Pulsed Power Engineering Diagnostics

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Diagnostic Techniques and Considerations in Pulsed Power Systems

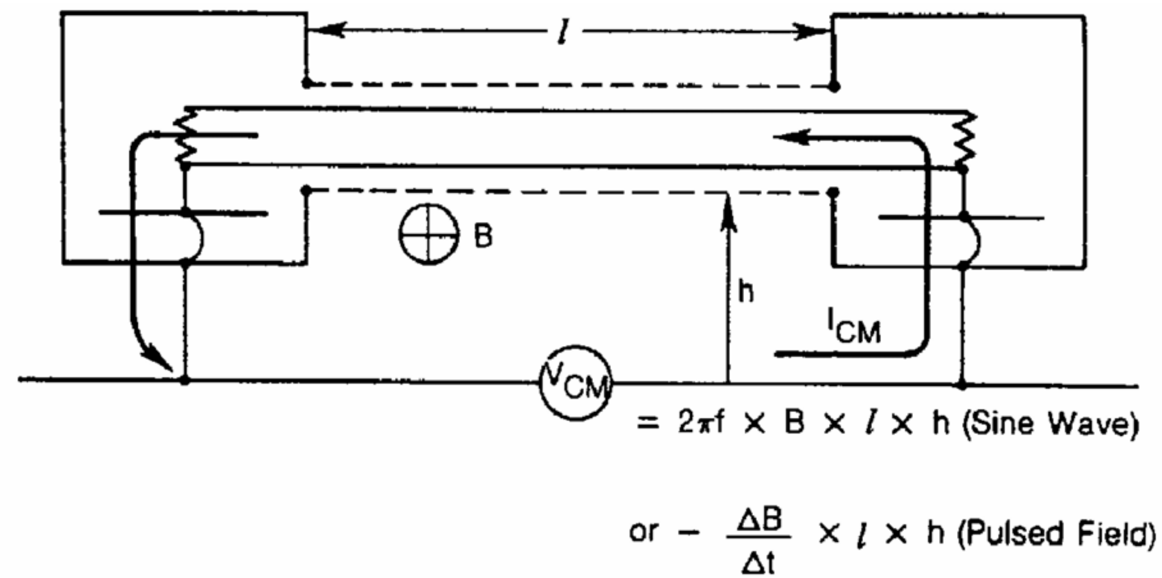
- Grounding
  - Proper grounding
  - Ground loops
- Voltage measurement
  - Voltage divider
    - Resistive
    - Capacitive
    - Balanced
  - Commercial voltage probes
- Current measurements
  - CVR
  - Rogowski
  - Self-integrating Rogowski

Grounding

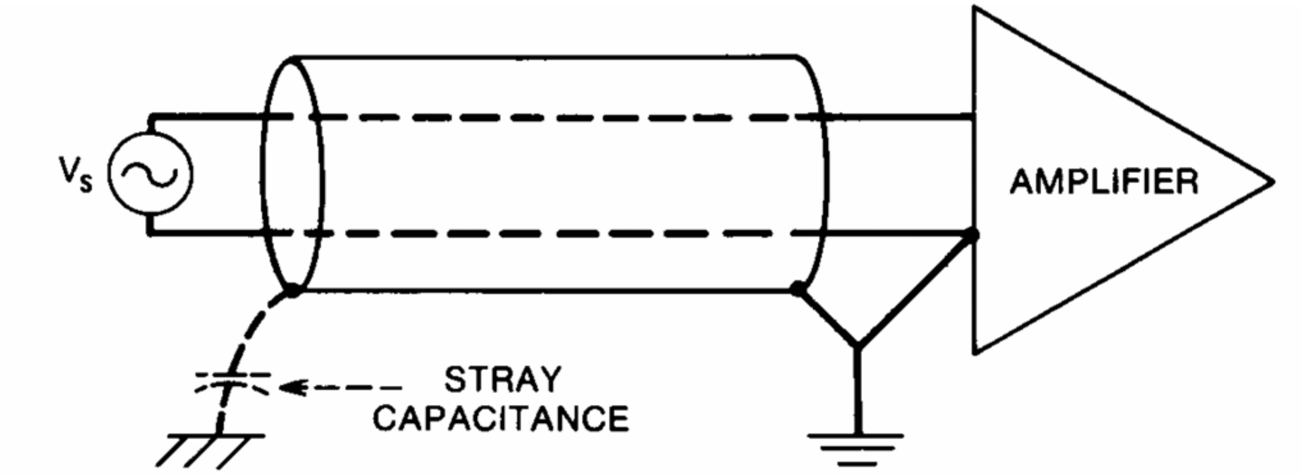
- Proper grounding is the single most important factor in making accurate experimental measurements in pulsed power systems: design it in
- kA/μs X nH = V, no two points in a high dI/dt system ever have the same potential which will induce "ground loop" currents
- Solid "earth" ground when possible
- "Single point" ground systems when possible
  - Almost anything with an AC plug has a ground lead
  - Safety requirements often result in additional grounds
- Use tri-axial cables instead of co-ax, outer shield can be non-current carrying connection required for grounding/bonding

Ground Loop

DC coupled

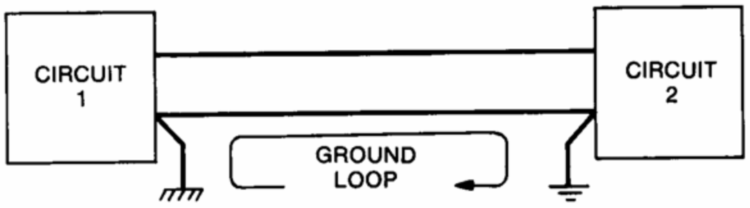


Capacitively coupled

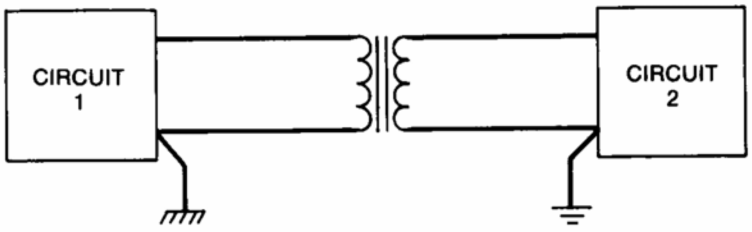


Isolation Techniques for Ground Loops

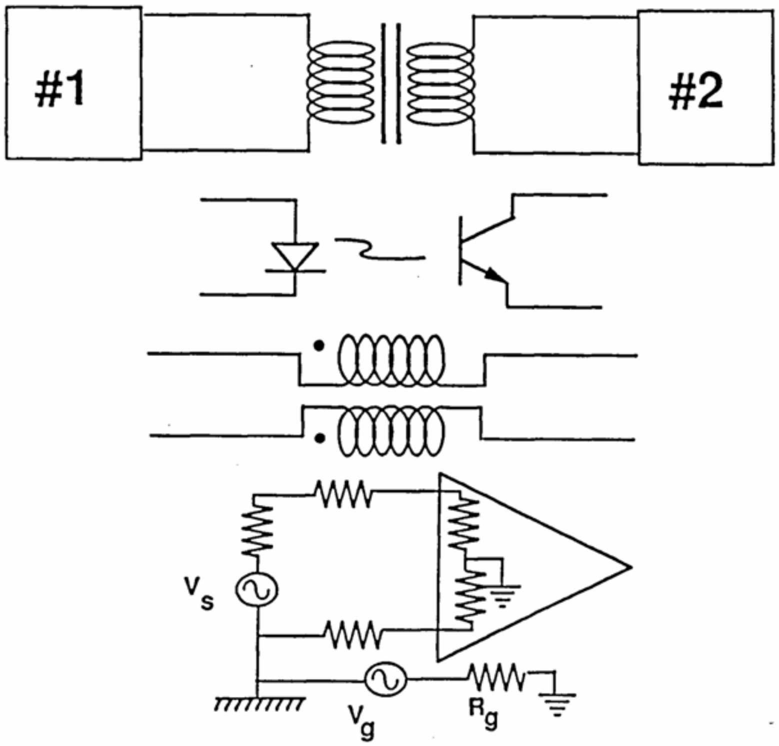
Ground loop from multiple-point grounding



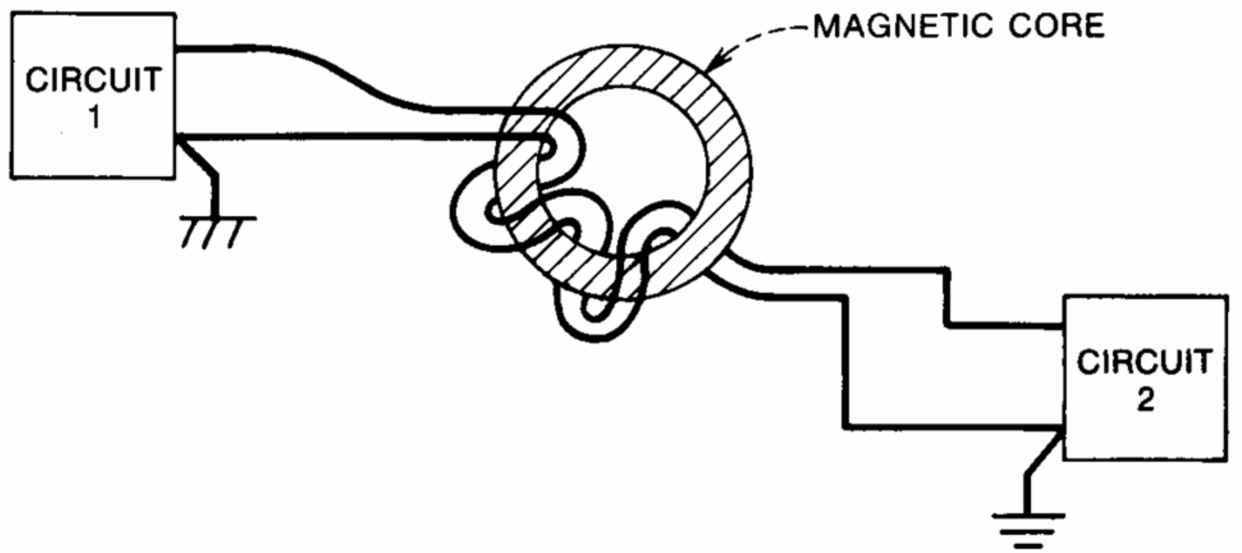
Interrupting ground loop current flow using transformer isolation



Additional isolation techniques



Common Mode Choke for Signal Cables



Measuring High Voltage

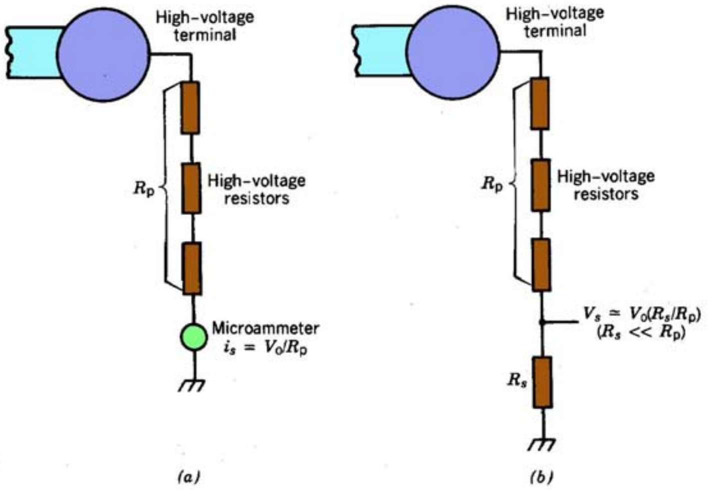


Figure 9.49 High-voltage measurements with resistor strings. (*a*) Resistive shunt. (*b*) Resistive divider.

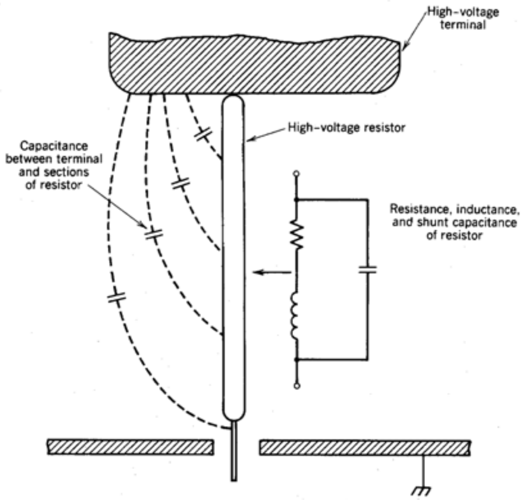


Figure 9.51 Effect of stray capacitance, shunt capacitance, and series inductance on resistive voltage divider.

- High voltage resistor strings are used to make HV measurements
  - Resistive shunts
  - Resistive dividers
- Parasitic effects (illustrated in Fig 9.51) can introduce waveform distortion at higher frequencies as illustrated in Fig 9.52
- Impact of parasitic elements is reduced as resistance of string is reduced, but dissipation and loss increases

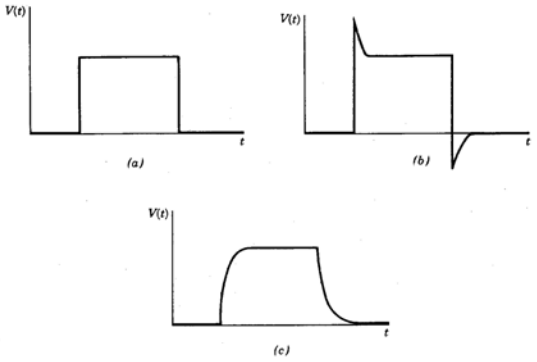


Figure 9.52 Waveforms from resistive voltage divider. (*a*) Ideal output voltage from a square-pulse input. (*b*) Output with significant shunt capacitance. (*c*) Output with significant series inductance.

High Frequency Voltage Dividers

- Most common alternatives
  - Capacitive divider
  - Balanced divider
    - Add capacitance to “swap” strays
    - Can be done with discrete components
    - Alt: physically divide resistive medium
      - Water
      - Thin film
    - Typical design of commercial HV probes
  - Inductive dividers used for dI/dt

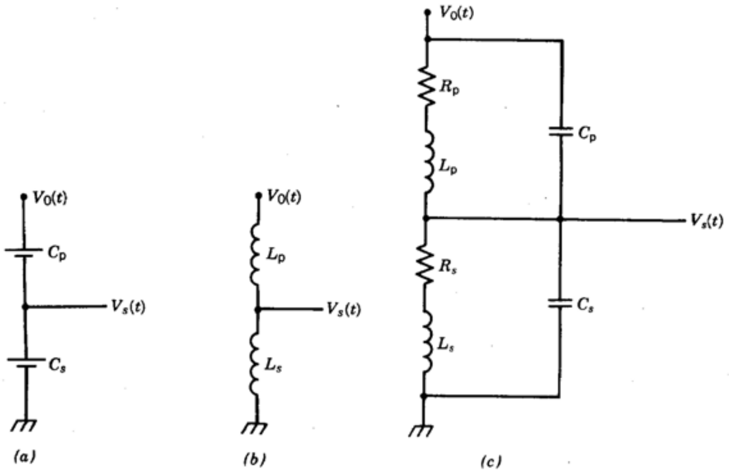


Figure 9.53 Voltage dividers. (*a*) Capacitive. (*b*) Inductive. (*c*) Balanced voltage divider.


VD5-DH


VD15-A


VD60-B


VD75-C

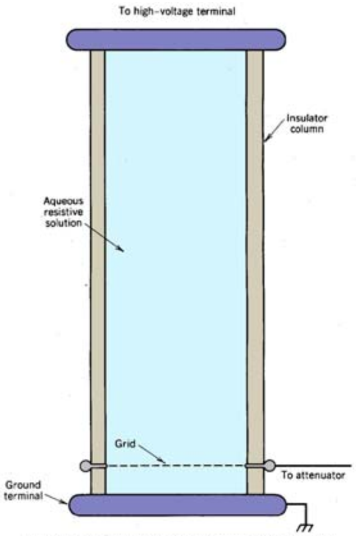


Figure 9.54 Balanced voltage divider with water solution resistor.

Scope Probes

- Balanced probes
  - Input impedance is frequency dependent
  - Scope impedance impacts response
- Bandwidth is limited
  - May be substantially less than rating, depending on ground connection
- HV versions require tuning to scope
- Pulsed power workhorses
  - P5100: 100X, 2.5 kV, 250 MHz
  - P6015: 1000X, 20 kV, 75 MHz
  - P5210 (differential): 5 kV, 50 MHz, 2 kV common-mode

Current Measurement

- Current viewing resistor
  - V = IR
- Time changing induced magnetic field, dB/dt
  - B-dot loop
    - $V = NA\, dB/dt$
      - Coil of area, A, with N turns
    - $V = NAB/RC$
      - Passive RC integrator
    - Calibration difficult, function of source and loop
      - Location
      - Size
      - Orientation
  - Rogowski coil
    - Encloses current source
    - Eliminates location/orientation calibration factors

Rogowski Coil

- Usual “air core” approximation, diagnamagnetic field of loop is negligible
  - $B_i = B$
- $B(r) = \mu I/2\pi\rho$
- $V = NA\, dB/dt$

$$= \mu A(N/2\pi\rho)\, dI/dt$$

$$= \mu A(N/\ell)\, dI/dt$$

$$= \mu A(N/\ell)I/RC \text{ (with RC integrator)}$$

ℓ is coil length

N/ℓ is number of turns/meter

- Can be built in the lab
  - Calibration challenges: accurately measuring A and N/ℓ
  - Signal attenuation from passive RC integrator yields small signals unless I very large or time constant short
- Commercially available

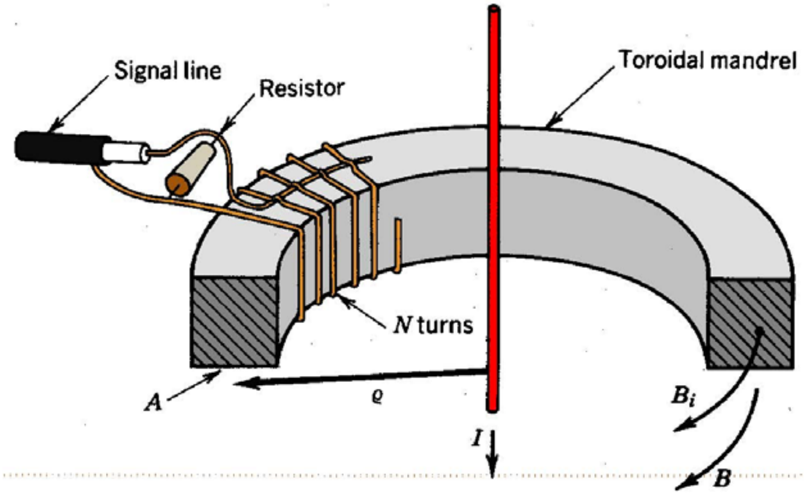


Figure 9.58 Rogowski loop—self-integrating current probe.

Self-integrating Rogowski

- More rigorously, the field B_i, in Fig 9.58

  $B_i = B - \mu i\ (N/2\pi\rho)$

  where i is the current flowing in the coil

  $i = NA\ (dB_i/dt)/R$

- Combining the above and solving for B

  $B = B_i + (dB_i/dt)\ (\mu N^2 A/2\pi\rho R)$

  $= B_i + (dB_i/dt)\ (L/R)$ inserting the identity for a solenoid inductor

- When the time constant L/R is large compared to the time scale of current variations: $(d/dt)\ (L/R) >> 1$, then the left term above can be neglected and:

  $B \approx (dB_i/dt)\ (\mu N^2 A/2\pi\rho R)$

- Recognizing $B = \mu I/2\pi\rho$ and solving for dB_i/dt as a function of coil current

  $i = I/N$

- Typically, L is made large by using a ferrite core
- Commercial current transformer