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
- \( \text{kA/\mu s} \times nH = V \), 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

\[ V_{CM} = 2\pi f \times B \times l \times h \text{ (Sine Wave)} \]

or \[ -\frac{\Delta B}{\Delta t} \times l \times h \text{ (Pulsed Field)} \]

Capacitively coupled

\[ V_s \]

AMPLIFIER

STRAIGHT CAPACITANCE
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

- 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
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.

Figure 9.54 Balanced voltage divider with water solution resistor.

VD6-DH  VD15-A  VD80-B  VD75-C
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
    • \( V = NA \frac{dB}{dt} \)
      – 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, diamagnetic field of loop is negligible
  - \( B_i = B \)
- \( B(r) = \mu I/2\pi\rho \)
- \( V = NA \frac{dB}{dt} \)
  - \( = \mu A(N/2\pi\rho) \frac{dI}{dt} \)
  - \( = \mu A(N/\ell) \frac{dI}{dt} \)
  - \( = \mu A(N/\ell) I/RC \) (with RC integrator)
    - \( \ell \) is coil length
    - \( N/\ell \) is number of turns/meter
- Can be built in the lab
  - Calibration challenges: accurately measuring \( A \) and \( N/\ell \)
  - Signal attenuation from passive RC integrator yields small signals unless \( I \) very large or time constant short
- Commercially available
Self-integrating Rogowski

- More rigorously, the field \( B_i \), in Fig 9.58
  \[ B_i = B - \mu i \left( \frac{N}{2\pi \rho} \right) \]
  where \( i \) is the current flowing in the coil
  \[ i = NA \frac{(dB_i/dt)}{R} \]
- Combining the above and solving for \( B \)
  \[ B = B_i + \frac{(dB_i/dt)}{R} \left( \frac{\mu N^2 A}{2\pi \rho R} \right) \]
  \[ = B_i + \frac{(dB_i/dt)}{R} \left( \frac{L}{R} \right) \]
  inserting the identity for a solenoid inductor
- When the time constant \( L/R \) is large compared to the time scale of current variations: \( (d/dt) (L/R) \gg 1 \), then the left term above can be neglected and:
  \[ B \approx \frac{(dB_i/dt)}{R} \left( \frac{\mu N^2 A}{2\pi \rho R} \right) \]
- Recognizing \( B = \frac{\mu I}{2\pi \rho} \) and solving for \( dB_i/dt \) as a function of coil current
  \[ i = \frac{I}{N} \]
- Typically, \( L \) is made large by using a ferrite core
- Commercial current transformer