Using Rogowski Coils Inside Protective Relays

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Rogowski Coils

- Well known (originated in 1912)
- Applicable to ac current measurements
- Well suited for high currents
- Work best with low-power electronics
- Quietly gaining momentum
  - GIS systems, NCIT, and medium-voltage sensors
  - Low-voltage circuit breakers

Current Measurement Technologies

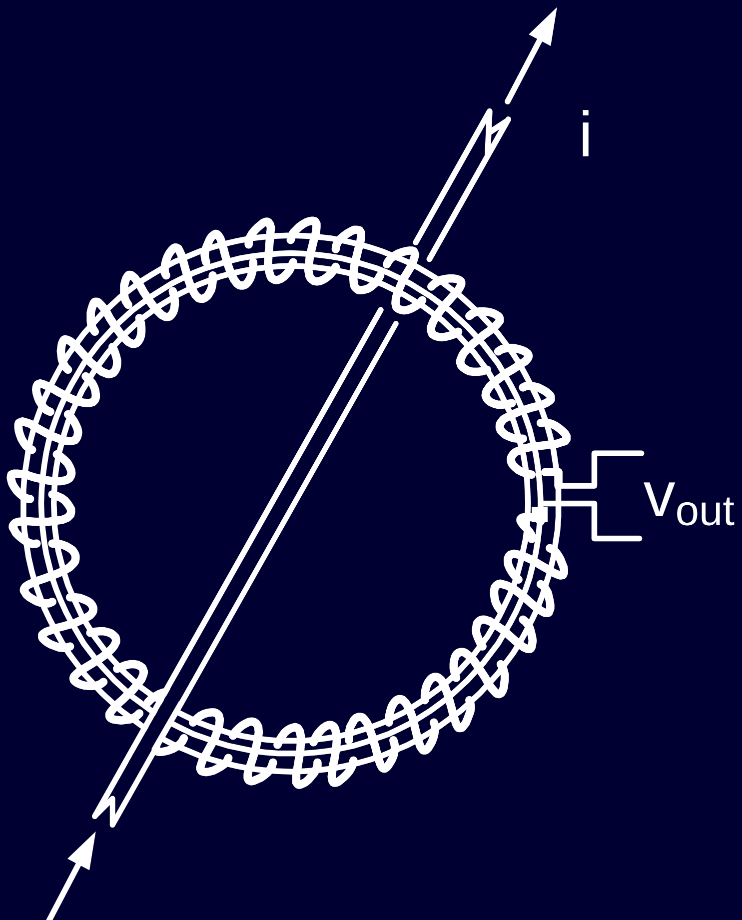
	Conventional CT	Rogowski Coil	Resistive Shunt
DC Response	No	No	Yes
Saturation	Yes	No	No
Weight	Depends / High	Low	Depends
Dynamic Range	Good	Excellent	Good
Robustness	Excellent	Excellent	Good
External Field Rejection	Excellent	Good	Excellent
Output	Current	Voltage	Voltage
Use	Industry Standard	Low	Low
Isolation	Yes	Yes	No
Multiple Loads	Yes	Limited	Limited

Industry Standards

- IEC 60044-8 for electronic current transformers
- IEEE C37.92 for low-energy relay inputs
- IEEE C37.235 for Rogowski coil application guidelines
- IEC 61869-10 for low-power current sensors (in development: IEC TC38, WG37)

Rogowski Coil

Produces Voltage Output Proportional to Derivative of Primary Current

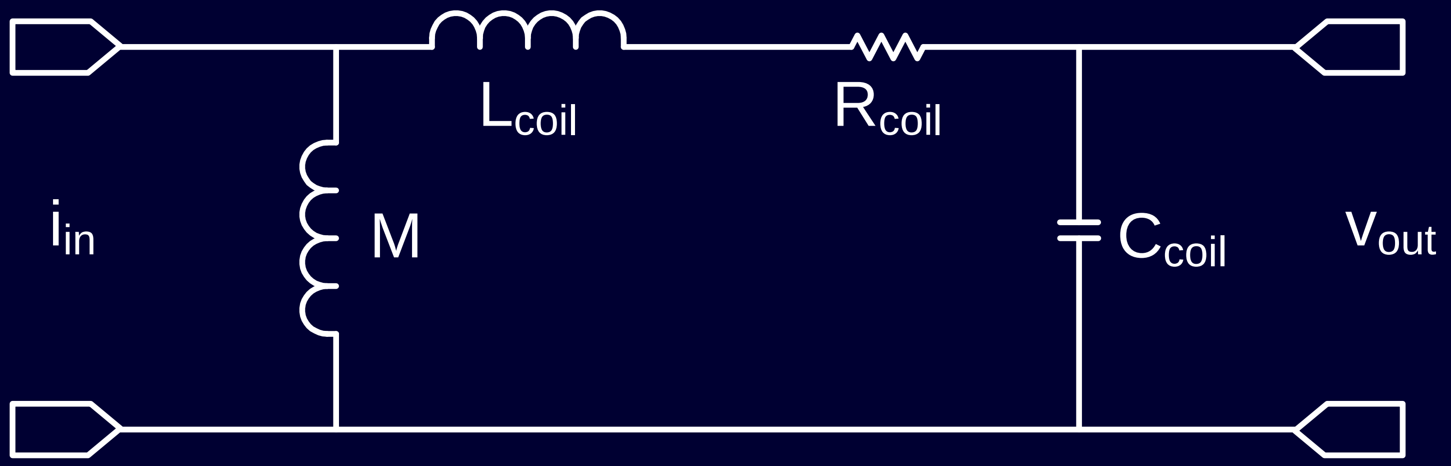


$$v_{out} = -\frac{d\psi}{dt} = -M\frac{di}{dt}$$

Coil Construction

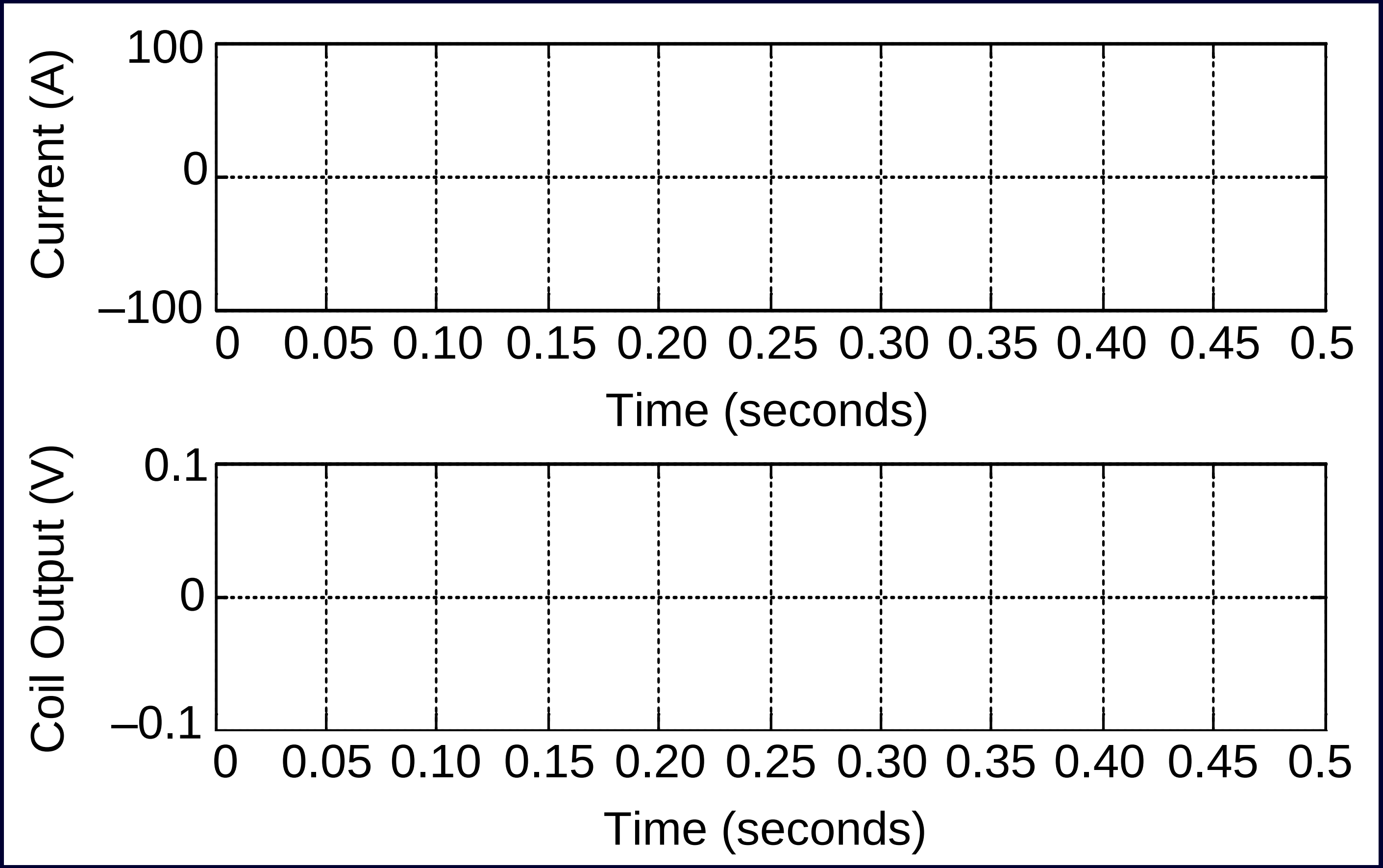
Conventional CT construction shown in the middle

Equivalent Circuit Model



- Familiar
- Similar to conventional CT model
- Very small M (µH)

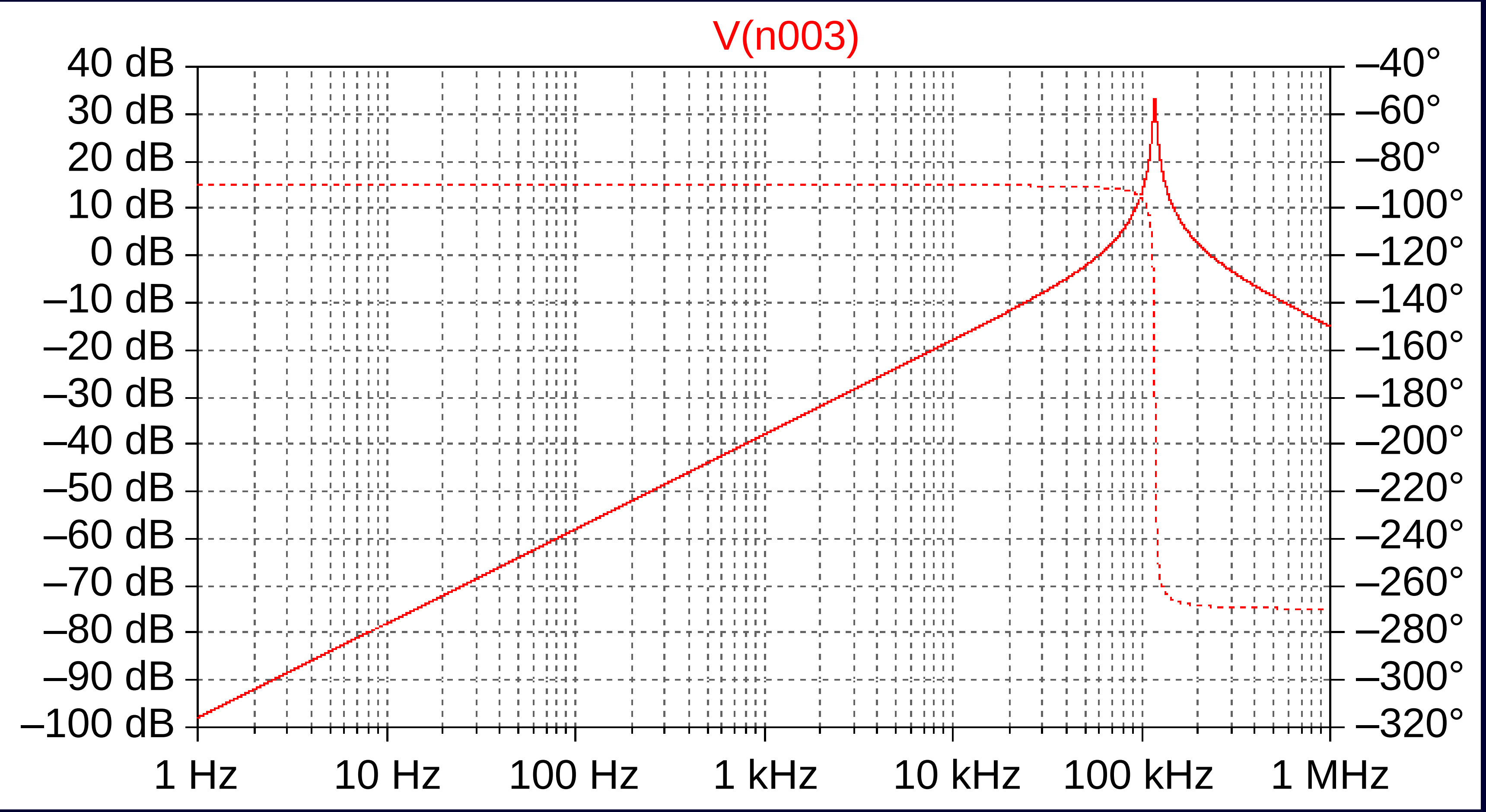
Rogowski Coil Output



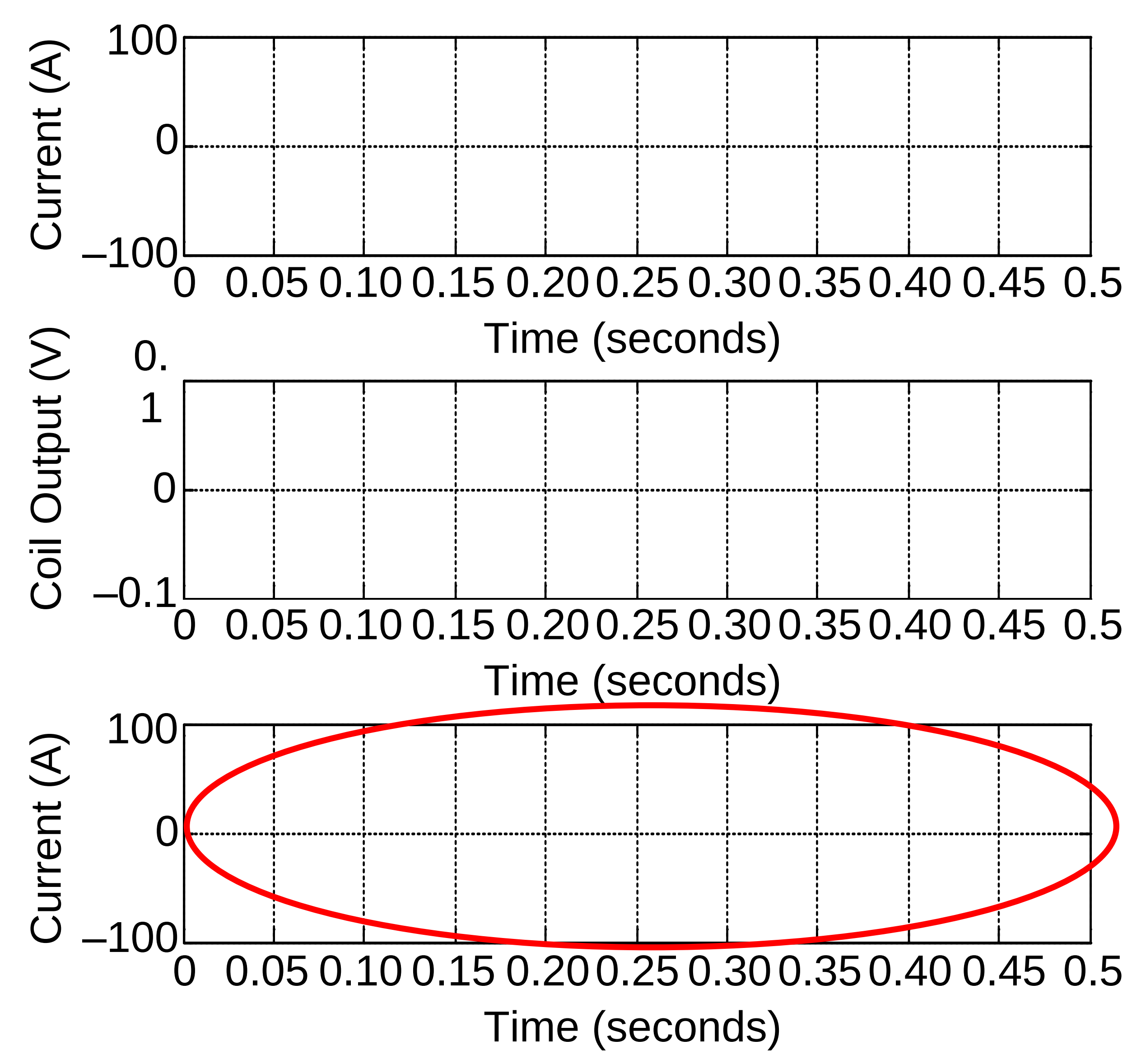
- Output is 90 degrees out of phase
- DC offset is attenuated

Rogowski Coil Frequency Response

Primary Current Can Be Restored With an Integrator



Coil Output Integration



Practical Application Considerations

Advantages

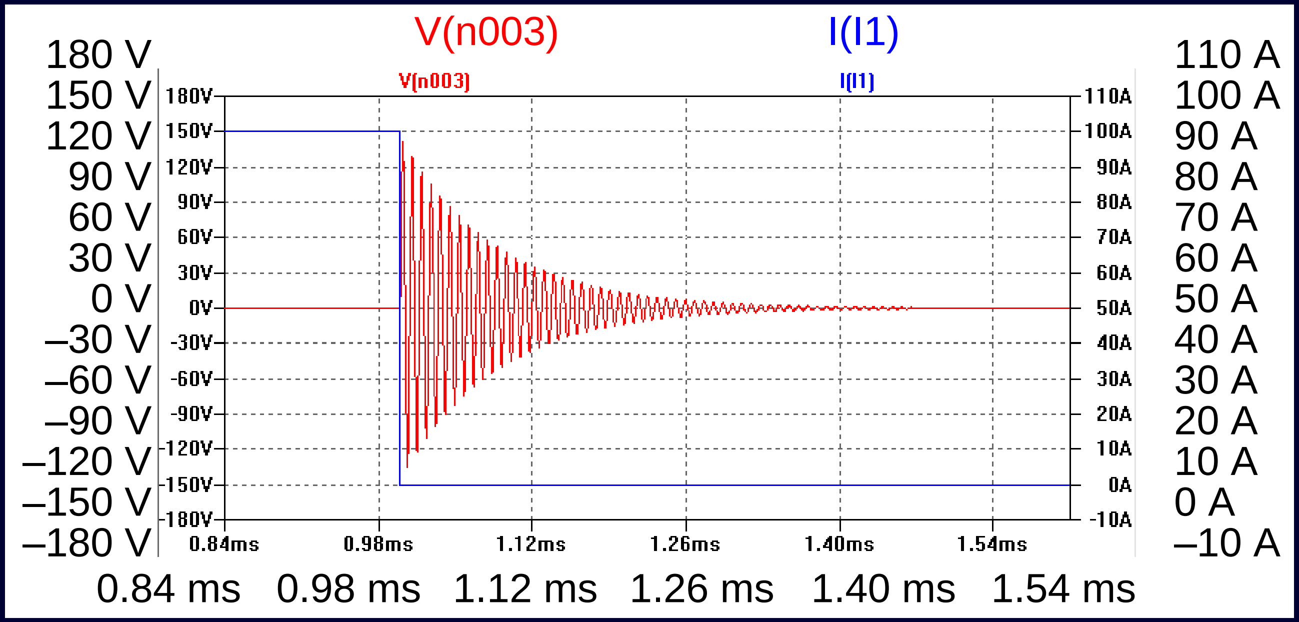
- No saturation, linear, and not affected by dc
- Electrically safe when open
- Potential for lower cost
- Smaller size and lower weight
- Wide dynamic range
- Very low primary burden
- No magnetizing current error

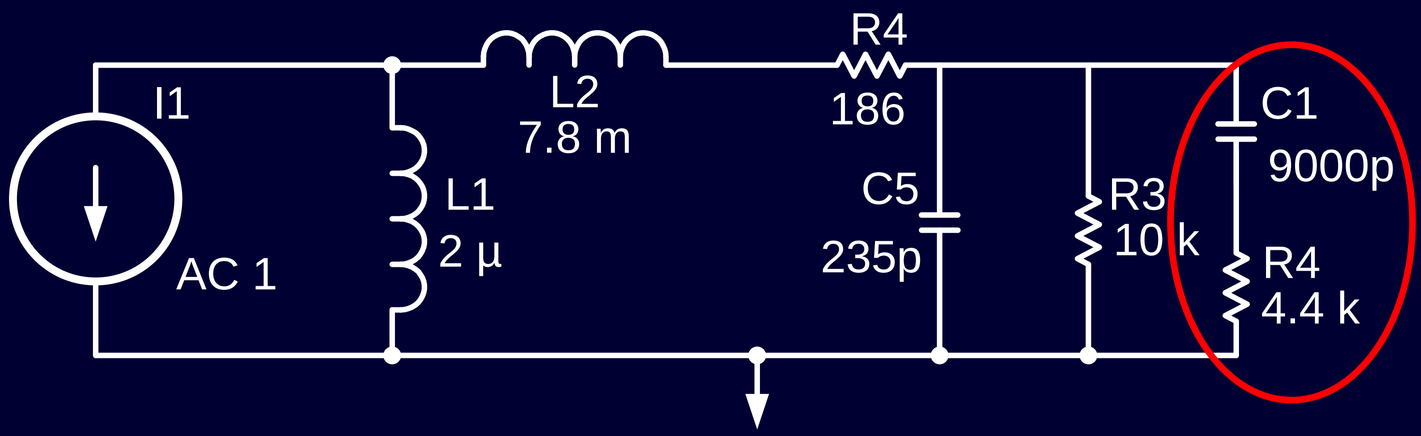
Practical Application Considerations

Limitations

- Coil resonance
- Low sensitivity and shielding
- Temperature stability
- Integrator implementation
- Low-frequency noise magnification
- Conductor position sensitivity, limited external field rejection, and manufacturing tolerance
- Inability to drive multiple loads

Coil Resonance



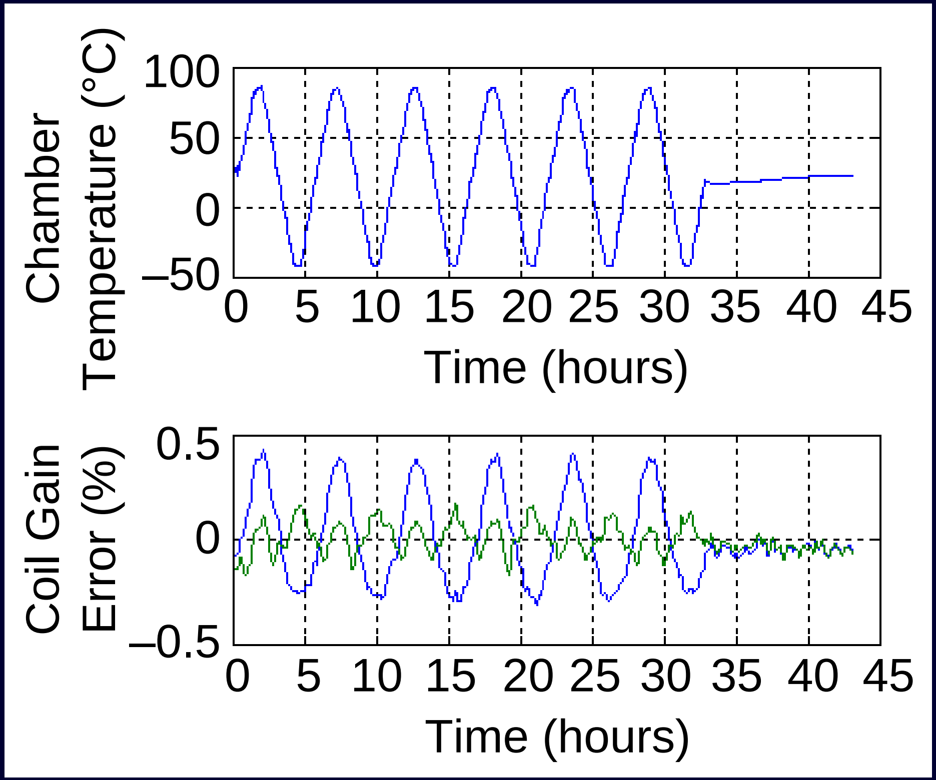


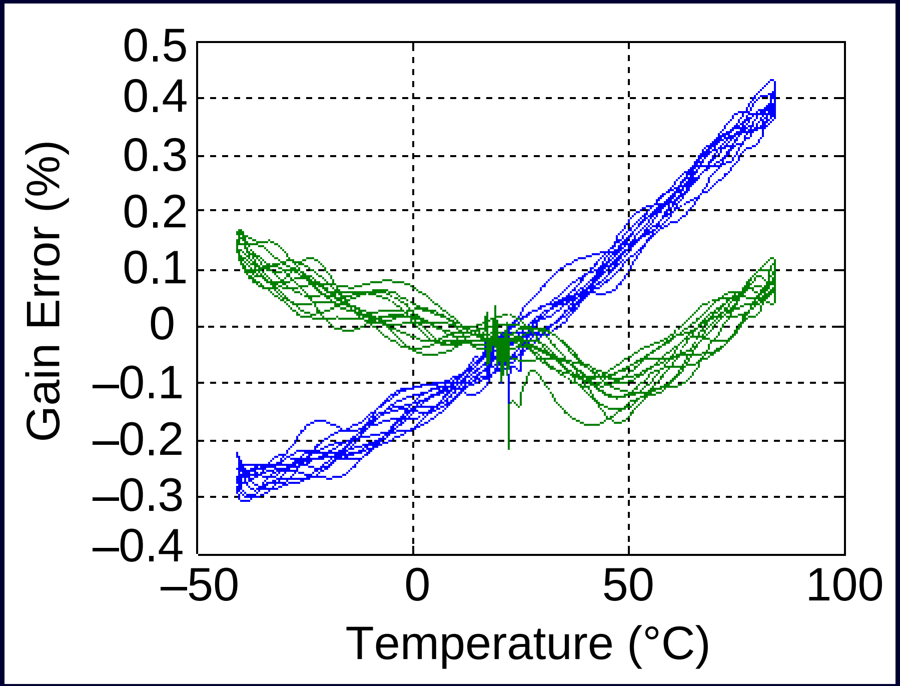
Passive components can provide additional damping

Low Output and Shielding

- Typical output: 100 µV/A at 60 Hz
- Capacitive-based primary voltage coupling

Temperature Stability

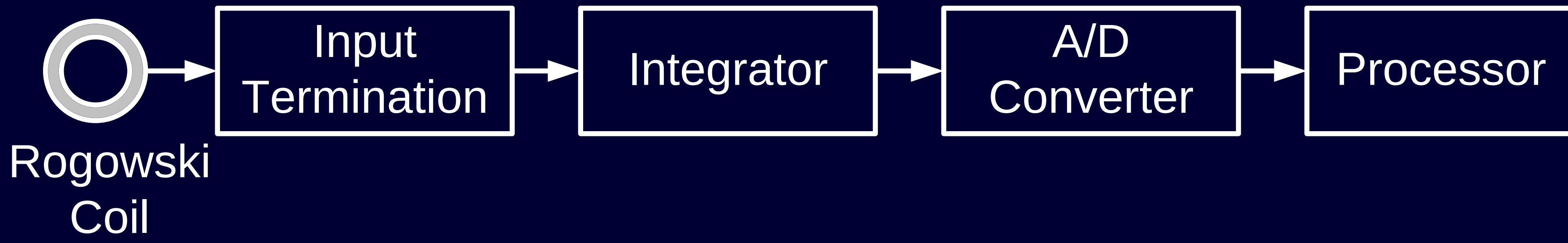




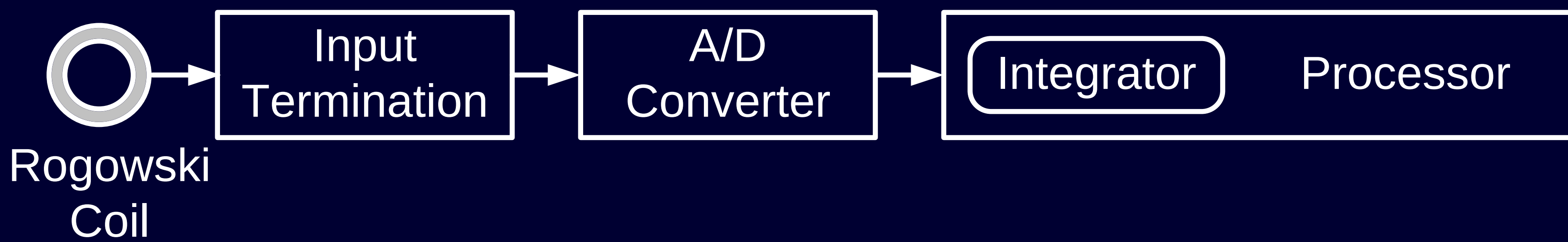
Resistive burden provides temperature compensation

Integrator Design

Analog Integrator

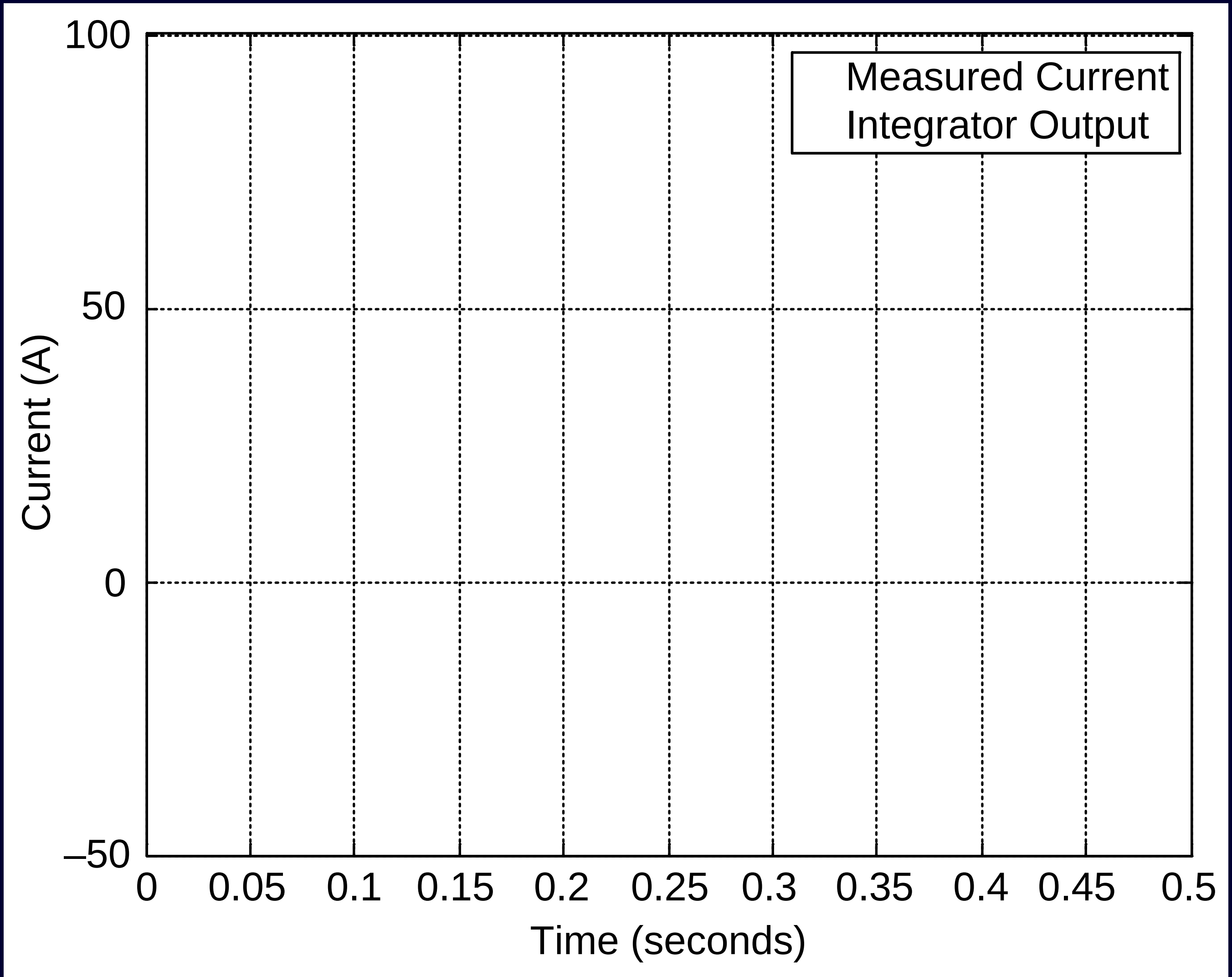


Digital Integrator

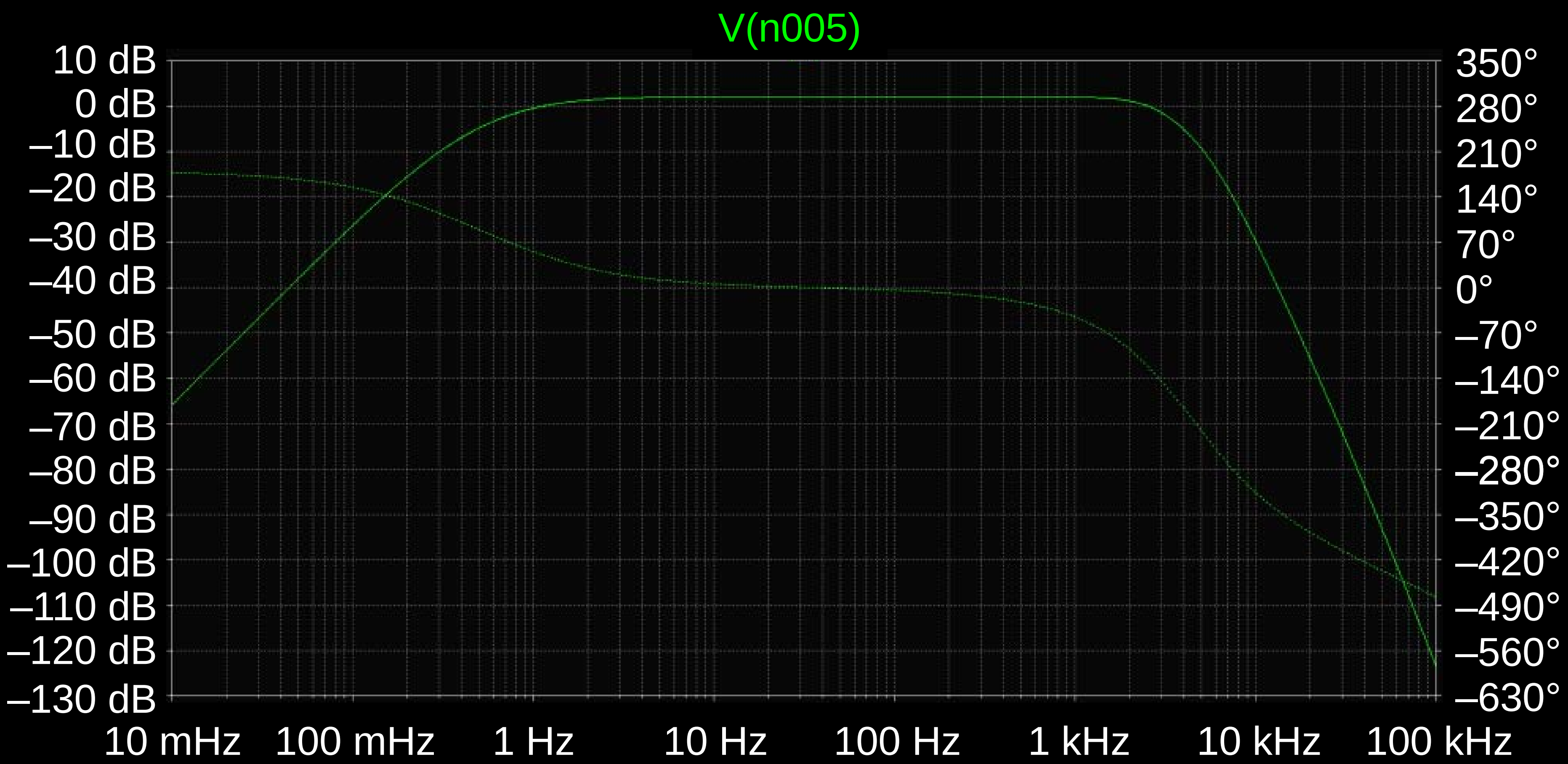


Low-Frequency Cutoff Effect

Consequences of Finite DC Gain



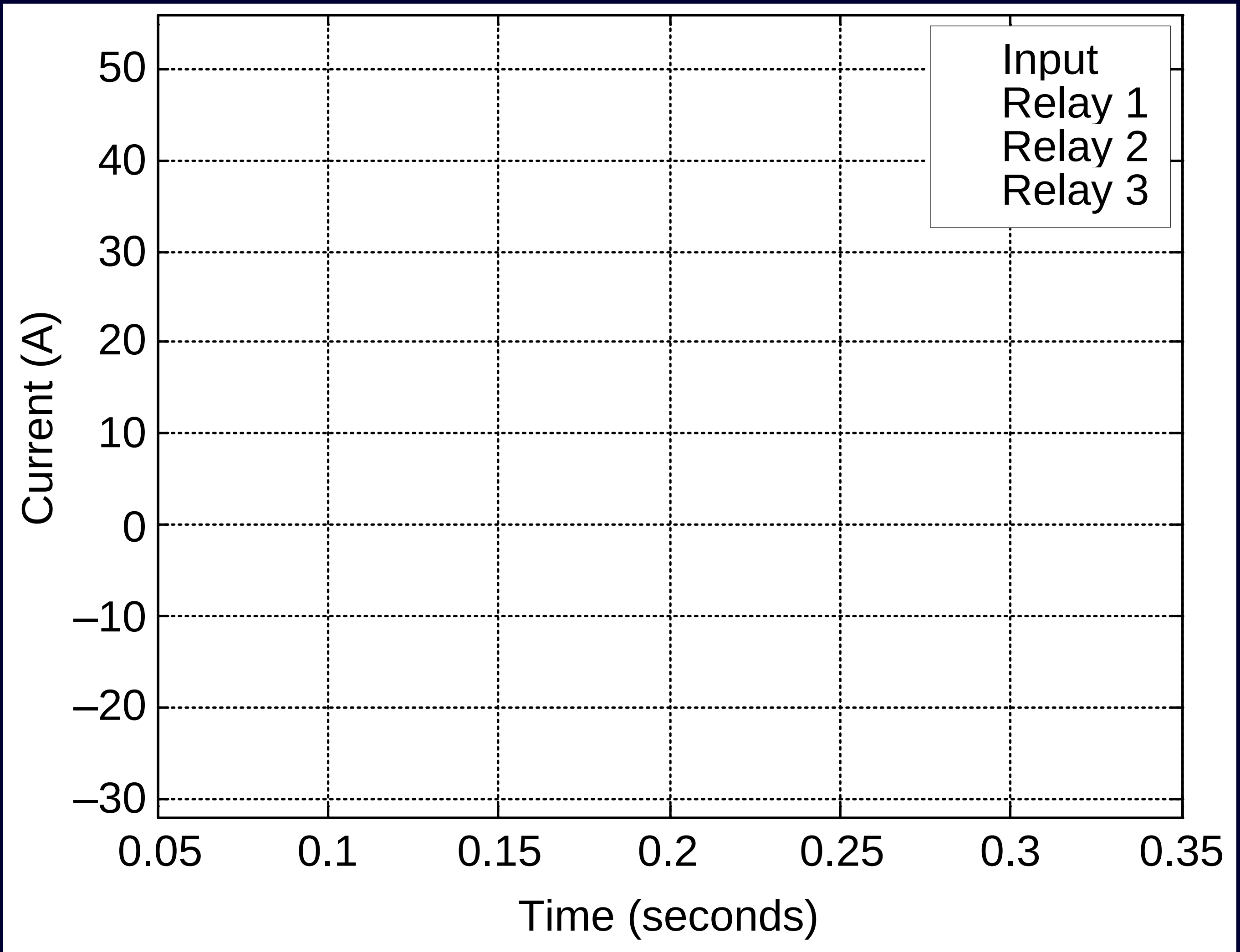
Frequency Domain View



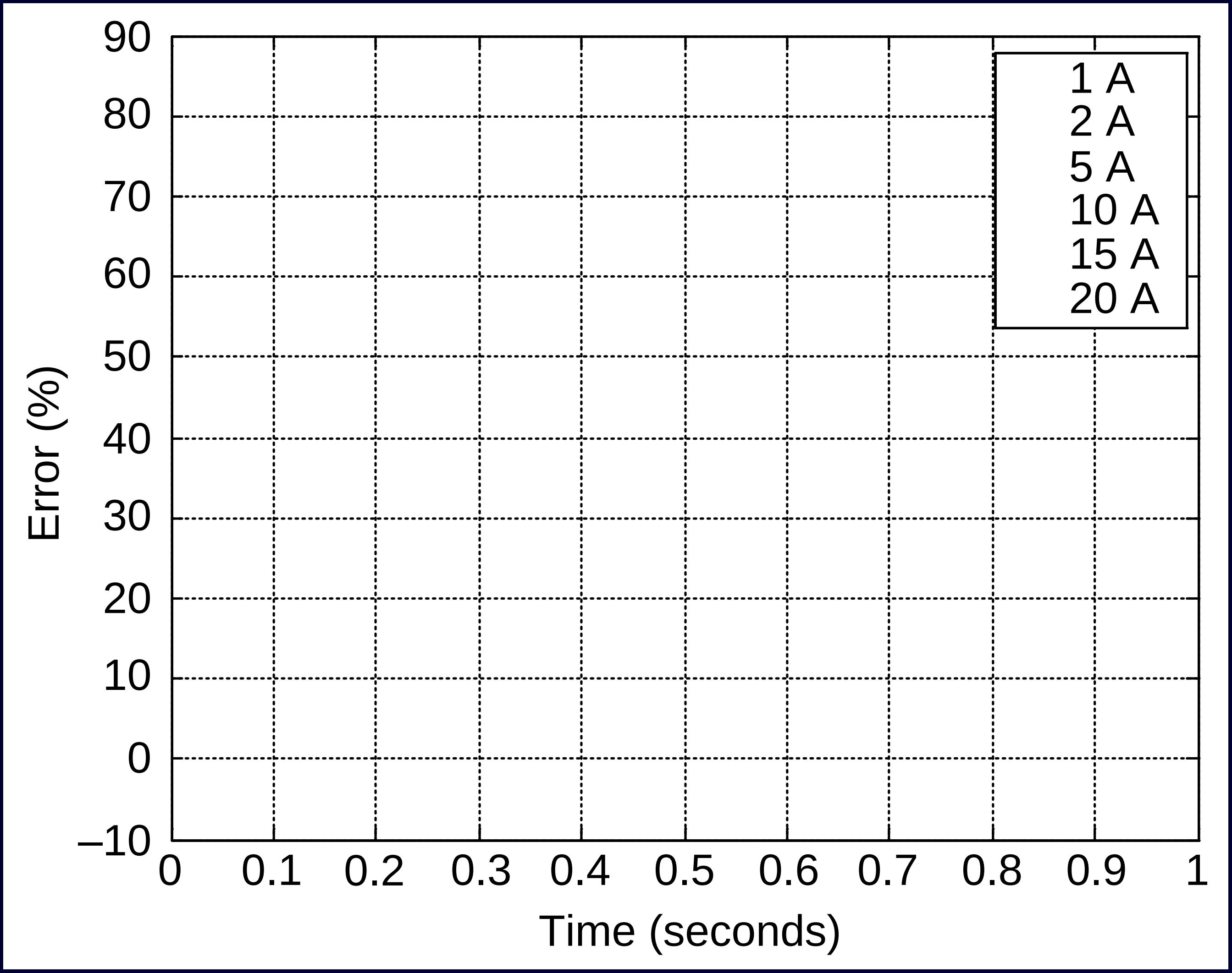
- Flat pass band
- Rolls off on both ends

Conventional Input CT Behavior

What Relays Typically See



Instantaneous CT Error
Expressed Per IEC 60044-8

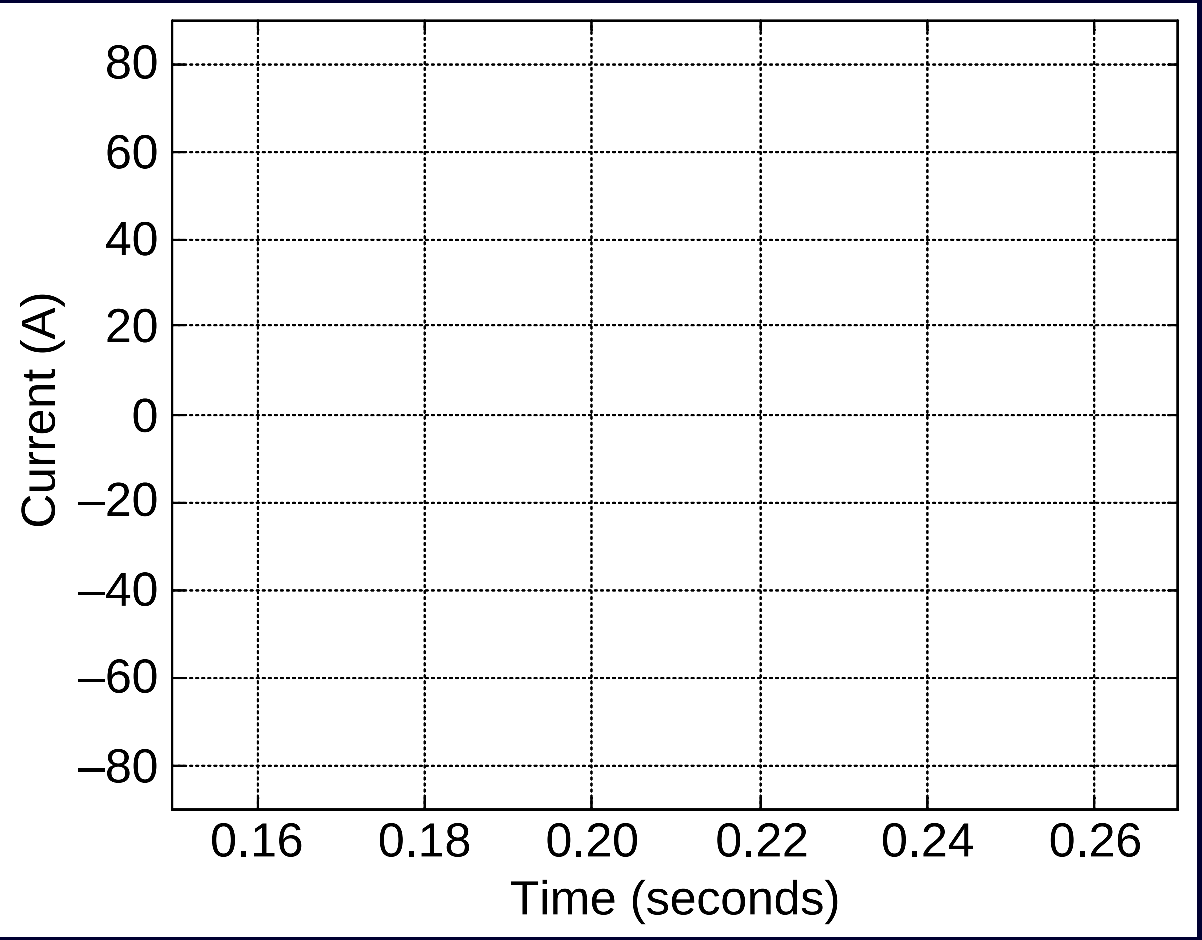


CT as High-Pass Filter

Fault Current Level	1 A	2 A	5 A	10 A	15 A	20 A
Corner Frequency	0.5 Hz	0.42 Hz	0.7 Hz	1.9 Hz	2.5 Hz	3 Hz

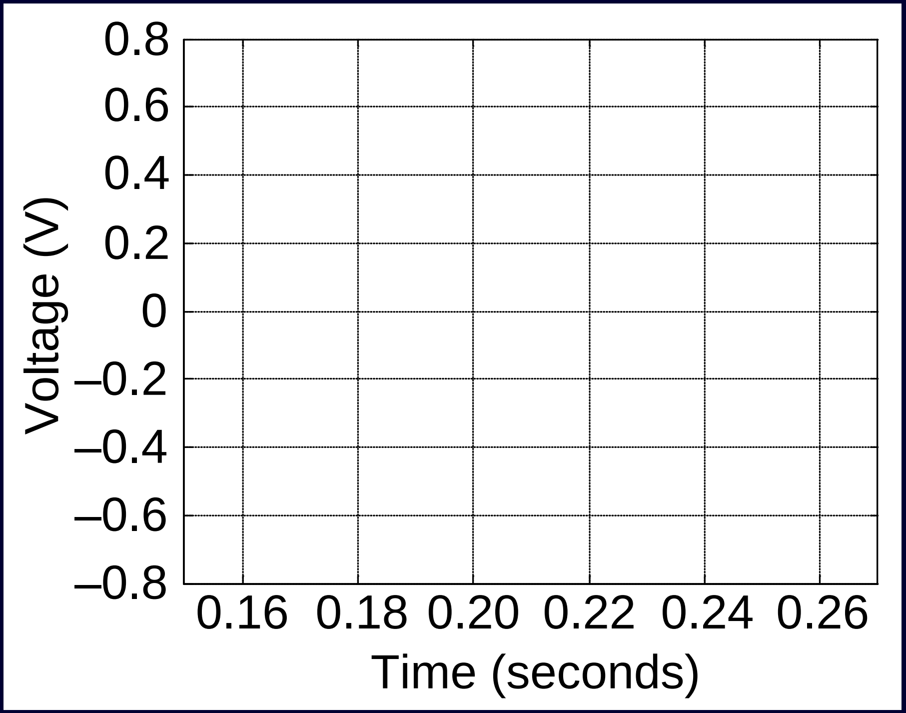
- Before saturation, CT response can be approximated with a first-order high-pass filter
- To match conventional CTs, integrator cutoff should be set between 0.1 and 1 Hz

Real-Life Waveform at CT Secondary

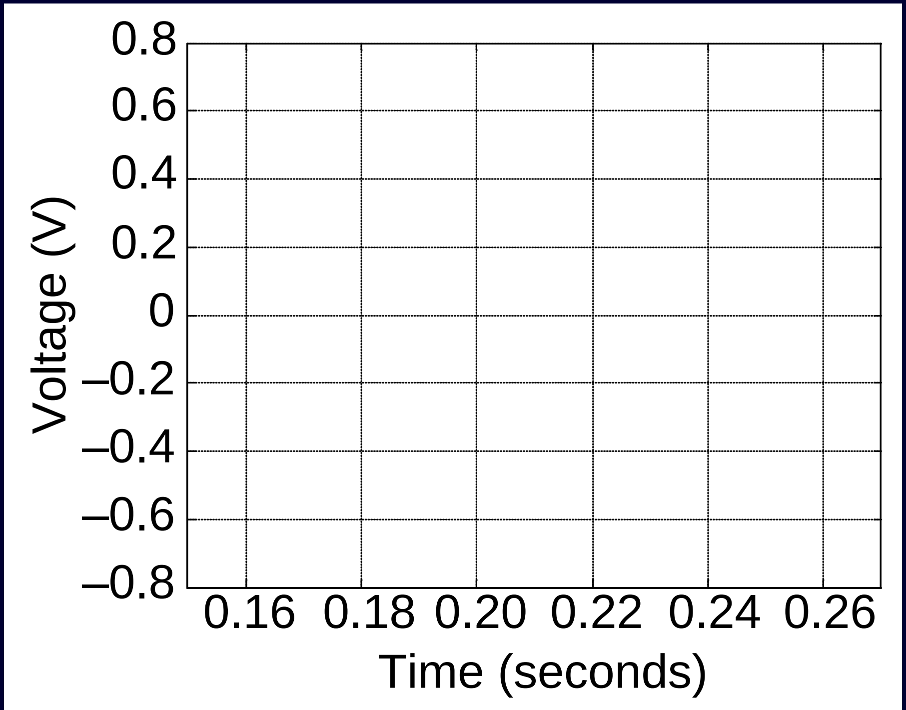


Can we use Rogowski coils to measure CT output?

Saturated CT Waveform Derivative



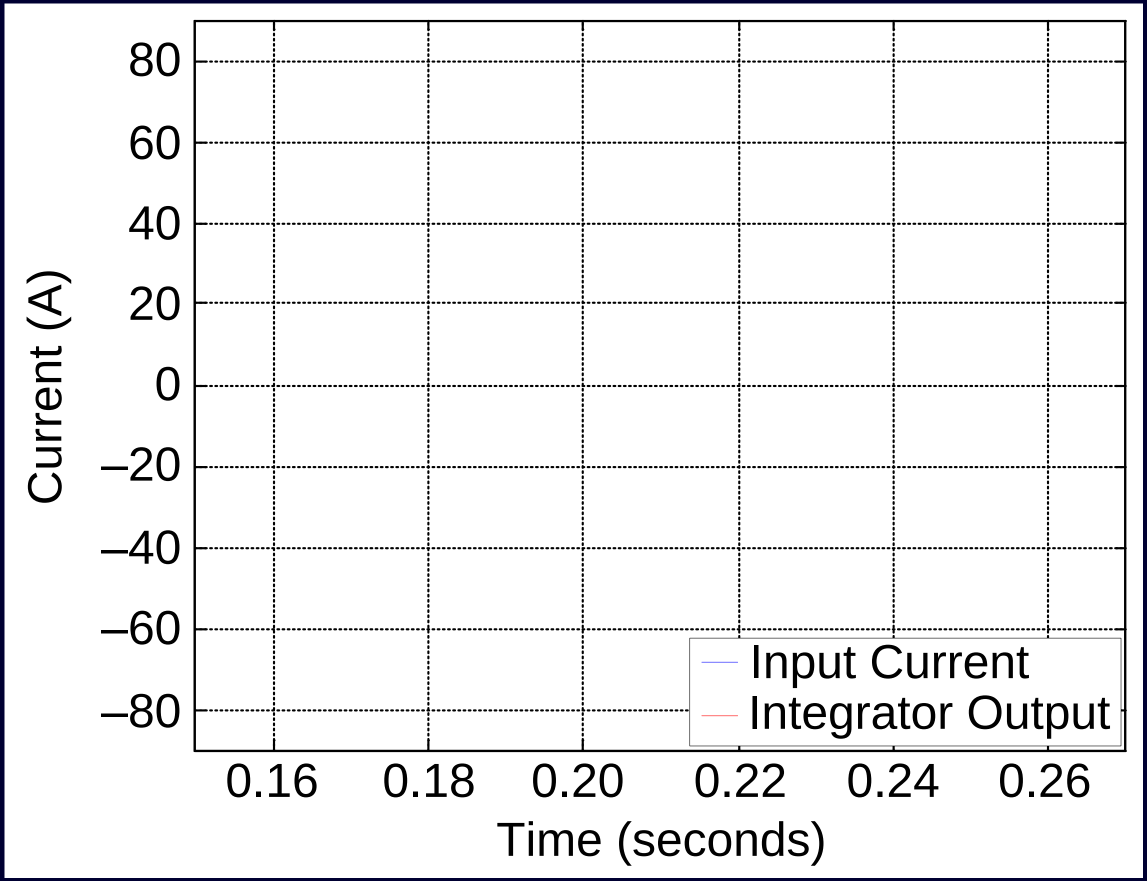
Large peaks caused by CT current collapse…



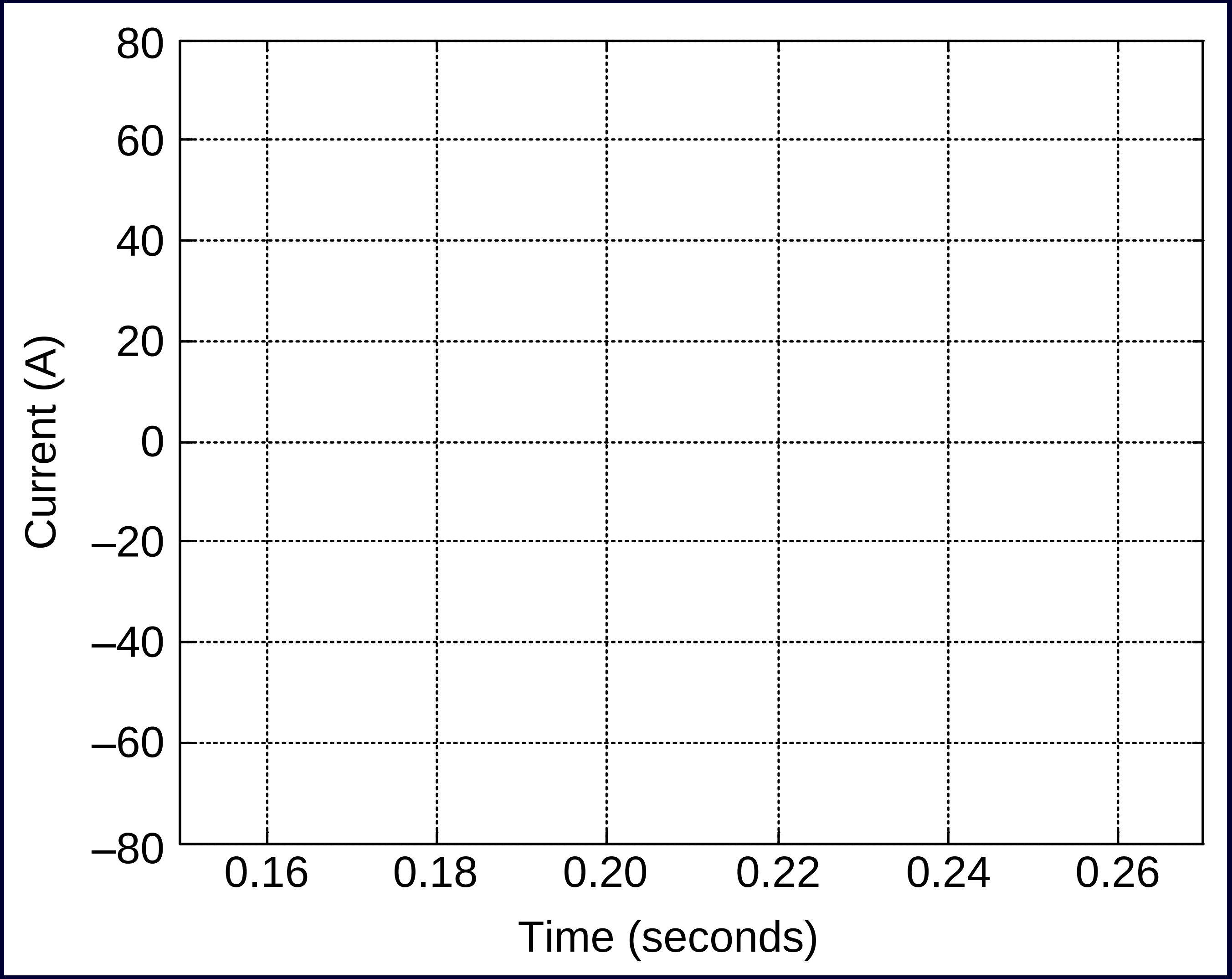
…create difficulties for the digital integrator approach

Digital Integrator Response to Clipping

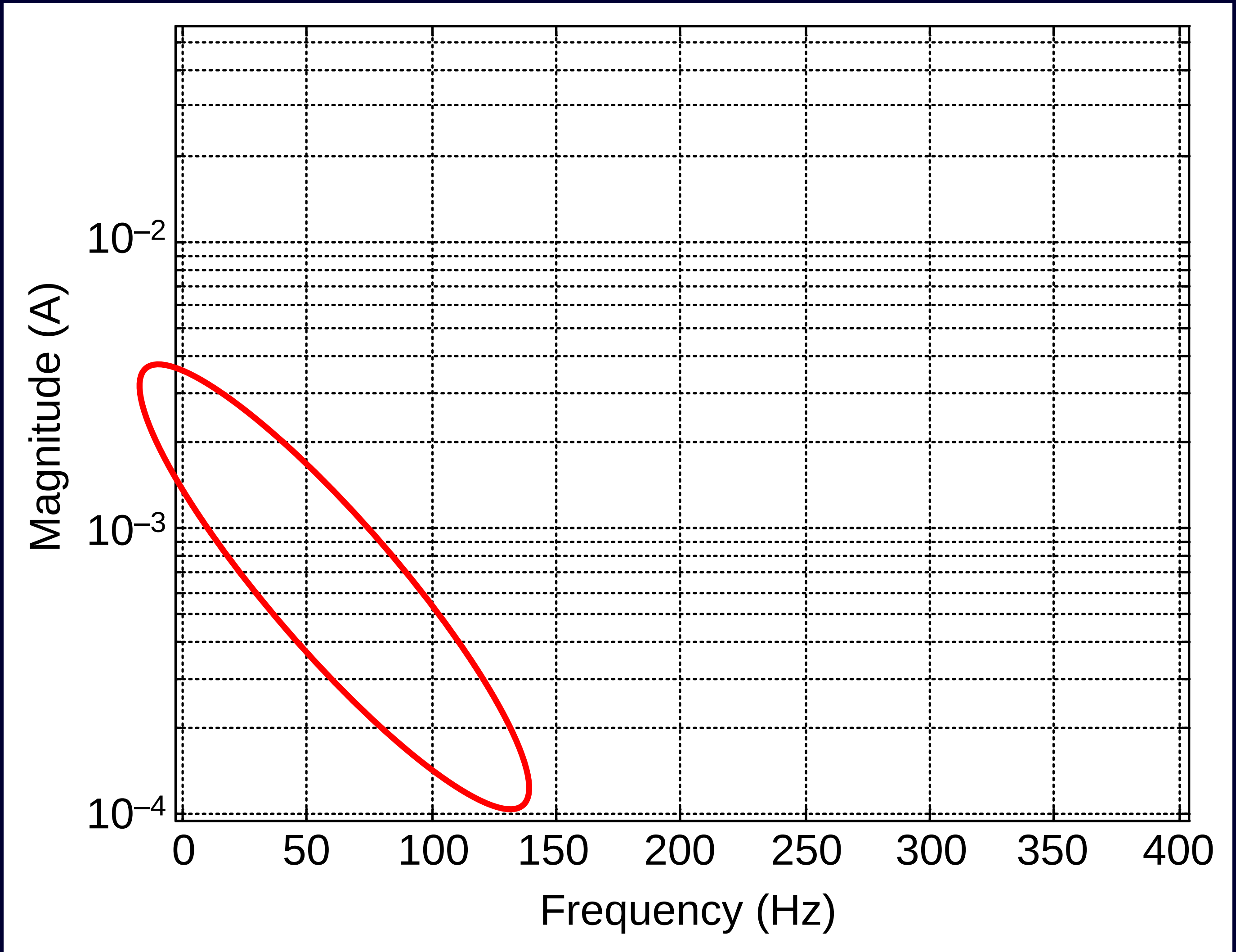
DC Component Runaway



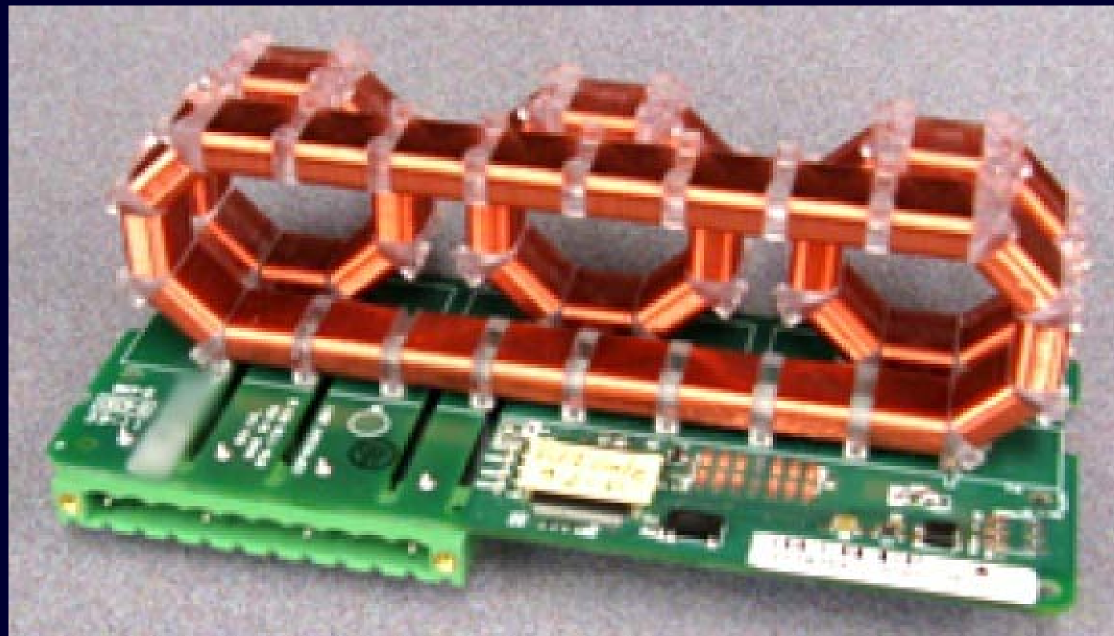
Stabilized Integrator Output



Low-Frequency Noise Magnification



Conductor Position Sensitivity



Conventional CTs are superior in
zero-sequence current measurement

Conclusion

- Rogowski coil technology is very promising
- Advantages of technology are real
- Coils can be used in the primary and in the CT secondary circuits (relay inputs)
- Paper discusses real-life constraints and presents methods to address them

Questions?