse is delayed by one line transit time ($l/v$) relative to the time the switch is closed.

*3.5 Blumlein Fitch generator*

Since the Blumlein is the distributed equivalent of the LC doubler, it is possible to build a Fitch generator using Blumleins instead of LC doublers.

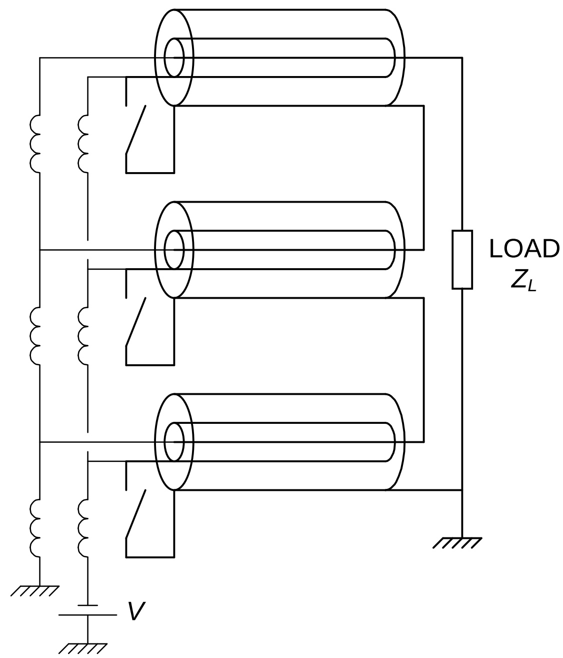


*Figure 3.9: Three stages Blumlein 'Fitch' pulse generator*

The output pulse is similar to a Blumlein except that the output voltage is multiplied by the number of stages $n$. For the load to be matched, its impedance needs to be equal to 2 $nZ_C$.

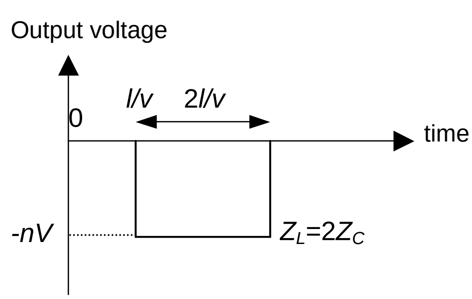


*Figure 3.10: Blumlein-Fitch pulse waveform*

## III - TRANSMISSION LINE PULSE TRANSFORMER

Transmission lines are used to connect elements together, or as a distributed energy storage. A less common but useful application is its use as a pulse transformer or polarity inverter.

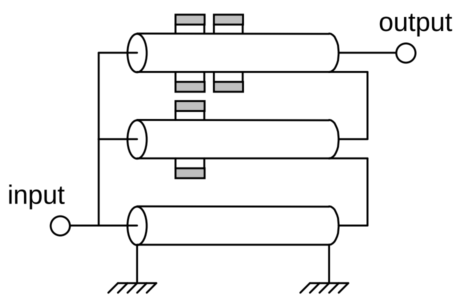


*Figure 4.1:1:3 transmission line pulse transformer*

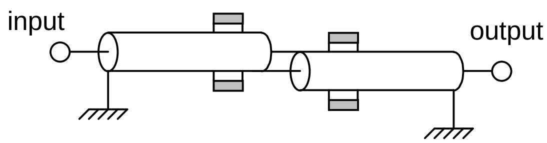


*Figure 4.2: Pulse polarity inverter*

## IV - PULSED POWER INDUSTRIAL APPLICATIONS

High voltage pulsed power based technologies are rapidly emerging as a key to efficient and flexible use of electrical power for many industrial applications.

Here is a list of some pulsed power applications *Physique & industrie* has been working on:

- Laser supplies : Excimer, $CO_2$ , Nitrogen, Copper Vapor
- Pulsed Electric Field Sterilization of Liquids by electroporation
- Electric Pulse Rock Crushing
- Plasma Immersed Ion Implantation (PIII)
- Klystron / Magnetron supply
- Corona Plasma discharge oxidation for sterilization and de-pollution
- Electromagnetic forming (or Electroforming)
- Fruit & vegetable juice extraction
- Particles accelerators

## V - REFERENCES


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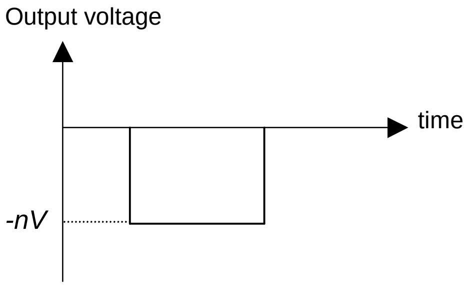
Output voltage
time
-nV