# Basic Topologies II
# Hard Tube and Line-type Modulators

Pulsed Power Engineering
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# Hard Tube and Line-type Modulators

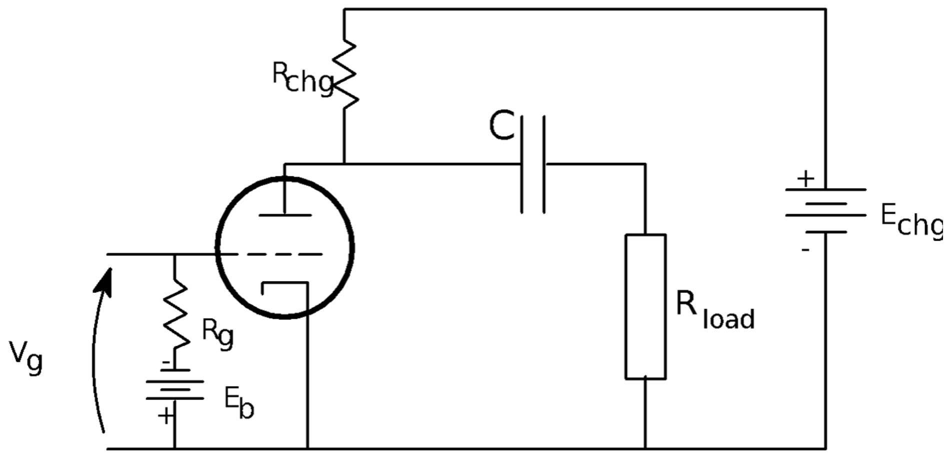
- Hard Tube Modulators

- Line-type Modulators
  - Transmission Line Characteristics
  - Pulse Forming Lines
  - Pulse Forming Networks
  - Examples of Hardware

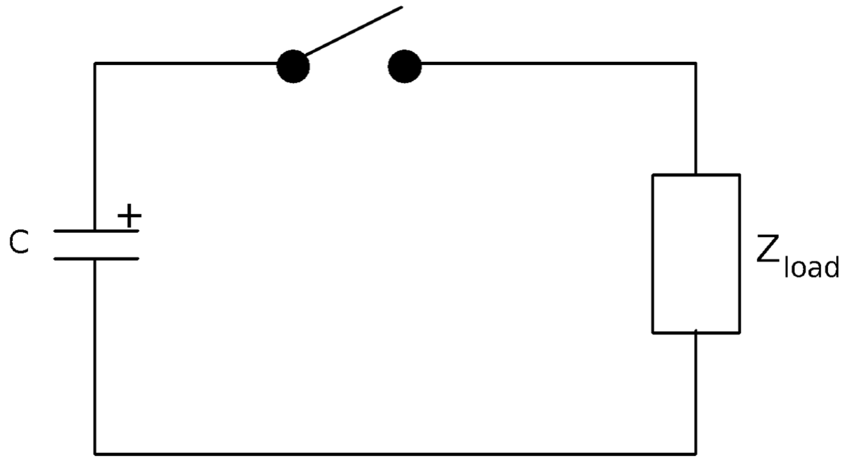
- References

# Hard Tube Modulators

- Pulsers in which only a portion of the stored electrical energy is delivered to the load.  Requires a switch that can open while conducting full load current.
  - Switch must open/close with required load voltage and current
  - Voltage regulation limited by capacitor voltage droop
  - Flat output pulse → large capacitor/large stored energy
    - Cost
    - Faults



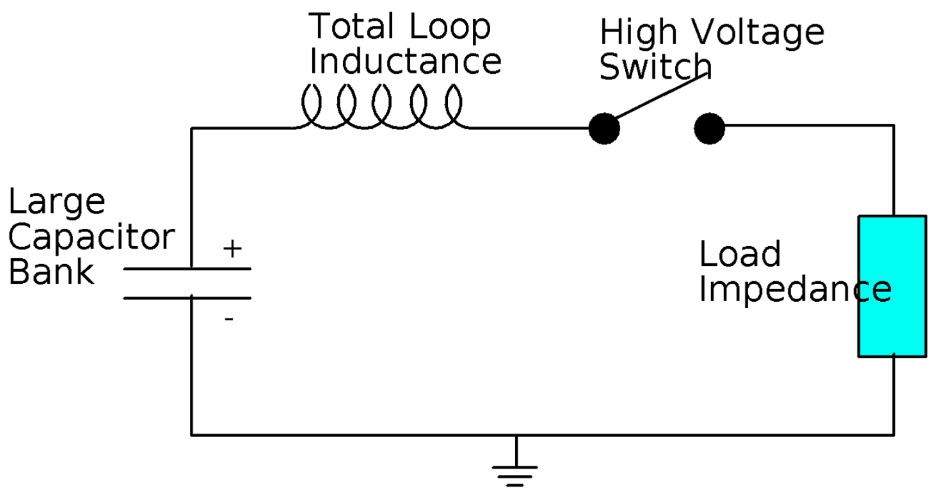

- Name refers to “hard” vacuum tubes historically used as switch



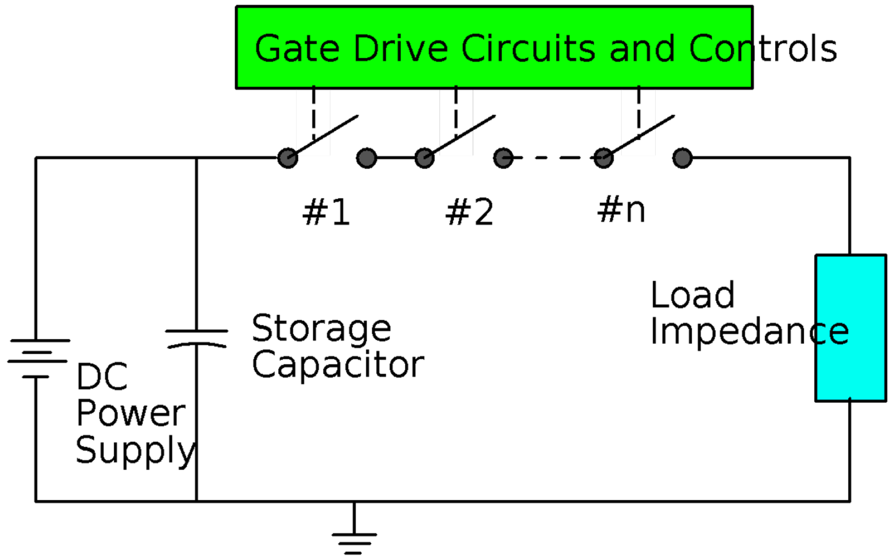

- Today’s fast solid-state devices are being incorporated into designs previously incorporating vacuum tubes

# Hard Tube: Topology Options

- Capacitor bank with series high voltage switch gives pulse width agility but requires high voltage switch




- Variations
  - Add series inductance: zero current turn on of switch
  - Series switches: reduces voltage requirements for individual switches

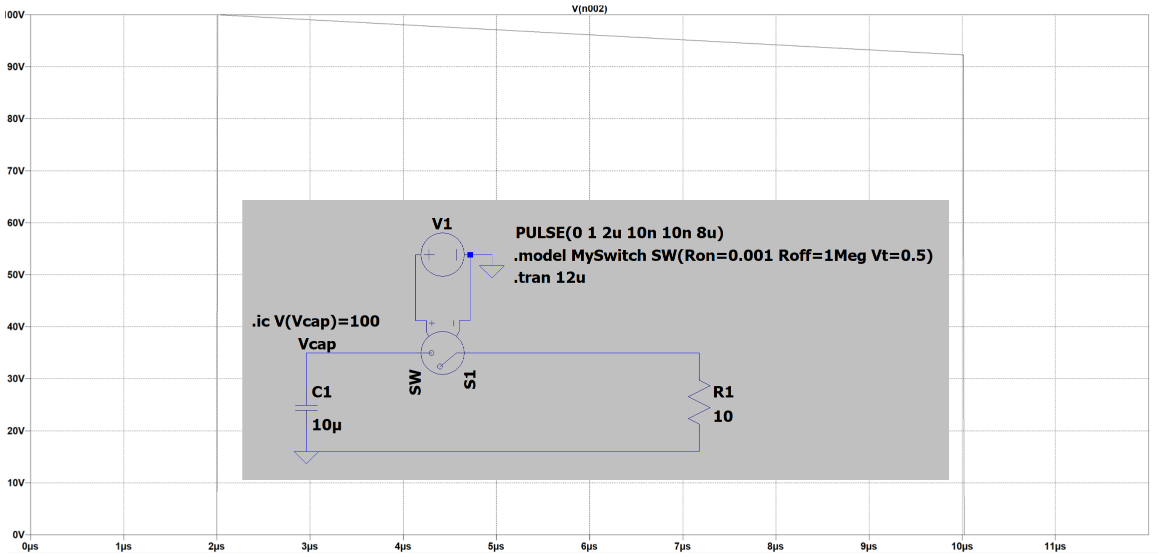


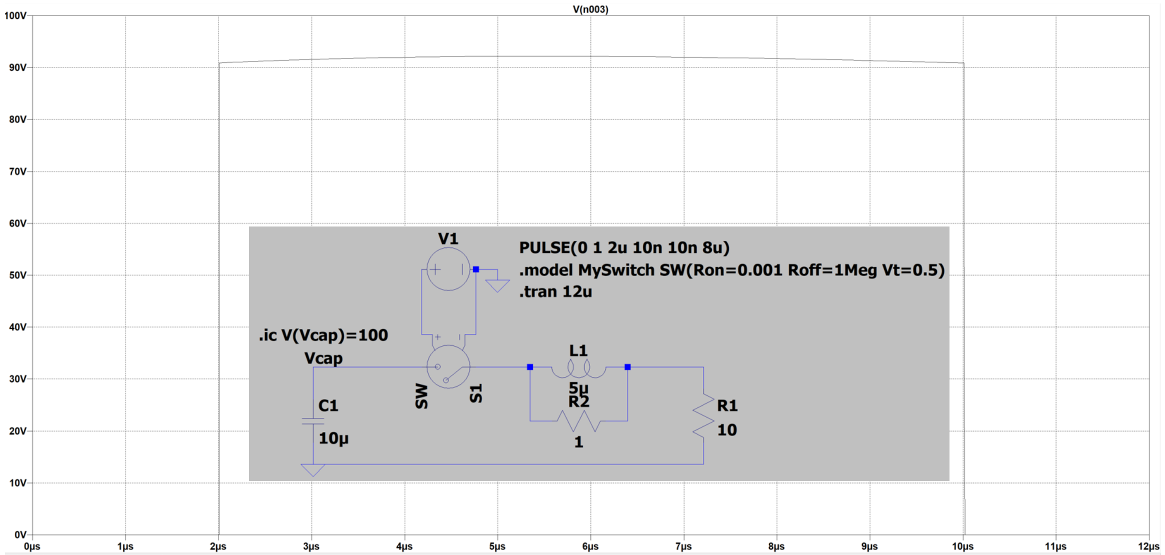
# Equivalent Circuit

- RC discharge circuit is the ideal case (with no stray L or C)

$$V(t) = V_0 e^{-\frac{t}{RC}}$$

- Voltage droop from capacitor discharge can be offset
  - Lossy passive circuits (parallel RL network)
  - Active circuits (slide 11)



# Hard Tube: Topology Options (cont.)

- Issues:
  - Capacitor droop
  - Large stored energy (and fault energy)
  - Reliability of the switch array
    - Switches must have very low time jitter during turn-on and turn-off
    - Voltage grading of series connected switches, especially during switching
    - Switch protection circuits (load and output faults)
  - Isolated triggers and auxiliary electronics (e.g. power, diagnostics)
  - Load protection circuits
  - For many lower repetition-rate systems without a step-up transformer, the main capacitor and one end of the switch array sits at full charge DC voltage

# Commercial Series Stack Modulator - Diversified Technologies Inc.

PowerMod™

## The Power You Need

### PowerMod™ HVPM 100-150

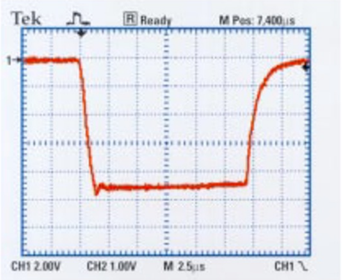
Diversified Technologies, Inc. (DTI) has applied its extensive background in high power electronics to design and build a 100 kV, 150A solid-state modulator for use in demanding commercial applications. The PowerMod™ HVPM 100-150 utilizes DTI's patented solid-state technology. The configuration shown fits in an oil tank approximately 50" x 36" x 64".

DTI's HVPM 100-150 utilizes the same breakthrough technology found in the HVPM 20-150 which received an R&D Magazine award as one of the 100 most technologically significant products of 1997. DTI's PowerMod™ high voltage, solid-state modulators are available from 1-200 kV, and up to 2,000A peak.

High power, high current modulators based upon DTI's design offer customers increased efficiency, enhanced reliability, increased pulse flexibility, and cost-effective high power switching capability.

DTI has pioneered the state-of-the-art in solid-state electronics since 1987. Our modulators have become essential components in applications for ion implantation (PSII), particle accelerators, and semiconductor and flat panel display manufacturing.

*PowerMod™ HVPM 100-150 Solid-State Modulator*




*HVPM 100-150 Pulse, 80kV, 90A Into Water Resistor*

| HVPM 100-150 Specifications | |
|---|---|
| Control Voltage | 120V AC |
| High Voltage Input: | 1-100 kV DC peak |
| Average Pulse Current: | 75A |
| 1 µs Peak Current | 150A |
| Rise Time*: | <1 µs |
| Fall Time*: | <1 µs |
| Nominal Pulse Width: | 1 µs - 100 µs |
| Nominal Pulse Frequency: | 0-5,000 Hz |

*into resistive load

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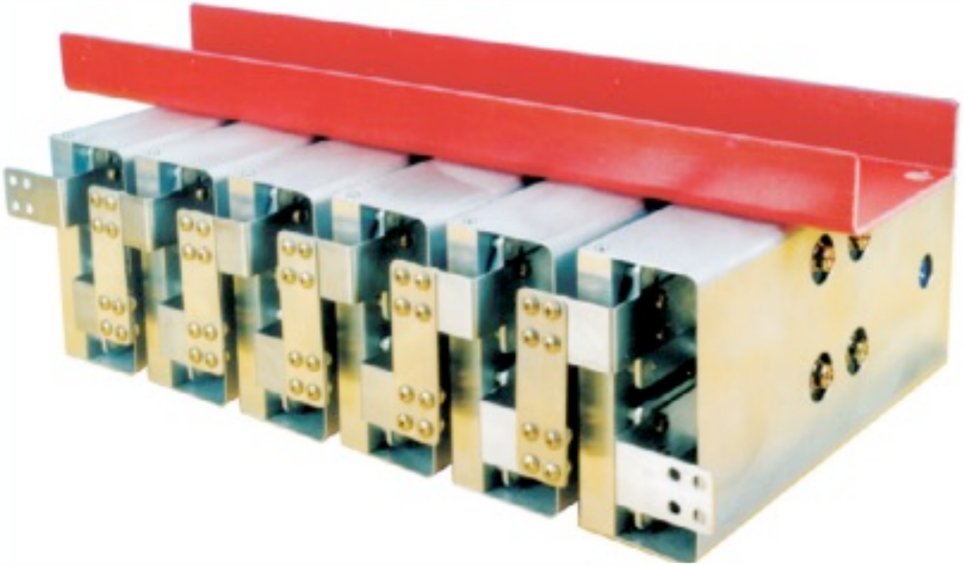
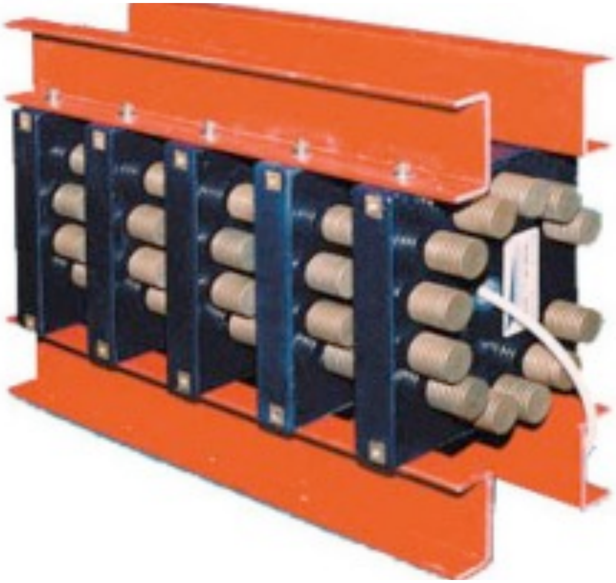




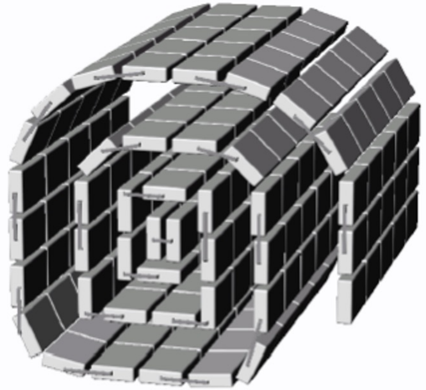
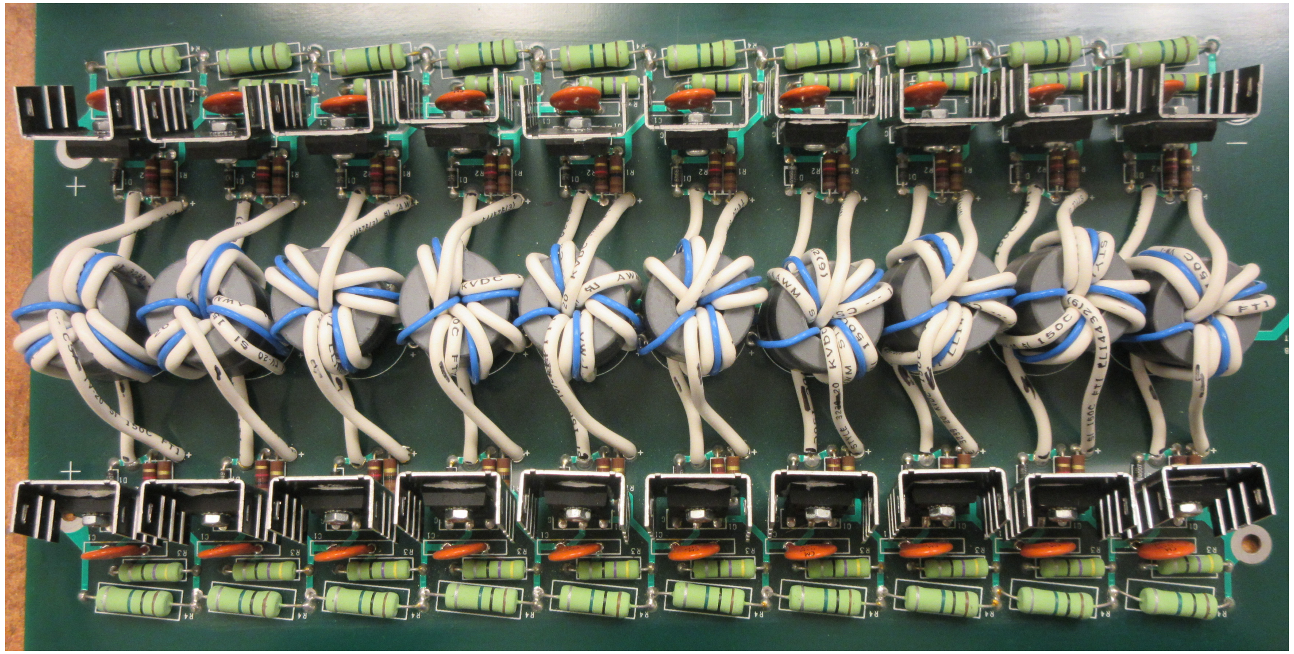


*Figure 4: Solid model of the 500 kV hard switch – note the spiral wrap of the series string of switch modules to reduce effective parasitic capacitance. The output (pulsed) end of the modulator is on the axis, and the input (DC) end is on the outer surface.*

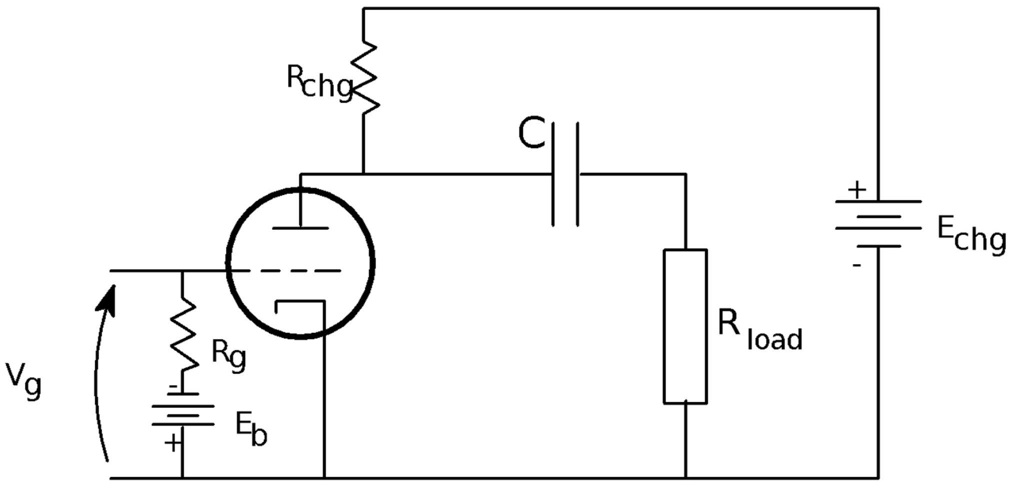
# Features of many hard tube modulator switch assemblies

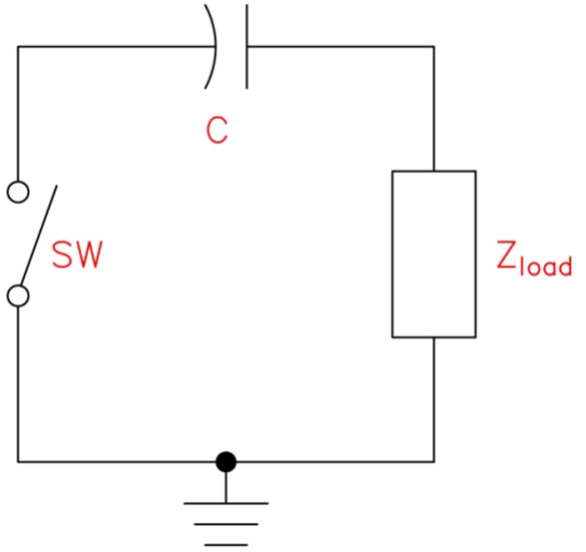
- Series and parallel combinations of MOSFETs or IGBTs
- Isolated trigger system
- DC voltage grading (Resistors) across series switches
- Transient voltage grading (RC network, MOVs) across series switches
- Overvoltage protection (MOVs, TVS diodes) across series switches
- Current-sharing features for parallel switch configurations
  - Matched devices (e.g., IGBT saturation voltage)
  - Coupling/decoupling switches thermally
  - Added resistance in series with parallel switches to minimize switch-dependent circuit resistance variation (but adds significant losses)



# Hard Tube: Topology Options

- Grounded switch – simplifies switch control
- Issues:
  - Only works for one polarity (usually negative)
  - HVPS must be isolated from energy storage cap during pulse
  - Lose switch control benefit with series switch array

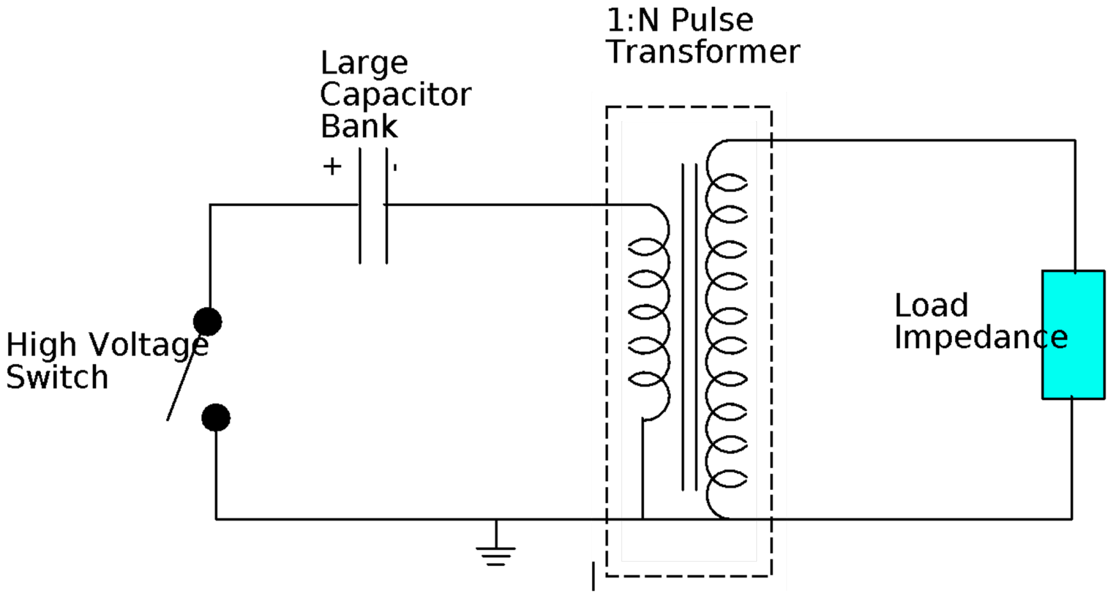


# Hard Tube: Topology Options

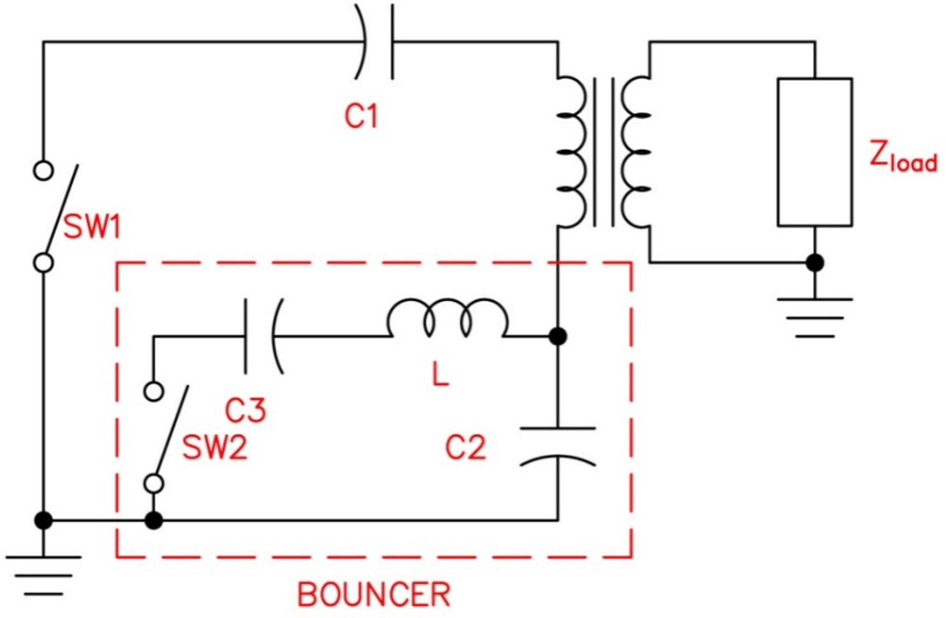
- Pulse Transformer - reduces the high voltage requirements on switch

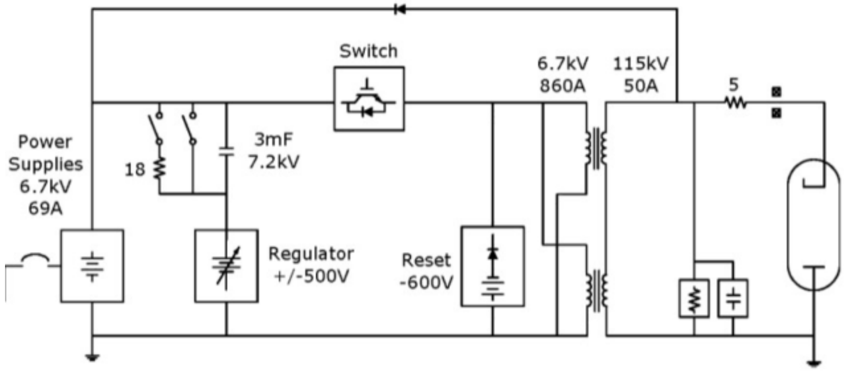
- Issues:
  - Very high primary current ($N*I_{load}$) and large di/dt for fast rise times
  - Requires very low primary loop inductance and very low leakage inductance: exacerbated by high turns ratio; L, C, Z scale with $N^2$
  - Fast opening switch required capable of interrupting primary current
  - Distortion of waveform by non-ideal transformer behavior



# Hard Tube: Topology Options

- Bouncer modulator – compensates energy storage capacitor droop
  - Initially, SW2 is closed, voltage on C3 is transferred to C2
  - Then SW1 is closed, applying output pulse to load
  - Energy transferred from C3 to C2, during linear portion of waveform, compensates for voltage droop of C1
  - After output pulse is finished, energy from C2 rings back to C3, low loss
  - Can also regulate the low side of the capacitor bank (high frequency H bridge(s) regulator in lower figure)
- Issues:
  - Extra components
  - Timing synchronization
  - Bouncer frequency low
    → large L and C's




Roth, et al., Pulsed Power Systems for ESS Klystrons, 2015 IEEE International Vacuum Electronics Conference Proceedings

# Line-Type Modulators

- Based on the properties of transmission lines as pulse generating devices

- Advantages

  - Minimum stored energy, 100% → load (neglecting losses)
    - Voltage fed, capacitive storage (E-field), closing switch
    - Current fed, inductive storage (B-field), opening switch

  - Fault (short circuit) current ≤ twice operating current (matched load)

  - Relatively simple to design and fabricate, inexpensive

  - Switch action is closing OR opening, but not both

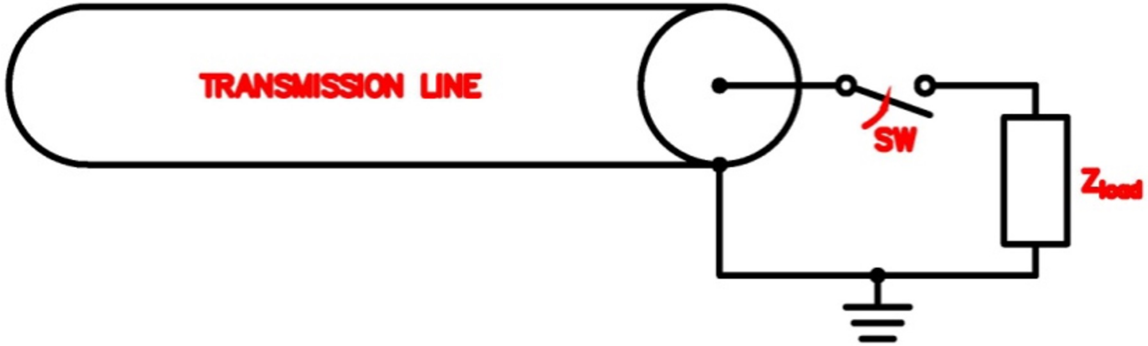
# Line-Type Modulators

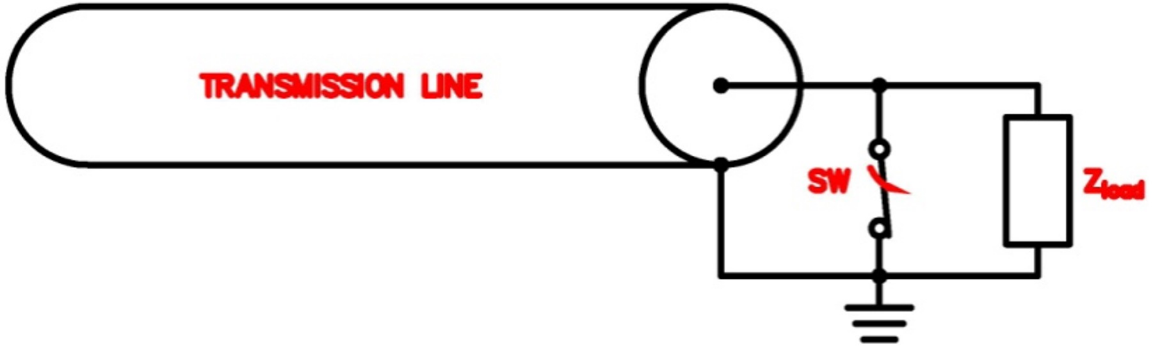
- Disadvantages
  - Fixed (and limited range) output pulse length
  - Fixed (and limited range) output pulse impedance
    - Output pulse shape dependent on relative modulator/load impedance
    - $Z_{load} < Z_{pulser}$ → voltage reversal, may damage switch or other components
  - Switch operates at twice the voltage (or current) delivered to load
  - Must be fully recharged between pulses: may be difficult at high PRF

# Transmission Line Modulator

- Square output pulse is intrinsic

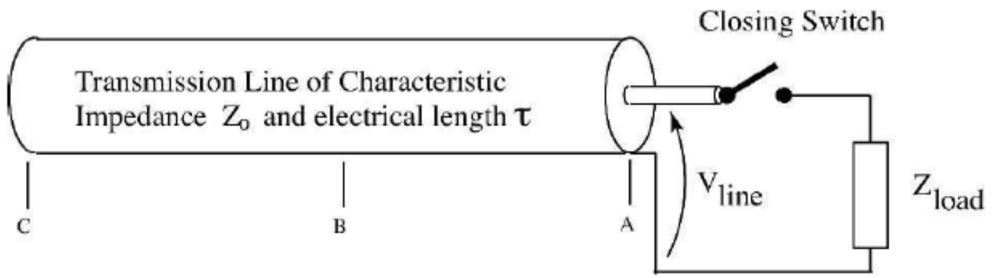
- Pulse length is twice the single transit time of line: $\tau = 2\ell/(c/\varepsilon^{1/2})$
  - Vacuum: 2 ns/ft
  - Poly & oil: 3 ns/ft
  - Water: 18 ns/ft
  - Limited to ~1 µs, physical length, dispersion




- Impedance of HV transmission lines limited:
  - ~2 Ω ≤ Z ≤ ~200 Ω
  - ~30 Ω ≤ Z ≤ ~100 Ω for commercial coax
  - However, impedance can be rescaled using a pulse transformer

# Reminder of Coaxial Transmission Line Behavior (into a matched load)

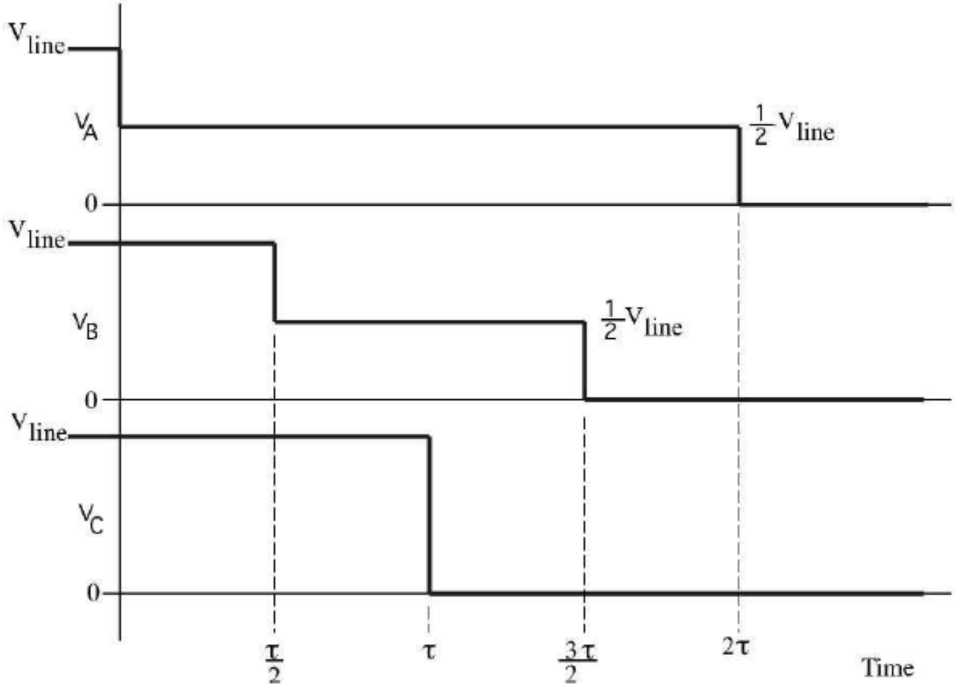



**When switch closes:**

**$V_A$ drops by the voltage divider ratio $Z_L/(Z_L + Z_o)$**

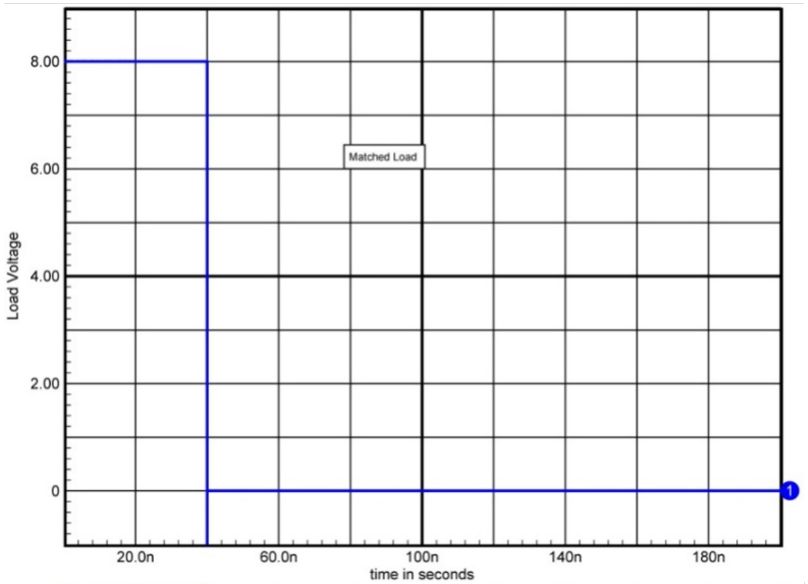
**V/2 propagates from load end to charge end**

**V/2 reflects off open end and propagates to load end discharging the line until it reaches the load (end of the V/2 pulse on load)**

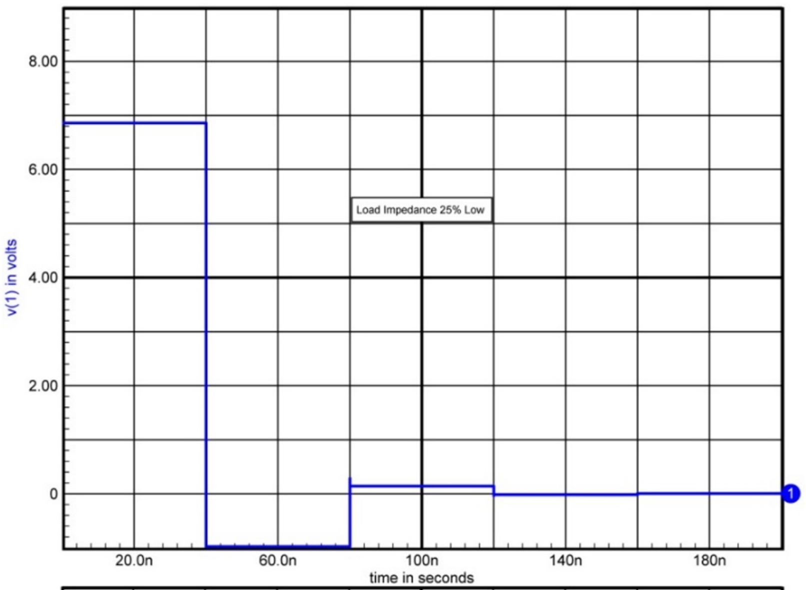


# 10 Ω, 40 ns TL Modulator: Impact of Load Mismatch

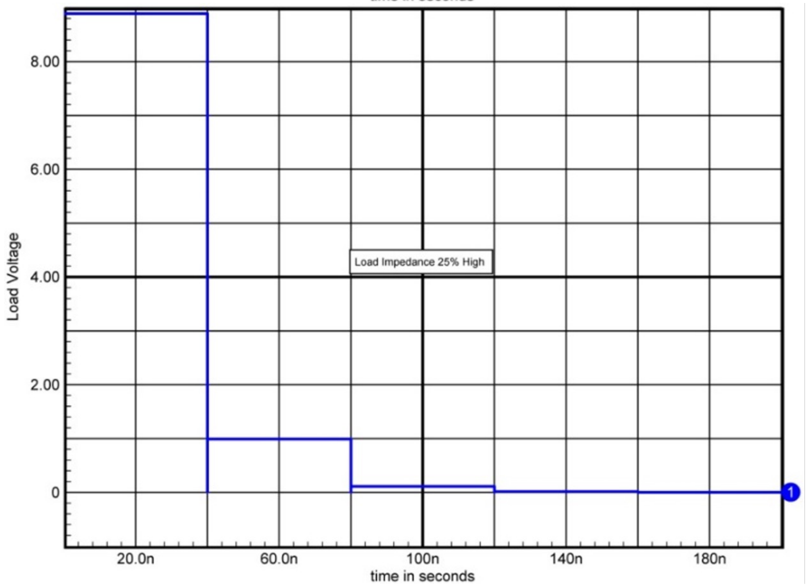
Matched
R = Z



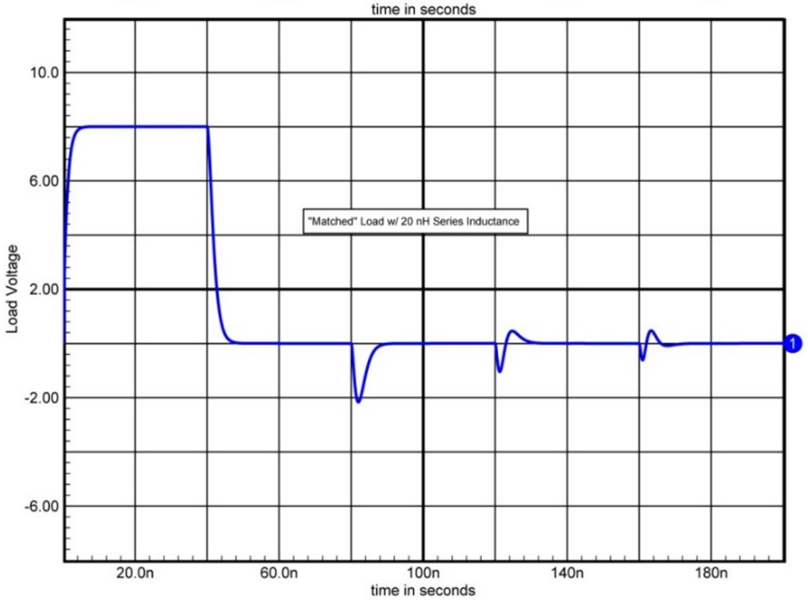

Undermatched
R = 0.75 Z




Overmatched
R = 1.25 Z

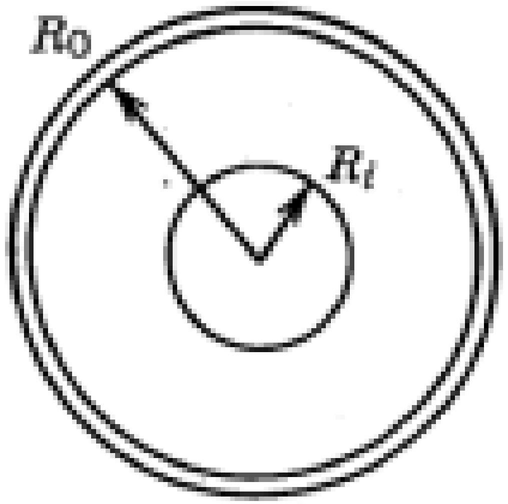



Series
Inductance
(20 nH)



# Coaxial Pulse Forming Line Equations

$$\mathscr{C} = 2\pi\varepsilon / \ln(R_0/R_i)$$
$$\mathscr{L} = (\mu/2\pi)\ln(R_0/R_i)$$
$$Z_0 = (\sqrt{\mu/\varepsilon}/2\pi)\ln(R_0/R_i)$$




$^a\mathscr{C}$ = capacitance per unit length (farads/meter); $\mathscr{L}$ = inductance per unit length (henries/meter); $Z_0$ = characteristic impedance (ohms).

| | | |
|---|---|---|
| $\varepsilon_o$ | Free Space Permittivity | 8.8541(-12)F/m |
| $\mu_o$ | Free Space Permeability | 1.2566(-6)H/m |

**The peak electric field is on the inner conductor:**

**E = V / (Ri * ln (Ro / Ri))**

**The one-way transit time:**

**t = (L * C) ^ 0.5**

**Oil relative permittivity = 2.3**
**Water relative permittivity = 80**

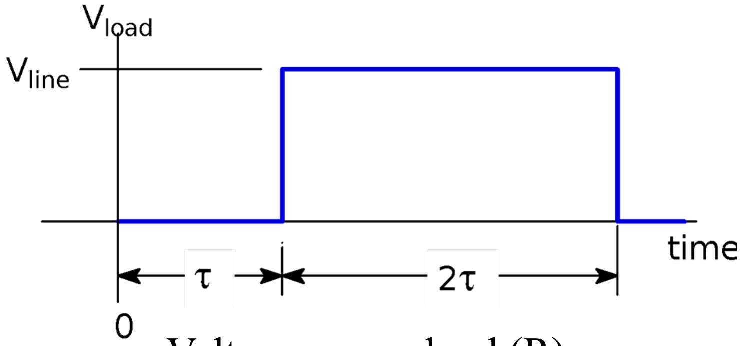
# Transmission Line Modulator Issues/Limitations

- Energy density of coaxial cable is low (vs. capacitors) → large modulator
- Finite switching time and other parasitic elements introduce transient mismatches
- Modulator/load impedance mismatches produce post-pulses
- Fast transients (faster than dielectric relaxation times) stress solid dielectrics

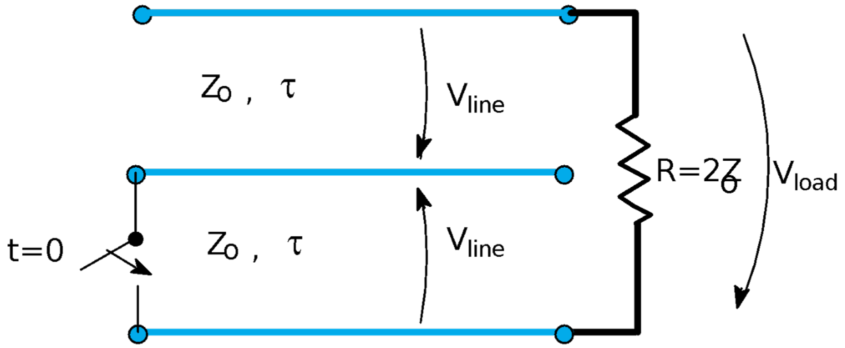
# Blumlein Modulator

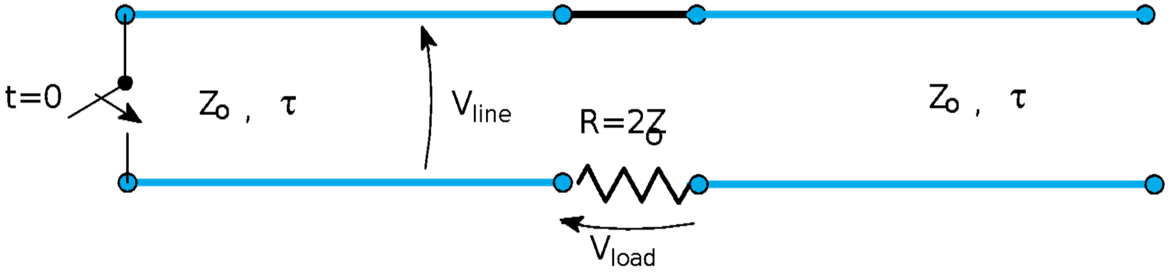
- Major limitation of TL modulator: switch voltage twice load voltage

- Blumlein Line
  - Requires Two Transmission Lines
  - Load voltage equals charge voltage
  - Switch must handle current of $V_o/Z_o$, twice the load current



Voltage across load (R)

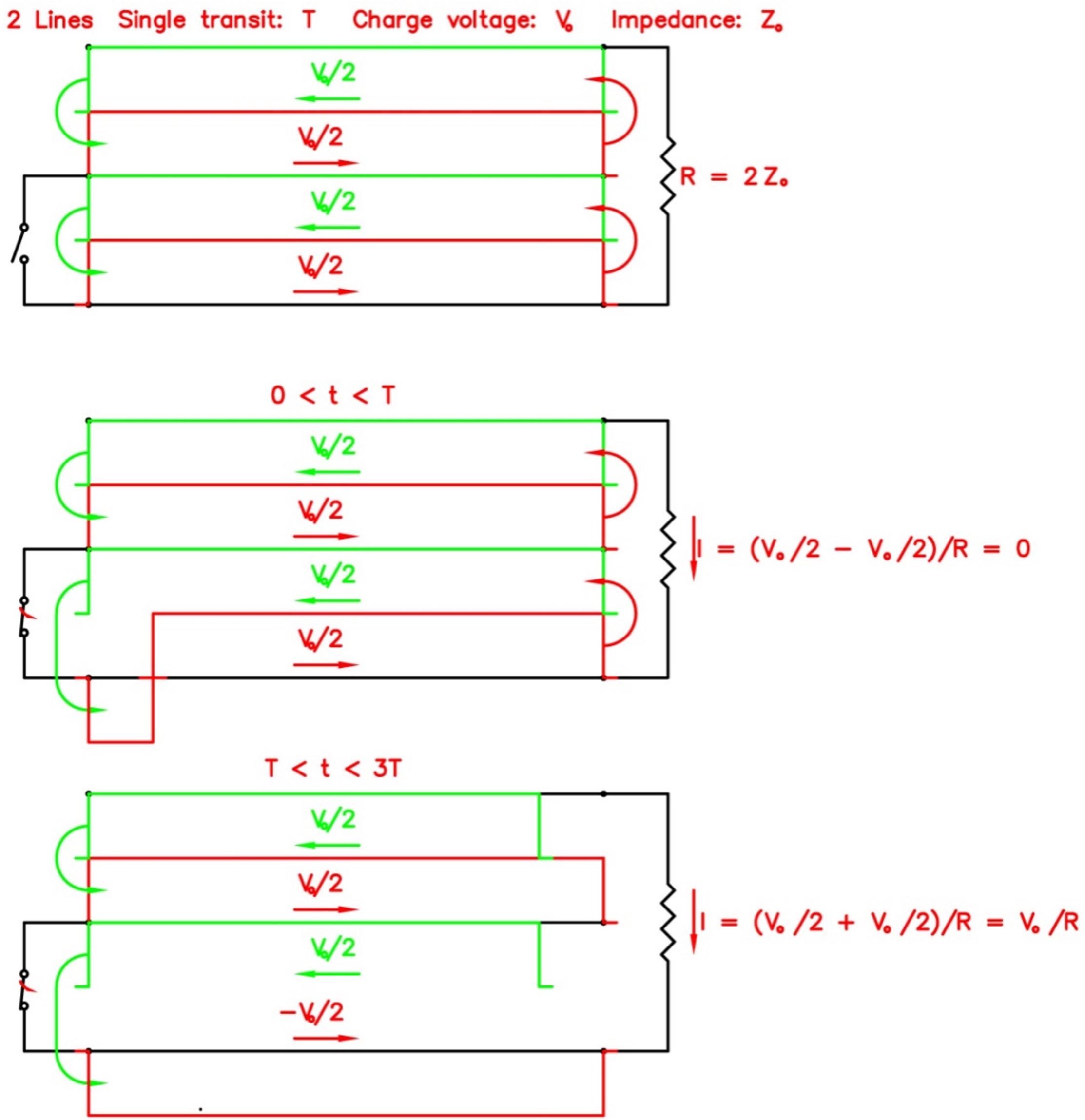


Circuit “unfolded”

# Blumlein "Wave Model"

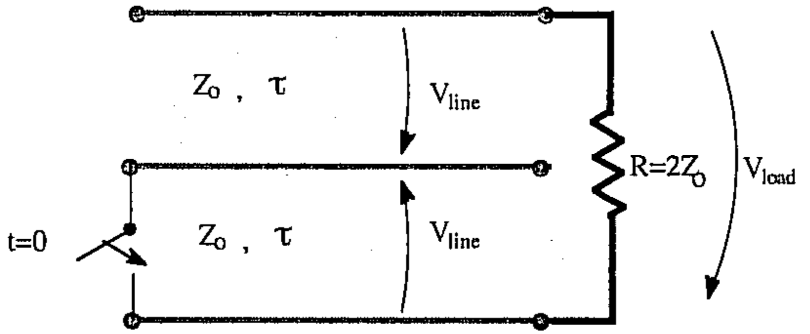
- Initial conditions
  - 2 TL with a common electrode
  - TLs charged to $V_o$
  - TL Impedance: $Z_o$
  - Load impedance: $R = 2\ Z_o$
- Switch closes at $t = 0$
  - Wave that hits short, reflects with inverted polarity
  - Voltage of $V_o/2$ on both ends of load, no load current
  - Wave in upper TL unchanged
- $t = T$
  - Inverted wave reaches load
  - Load voltage: $V_o/2 - (-V_o/2) = V_o$
  - Load current: $V_o/R$
  - Load matched, no reflected wave in either TL
- $t = 3T$: energy depleted

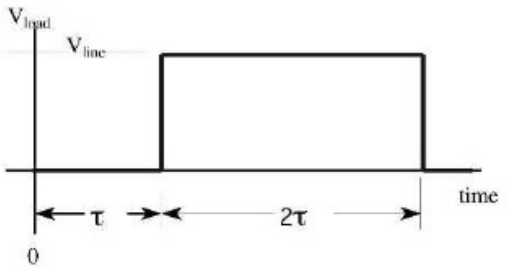


# Blumlein Description 1 - Ed Cook, Pulse Generators for Accelerator Applications (USPAS)

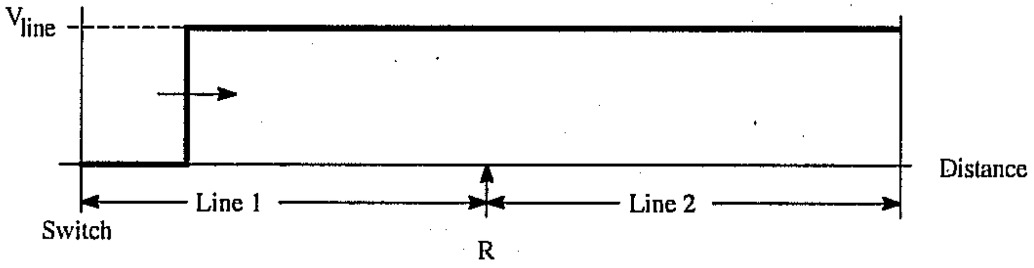
When the switch closes at t=0, the voltage on line 1 collapses and a voltage wave of amplitude $-V_{line}$ begins propagating towards R. The voltage on line 1 is reduced to zero as the wave moves towards the load.

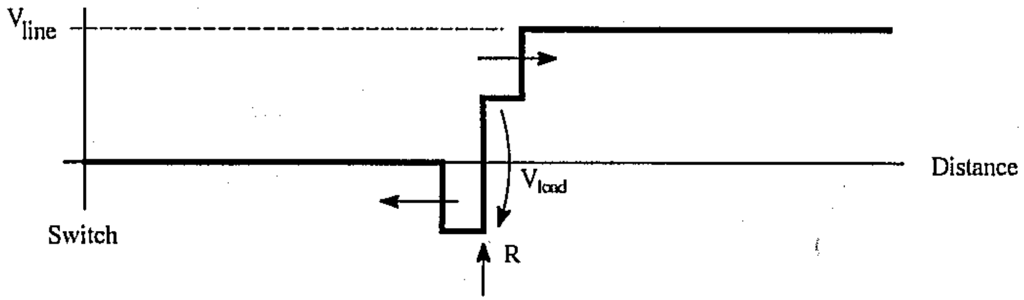
When the voltage wave gets to the load 1/2 of the voltage wave is reflected back towards the switch and 1/2 is transmitted through to line 2. The voltage on line 1 is then -Vline/2 and voltage on line 2 is Vline/2. The voltage waves are propagated to the ends of their respective lines where they are reflected and continue propagation back towards the load (reducing the voltage behind them to zero as they propagate. When the voltage waves reach the load, both lines are completely discharged.



Output of Blumlein Line




$$\Gamma_R = \frac{Z_L - Z_o}{Z_L + Z_o} = .5 \quad when\ Z_L = R + Z_o = 3Z_o$$

# Blumlein Description 2 - Transient Electronics – Pulsed Circuit Technology, Smith, 2002

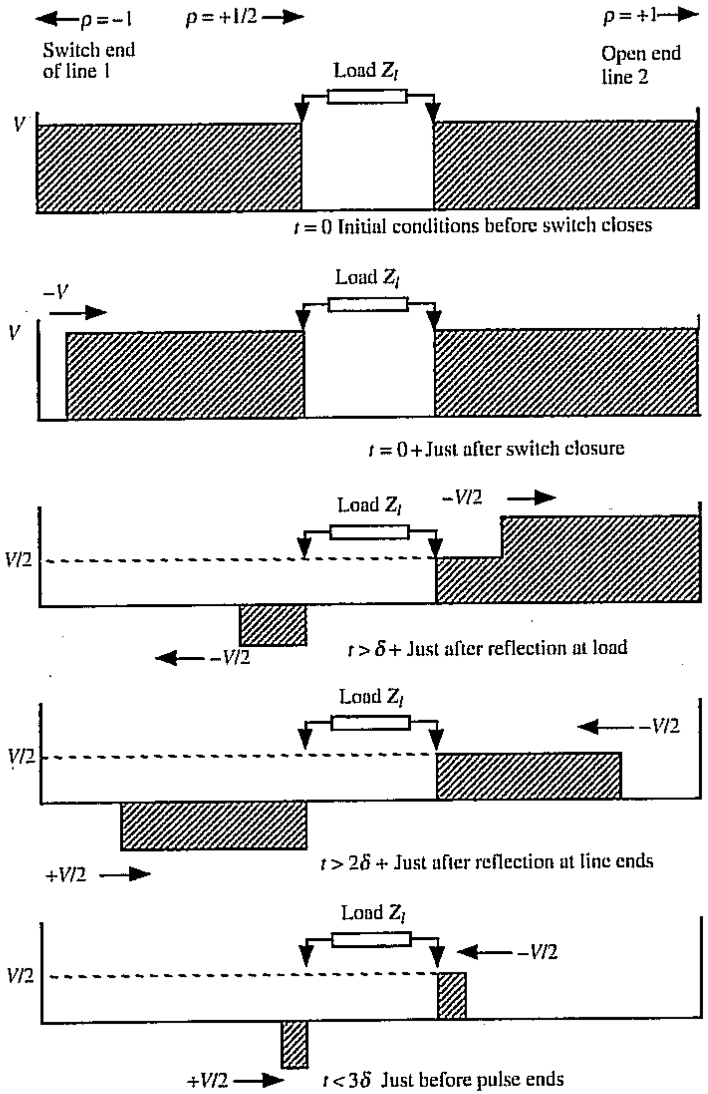



**Figure 3.7** The potential distribution on the two lines at various times after switch closure

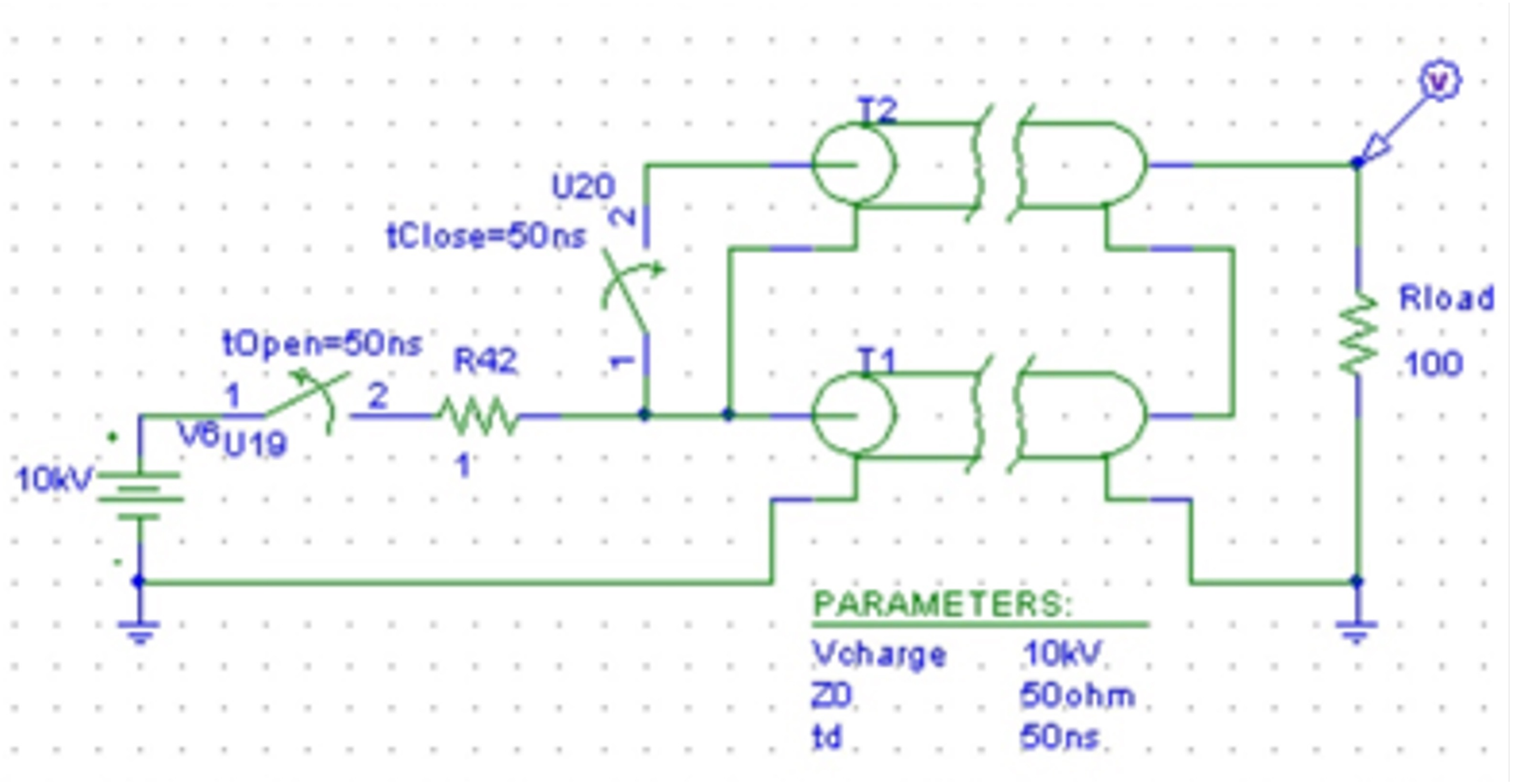
# Blumlein in Comparison to Transmission Line

- Switching
  - Blumlein charge (switch) voltage equals load voltage
  - Blumlein switch current is twice the load current
  - Peak switch power is twice the peak load power for both topologies
  - However, it is generally easier to get switches that handle high current than high voltage

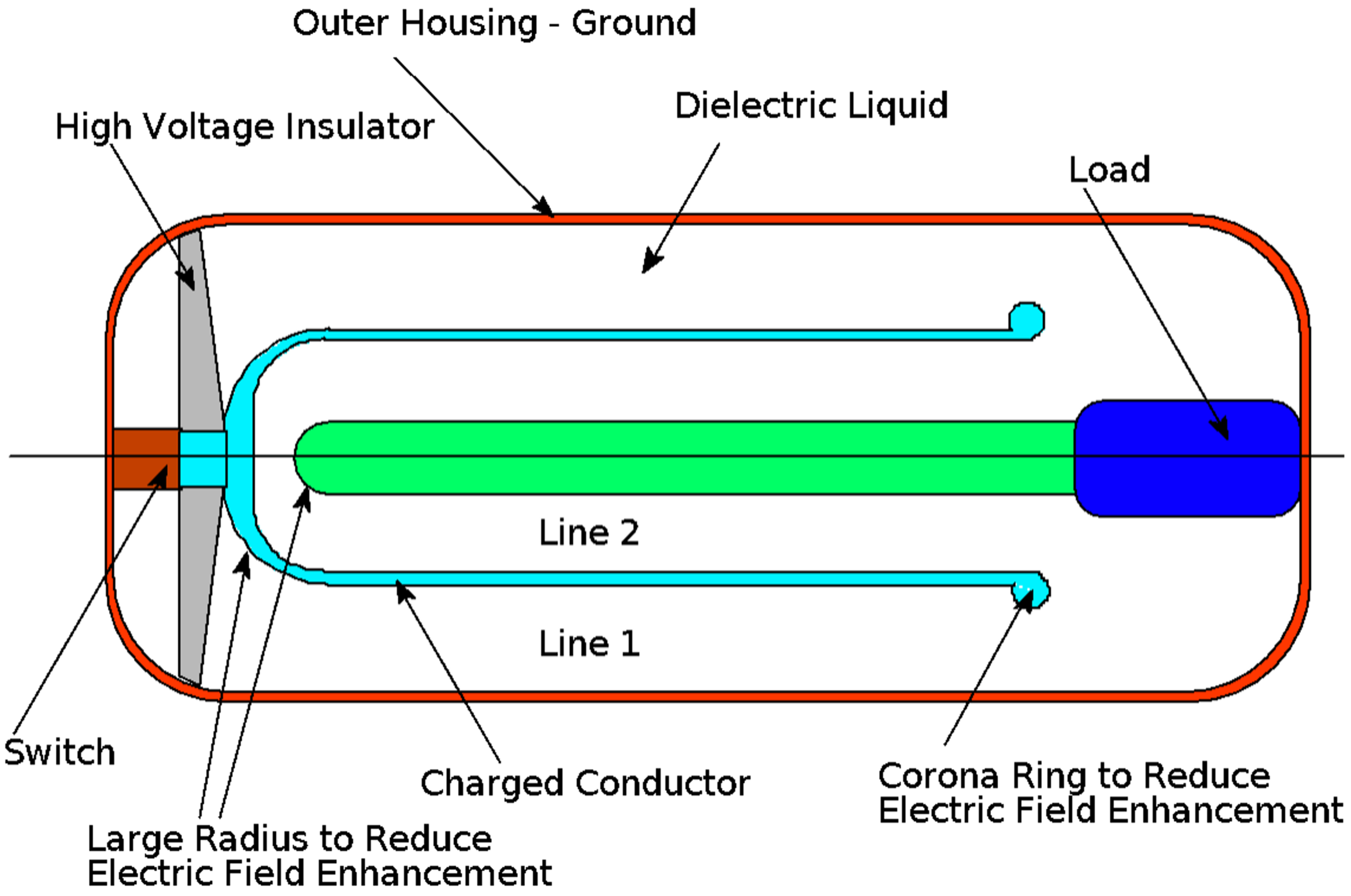
- Blumlein is more complicated
  - Either nested transmission lines or exposed electrode → half load voltage during pulse
  - More sensitive to parasitic distortion (e.g. switch inductance)

- Both are important modulator topologies

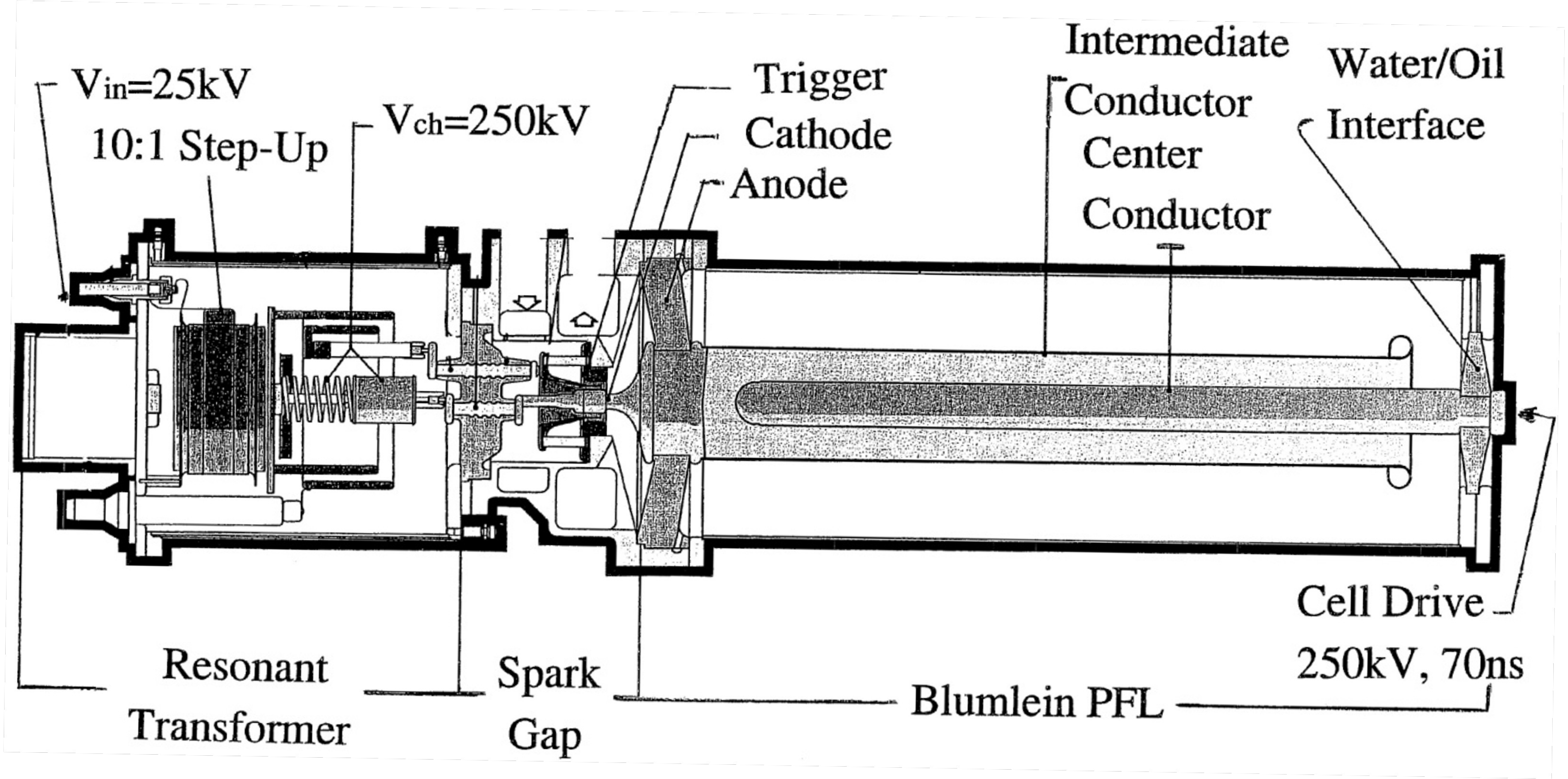
# Blumlein SPICE Model



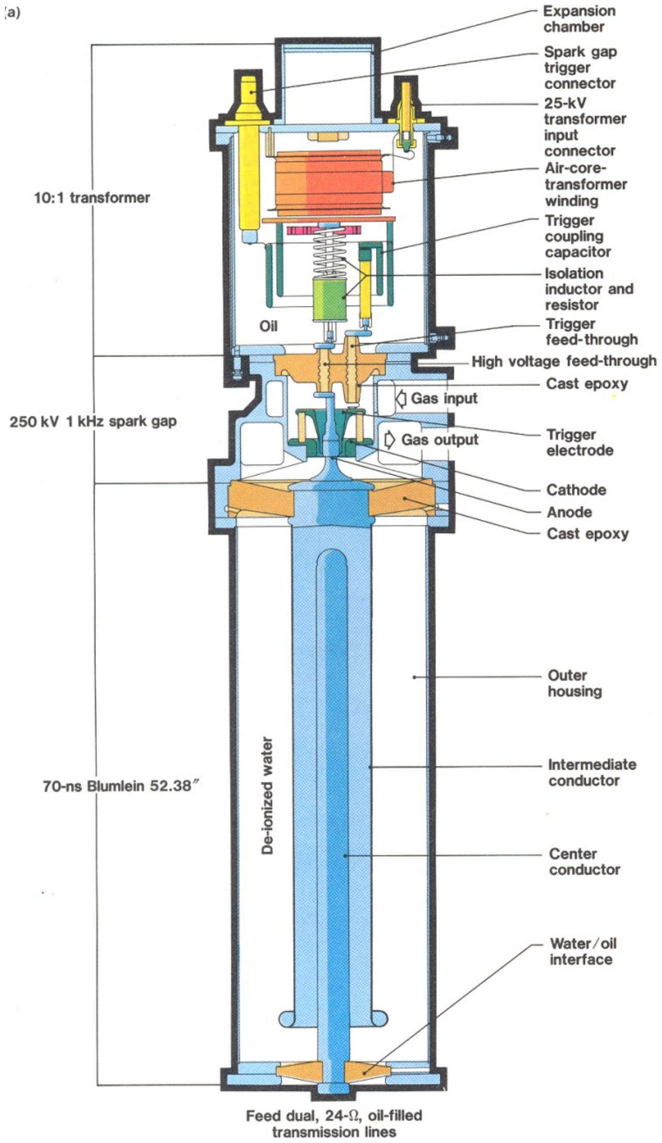
# Blumlein Geometry

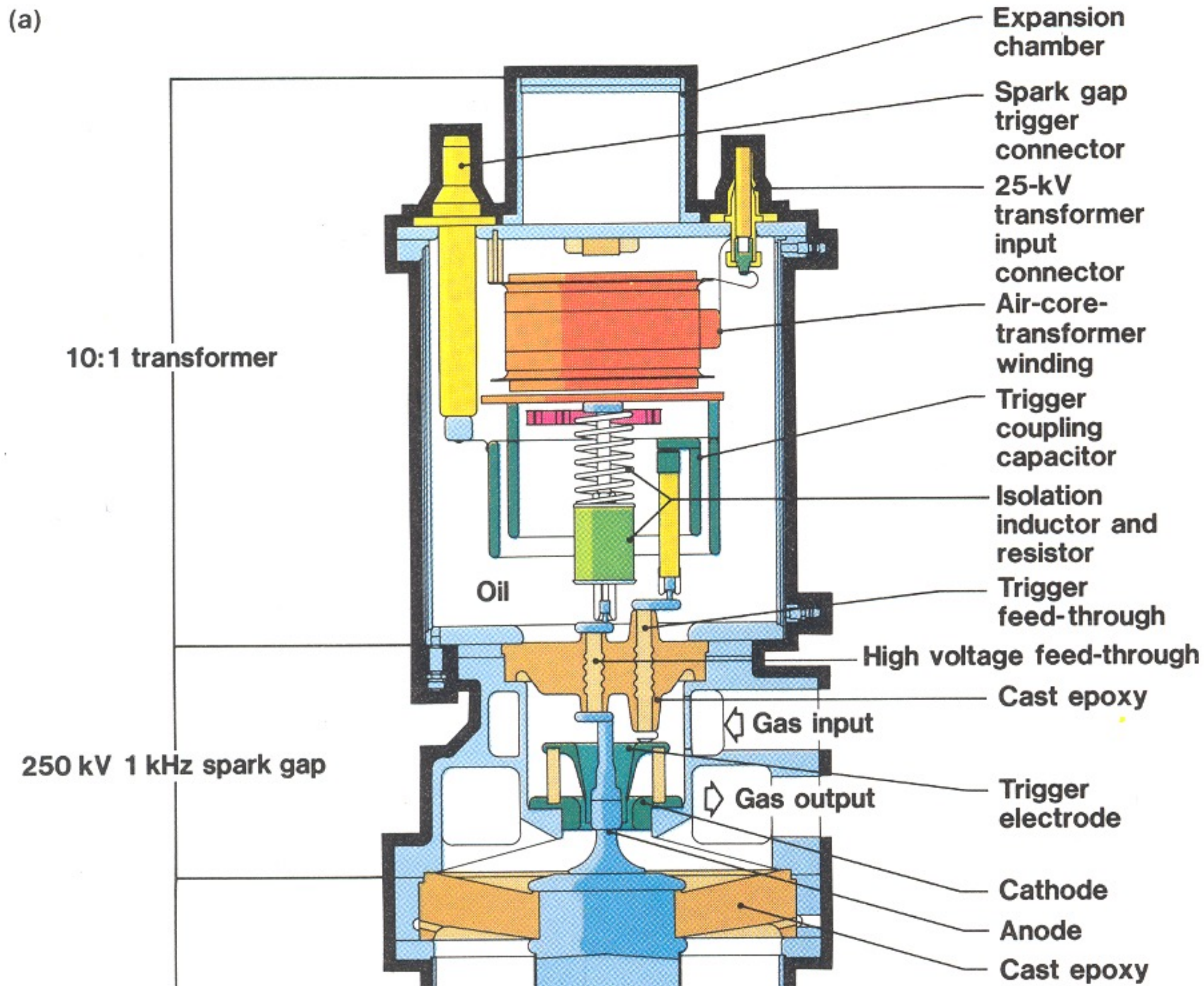


# Advanced Test Accelerator Blumlein (LLNL)

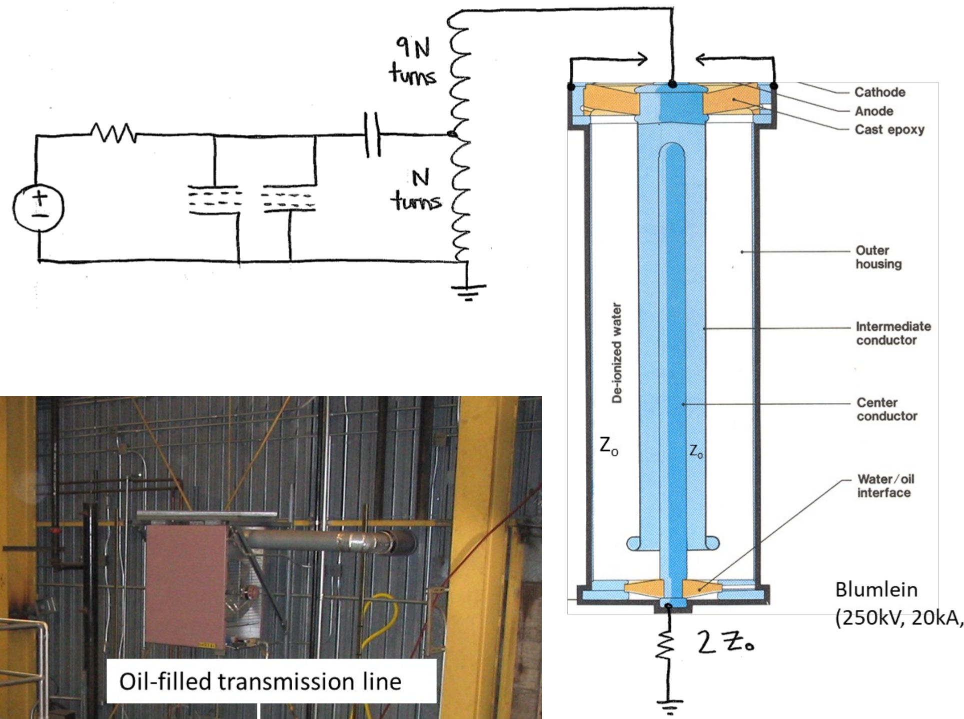


# ATA Blumlein (LLNL)

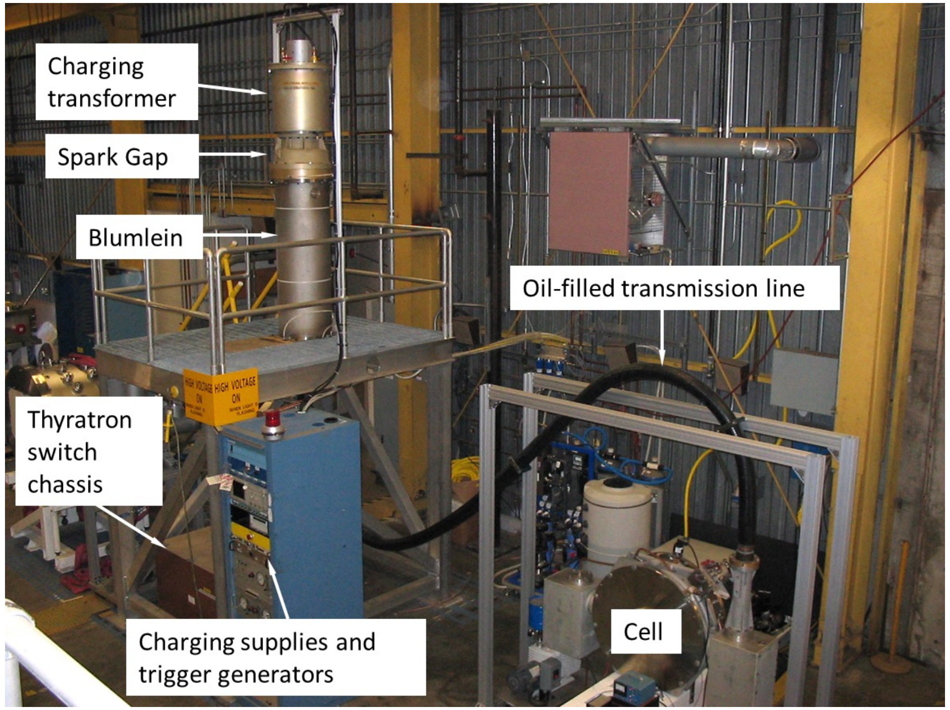


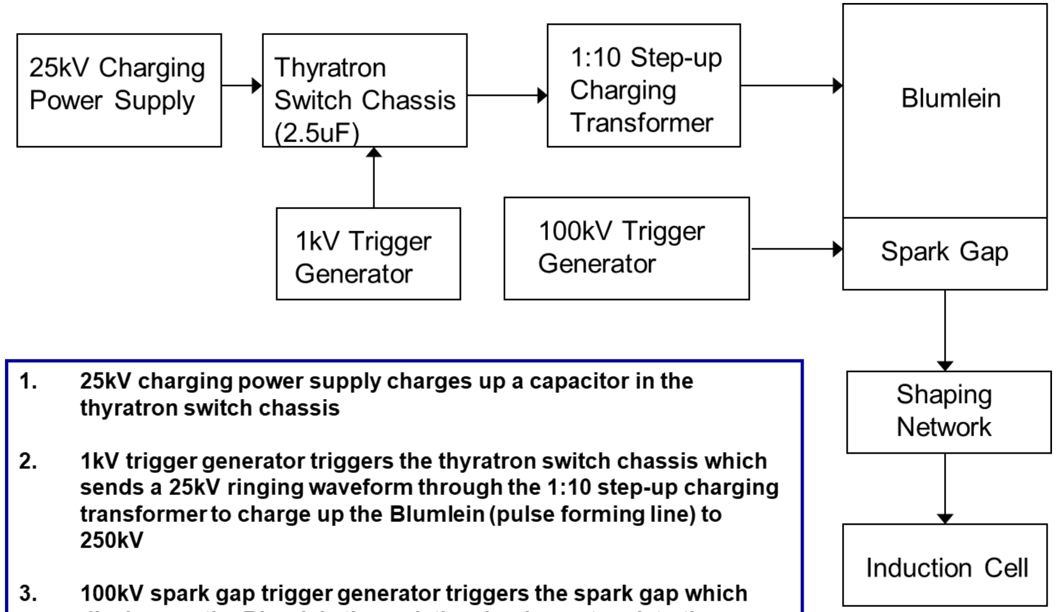



# Blumlein Example with ATA hardware on NDCX-II (LBNL)




Blumlein (250kV, 20kA, 70ns)

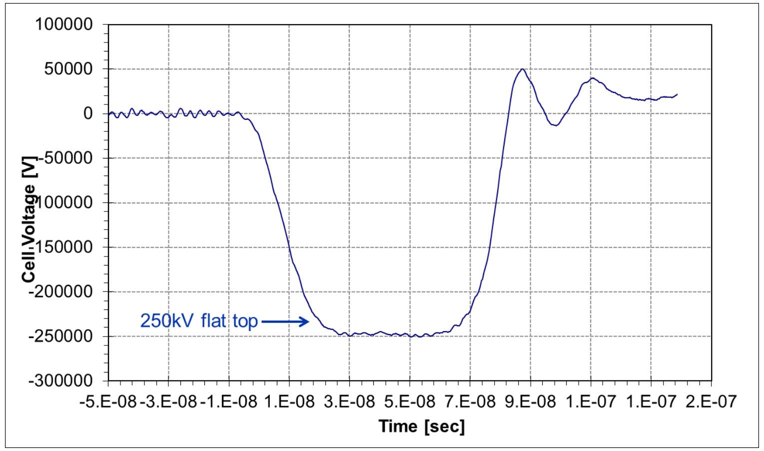



1. **25kV charging power supply charges up a capacitor in the thyratron switch chassis**

2. **1kV trigger generator triggers the thyratron switch chassis which sends a 25kV ringing waveform through the 1:10 step-up charging transformer to charge up the Blumlein (pulse forming line) to 250kV**

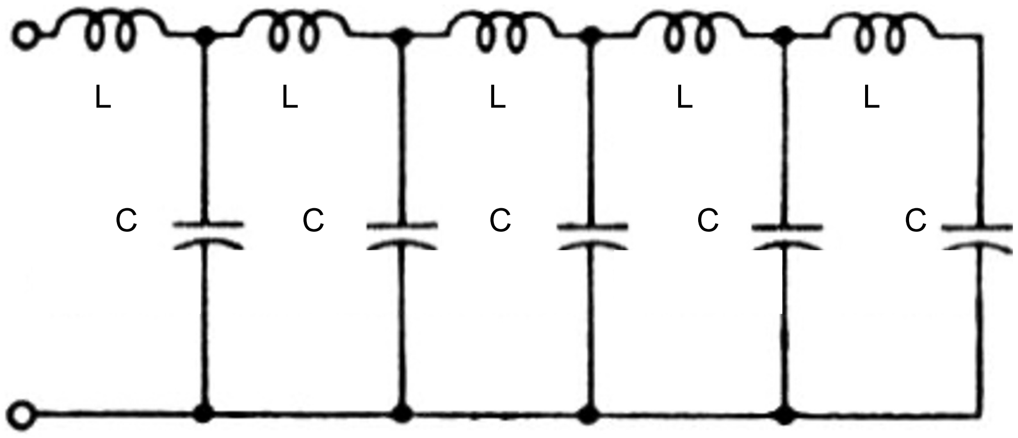
3. **100kV spark gap trigger generator triggers the spark gap which discharges the Blumlein through the shaping network to the induction cell**



# Pulse Forming Networks (PFNs)

- The maximum pulse duration of transmission line pulsers is limited by the physical length of the line, at 3 ns/ft, a 1 µs TL would be 330' long

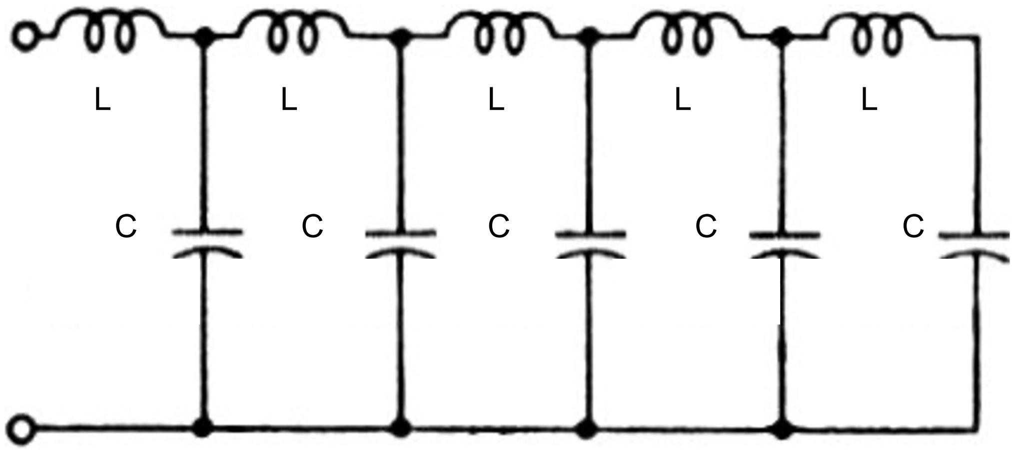
- Transmission line can be approximated by an LC array




  - Higher energy density in capacitors
  - Higher energy density in solenoidal inductors
  - PFNs can produce long duration pulses in a compact package

# Pulse Forming Networks (PFNs)

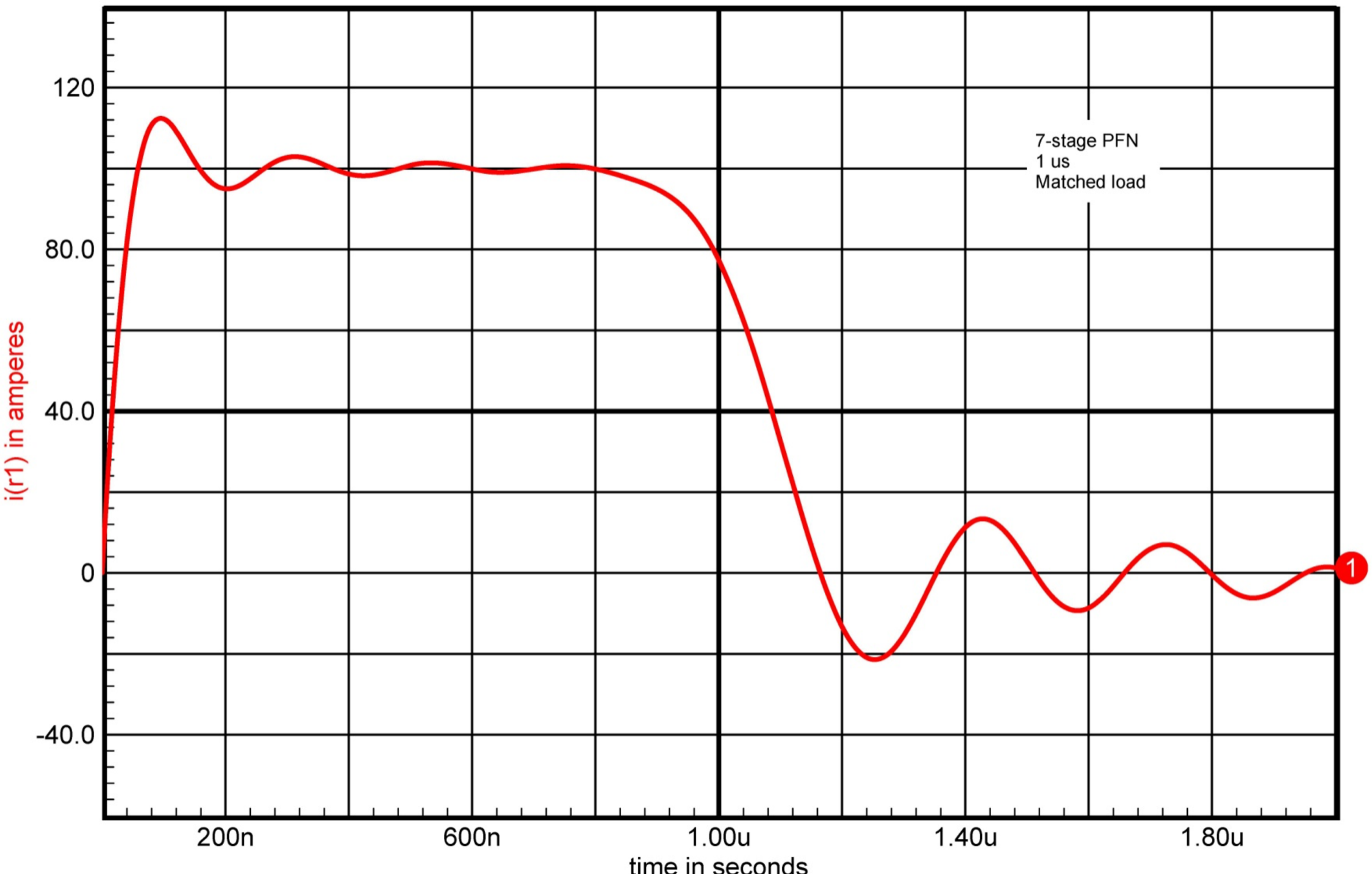
- Design equations
  - $Z = (L/C)^{0.5}$
  - $\tau = 2N(LC)^{0.5}$ (output pulse length)
  - For N-stages of inductance, L, and capacitance, C




- However, the discrete element model of the TL is only accurate as the number of stages, $N \rightarrow \infty$

- Example
  - N = 7
  - Z = 10Ω
  - T = 1 μs
    - C = 7.14 nF
    - L = 0.714 μH

# Example PFN Output Into Matched Load



# The Trouble with Pulse Forming Networks

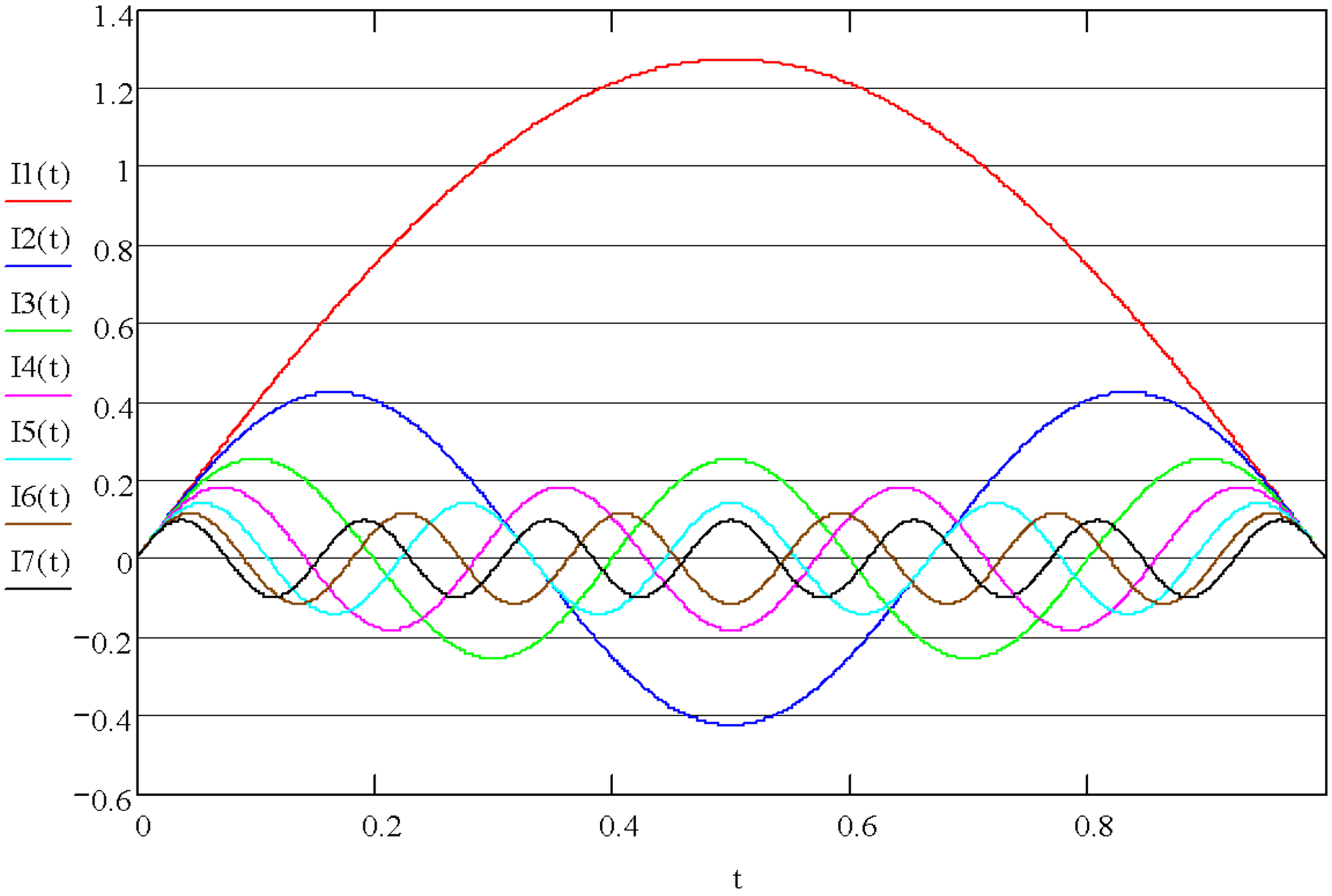
- Ripple on flattop
- Pulse rise and fall are not sharp
- Why?

  - Attempting to reproduce a rectangular pulse, which is non-causal
    - $\omega_{max} = \infty$, therefore, N must $\longrightarrow \infty$
    - PFNs constructed with finite N

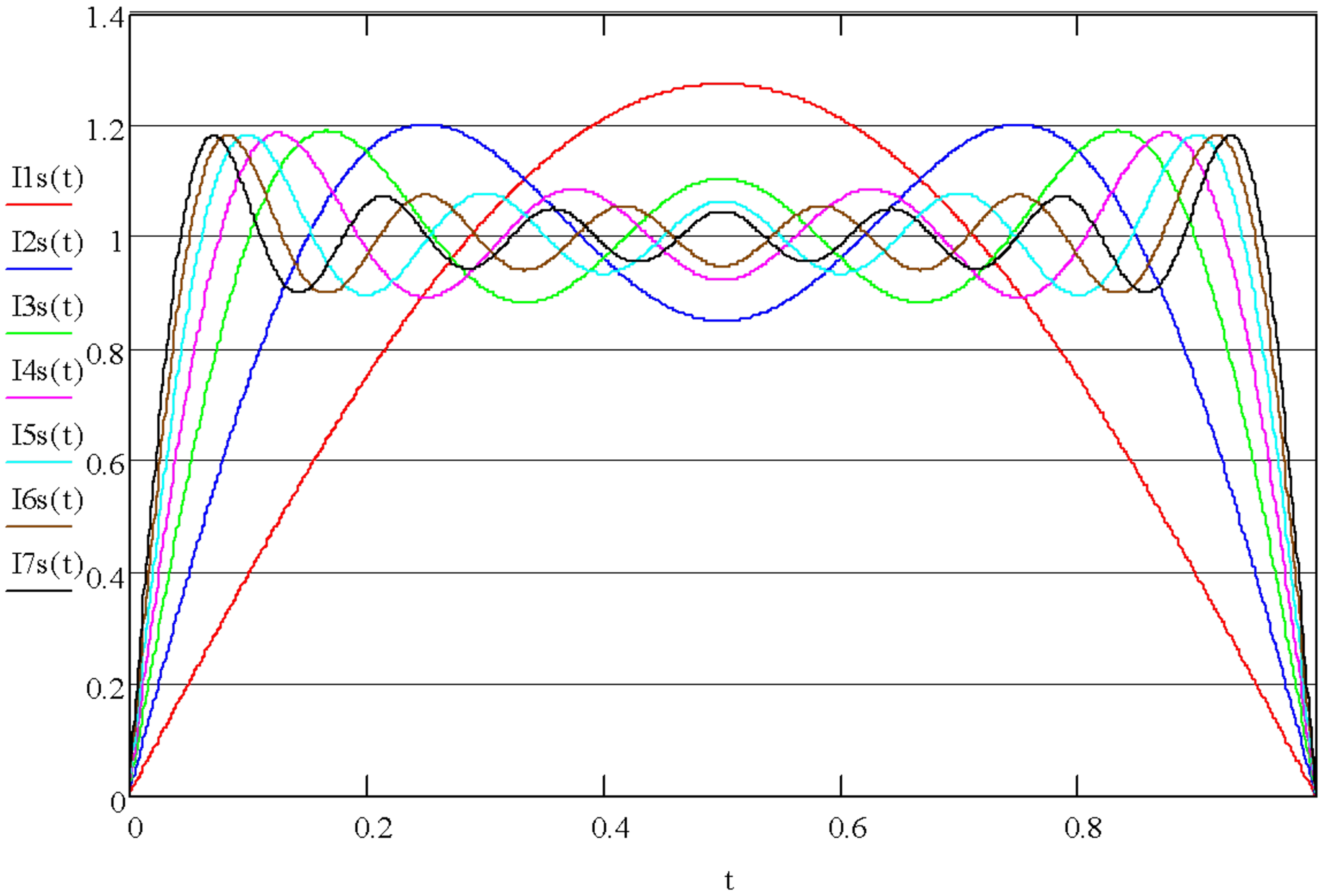
  - Fourier series expansion of a rectangular pulse (period 0 to $\tau$)
    - $I(t) = (2 I_{peak}/\pi) \sum^{\infty}_{n=1} b_n \sin(n\pi t/\tau)$
      - $b_n = (1/n)(1 - \cos(n\pi))$ = 0 for even n, 2/n for odd n
    - $I(t) = (4 I_{peak}/\pi) \sum^{\infty}_{n=1} (1/n) \sin(n\pi t/\tau)$ over only odd terms, n = 1,3,5,...

  - Magnitude of the $n^{th}$ term $\alpha$ 1/n, sets convergence rate for a rectangular pulse

# Fourier Components (Normalized) for a Rectangular Pulse



# Fourier Approximation to a Rectangular Pulse



# Guillemin Networks: A Solution to "The Trouble with PFNs"

- E.A. Guillemin recognized that the discontinuities due to
  - Zero rise/fall time, and
  - Corners at the start/stop of the rise and fall

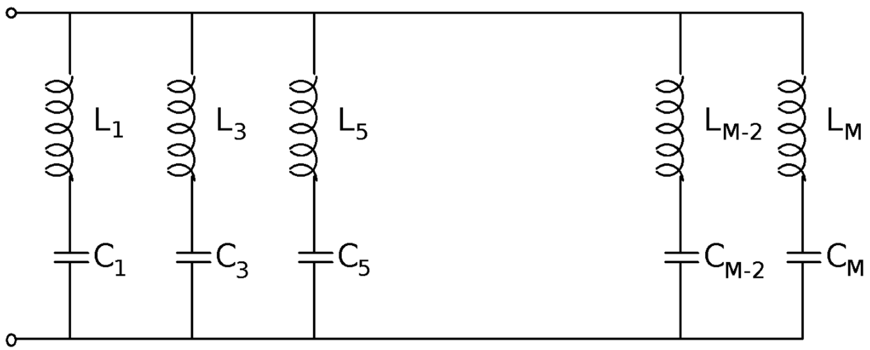
  are the source of the high frequency components that challenge PFN design. "Communication Networks," 1935

- Further, since such a perfect waveform cannot be generated by this method, that better results can be obtained by intentionally design for finite rise/fall times (i.e. trapezoidal pulse) and by rounding the corners (i.e. parabolic rise/fall pulse)

- Faster convergence of the Fourier approximation
  - Trapezoidal: $n^{th}$ term α $1/n^2$
  - Parabolic: $n^{th}$ term α $1/n^3$

# Guillemin Network Design

- Assume circuit topology



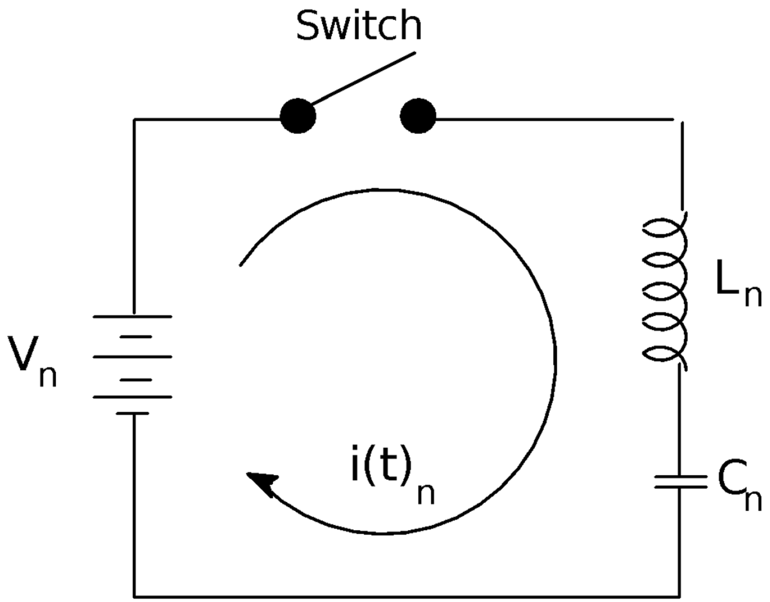

- Each element of the series

$$i(t) = I_{pk} \sum_{n=1,3,5,\ldots}^{\infty} b_n \sin\frac{n\pi t}{\tau}$$

- Can be produced by the circuit

$$i(t)_n = \frac{V_n}{\sqrt{\frac{L_n}{C_n}}} \sin\left(\frac{t}{\sqrt{L_n C_n}}\right)$$

$$i(t)_n = \frac{V_n}{Z_n} \sin \omega_o t$$



# Guillemin Network Design (cont.)

$$I_{pk} b_n \sin \frac{n\pi t}{\tau} = \frac{V_n}{\sqrt{\frac{L_n}{C_n}}} \sin(\frac{t}{\sqrt{L_n C_n}})$$

- Comparing the amplitude and frequency terms for the Fourier coefficients and the LC loop

$$I_{pk} b_n = \frac{V_n}{\sqrt{\frac{L_n}{C_n}}} \text{ and } \frac{n\pi}{\tau} = \frac{1}{\sqrt{L_n C_n}}$$

- Solving for $L_n$ and $C_n$

$$L_n = \frac{Z_n \tau}{\mathrm{n}\pi \mathrm{b}_\mathrm{n}} \text{ where } Z_n = \frac{V_n}{I_{pk}}$$

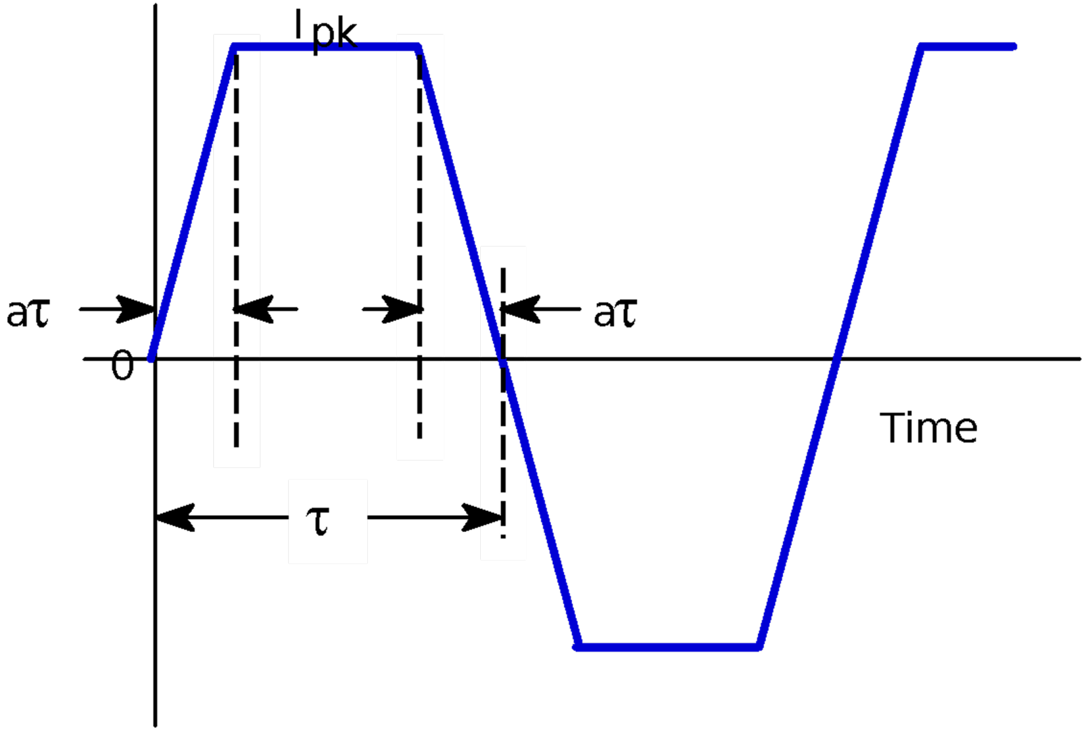
$$C_n = \frac{\tau b_n}{n\pi Z_n}$$

# Fourier Coefficients for Trapezoidal Waveform

- For a trapezoidal waveform the series expansion is:

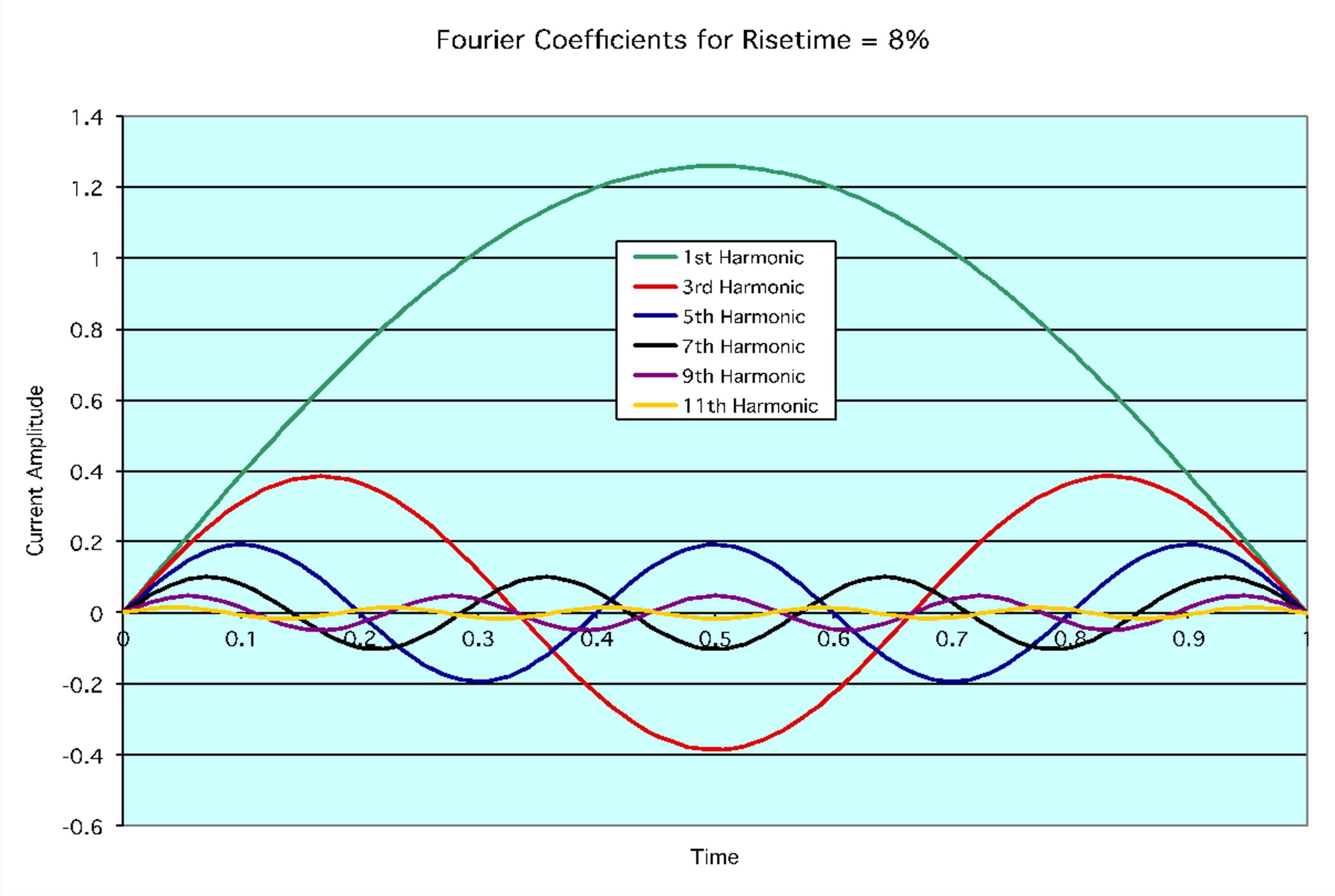
$$i(t) = I_{pk} \sum_{n=1,3,5,\ldots}^{\infty} b_n \sin \frac{n\pi t}{\tau}$$

$$b_n = \frac{4}{n\pi} \frac{\sin n\pi a}{n\pi a}$$

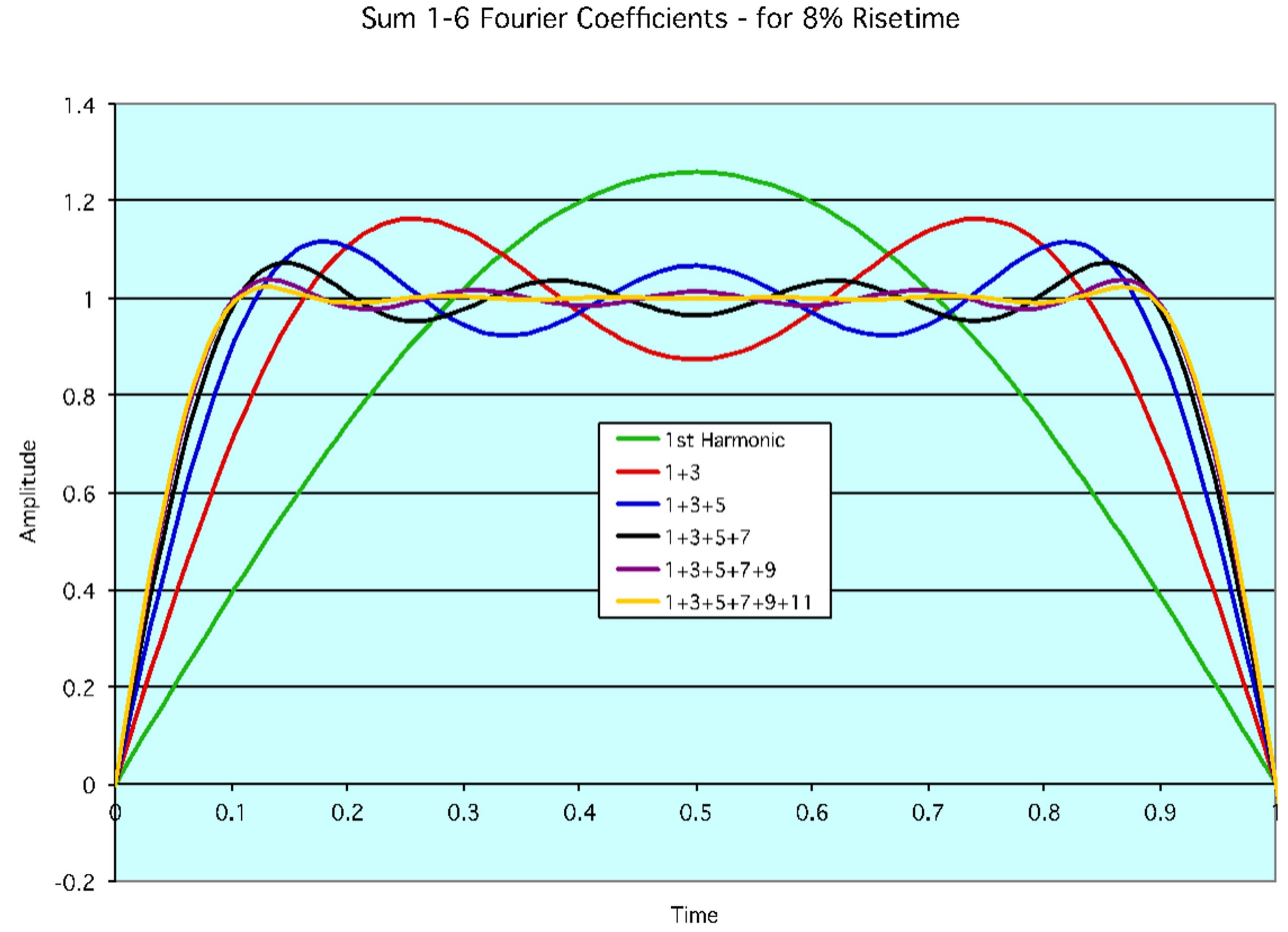



- where n = 1,3,5,...
- a = risetime as % of pulsewidth τ

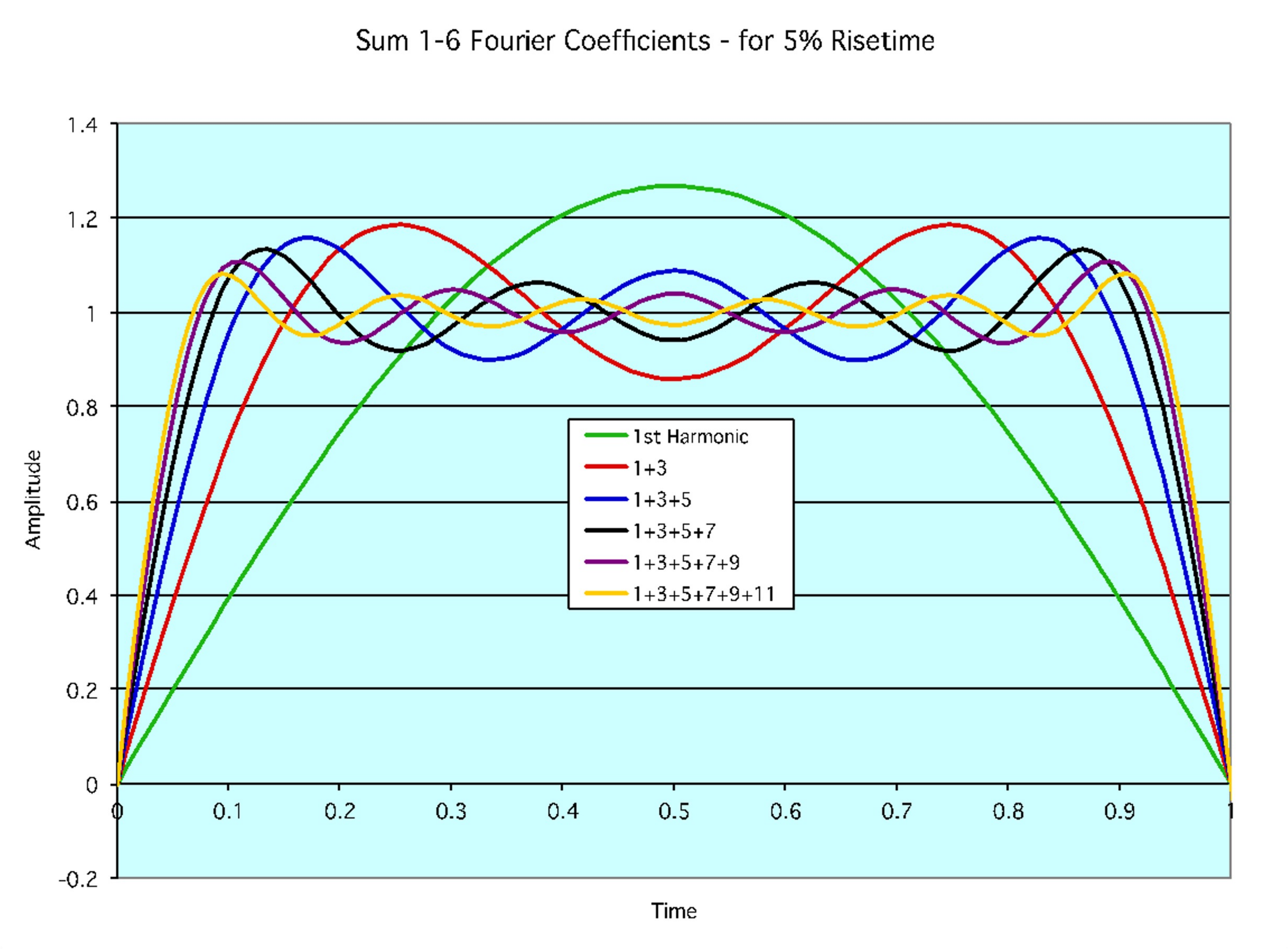
# Fourier Coefficients for Trapezoidal Waveform, 8% Risetime



# Fourier Approximation; Trapezoidal Waveform, 8% Risetime

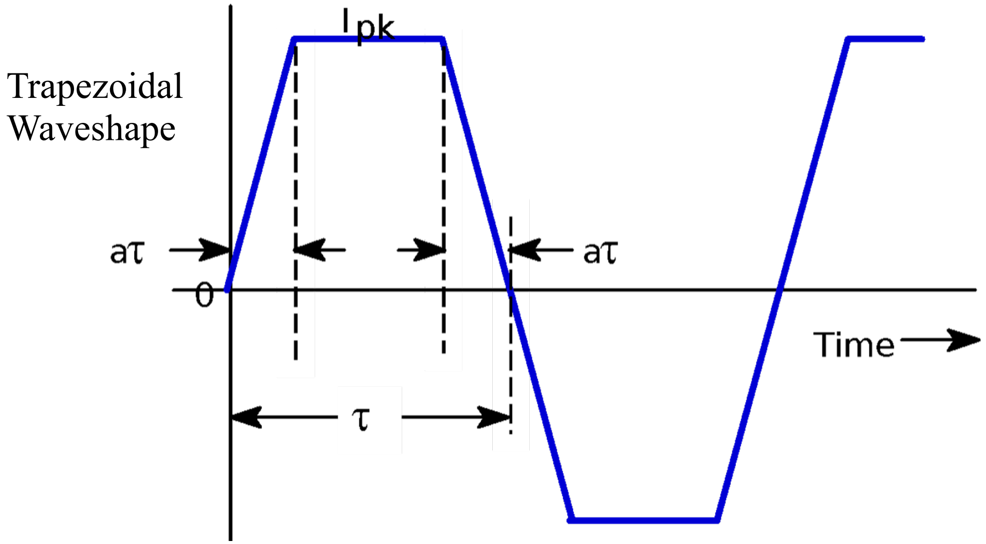


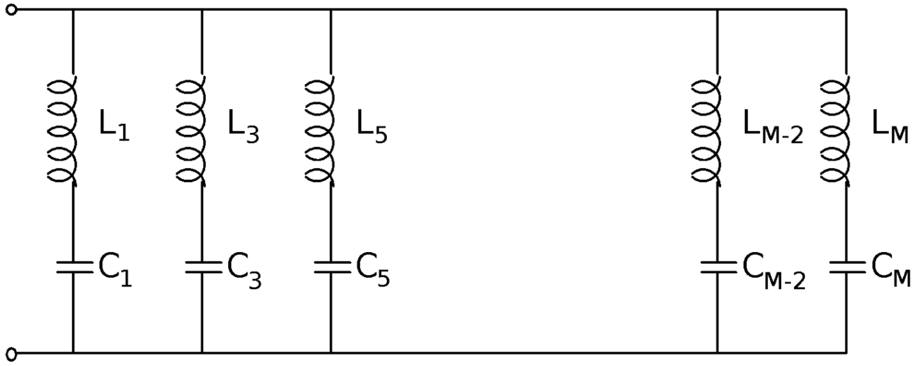
# Fourier Approximation; Trapezoidal Waveform, 5% Risetime

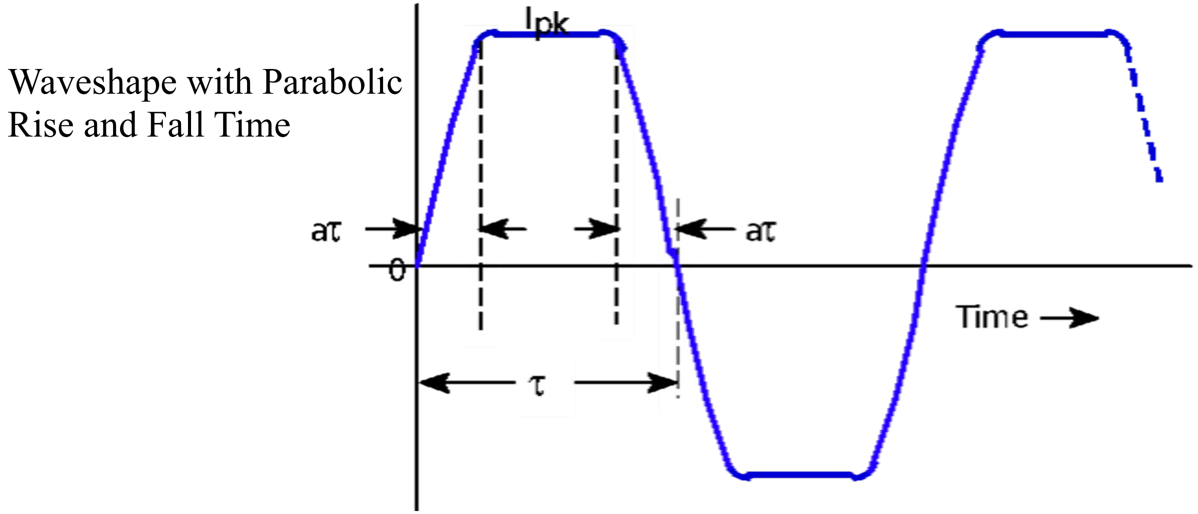


# Trapezoidal and Parabolic Waveshapes; General Solution Values of $b_n$, $L_n$, and $C_n$

| Waveform | $b_n$ | $L_n$ | $C_n$ |
|---|---|---|---|
| Rectangular | $\frac{4}{n\pi}$ | $\frac{Z_N\tau}{4}$ | $\frac{4\tau}{n^2\pi^2Z_N}$ |
| Trapezoidal | $\frac{4}{n\pi}\left(\frac{\sin n\pi a}{n\pi a}\right)$ | $\frac{Z_N t}{4\left(\frac{\sin n\pi a}{n\pi a}\right)}$ | $\frac{4\tau}{n^2p^2Z_N}\left(\frac{\sin n\pi a}{n\pi a}\right)$ |
| Flat top and parabolic rise and fall | $\frac{4}{n\pi}\left(\frac{\sin\frac{1}{2}n\pi a}{\frac{1}{2}n\pi a}\right)^2$ | $\frac{Z_N\tau}{4\left(\frac{\sin\frac{1}{2}n\pi a}{\frac{1}{2}n\pi a}\right)^2}$ | $\frac{4\tau}{n^2\pi^2Z_N}\left(\frac{\sin\frac{1}{2}n\pi a}{\frac{1}{2}n\pi a}\right)^2$ |



# Fourier Coefficients for Other Waveshapes; L and C Values for Five-Section PFN

| Waveform | $a$ | Fourier coefficients | | | | | Inductance | | | | | Capacitance | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $b_1$ | $b_3$ | $b_5$ | $b_7$ | $b_9$ | $L_1$ | $L_3$ | $L_5$ | $L_7$ | $L_9$ | $C_1$ | $C_3$ | $C_5$ | $C_7$ | $C_9$ |
| Rectangular | 0 | 1.2732 | 0.4244 | 0.2547 | 0.1819 | 0.1415 | 0.2500 | 0.2500 | 0.2500 | 0.2500 | 0.2500 | 0.4053 | 0.04503 | 0.01621 | 0.00827 | 0.00500 |
| Trapezoidal | 0.05 | 1.2679 | 0.4089 | 0.2293 | 0.1474 | 0.0988 | 0.2510 | 0.2595 | 0.2777 | 0.3578 | 0.3578 | 0.4036 | 0.04318 | 0.01459 | 0.00670 | 0.00349 |
| Trapezoidal | 0.08 | 1.2601 | 0.3854 | 0.1927 | 0.1015 | 0.0482 | 0.2526 | 0.2753 | 0.3303 | 0.4478 | 0.7340 | 0.4011 | 0.04089 | 0.01227 | 0.00462 | 0.00170 |
| Trapezoidal | 0.10 | 1.2524 | 0.3643 | 0.1621 | 0.0669 | 0.0155 | 0.2542 | 0.2912 | 0.3927 | 0.6796 | 2.2875 | 0.3987 | 0.03865 | 0.01032 | 0.00304 | 0.00055 |
| Trapezoidal | 0.20 | 1.1911 | 0.2141 | 0 | −0.0393 | −0.0147 | 0.2672 | 0.4455 | ∞ | −1.1561 | −2.4052 | 0.3791 | 0.02272 | 0 | 0.00179 | −0.00052 |
| Parabolic rise | 0.05 | 1.2699 | 0.4166 | 0.2418 | 0.1640 | 0.1194 | 0.2507 | 0.2547 | 0.2632 | 0.2773 | 0.2961 | 0.4042 | 0.04420 | 0.01539 | 0.00745 | 0.00422 |
| Parabolic rise | 0.10 | 1.2627 | 0.3939 | 0.2064 | 0.1194 | 0.0691 | 0.2521 | 0.2694 | 0.3084 | 0.3808 | 0.5122 | 0.4019 | 0.04179 | 0.01314 | 0.00543 | 0.00244 |
| Parabolic rise | 0.20 | 1.2319 | 0.3127 | 0.1032 | 0.0246 | 0.0017 | 0.2584 | 0.3393 | 0.6168 | 1.8472 | 20.94 | 0.3921 | 0.03318 | 0.00657 | 0.00112 | 0.00006 |
| Parabolic rise | 0.25 | 1.2092 | 0.2610 | 0.0564 | 0.00353 | 0.0017 | 0.2632 | 0.4065 | 1.1292 | 12.887 | 21.37 | 0.3849 | 0.02769 | 0.00359 | 0.00016 | 0.00006 |
| Parabolic rise | 0.33 | 1.1609 | 0.1720 | 0.00930 | 0.00338 | 0.0064 | 0.2742 | 0.6168 | 6.8493 | 13.44 | 5.5556 | 0.3695 | 0.01825 | 0.00059 | 0.00015 | 0.00023 |
| Parabolic rise | 0.40 | 1.1142 | 0.1080 | 0 | 0.0085 | 0.0015 | 0.2857 | 0.9821 | ∞ | 5.346 | 23.15 | 0.3547 | 0.01146 | 0 | 0.00039 | 0.00005 |
| Parabolic rise | 0.50 | 1.0319 | 0.0382 | 0.00825 | 0.00300 | 0.0014 | 0.3085 | 2.7747 | 7.7160 | 15.15 | 25.00 | 0.3285 | 0.00406 | 0.00053 | 0.00014 | 0.00005 |

Multiply the inductances by $Z_N\tau$ and the capacitances by $\tau/Z_N$ . The inductances are given in henrys and the capacitances in farads if the pulse duration is expressed in seconds and the network impedance is in ohms. *"a"* is the fractional risetime of pulse.

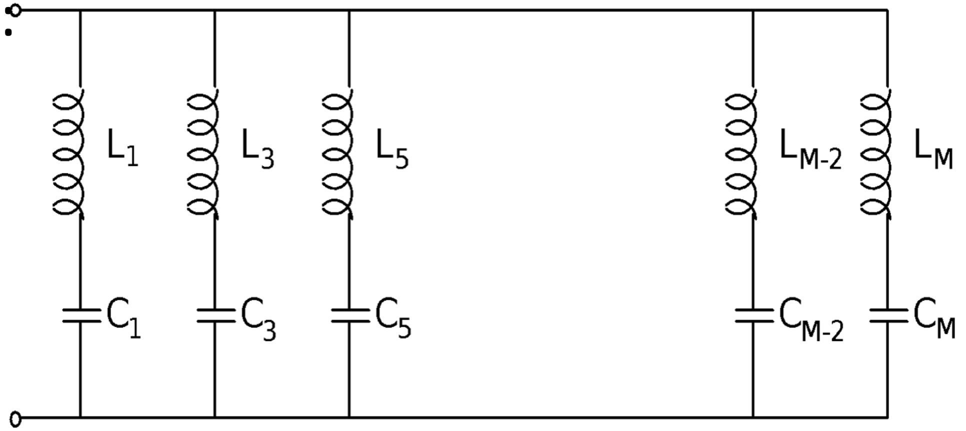
$$i(t) = \frac{V_N}{Z_N} \sum_{n=1,3,5,\ldots}^{\infty} b_n \sin\frac{n\pi t}{\tau} = I_{pk} \sum_{n=1,3,5,\ldots}^{\infty} b_n \sin\frac{n\pi t}{\tau}$$

# Practical Implementation of Guillemin Networks

- Challenge:
  - Wide range of capacitor and inductor values may not be practical to implement
- Solution:
  - Formulate impedance function of Guillemin
  - Derive network with same impedance function, but more practical topology
  - 5 additional topologies are presented

# Synthesis of Alternate LC Networks using the Laplace Transform

The admittance function for the shown circuit has the form:




$$Y(s) = \frac{C_1 s}{L_1 C_1 s^2 + 1} + \frac{C_3 s}{L_3 C_3 s^2 + 1} + \ldots..$$

$$Z(s) = \frac{1}{Y(s)}$$

**Z(s) in turn can be expanded about its poles to yield equivalent networks**

# Equivalent Guillemin Networks

- Type A:
  - Capacitances vary
  - Little used
- Type B:
  - Capacitances vary
  - Similar in layout to Type E
- Type C:
  - Capacitances vary
  - Straightforward design
  - Often used
- Type D
  - Fixed capacitance
  - Negative inductances
  - Basis for Type E
- Type F
  - Capacitances vary

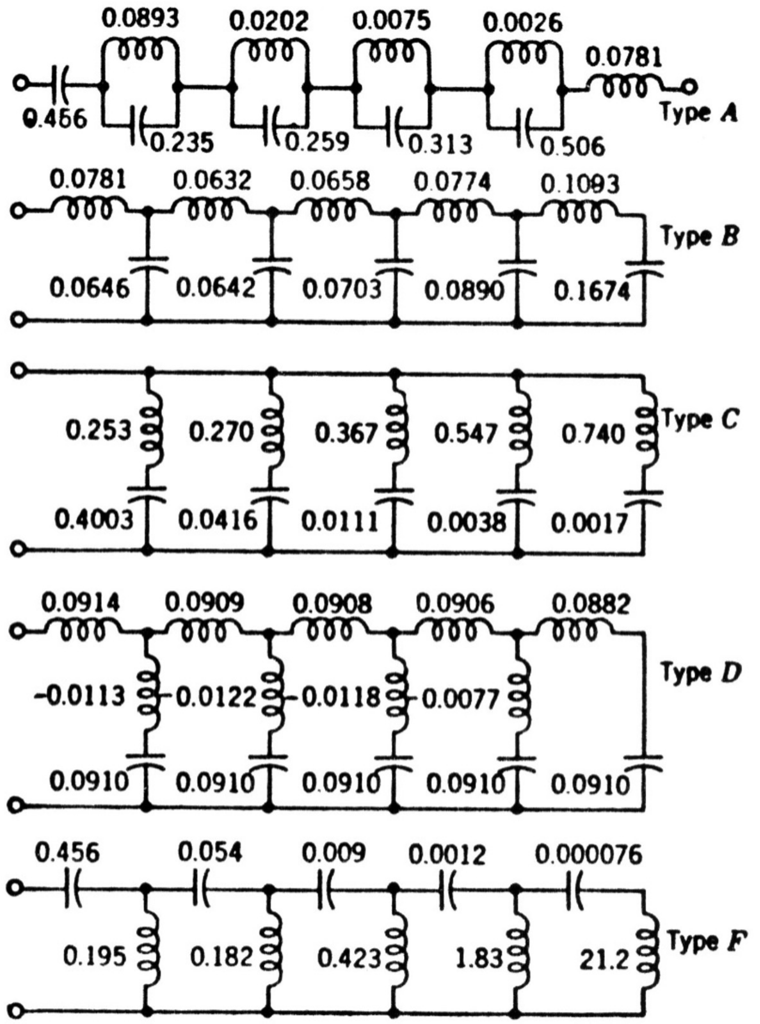
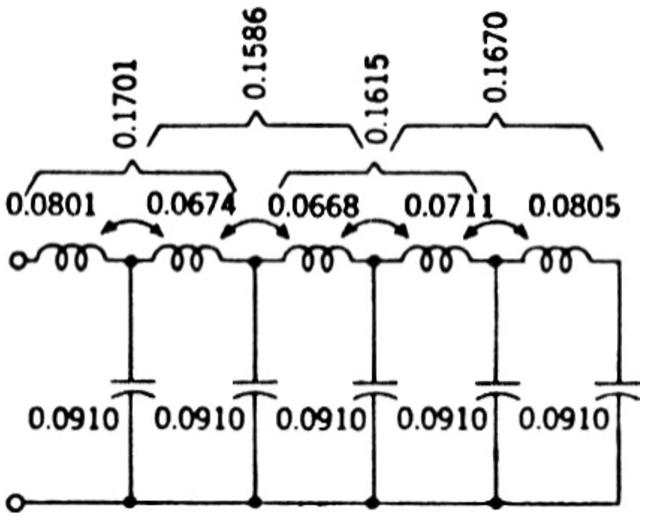



FIG. 6·22.—Equivalent forms for five-section Guillemin voltage-fed network. Multiply the values of the inductances by $Z_{NT}$ and the values of the capacitances by $\tau/Z_N$. The inductances are in henrys and the capacitances in farads if pulse duration $\tau$ is expressed in seconds and network impedance $Z_N$ in ohms.

# Type E PFN

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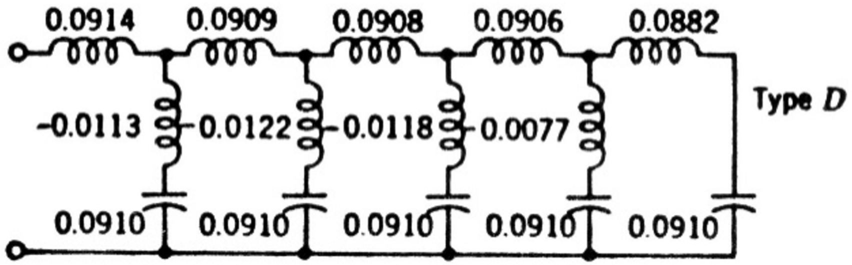



The negative inductance that are seen in the Type D PFN represent the mutual inductance between adjacent inductors and may be realized in physical form by winding coils on a single tubular form (solenoid) and attaching the capacitors to the inductor at appropriate points on the inductor.

The quality of the output pulse is dependent on the number of sections used. For a waveform having a desired risetime/falltime of ~ 8% of the total pulsewidth, five sections (each consisting of one inductor and one capacitor) prove to be adequate to produce the desired waveshape. A sixth section provided only slight improvement. This corresponds to the relative magnitude of the Fourier-series components for the corresponding steady-state alternating current wave. The relative amplitude of the fifth to the first Fourier coefficient is ~4% while the sixth to the first is ~ 2%.

Note: If faster risetimes/falltimes are required, the number of sections needed to satisfy that risetime increases.

# Type E PFN: Practical Design Parameters

- For :
  - PFN Characteristic Impedance = $Z_o$
  - PFN Output Pulse Width = $2\tau$
    - where $L_N$ = total PFN inductance and
      $C_N$ = total PFN capacitance

$$Z_o = \sqrt{\frac{L_N}{C_N}}$$

$$\tau = \sqrt{L_N C_N}$$

- The total PFN inductance (including mutual inductances) and capacitance is divided equally between the number of sections.

- Empirical data have shown that the best waveshape can be achieved when the end inductors should have ~20-30% more self inductance. The mutual inductance should be approximately 15% of the self inductances.

# Type E PFN: Practical Design Parameters (cont.)

- Bottom line: don’t bust your pick designing a “perfect” PFN
  - Capacitance values vary from can-to-can and with time
  - Inductor values are never quite as designed
  - Strays; inductance, capacitance, resistance, distort the waveform
  - and should you somehow overcome all of the foregoing, you can be certain that the technicians will “tune” the PFN and your “perfect” waveform will be but a memory

# PFN Design for Time Varying Load

- Within a limited range, the impedance of individual PFN sections may be adjusted to match an impedance change in the load.

  - For example:  Each section of a 5 section roughly drives 20% of the load pulse duration.  If the load impedance is 10% lower for the first 20% of pulse, designing the first section of the PFN (section closest to the load) to be 10% lower than rest of the PFN will make a better match and generate a flatter pulse.

  - This approach works only if the load impedance is repeatable on a pulse-to-pulse basis

# PFN: Practical Issues

- Switch: In addition to voltage and peak current requirements, must also be able to handle peak dI/dt (highest frequency components will be smaller magnitude and may be difficult to observe)
  - SLC modifications to 6575 doubled dI/dt
  - Even with 2 thyratrons, short tube life
  - Solved by adding “anode reactor” (magnetic switch in series with tube)

- Positive mismatch, $Z_{load} > Z_{PFN}$
  - “Prevents” voltage reversal (may still get transient reversals), improves lifetime
    - Switch
    - Capacitors
    - Cables
  - Incorporate End Of Line (EOL) clipper to absorb mismatch energy

# PFN: Practical Issues

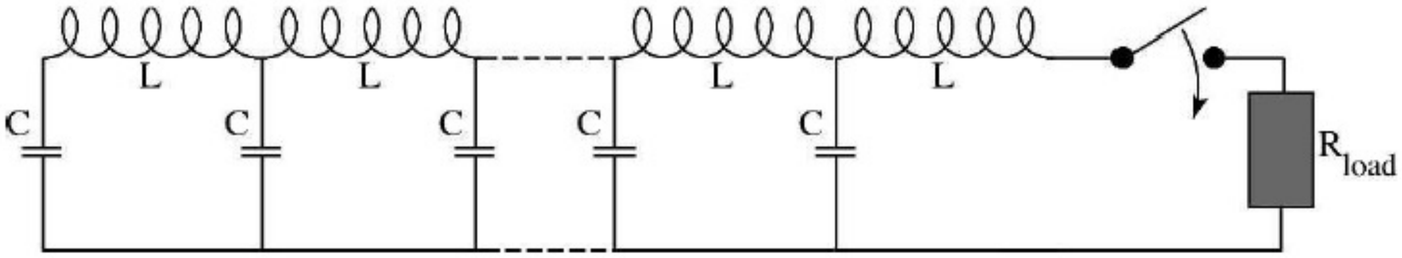
- Inductors
  - Must not deform under magnetic forces
  - Tuneable
    - Movable tap point
    - Flux exclusion lug

- PFN impedance range is limited (just like PFLs), as is maximum switch voltage
  - Transformers can be used to match to klystron load
  - SLAC 6575 modulators are matched to 5045 klystrons with a 1:15 transformer

# Pulse Forming Networks

- Lumped element approximation of a transmission line – usually used for increased pulsewidth when PFLs become too long
- Discrete Ls and Cs and limited number of sections produces waveform imperfections (overshoot, oscillations, etc.)
- Tunable impedance and pulsewidth by varying component values
- Many configurations but type E is typical
  - Convenient
  - Equal L and C values
  - Easy to visualize approximated transmission line

# PFN Hardware Examples




DARHT-II at LANL, 2us, tapered impedance with decreasing inductance values

STS-500 at LLNL, 20us

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