UTM
UNIVERSITI TEKNOLOGI MALAYSIA

Chapter 7

Pulsed power
- principles and applications

Course Outcomes

1. Understand the main requirements for pulsed power technology
2. Describe the key pulsed power circuit topologies
3. Elaborate various pulsed power technology applications

1 Key requirements for pulsed power technology

   1 Storage
   2 Pulse compression
   3 Pulse forming

2 Pulsers and topologies

   a. Capacitive Energy Storage Systems
   b. Inductive Energy Storage Systems

3 Applications

Introduction

- Power modulators used to drive radar magnetrons at ~100 kW in 2nd world war. The magnetron requires a repetitive pulse driver developing typically 10-50 kV at 1-10A, 1-10 kHz, microsec pulse widths

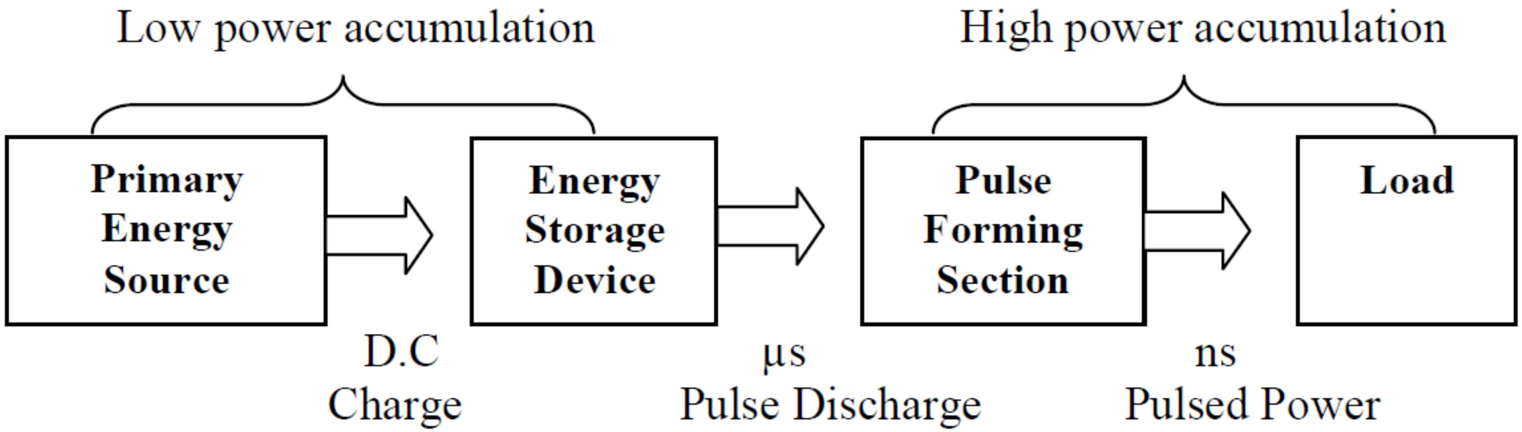
  Spark gaps could not conduct the required current levels, and still recover in the available timescale, due to high repitition rate

- Solution found in magnetic compression

  – a series of saturable magnetic stages are driven by the primary closing switch and energy is transferred between stages in progressively shorter timescales.

- Hydrogen thyratron and other tubes replaced the magnetron
- Renaissance 1980s in power lasers, ultrawideband radars, corona reactors etc.

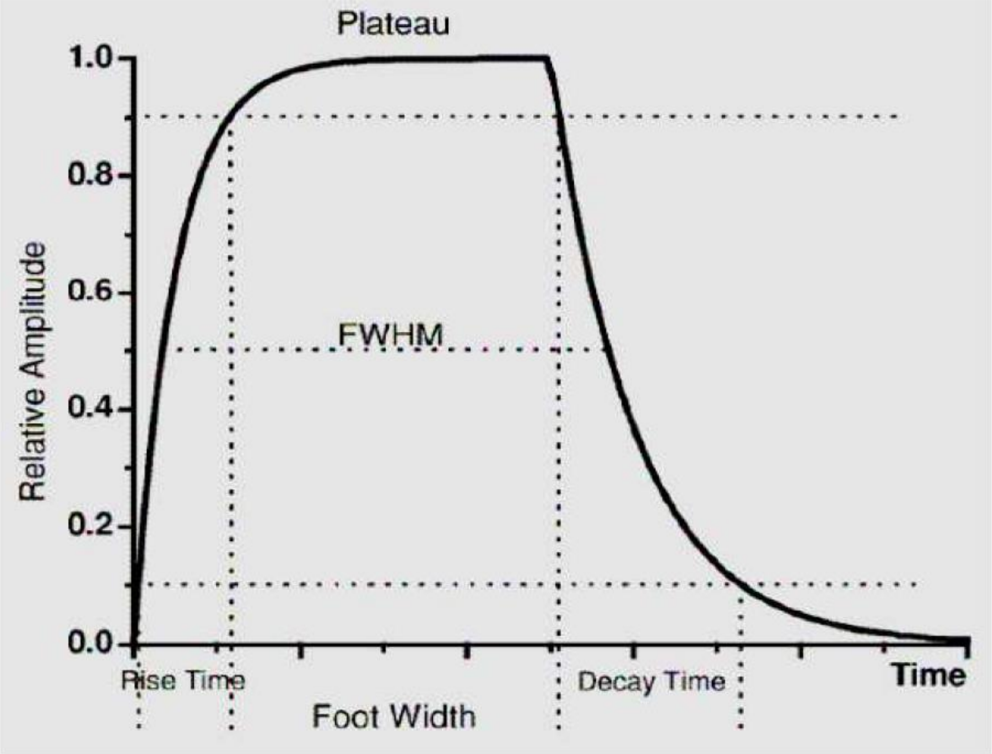
Main Requirements



Main Requirements

Energy	10 J – 100 MJ
Power	1 MW – 1 TW
Voltage	1 kV – 10 MV
Current	100 A – 10 MA
Pulse width	100ps - 100µs

Main Requirements



Main Requirements

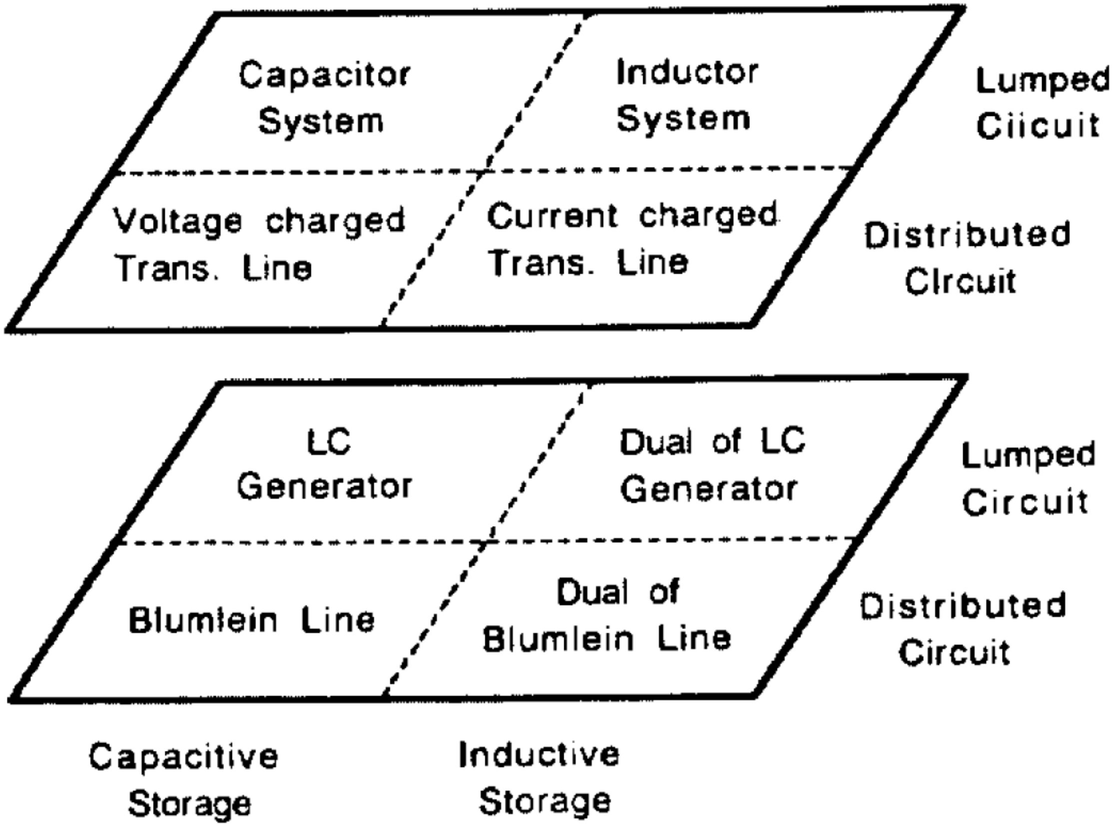
- Two important concepts in pulsed power are **pulse compression** and **pulse forming**.

- **Pulse compression** involves the **discharge of energy** from a **storage device** at **a faster rate than it has been charged**.

  An example is a **capacitor discharge system**. There are also other forms of energy storage and discharge.

- **Pulse forming** is the use of **circuit, switching and transmission line techniques** to achieve the **pulse shape** required by the **load**.

2. Pulsers and Topologies

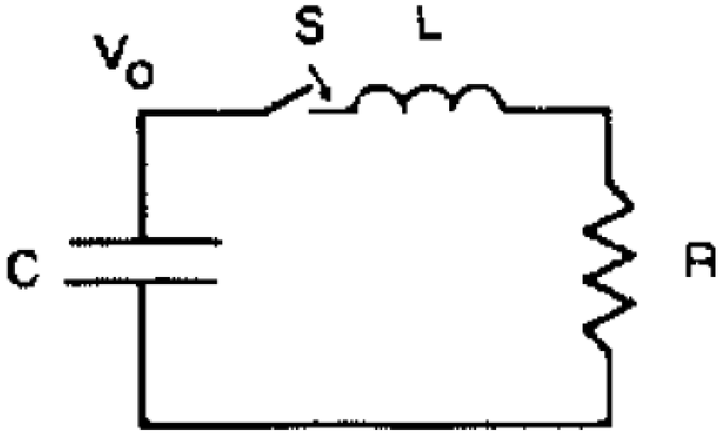


2. Pulsers and Topologies

2.1 Capacitive Energy Storage Systems

- **Lumped Capacitor System**
- **Voltage Charged Transmission Line**
- **LC Generator**
- **Blumlein Line**

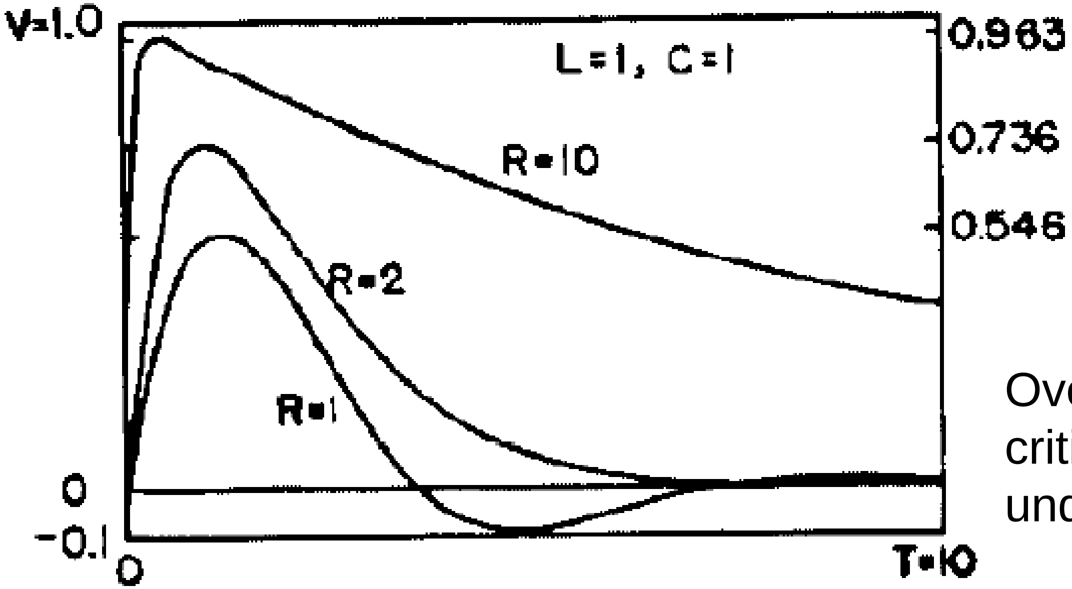
Lumped Capacitor System



Schematic of lumped capacitor system

- Lumped Capacitor System

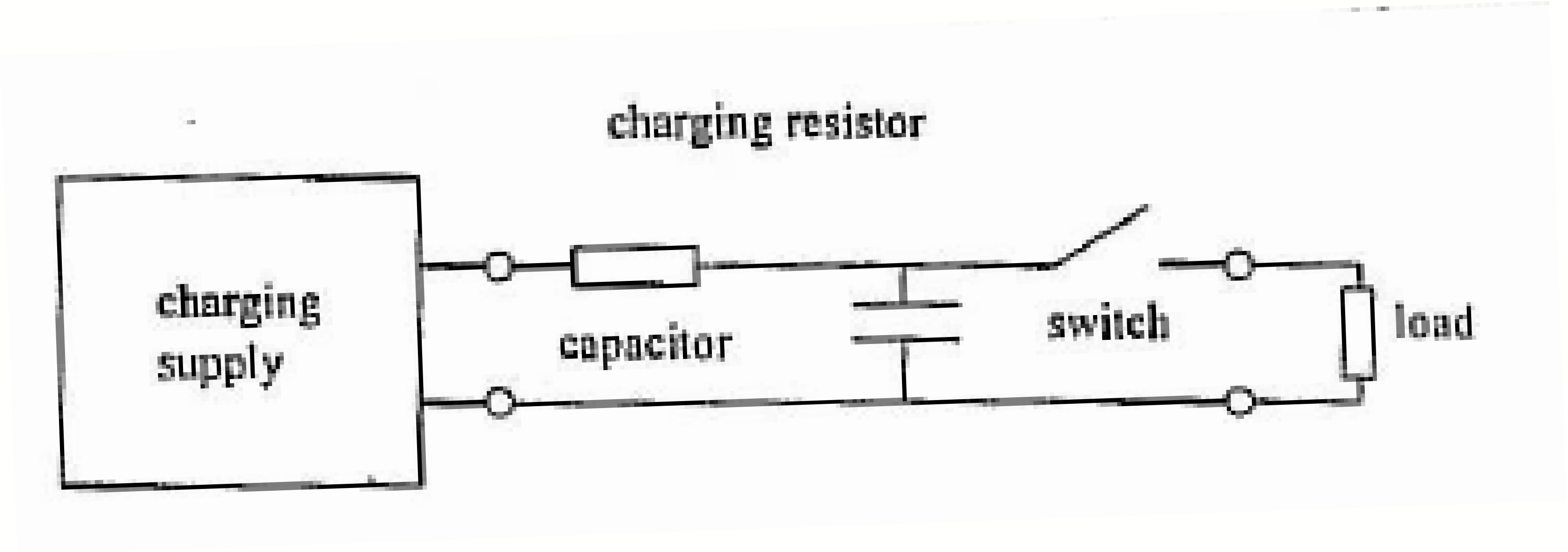
$$L\frac{d^2i}{dt^2} + R\frac{di}{dt} + \frac{i}{C} = 0.$$



Overdamped, critical damping, underdamped

Capacitive Discharge System

- Capacitive discharge circuits are the most widely used pulsed power topology
- Figure below shows a generalised discharge circuit consisting of a **charging unit**, a **storage device**, a **switch/gap**, and the **load**.



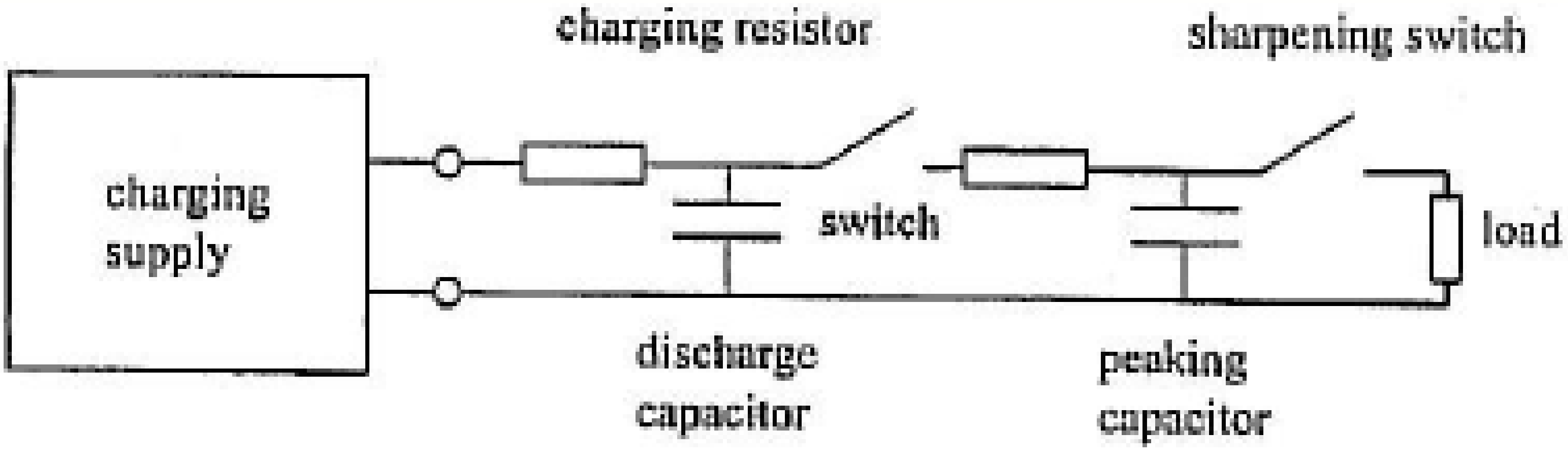
- A suitable **charging system** is used to charge the capacitor to the required energy and voltage
  - eg 1uF capacitors, 50-100 kV, 1 min charging

- Milliseconds charging for 1 nF capacitors in high repetition rate system

- **Time constant** $\tau = C\,R_{load}$ define the **pulse width**

- **Rise time** is more important- determined by the **closing switch/gap** and **inductance** of the load circuit

- One means of obtaining a more **rapid voltage rise** onto the **load** is by use of **a sharpening gap (see next Figure)**



Capacitor discharge circuit with **peaking capacitor** and **sharpening switch**

- The **‘peaking’** capacitor has much lower value - A **second capacitor** intermediate **between** the **source capacitor** and the **load**

- When the **primary switch** is closed, the intermediate capacitor **charges at a rate determined by the closing switch circuit**.

- The **sharpening gap/switch** is designed to **self-break** as the intermediate capacitor reaches a suitable high voltage, and thereby connects the intermediate capacitor across the load

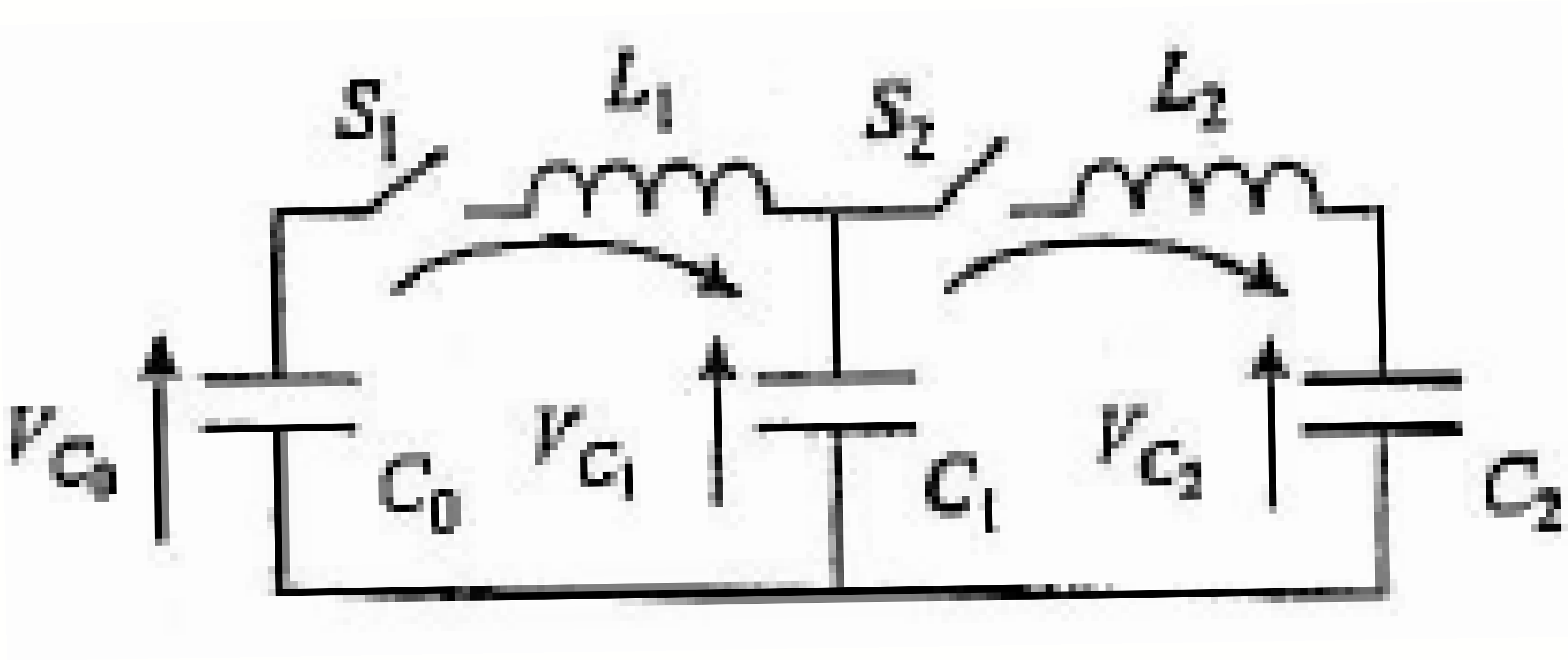
- The **load voltage rise time** may then be very **rapid** since the **inductance** of the **peaking capacitor load loop** can be made very low

Pulse compression

- Energy may be transferred **resonantly** between two capacitors by a circuit with a suitable closing switch and inductor.

- If a second **LC loop** is added, energy can then be transferred into the third capacitor via the second closing switch.

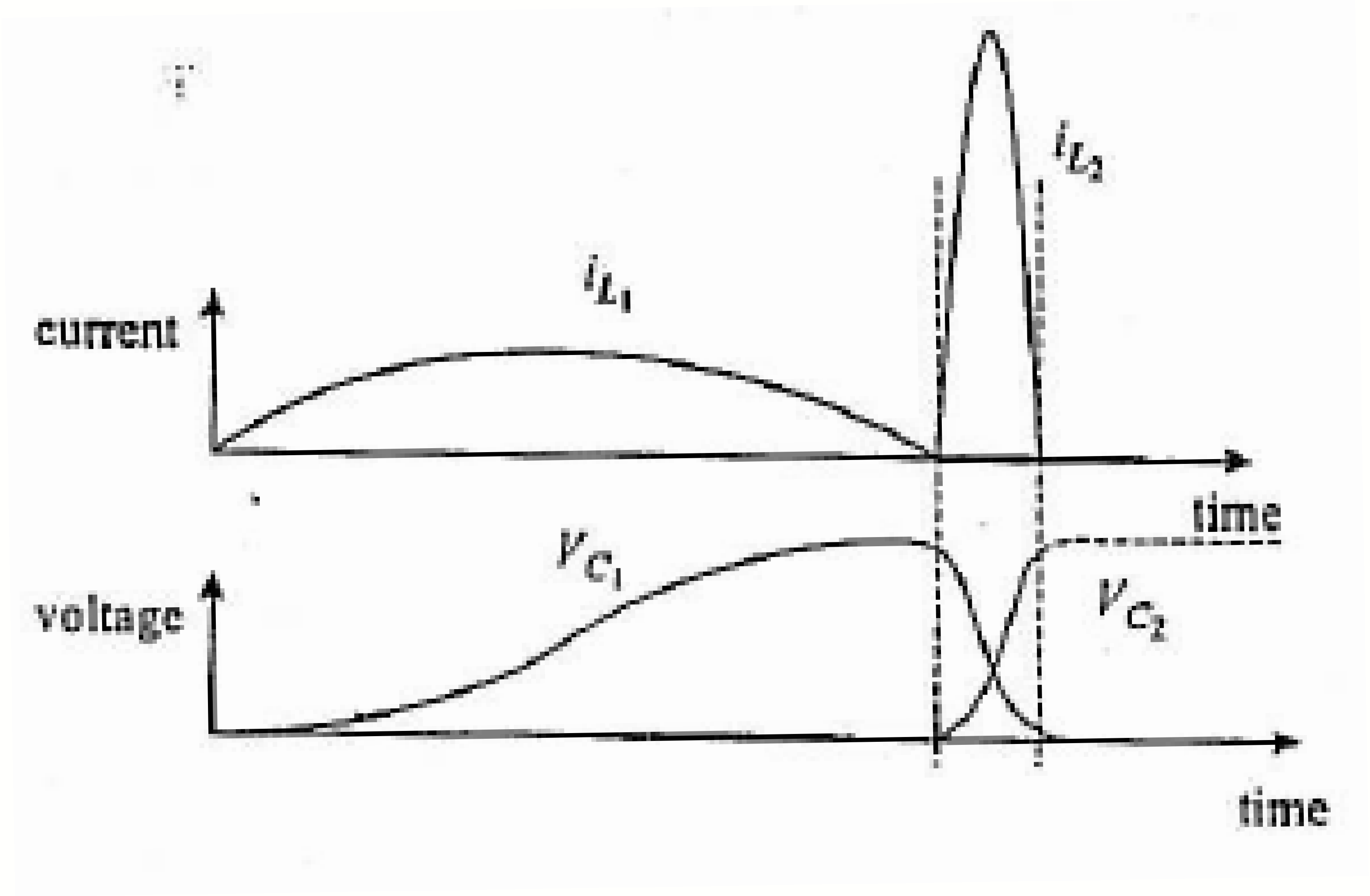
- If the $\sqrt{LC}$ **resonant period** of the second loop is made shorter, **the energy transfer occurs in a shorter period** and **with a higher associated peak current.**



LC (shorter $\sqrt{LC}$ resonant period) pulse compression circuit

The time constant of the first and second loop,

$$\tau_1 = \pi\sqrt{L_1\frac{C_0C_1}{C_0 + C_1}} \qquad \tau_2 = \pi\sqrt{L_2\frac{C_1C_2}{C_1 + C_2}}$$



Idealised current and voltage waveforms in the pulse compression circuit

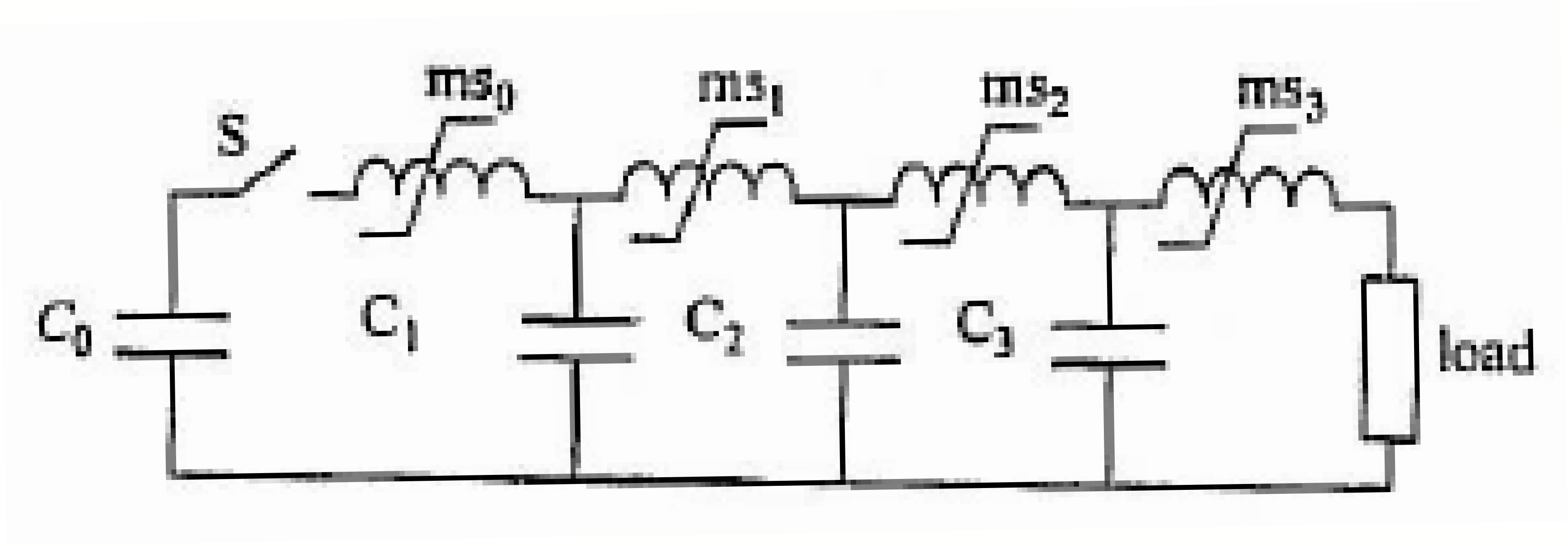
- This process is termed **pulse compression**.

- The switching of the second circuit will usually be made to depend upon the state of the circuit. A **self-breaking spark gap** could be used

- **Higher power levels and more arduous switching duty for later stages, if more used.**

Magnetic pulse compressor

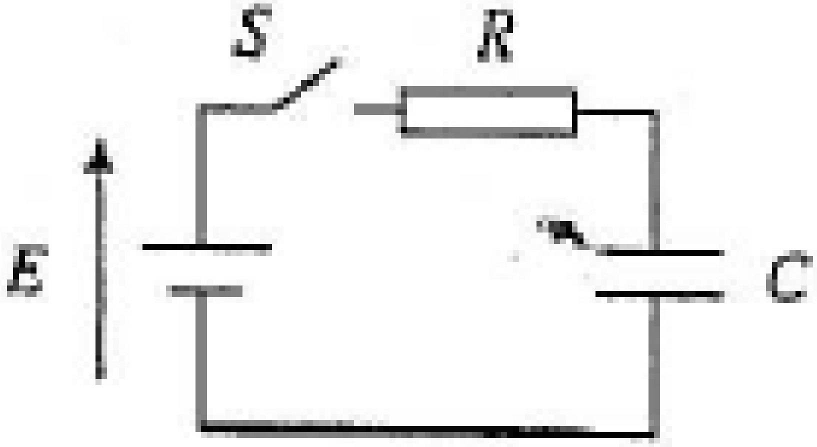
- Melville (1940s) use **automatic pulse compression switching (a 3-stage magnetic pulse compressor circuit is shown below)**



- The **inductors** have **saturating soft magnetic cores** (NiFe ferrite or amorphous metal) -> **magnetic switching characteristic**
- While core **unsaturated** ($\mu_o\mu_r$), the inductors present a **high impedance to current flow**.
- When **driven into saturation**, the inductor presents a **low impedance** (μ_o), and **current is able to flow** according to the value of L_{sat}.
- The **transition between unsaturated and saturated states** can occur in **10-100 ns timescale**, which means that the **inductor exhibits a quite rapid magnetic switching characteristic**.
- Two main parameters – the **volt-second hold-off** and the **saturated inductance**.
- Wide applications including driver circuits for CO_2 gas lasers etc.

- MSo initial high inductance state
- S closed (thyristor), MSo driven into saturation and the process repeats through MS1, MS2 and MS3
- Co resonantly transfers its charge to C1
- Inductor MS1 is designed to remain in a high L until the point when C1 is fully charged
- MS1 then saturates, and resonant current flows between C1 and C2.
- Reverse current between C1 and Co is blocked by the fact that MSo requires to be driven into negative saturation before it is closed for current in the reverse direction.

Charging supplies



- **Resistive** charging has the benefit of simplicity and low cost
- **DC source** – transformer with rectifier, Cockroft-Walton multiplier, switch-mode HVDC supply
- ***Disadvantage-*** an energy equal to that stored in the capacitor is dissipated in the charging resistance
- Switched-mode power electronic charging units (capacitor charges) is becoming increasingly common especially in rep-rate applications

- Charger units range from the miniature systems found in camera flash systems to multi-kW systems with outputs of up to 50-100 kV
- The benefit of specialised capacitor charging systems is that the instantaneous output voltage during charging is generally controlled to maintain a constant charging current into the capacitor, giving very high efficiency
- Battery storage is often employed for mobile systems, for systems with extremely high current demands, or where EMI/EMC concerns can otherwise cause problems.
- LV ultracapacitors (several F and few volts) my provide an interface between batteries and faster pulsed circuits (eg electric vehicles)
- Railgun and coilgun will require MW-GW of prime power for several ms pulse duration, using pulsed alternators such as compulsators.

Capacitors

- **Electrolytic** (**ms timescale discharge**), **wound paper and foil** (**100s ns**), **metallised plastic film** (**100s ns**), and **ceramic** dielectric (**ns**).
- **Lifetime** highly dependent on the **degree of voltage reversal**
- The greater the voltage reversal, the lower the voltage rating. Reversal characteristics **are** standard data sheet item

Voltage multiplication: the Marx bank

- **Limitations** by **DC corona, DC insulation, power electronics** and **transformer design** means 50-100 kV cap
- But pulsed power is 100kV – 2 MV
- Hence Marx generator
- Disadvantaged - loading by resistive charging stacks and switches

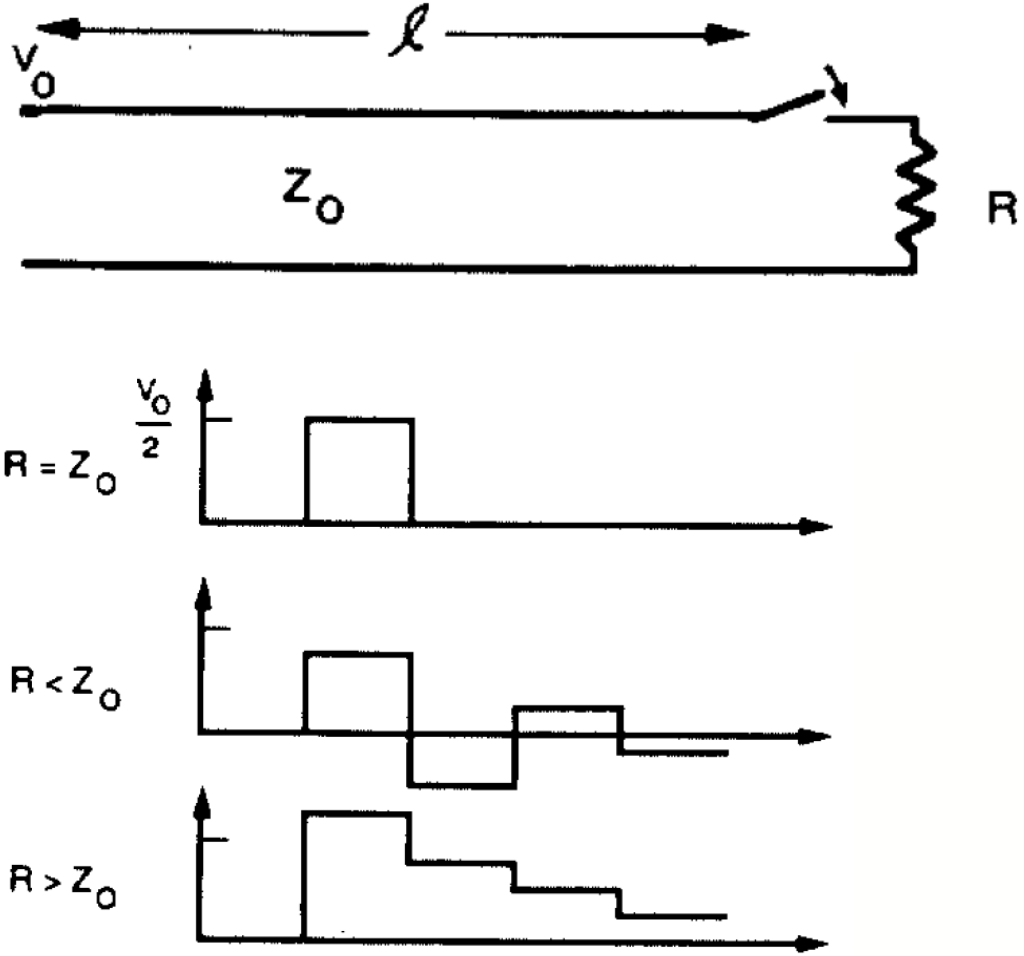
Compact, fast rise time Marx banks

- Ceramic capacitors (*manufacturers: eg. TDK, Murata*)
- **Low series inductance** hence **fast load rise time** of 10-100ns
- **Low inductance spark gap**, **hydrogen filled**, **1kHz**
- **Pressurised SF6** around Marx components is common

- As with semiconductor switching and DBD (dielectric barrier) lines, a degree of sharpening can occur as the output pulse propagates and builds up between successive spark gaps along the Marx stack

- Example of applications of ultrafast Marx generator-ultrawideband radar and directed energy

Voltage Charged Transmission Line



Schematic and typical outputs

- Voltage Charged Transmission Line
- In lieu of the capacitor and inductor in the RLC circuit, a transmission line is employed as a pulse forming network.
- The transmission line is initially charged to Vo and switched to the load resistance, R, which is matched to the characteristic impedance of the transmission line Zo.
- The ouput is a square wave of voltage V0/2, current Vo/2Zo, and pulse duration 2t=2l/v, where l is the length of the transmission line and v is the propagation velocity of wave in the transmission line.
- If the load resistance is mismatched, the pulse is reflected backwards and forwards in the transmission line giving successive pulses of the same duration 2t with gradually decreasing amplitude.

Transmission line circuits

- When **electrical energy** is required to be **delivered** in the form of **short pulses**, the physical separation between circuit elements often makes it necessary to these pulses to be delivered along some form of transmission lines

- The **transmission lines** will be **two-conductor lines** e.g. **coaxial or parallel-plate**, supporting TEM mode waveforms as the main principal mode

- Transmission line cables used as energy stores and pulse sources
- Since T is cable transit time, load pulse has duration of 2T

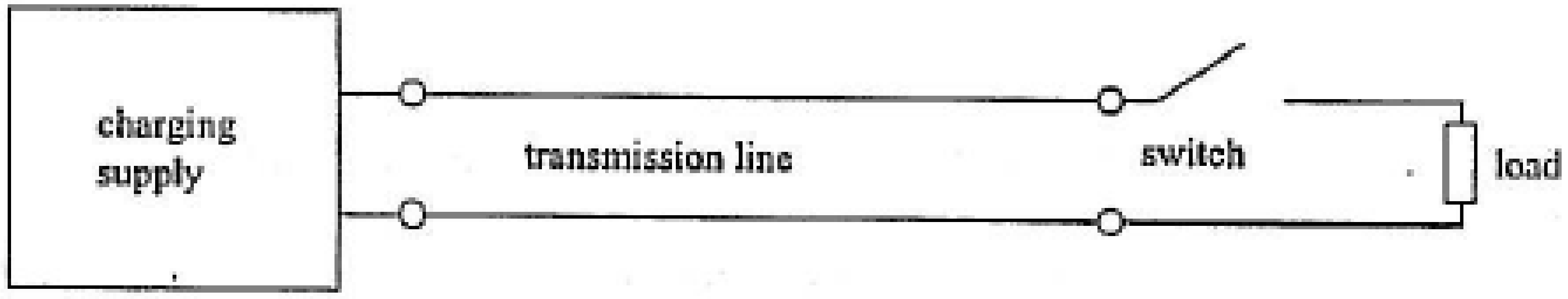
$$T = \frac{l\sqrt{\varepsilon_r}}{c_0}$$

$c_o = 3 \times 10^8$ m/s

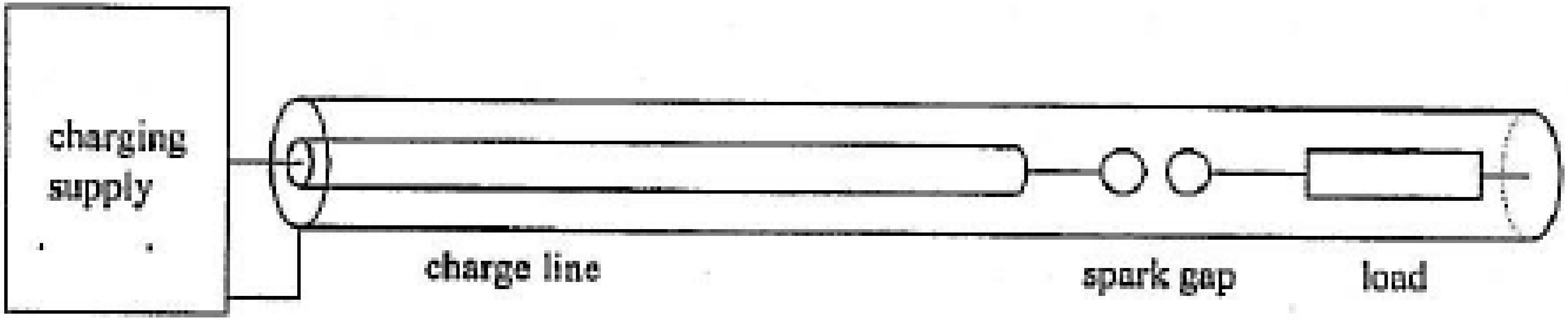
l = cable length, ε_r is of cable dielectric

- **2T for TL to completely discharged; pulse is rectangular, with rise and fall times defined by the turn-on time of the switch and the inductance of the circuit**
- **Length of transmission line required is dependent on ε_r**
- ε_r Air/vacuum, oil and water -> 1.2, 2.1, and 81
- Lentgh of 1 m -> 6.6ns, 10 ns and 90 ns pulse widths respectively.

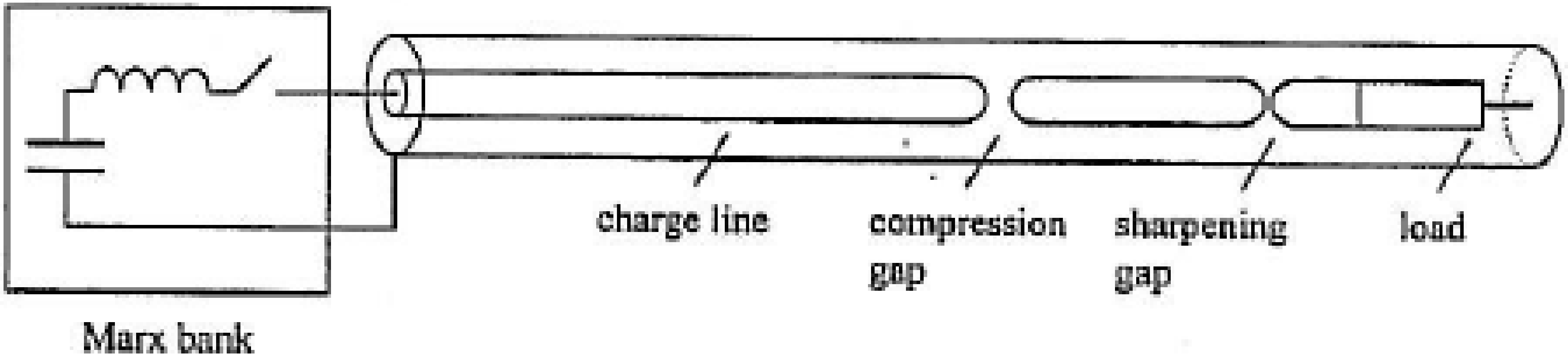
- Marx generator takes **1-2 us**, compression gap initiates a transmission line pulse discharge within a pulse width of typically **100-400 ns** – this represents the **pulse compression phase**.
- The **sharpening gap** holds off the initial voltage rise until near peak voltage, then closes. The rise time through the sharpening switch is typically **10-20 ns**, and this then propagates forward to the load.



Single charge line
- Parallel line with switched load



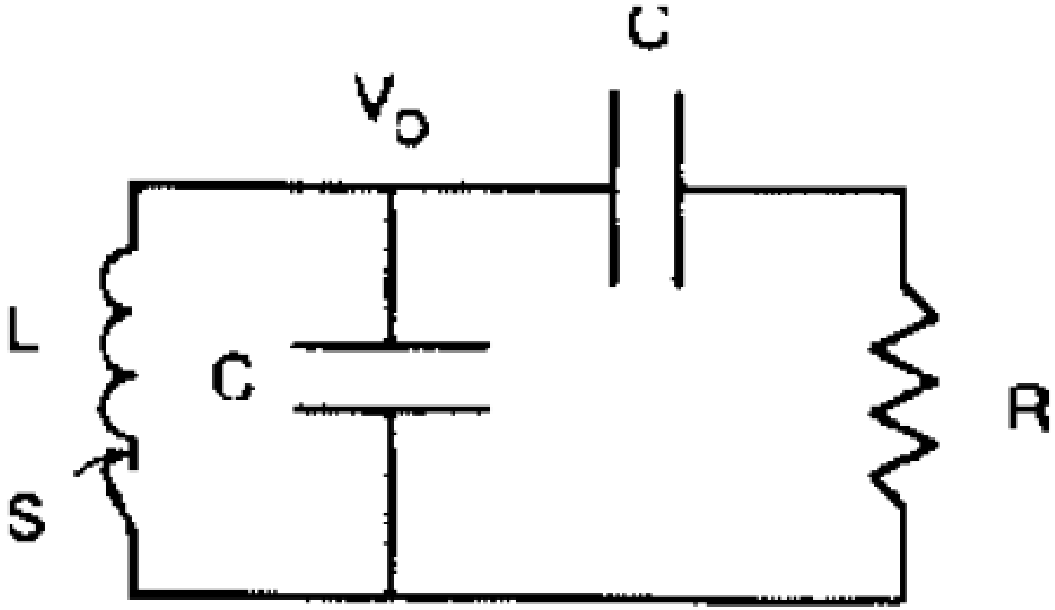
Single charge line
- Coaxial line with spark-gap switched load



Single charge line with **pulse compression and pulse sharpening**

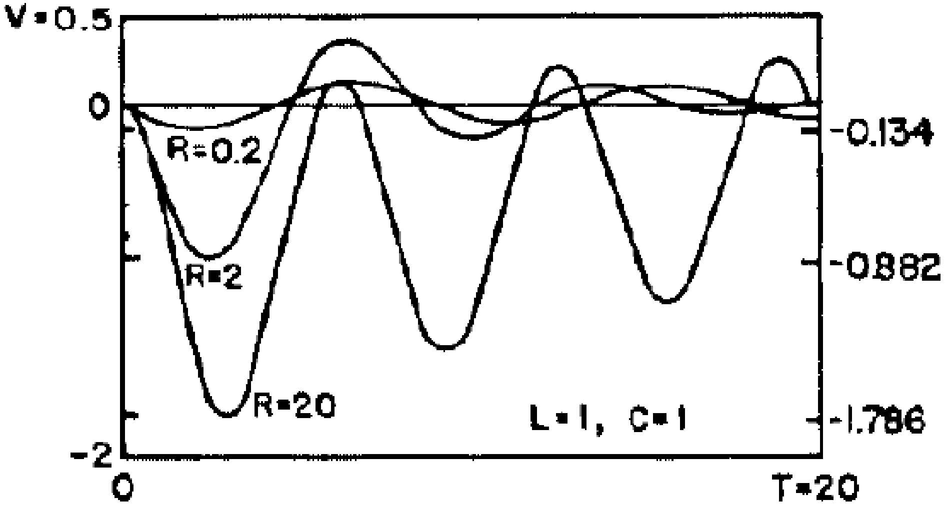
- Coaxial line – gap connected load

LC Generator

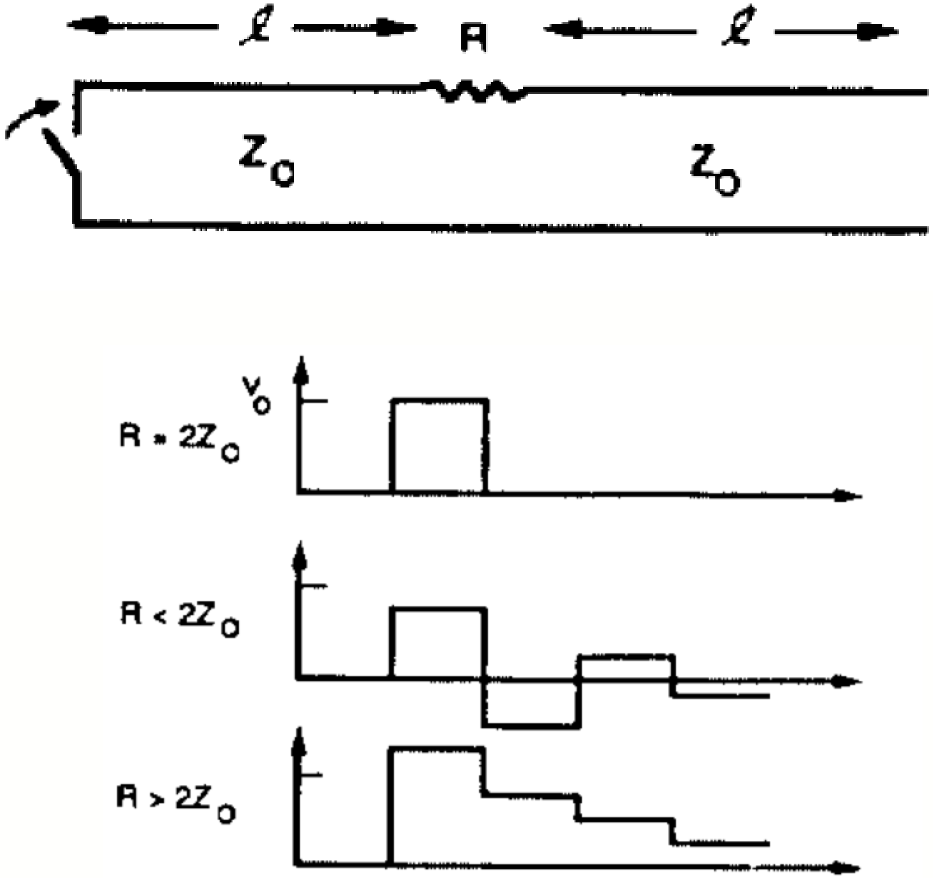


- LC Generator
- The main advantage of this system over the simple capacitor system is that with a given charging voltage, the output voltage is nearly twice that obtained from the simple capacitor system.

$$RC\frac{d^3 i}{dt^3} + 2\frac{d^2 i}{dt^2} + RL\frac{di}{dt} + \frac{i}{LC} = 0.$$



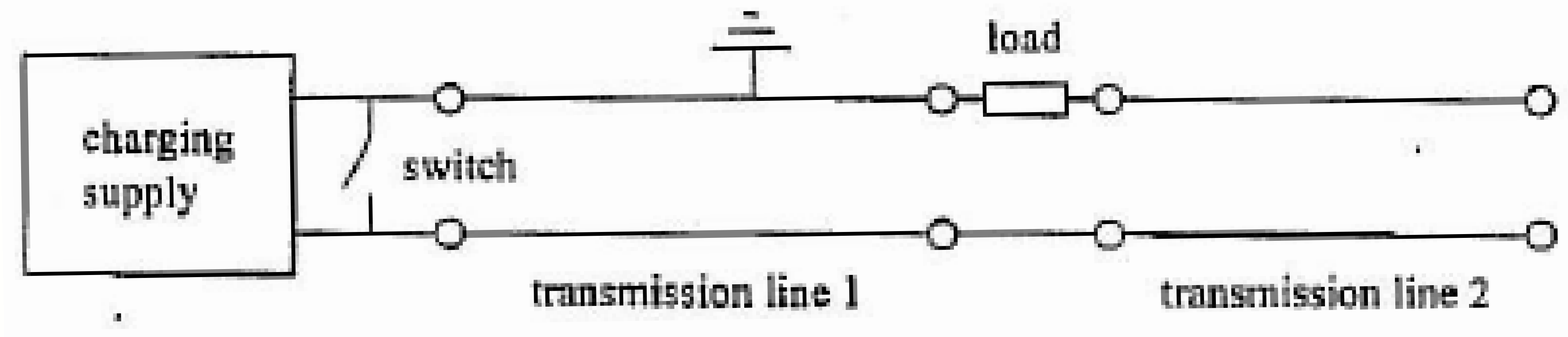
Blumlein Line



- Blumlein Line
- The counterpart of the LC generator in transmission line systems.
- Two identical transmission lines are series connected with a resistor which is twice the characteristic impedance of the transmission line to be matched.

The Blumlein circuit

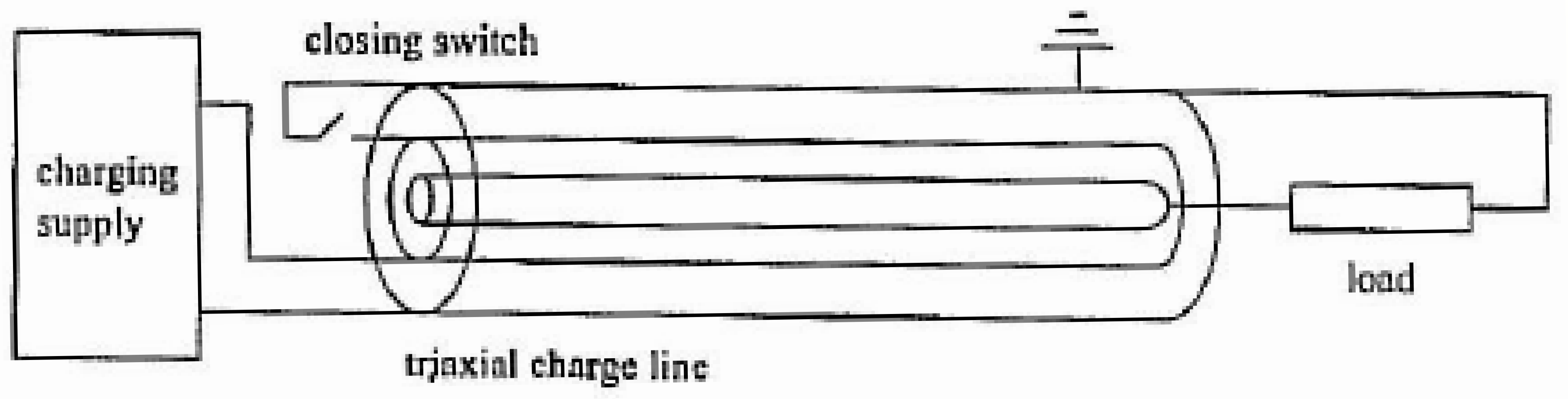
- A variation of the **charge line circuit** by A.D. Blumlein
- Uses **two charge lines** with the **load interposed**



- For matched operation, the **impedance of each of the charge lines** should be **one-half of the load impedance**
- The **two lines** are **initially charged** by some suitable charger (the RH line charging path is through the load impedance)
- The **closing switch** is between **two plates/conductors of the LH line**
- **Closing the switch launches a travelling wave onto the LH line**, and when this wave reaches the load, the load voltage is developed.
- For **matched** operation, the magnitude of the load voltage impulse is equal to the charge voltage V
- The **duration** of the load impulse is 2T (T transit time of each line)

- **Benefit** – the load pulse is equal to the full charge voltage, rather than 1/2 as in the single line configuration.

- Coaxial configuration is also possible.



Coaxial Blumlein

2. Pulsers and Topologies

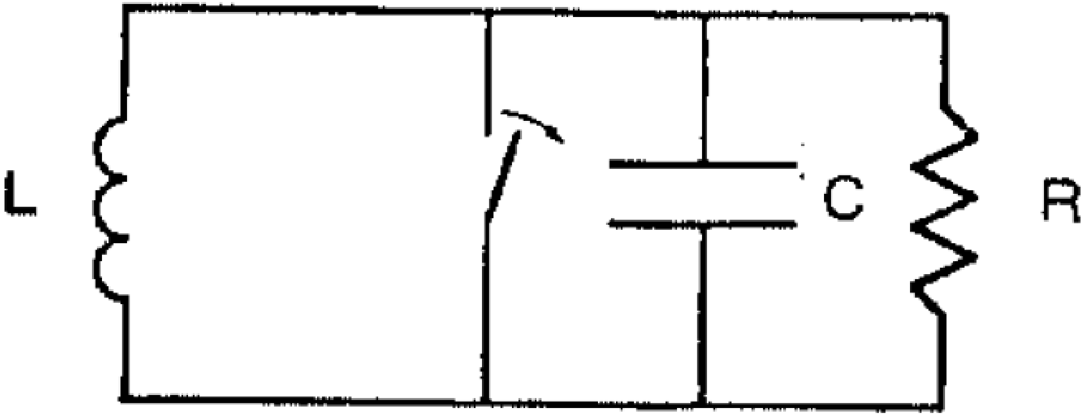
2.2 Inductive Energy Storage Systems

- Lumped Inductor System
- Current Charged Transmission Line
- Dual of LC Generator
- Dual of Blumlein Line

Inductive energy storage

- Although the **capacitive storage has the merit of simplicity**, **inductive storage** potentially offers **energy densities around 100-1000 higher**
- ~25 MV/cm vs 10T
- For inductive energy to be extracted, it is necessary to open a switch in order to divert the inductor current into the load
- Current interruption is inherently extremely difficult
- Two major opening switch types – plasma erosion opening switch (PEOS) and semiconductor switches
- PEOS addresses MA current range, MOSFETs and GTOs ~0.1-5 kA

Lumped Inductor System



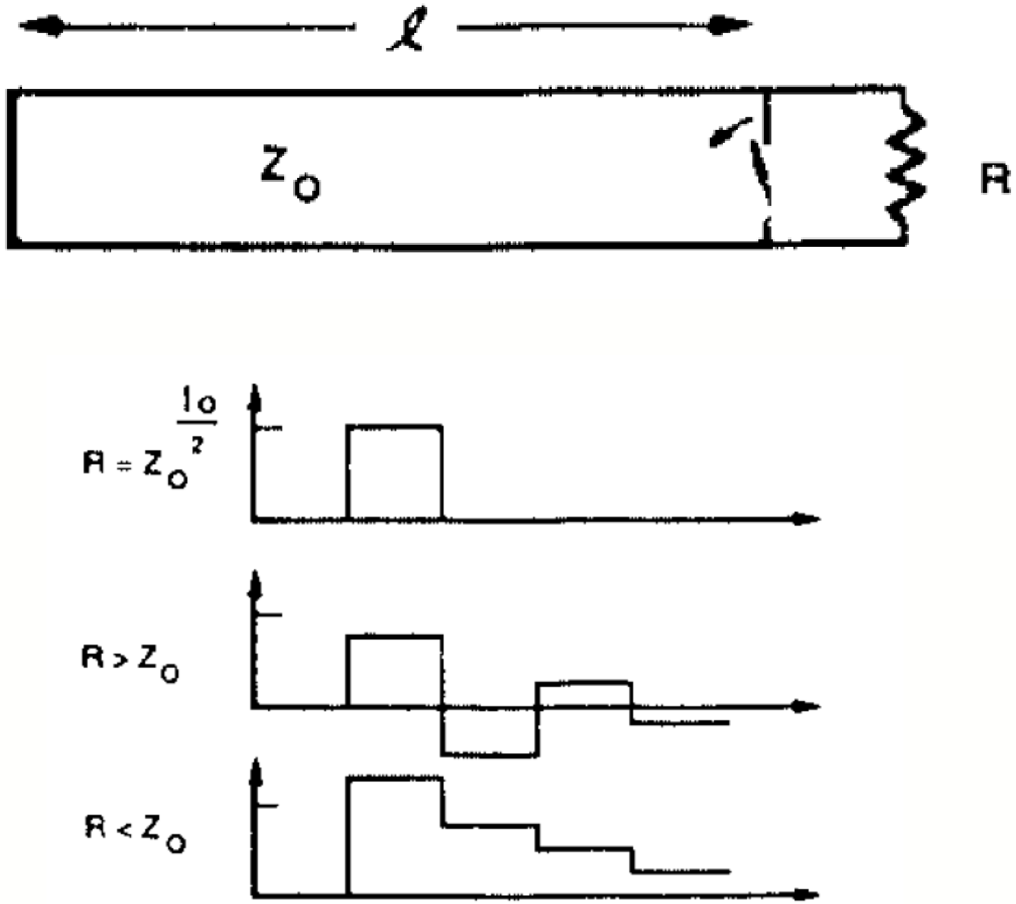
Schematic of lumped inductor system

- Lumped Inductor System

$$c\frac{d^2v}{dt^2} + \frac{1}{R}\frac{dv}{dt} + \frac{v}{c} = 0$$

Schematic of lumped inductor system

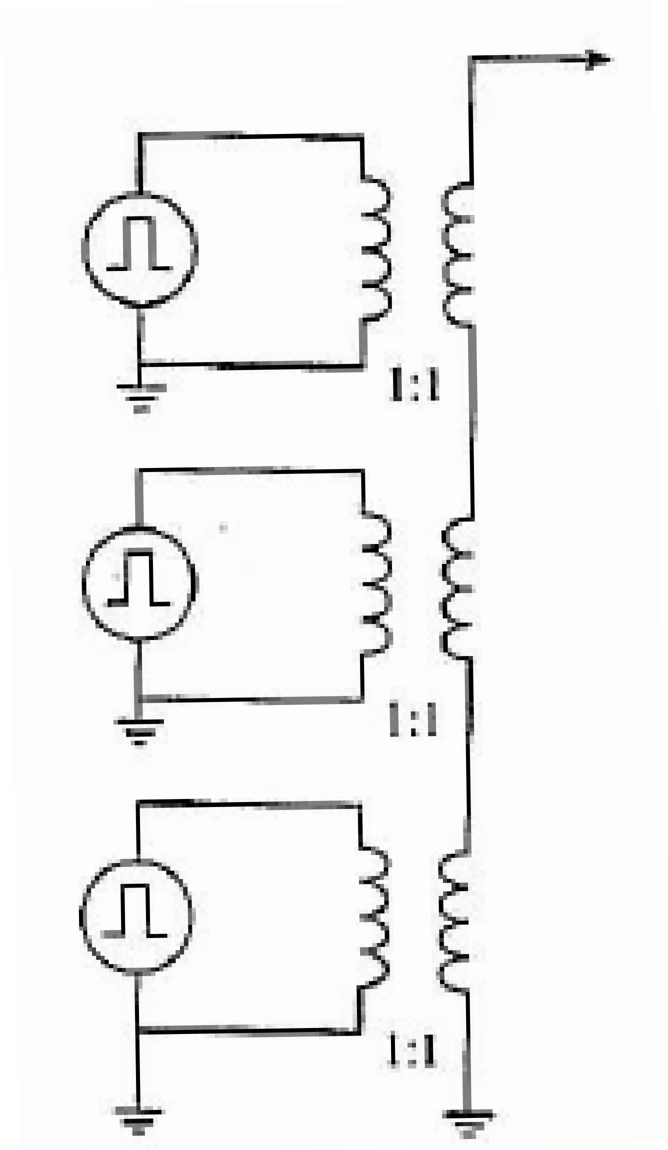
Current Charged Transmission Line



Schematic
and typical
outputs

Inductive voltage adders

- Means of achieving multi-MV pulses for radiographic and gamma-ray generators
- Eg 20 MV Hermes system
- A series-coupled set of 1:1 transformers
- Each primary is fed by a separate pulse generator, which may be referenced to ground, and all of the secondaries are coupled in series
- The output voltage is the summation of the secondary inputs



3-stage inductive adder circuit using 1:1 transformers

- A series connection of identical pulse forming stages which are coupled with each other through suitable sections in which the EMFs are vector added, in contrast to competing concepts like Marx generators
- All stages at ground potential during pulse forming

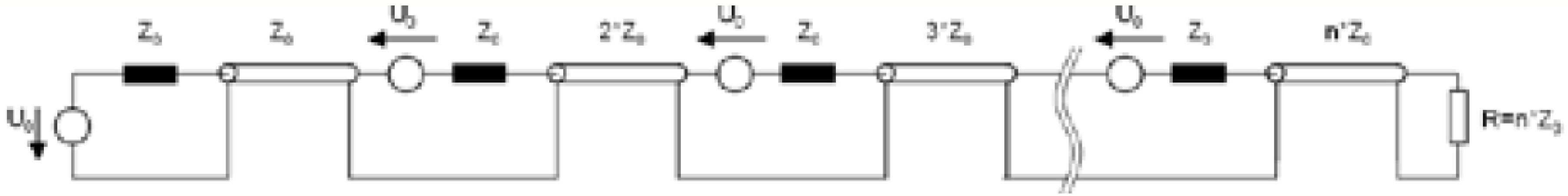


Figure 1. Equivalent circuit model of a voltage adder with self- magnetic insulation [5].

- A series connection of identical pulse forming stages which are coupled with each other through suitable sections in which the EMFs are vector added, in contrast to competing concepts like Marx generators
- All stages at ground potential during pulse forming

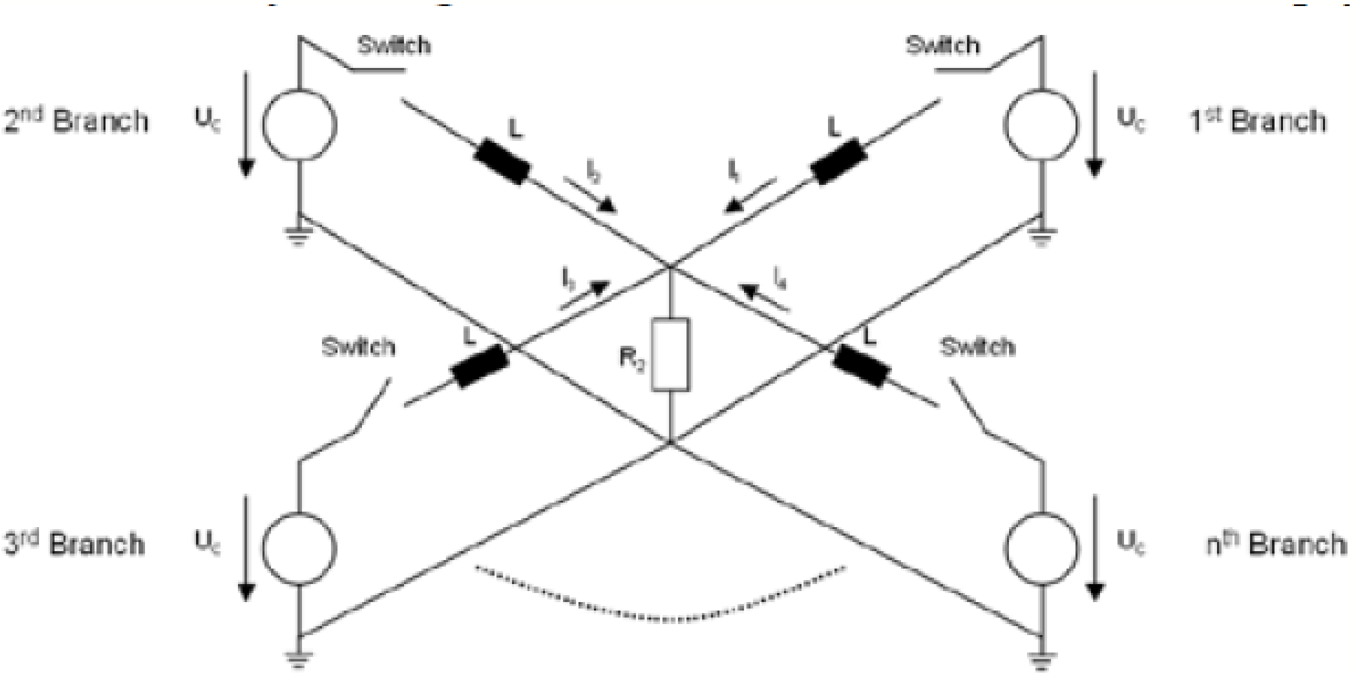
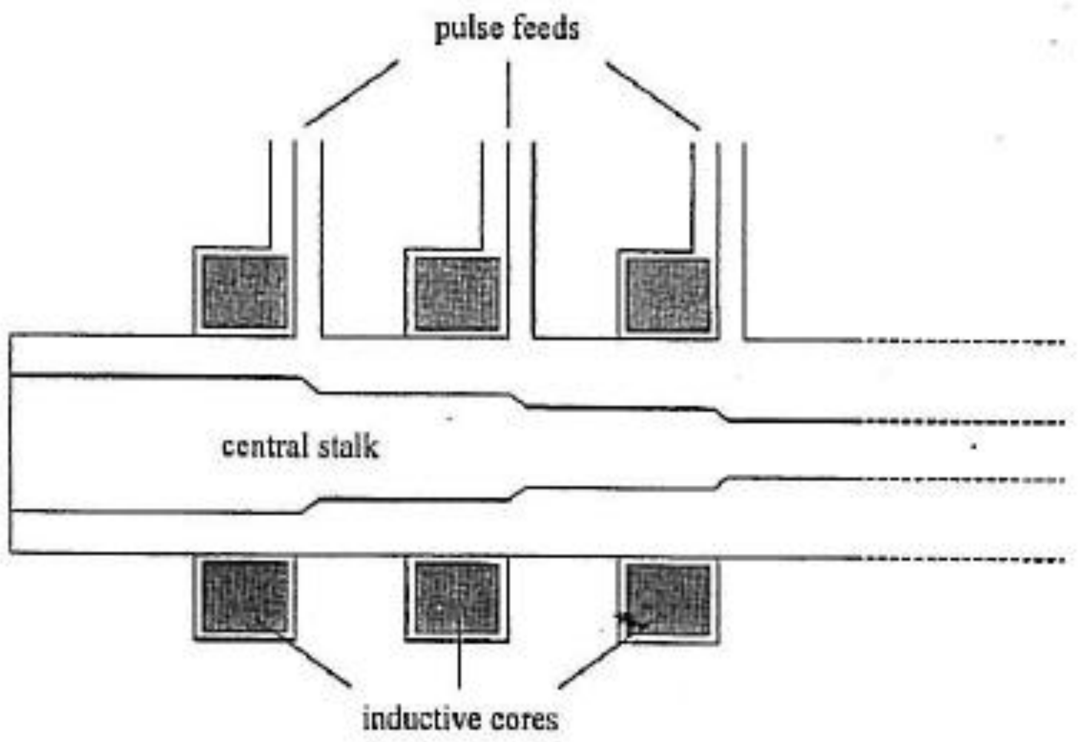


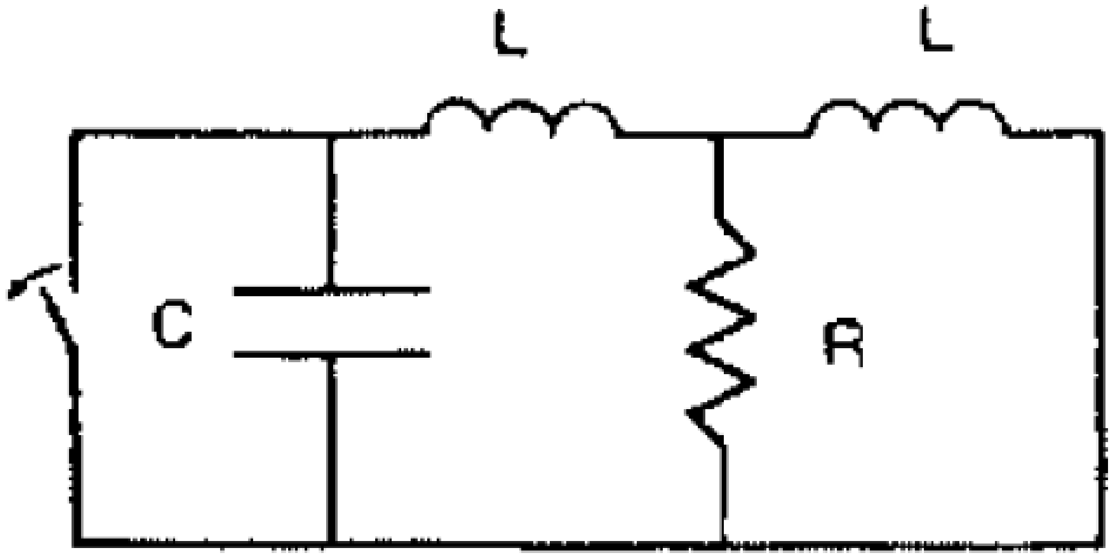
Figure 3. Schematic of an IVA stage module consisting of several parallel pulse modules which feed into a common radial transmission line.

- Transmission inductive adder, the secondary forms the centre conductor (stalk) of a coaxial line which leads to the anode or cathode of the load, typically an e-beam generator

- First 3-stage:



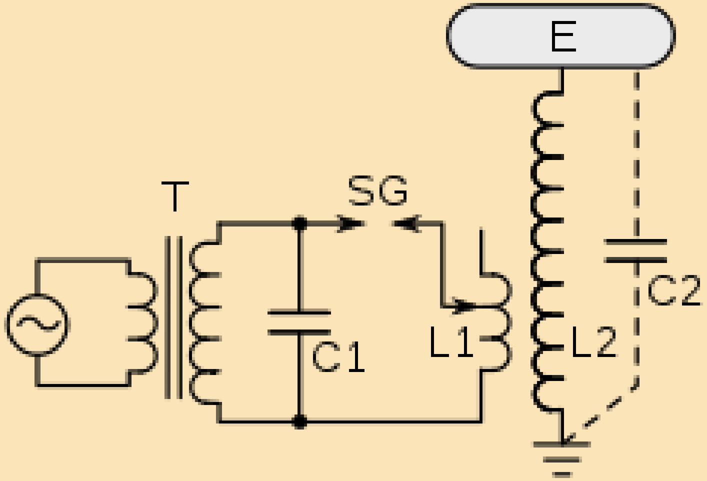
Dual LC Generator



- LC Generator

$$\frac{L}{R}\frac{d^3v}{dt^3} + 2\frac{d^2v}{dt^2} + \frac{1}{RC}\frac{dv}{dt} + \frac{v}{LC} = 0$$

The Tesla transformer



- A Tesla coil is an electrical resonant transformer circuit designed by inventor Nikola Tesla in 1891. It is used to produce high-voltage, low-current, high frequency alternating-current electricity.

The Tesla transformer

- The power source is hooked up to the primary coil.
- The primary coil's capacitor acts like a sponge and soaks up the charge.
- The primary coil itself must be able to withstand the massive charge and huge surges of current, so the coil is usually made out of copper, a good conductor of electricity.
- Eventually, the capacitor builds up so much charge that it breaks down the air resistance in the spark gap.
- Then, similar to squeezing out a soaked sponge, the current flows out of the capacitor down the primary coil and creates a magnetic field.

The Tesla transformer

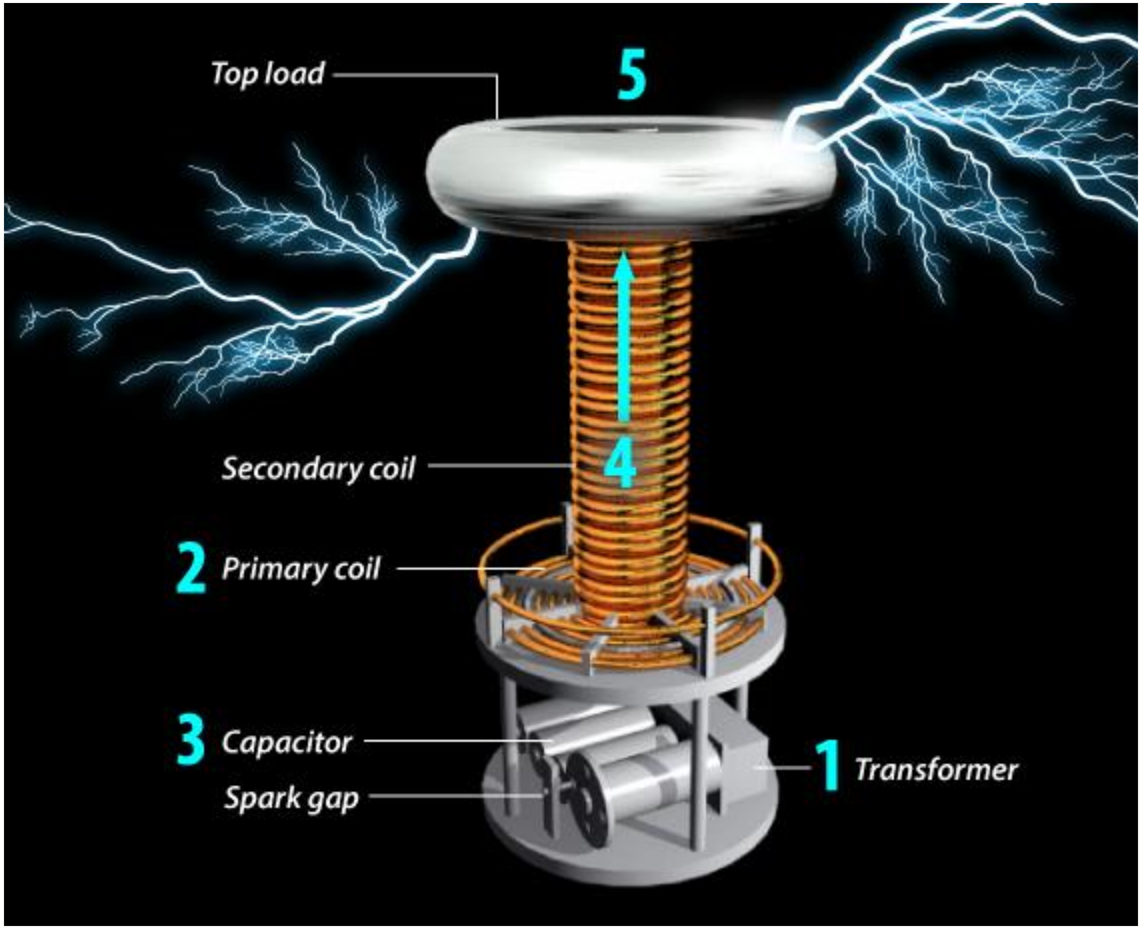
- The massive amount of energy makes the magnetic field collapse quickly, and generates an electric current in the secondary coil.
- The voltage zipping through the air between the two coils creates sparks in the spark gap.
- The energy sloshes back and forth between the two coils several hundred times per second, and builds up in the secondary coil and capacitor.
- Eventually, the charge in the secondary capacitor gets so high that it breaks free in a spectacular burst of electric current.

- The resulting high-frequency voltage can illuminate fluorescent bulbs several feet away with no electrical wire connection

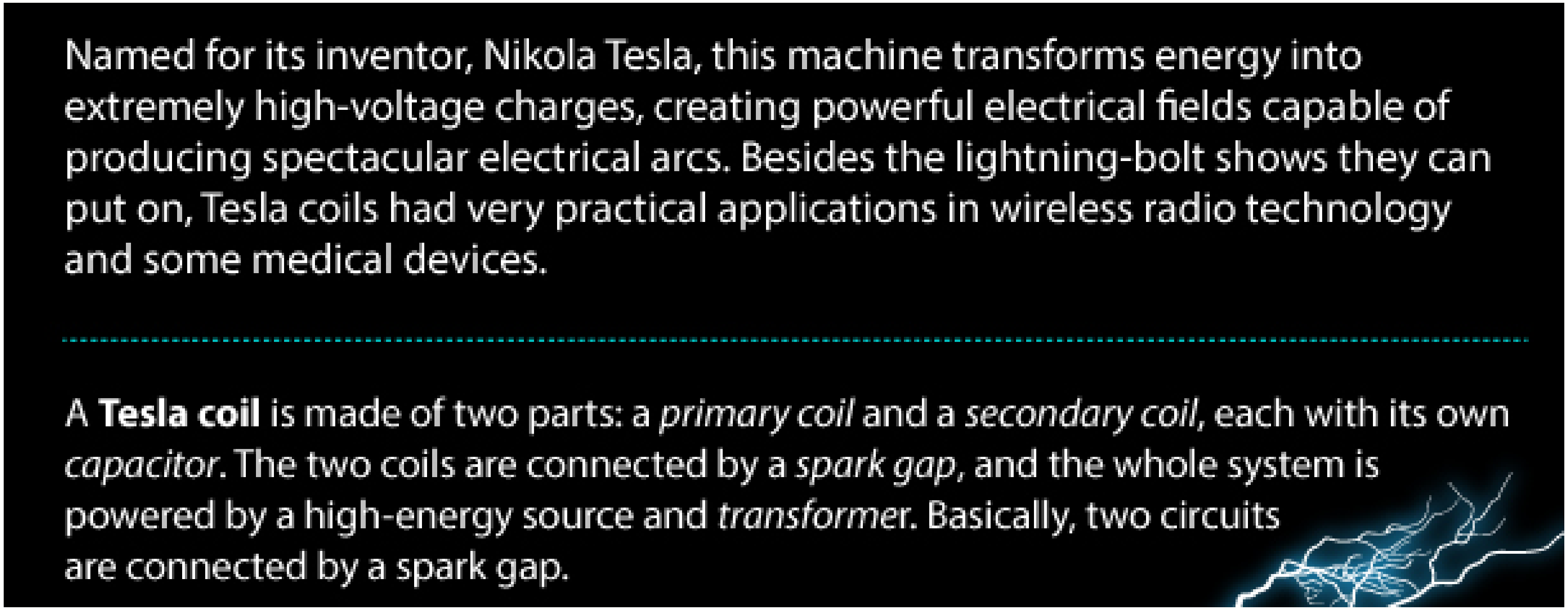
The Tesla transformer

- Unsuitable for power distribution applications
- Can produce radio frequency outputs with amplitudes up to several MV and capable of producing lengthy ionised channels in air
- Magnetization current is high, coupling coefficient (0.5-0.8) and pulsed output voltage up to 1 MV
- Primary windings of a few turns are used (axially spaced coils or foils)
- Turn ratios 1:1200 are typical
- The principle (of a pulse transformer): a thyristor or other primary switch is triggered in the primary circuit and this applies a capacitor voltage to the transformer. Rise times of the order of μs are produced on the secondary winding.
- Typically, a transmission line or charge line is capacitively charged by the Tesla coil output.

- Closure of a self-breaking or triggered high pressure spark gap then initiates pulse discharge of the transmission line into the load with a pulse width defined by the charge line length, and subns rise times can be achieved
- Typical loads include UWB emitters and high [power Xband oscillators (10GHz at 150MW pulse power) (20-150 ohm)

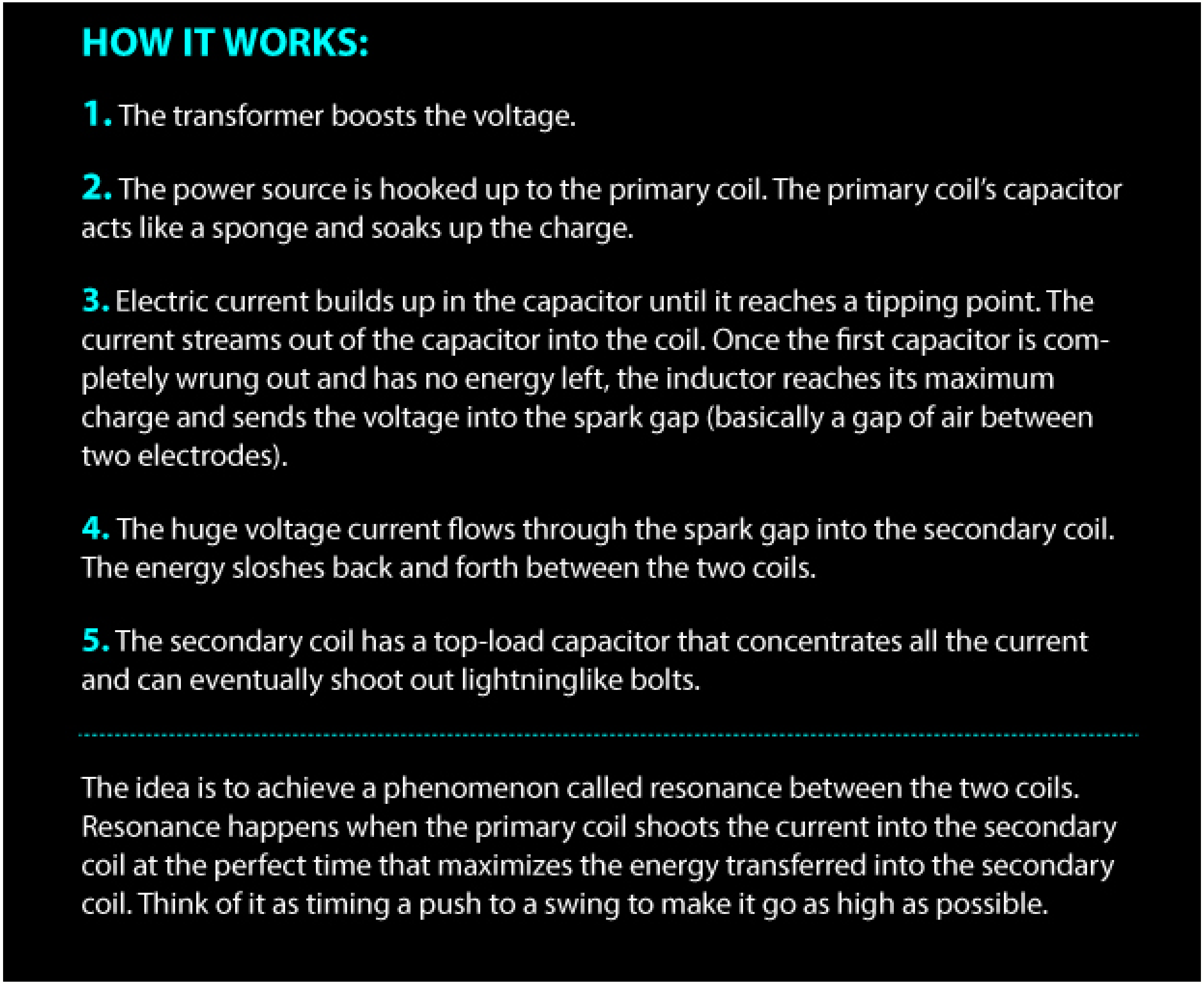


Concentric primary and secondary spiral windings for the Tesla transformer



Named for its inventor, Nikola Tesla, this machine transforms energy into extremely high-voltage charges, creating powerful electrical fields capable of producing spectacular electrical arcs. Besides the lightning-bolt shows they can put on, Tesla coils had very practical applications in wireless radio technology and some medical devices.

A **Tesla coil** is made of two parts: a *primary coil* and a *secondary coil*, each with its own *capacitor*. The two coils are connected by a *spark gap*, and the whole system is powered by a high-energy source and *transformer*. Basically, two circuits are connected by a spark gap.



HOW IT WORKS:

1. The transformer boosts the voltage.

2. The power source is hooked up to the primary coil. The primary coil's capacitor acts like a sponge and soaks up the charge.

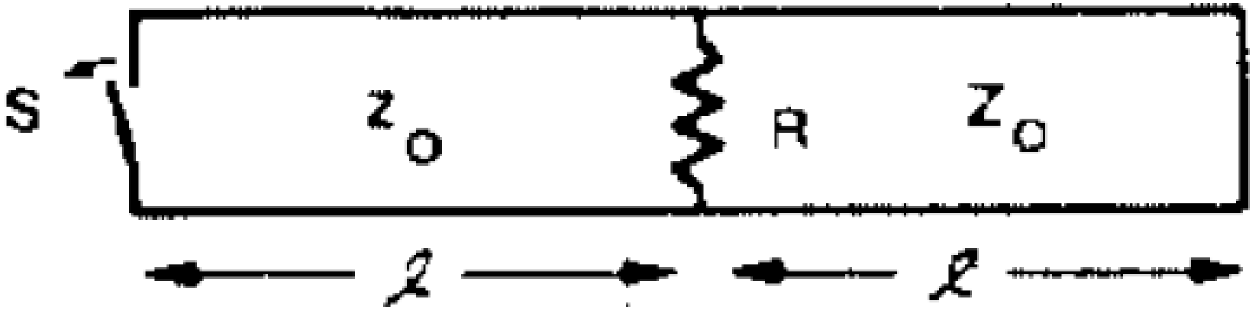
3. Electric current builds up in the capacitor until it reaches a tipping point. The current streams out of the capacitor into the coil. Once the first capacitor is completely wrung out and has no energy left, the inductor reaches its maximum charge and sends the voltage into the spark gap (basically a gap of air between two electrodes).

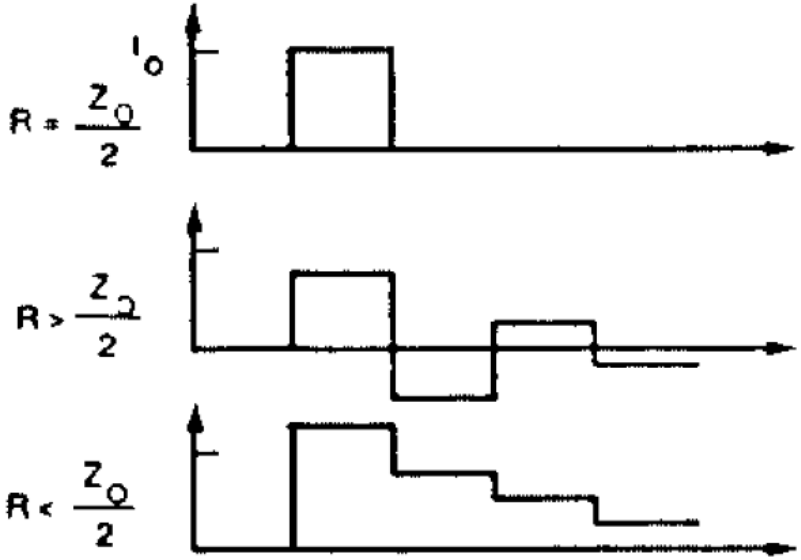
4. The huge voltage current flows through the spark gap into the secondary coil. The energy sloshes back and forth between the two coils.

5. The secondary coil has a top-load capacitor that concentrates all the current and can eventually shoot out lightninglike bolts.

The idea is to achieve a phenomenon called resonance between the two coils. Resonance happens when the primary coil shoots the current into the secondary coil at the perfect time that maximizes the energy transferred into the secondary coil. Think of it as timing a push to a swing to make it go as high as possible.

Dual Blumlein Line





3. Pulsed power applications

a. Ion beam materials treatment
b. Air treatment and pollution control
c. Pulsed corona precipitators
d. Biological applications
e. Biofouling and ballast water treatment
f. Food processing
g. Water purification
h. Mechanical applications of spark discharges
i. Medical application
j. Ultrawideband and HPM applications
k. X-ray simulators

Typical applications

  - Weapons – declining after cold war
  - Industrial applications into categories:
  - Environmental cleanup
  - Materials treatment
  - Biotreatments
  - Food treatment
  - Rock breaking
  - Particle generation

- Applying Pulsed power is better than that for DC or AC because…
  - Real case: electric field application in water (only pulsed fields may be realistically applied at the kV/cm level and above)
  - Some systems may have non-linear response which can be driven effectively in pulsed mode