The Short Story

- CB can break currents quickly

\[ V = L \frac{di}{dt} \]
Circuit Breakers

- Most Often SF6 or Air-Blast
- Happens at low levels of inductive current

Simplistic Equivalent Circuit

- L: inductance of coil
- C: capacitance of coil + bushing capacitance
- Rc: core loss resistance
Overvoltage

• Assumptions:
  No losses, Linear inductance

• Stored energy in inductor:

  \[ \text{Energy} = \frac{1}{2} L_M I_0^2 \]

• Capacitor – Inductor Oscillation

  \[ \frac{1}{2} CV^2 = \frac{1}{2} L_M I_0^2 \Rightarrow V = I_0 \left( \frac{L_M}{C} \right)^{\frac{1}{2}} = I_0 Z_0 \]

Example

Transformer: 1 MVA, 13.8 kV,
\[ I_{\text{exciting}} = 1.5 \text{ A rms, } C = 5000 \text{ pF, } I_0 = 2.5 \text{ A} \]

\[ L_M = \frac{V}{\omega I_{\text{exciting}}} = \frac{13,800}{\sqrt{3 \times 377 \times 1.5}} = 14 \text{H} \]

\[ Z_0 = \left( \frac{L_M}{C} \right)^{\frac{1}{2}} = \left( \frac{14}{5 \times 10^{-9}} \right)^{\frac{1}{2}} = 53,000 \Omega \]
Example p.2

\[ f = \frac{(1/L_M C)^{1/2}}{2\pi} = 602 \text{ Hz} \]

\[ V = I_0 \left( \frac{L_M}{C} \right)^{1/2} = I_0 \times Z_0 = 2.5 \times 53,000 = 132kV \]

With Saturation

Only about 30% of stored energy is released

\[ V \approx I_0 \left( 0.3 \frac{L_M}{C} \right)^{1/2} = 72.7kV \]
Formal Analysis

\[ I_C + I_R + I_L = 0 \]

\[ I_C = C \frac{dV}{dt} \quad I_R = \frac{V}{R} \quad I_L = \frac{1}{L_M} \int V \cdot dt \]

Formal Analysis 2

\[ \frac{d^2V}{dt^2} + \frac{1}{RC} \frac{dV}{dt} + \frac{V}{L_MC} = 0 \]

\[ V(s) = \frac{sV_0}{s^2 + \left(\frac{s}{RC}\right) + \left(\frac{1}{L_MC}\right)} + \frac{V_0}{RC} \frac{1}{s^2 + \left(\frac{s}{RC}\right) + \left(\frac{1}{L_MC}\right)} \]

\[ -\frac{I_0}{C \left[ s^2 + \left(\frac{s}{RC}\right) + \left(\frac{1}{L_MC}\right) \right]} \]
Characteristics of Transients

- Frequency of oscillation is a few kHz for iron core reactors, hundreds of kHz for dry, air-core reactors
- Relatively little energy is trapped
  Surge arrestors can usually deal with it

Detailed Reactor Model

Rc: Core loss; ≈ 1000 pu for iron core, infinite for air core
Rw: Winding resistance; same value as similar transformer winding, ≈ 0.5%
L: Reactor inductance, nameplate value
CL: \( \frac{1}{2} \) Winding capacitance; iron core - same as similar transformer winding (See Ch 13, Greenwood); air core: 75 – 150 pF
Cb: Bushing capacitance; 150 – 600 pF

See also: C37.011 Appendix B
Tables B1 → B7
Restrikes

When breaking low level highly reactive currents:

- The arc is weak because the current is not large
- The contacts are not far apart when the arc extinguishes
- The system voltage is near its peak so the recovery voltage can be large

Dependent on how quickly the dielectric strength between the contacts recovers

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Restrike Equivalent Circuit

Cp, Lp: Parasitic capacitance and inductance of the CB; value ?, use potential grading cap
Ls: Equivalent system inductance
Lo: bus work inductance
Cs: System capacitance; CB bushing and buswork
C: Reactor equivalent capacitance; CB bushing, reactor bushing, winding cap
Frequencies of Oscillation

High f Equivalent Circuit

With high frequency waves, series capacitance forces uneven voltage distribution. Terminal end sees highest voltage.
Example: Parkers Lake

2 dry type, air core reactors on 13.8 kV tertiary

Reactor 1: 7 \( \Omega \) \( \rightarrow \) 27.2 Mvar \( \rightarrow \) 18.57 mH

Very little capacitance; use 200 pF

Assume \( R_{\text{winding}} = 0.1\% \), \( R_{\text{core}} = \infty \)

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Reactor 1 Predictions

Surge Impedance: \( Z_0 = \sqrt{\frac{L}{C}} = 9.64k\Omega \)

Frequency: \( f_0 = \sqrt{\frac{1}{LC}} \div \frac{2 \pi}{1} = 82.6k\text{Hz} \)

\( \text{peak} \approx I_{\text{chop}} \times Z_0 \)
Reactor Opening: Simulation

- Top = 0.01
- Imar = 10

Switch dialog box:
Imar – current margin
switch opens if t > T-op AND || < Imar

Reactor 2

Reactor 2: 12.7 Ω -> 15 Mvar -> 33.69 mH

Has parallel capacitor to lower surge impedance and frequency.

What’s the value?
My guess: 0.2 μF

Assume $R_{\text{winding}} = 0.1\%$, $R_{\text{core}} = \infty$
Reactor 2 Predictions

Surge Impedance: \( Z_0 = \sqrt{\frac{L}{C}} = 410.4\,\Omega \)

Frequency: \( f_0 = \frac{\sqrt{1/LC}}{2\pi} = 1.94\,kHz \)

\[ peak \approx I_{chop} \times Z_0 \]

Reactor Opening: Simulation

[Diagram showing a reactor circuit with components labeled as follows: Top = 0.001, Imar = 10, 40 nF, .0127, 12.7 ohm.]
Try using a saturable inductor

Use: L(i) Type 98 – Dialog Box
CURR: peak current in A
FLUX: flux in Volt-sec

Current/Flux Data

Need $I_{\text{peak}}$ and magnitude ($\int V \, dt$)

$13.8 \text{ kV} \rightarrow 7967 \text{ V l-n}$

$I = \frac{V}{Z} \rightarrow I = 1138 \text{ A rms} \rightarrow 1610 \text{ A peak}$

$\text{Volt-sec} = \frac{7967 \times 2^{1/2}}{2 \pi 60} = 29.888 \text{ V-sec}$
Saturation Data

<table>
<thead>
<tr>
<th>V (pu)</th>
<th>Peak Current (A)</th>
<th>Flux (Volt-sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>1610</td>
<td>29.888</td>
</tr>
<tr>
<td>1.1</td>
<td>5506</td>
<td>32.877</td>
</tr>
</tbody>
</table>

"Characteristic" tab in "Component" dialog box

Add excitation losses

Lose ~ 70% of stored energy
Gives $R = 3750 \, \Omega$
Add a surge arrestor

Use "MOV Type 92"

Attributes: change default

\[ V_{ref} = 2 \times \text{system V} \]

Surge Arrester Data

<table>
<thead>
<tr>
<th>Current (A)</th>
<th>Voltage (V)</th>
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<tbody>
<tr>
<td>5*</td>
<td>13800*</td>
</tr>
<tr>
<td>1500</td>
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<td>20000</td>
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<tr>
<td>40000</td>
<td>65900</td>
</tr>
</tbody>
</table>

Need to know low current characteristic
Difficult to find (I made it up)