The Ping Test and Circuit Resonance
by Philip J Hopkinson, PE HVOLT Inc.

Low Energy dc test circuit to determine system switching resonance
The Ping Test and Circuit Resonance
by Philip J Hopkinson, PE HVOLT Inc.

The Circuit
The Test
The waveforms
Conclusions and Discussion
The Ping Test and Circuit Resonance
by Philip J Hopkinson, PE HVOLT Inc.

Typical Circuit at a Data Center

- Source
- Breaker
- Shielded Cable
- Inductive Load
- Transformer---especially a low loss transformer!
The Ping Test and Circuit Resonance
by Philip J Hopkinson, PE HVOLT Inc.

The Switching event:
Opening or closing the Vacuum or SF6 Breaker
Shielded Cable
Low Loss Transformer
Inductive Load
The Ping Test and Circuit Resonance
by Philip J Hopkinson, PE HVOLT Inc.

The Switching event:

Switching at a Light Rail Substation
Line 1 to Gr. Voltage
With 20:1 Attenuators & Arc Gap@ 5.5”

1. Circuit breaker contacts open and transient recovery voltage (TRV) rises by \(\frac{dI}{dt}\) to \((-)100\) kV in \(~90\) \(\mu\text{sec.}\).

2. Contacts reignite back into conduction, current rises to peak and decays to chopping level, inducing oscillatory transient. Voltage rises by +145 kV in <1 \(\mu\text{sec.}\), then oscillates to zero.

3. Current decays and is chopped out of conduction and voltage oscillates to zero.

4. Second TRV voltage rises to \((-)80\) kV, then breaker reignites, raising voltage by +120 kV in <1 \(\mu\text{sec.}\), etc.

5. Contacts open sufficiently to prevent reignition current and interruption is completed.
The Ping Test and Circuit Resonance
by Philip J Hopkinson, PE HVOLT Inc.

The High Frequencies from Current Chops:
Right view is expansion from 263-300 microseconds.

Ping Test on 34.5 kV Light Rail Transformer with 3.9 amps/pole: Line 1 to ground on 2/2/06, tap position 4,5 (2:1 attenuators and 4" gaps)

Ping Test #2 at 3.9 amp/pole on 34.5 kV Light Rail Transformer Line 1 to ground (2:1 attenuators and 4" gaps), Reignition/Current chop starting at 263.4 microsec. 1st rise 0.6 microsec., 714 kHZ
The Ping Test and Circuit Resonance
by Philip J Hopkinson, PE HVOLT Inc.

The Switching event:

Two dominant frequencies observed

• 20 kHZ Transient Recovery Voltage associated with total system impedance

• 700+ kHZ Circuit Breaker chops/reignitions, driven mostly by cable impedance
The Ping Test and Circuit Resonance
by Philip J Hopkinson, PE HVOLT Inc.

The Switching event:

HV SF6-insulated metal-enclosed switchgear (GIS)

![Diagram of electrical quantities](image.png)
The Ping Test and Circuit Resonance
by Philip J Hopkinson, PE HVOLT Inc.

The Switching event:

1. TRV initial surge at ~10-20 kHZ (50-90 μsec. Rise)
2. Envelope of initial TRV oscillations
3. Reignition transient rising in 0.6 μsec. to 150% of TRV
4. Current Chop with resulting 700 kHZ frequencies
5. Final envelope of TRV/reignition oscillations with combination 20 and 700 kHZ frequencies
6. Flashovers propelled by surface tracking and major gap breakdown

Reignitions
Current Increasing

TRV
Transient Recovery Voltage
Current Decreasing

% Winding

% Volts

20 kHZ Oscillations
700 kHZ on 20 kHZ Oscillations

0 20 40 60 80 100 120
The Ping Test and Circuit Resonance

by Philip J Hopkinson, PE HVOLT Inc.

The Effect Of Cable Resonance:

- Effect Of Cable Resonance Is Large Voltage Gradients Across High Voltage Coil Surface
  Produced by Multiple Voltage Swings (>30) per TRV Voltage Period!

1. TRV initial surge at ~10-20 kHZ (50-90 µsec. Rise)
2. Envelope of initial TRV oscillations
3. Current Chop with resulting 700 kHz frequencies
4. Final envelope of TRV/reignition oscillations with combination 20 and 700 kHz frequencies
5. Flashovers propelled by surface tracking and major gap breakdown
6. Flashovers propelled by surface tracking and major gap breakdown

Effect Of Cable Resonance Is Large Voltage Gradients Across High Voltage Coil Surface
Produced by Multiple Voltage Swings (>30) per TRV Voltage Period!
The Ping Test and Circuit Resonance
by Philip J Hopkinson, PE HVOLT Inc.

Relationship to Full-Wave Impulse:

IEEE/ANSI Full Wave Impulse Test applied to line terminal

Per IEEE C57.89

1.2 microseconds = time to crest of wave

Voltage rises from zero reference to crest BIL level in 1.2 µ sec.

150 Volts in kV

150 kV BIL

50% or 75 kV

0 10 20 30 40 50 60
Time in microseconds

50 microseconds = time to 50% of wave crest

Voltage decays slowly from crest BIL level to 50% of crest level in 50 µsec.

%Volts

20 40 60 80 100

% Winding

25 50 75 100

Envelope Of Oscillations

Initial Surge

Full Wave Impulse a single-event test with adjacent sections of windings oscillating together
The Ping Test and Circuit Resonance
by Philip J Hopkinson, PE HVOLT Inc.

Circuit Protection Objectives:

1. Minimize TRV Voltage excursion
2. Prevent Breaker reignitions

High Frequency switching energy must be dissipated
The Ping Test and Circuit Resonance
by Philip J Hopkinson, PE HVOLT Inc.

Circuit Protection Options:

1. Use much slower Breakers
   - Oil
   - Air
2. Increase transformer Losses
   - Magnetic Circuit
   - Windings
   - Dielectric System
3. Add Resistor-Capacitor Snubbers

Lightning Arresters alone generally not effective for Delta-Connected Windings
Circuit Protection Options:

1. Slower Breakers is contrary to 40-year Industry evolution

   • Oil generally considered objectionable due to maintenance, environment and safety
   • Air-breakers used for low current switching only
The Ping Test and Circuit Resonance  
by Philip J Hopkinson, PE HVOLT Inc.

Circuit Protection Options:

2. Lossy Transformers contrary to National and International push for higher Energy Efficiency
   • Modern magnetic circuits use high grade grain-oriented steels and wound or mitered cores.
   • Winding resistances kept low for efficiency, temperature rise and life
   • Dielectric loss normally associated with poor dielectric strength
Circuit Protection Options:

2. Resistor-Capacitor Snubbers Including ZORCS
   Costly but effective
The Ping Test and Circuit Resonance
by Philip J Hopkinson, PE HVOLT Inc.

Arrester Limitations For Delta-Connected Windings:

2 Basic Limitations Of Arresters

1. Arresters clip but do not damp
2. Arresters ground 1 corner only—protection requires 2 or more arresters to fire
Conclusions:

1. Switching Transients may produce a combination of 2 frequencies (20 and 700 kHZ).

2. Delta-connected high efficiency transformers with Very Low Power factor inductive loads are most susceptible, esp. Light Rail, Welders, Drives, Data Centers, and other Rectifier loads.

3. Switching Voltages can easily exceed BIL Levels.

4. R-C Snubbers or ZORCS are best system protectors.