Application of Power Circuit Breakers for Switching Capacitive and Light Inductive Currents

IEEE Circuit Breaker Tutorial

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Fellow
Nature of Capacitive and Small Inductive Currents

- Small in magnitude
  - Some technologies use current to assist in interruption
- Current and voltage 90 degrees out of phase
- Circuit breakers frequently called upon to deal with switching these currents
- Switching can result in extreme magnitudes of currents and extreme rates of change of voltage

This presentation is based on C37.012 and C37.015, the application guides for switching these currents. It is impossible to cover all the material in these in detail, and there are other important issues with switching these currents that are not covered in the application guides. This presentation is intended to provide an overview of all the issues associated with switching these currents.
Shunt Capacitor Bank Switching

- Continuous Current
  - Margins for capacitor tolerance
  - Margins for harmonic current
  - Margin of 35% typical

- Interrupting shunt capacitor bank current
What is a Restrike?
Restrike, Back to Back with CLR’s

![Breaker Restrike C Phase, Test IB-6](image)

- **Bus V**: 200 kV/Div
- **Cap V**: 200 kV/Div
- **Bnk 3 I**: 5000 A/Div

- **Beg**: 130.0 ms
- **End**: 170.0 ms
- **Breaker Restrike**: 16.0 kA
Energizing Shunt Capacitor Banks

Single or isolated bank
Back to back
500 kV Single Bank Energization
500 kV Back to Back Energization
Consequences of Capacitor Inrush Transients

- Dip to zero voltage
  - Interference with devices that use zero crossing detectors

- Back to back results in extremely high currents
  - Damage to primary and secondary equipment
  - Safety

- Restrike (trapped charge)
  - $2 \times$ the voltage, effects $2 \times$
Mitigation of Closing Transients

- Closing Resistor or Reactor
- Fixed Current Limiting Reactor
- Controlled closing
500 kV Back to Back Energization with CLR

![Graph showing voltage and current over time.](image-url)
Controlled Closing, Single Bank

![Graph showing voltage and current responses during controlled closing]

- **100 kv/div**
- **500 A/div**
- **Time 5 ms/div**

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Capacitor and Reactor Switching, J. H. Brunke, July 2008
Controlled Closing, Back to Back

![Graph showing voltage and current transients during controlled closing.](image)
Controlled Closing, Capacitor Banks, targeting

Absolute value of bus voltage

Target in a perfect world

Target in the real world
Switching Capacitor Through a Transformer

- Transformer Saturates
- Capacitor Bank Current
- Breaker Recovery Voltage
- Capacitor Bank Voltage
Faults Near Capacitor Banks

- Outrush, TRV effects, high source impedance voltage rises (or long lining), etc.
Line Fault, 500 kV system, with 430 Mvar of Connected Capacitors
# Circuit Breaker Standards

Restrike probability: C0, no rating, C1, ~ 1 restrike in 50 operations, C2, ~ 1 restrike in 300 operations

<table>
<thead>
<tr>
<th>Line No.</th>
<th>Rated Maximum Voltage</th>
<th>Rated Continuous Current</th>
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<tr>
<td>Col 1</td>
<td>Col 2</td>
<td>Col 3</td>
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<td>A, rms</td>
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## Circuit Breaker Standards

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<th>Line No.</th>
<th>Rated Maximum Voltage (kV, rms)</th>
<th>Rated Continuous Current (A, rms)</th>
<th>Class C1 or Class C2 Circuit Breakers (2) (4)</th>
<th>Back to back Capacitor Bank Switching</th>
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Switching Overhead Transmission Lines - Interruption
Switching Overhead Transmission Lines

![Graph showing voltage and current waves with annotations for unfaulted and faulted phase trips.]

- Voltage A ph 200 kV/Div
- Voltage B ph 200 kV/Div
- Voltage C ph 200 kV/Div
- Current C ph 1000 A/Div

Begin: 0.0 140 ms/div
End: 1.400 s
Charging Current and Recovery Voltage

![Graph showing charging current and recovery voltage]

**Charging Current in Amperes per Mile**

- **Single Conductor**
- **Two-Conductor Bundle**
- **Four-Conductor Bundle**

**System Voltage, Kilovolts**

**Recovery Voltage, p.u.**

- **Positive Sequence Capacitance**
- **Zero Sequence Capacitance**
Recovery Voltage on Unfaulted Phases

Neutral shift, coupling of transients
De-energization of a Line with Connected Transformer
Energization of Transmission Lines, Switching Surges

[Diagram showing voltage vs. time with peaks and voltages labeled]

1.91 PU peak

1.50 2.00 2.50 3.00 3.50
MILLISECONDS

0.00 1.00 2.00 3.00
VOLTAGE

0.00 1.00 2.00 3.00
PU
Switching Surge Overvoltages

![Graph showing switching surge overvoltages with voltage levels and phase close markers.](image-url)
Switching Surge Mitigation

- Only needed above 245 kV (rarely at 245 kV)
- Closing resistors
- Line connected surge arresters
- Controlled closing
- Trapped charge reduction (line connected PT’s – caution)
- Single pole reclosing (limited due to secondary arc)
- Controlled closing
- Staggered pole closing
Traveling Waves Present on Most Line Phenomena

Closing into a fault, 500 kV field test data.
Shunt Reactor Switching

1st Parallel 1 to 10 MHz

2nd parallel 50 to 1000 kHz

Load oscillation 1 to 5 kHz
225 Mvar Shunt Reactor Interruption

500 kV bus and reactor voltages, field test data
Time Expansion of Previous Slide
Re-ignition and Current Chopping

![Graph showing reactor voltage and current over time, with a notable re-ignition event highlighted.](Image)
Time Expansion of Previous Slide

[Graph showing Recovery Voltage and Reactor Current over time]
Reactor Current Interruption Failure

- Interruption still a difficult duty for circuit breakers
- Differences in the parameters make a standard test nearly impossible
Shunt Reactor Current Interruption w/o Controlled Opening

![Graphs showing bus voltage, reactor voltage, reactor current, and breaker contact position over time.](image-url)
Shunt Reactor Current Interruption with Controlled Opening
Energizing Shunt Reactors

- Inrush currents smaller than for power transformers (to be discussed next), and not generally considered a problem

- Can cause sympathetic inrush in nearby power transformers

- Problems have only been observed in certain configurations
Switching Transformer Magnetizing Currents
Transformer Core Characteristic

When current is zero, a residual flux remains.
Magnetizing Current Interruption

Magnetizing current interruption also showing core flux

Residual core flux remains (typical pattern)
Energizing a Transformer

\[ \text{FLUX} \]

Symmetrical Flux

Residual Flux

Instant of Energization

Peak Flux
Inrush Current
Controlled Closing Applied to Transformers

Core Flux

Residual Flux

Time

2 possibilities to energize

Bus voltage as a flux source - Prospective flux
Three Phase Transformers

\[ V_m \sin(\omega t) \]
Prospective and Dynamic Flux

Flux, residual 0%, -70%, 70%

Time ms

Flux kVs
Core Flux - No residual
Core flux with residual flux
Verification - Laboratory Tests

Delayed Closing Strategy

![Graph showing time vs voltage for laboratory tests. The graph indicates a delay in closing strategy with time (6 ms/div) and voltage (V_s) on the y-axis.](chart.png)
Test on Laboratory Transformer

Core Flux
0.2 V/seconds /div

Neutral current 5 A/div

Time 20ms/div
Controlled Closing on 500 kV Transformer
Summary

- Capacitive and light reactive currents are frequently seen and may be the most difficult duties for a circuit breaker.
- Switching surge/transient problems are typically associated with switching shunt capacitor banks, shunt reactors, transformers, cables, and lines (capacitive and light reactive currents).
- Due to the complexity, correct application for these duties can be among the most difficult application issues.
- Today solutions are available which were not in the past (modern circuit breaker technologies, controlled switching, MOSA’s, etc.).

Questions?