Capacitor Switching in Power Distribution Systems

Kirk Smith
Eaton Corporation
Horseheads, New York

Capacitor Switching

- **Capacitor switching – a special case of load current switching**
  - **Cable charging current switching**
  - **Line charging current switching**
  - **Single bank capacitor switching**
  - **Back-to-back capacitor bank switching**

Capacitor Switching

- **Capacitor switching is encountered for all load current switching devices**
  - **All load current switching devices**
    - **Cable charging current switching**
    - **Line charging current switching**
  - **Special duty load current switching devices**
    - **Single bank capacitor switching**
    - **Back-to-back capacitor bank switching**

Capacitor Switching

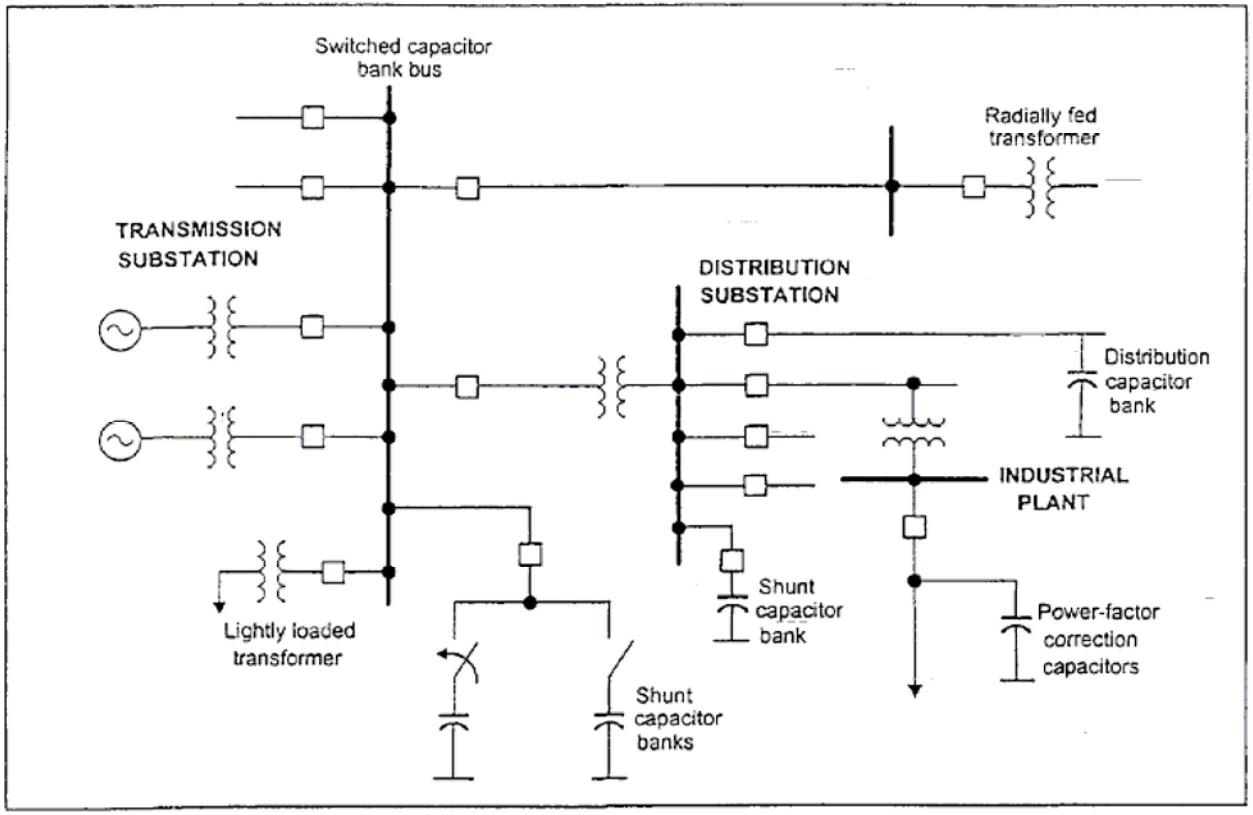

Figure 1. Schéma unifilaire d'un réseau typique indiquant les emplacements des matériels affectés par les transitoires résultant de la mise sous tension de bancs de condensateurs shunt [13].

Figure 1. One-line diagram of a typical power system, indicating the locations of power system equipment affected by transients resulting from energizing of shunt capacitor banks [13].

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Capacitor Switching

Ranges of typical capacitor switching currents

Line switching typically < 10A

Cable switching typically < 50A

Isolated Capacitor Bank switching:

12kV, 1 MVar – 48A; 10 MVar – 481A

24kV, 10 Mvar – 242A; 40 Mvar – 1157A

36kV, 10 Mvar – 150A; 40 Mvar – 770A

The Current Interruption Process - AC

- **Interruption stresses for a switch to withstand**
  - **Current to interrupt**
  - **Voltage to withstand**

The Current Interruption Process - AC

- **Current stress**
  - **Magnitude of current peak, Ip**
  - **Rate di/dt approaching Current Zero**
- **Voltage stress**
  - **Magnitude of voltage peak, Vp**
  - **Rate dv/dt after Current Zero**

The Current Interruption Process - AC

- **Three basic types of circuits**
  - **Resistive**
  - **Inductive**
  - **Capacitive**
- **Let's compare the currents and voltages in these 3 cases**
- **Examples from Garzon - HVCBs**

Resistive Circuit Interruption

- **Resistive Circuits - Fig 1.6**
  - **V and I in phase**
  - **Recovery voltage rise is slow**
    - **¼ cycle of power frequency to Vp**
    - **takes 4 to 5 milliseconds**
  - **Vp = to Vpeak of system voltage**

Resistive Circuit Interruption

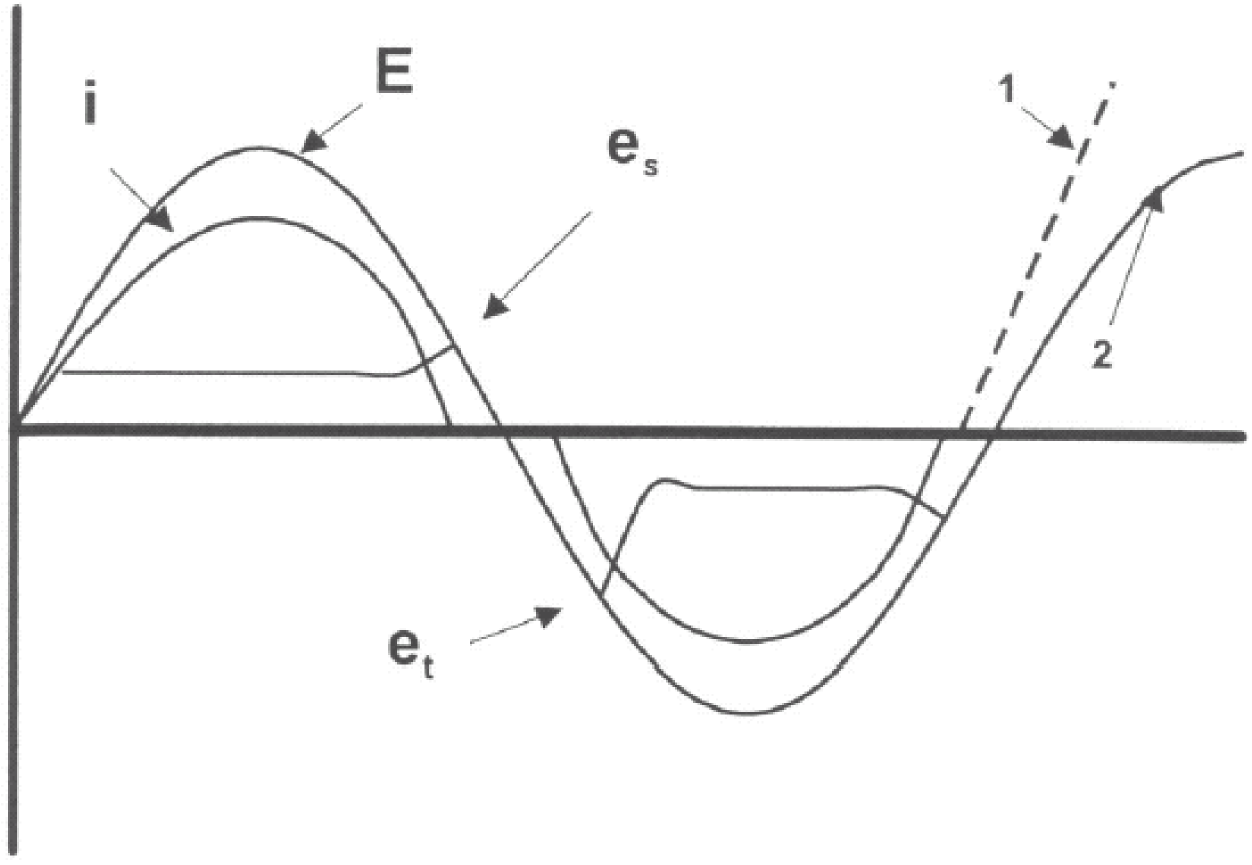


Figure 1.6 Interruption of a purely resistive circuit showing the current, voltages and recovery characteristics, for the electrode space (curve 1) and for the system voltage (curve 2).

Inductive Circuit Interruption

Inductive Circuits - Fig 1.7

- I lags V by 90 degrees
- Recovery voltage rise is fast
  - 10’s to 100’s of microseconds to Vp
  - Much faster than a resistive circuit
- Recovery voltage is high
  - Vp = 1.5 x Vpeak of system voltage
  - Higher Vp than a resistive circuit

Inductive Circuit Interruption

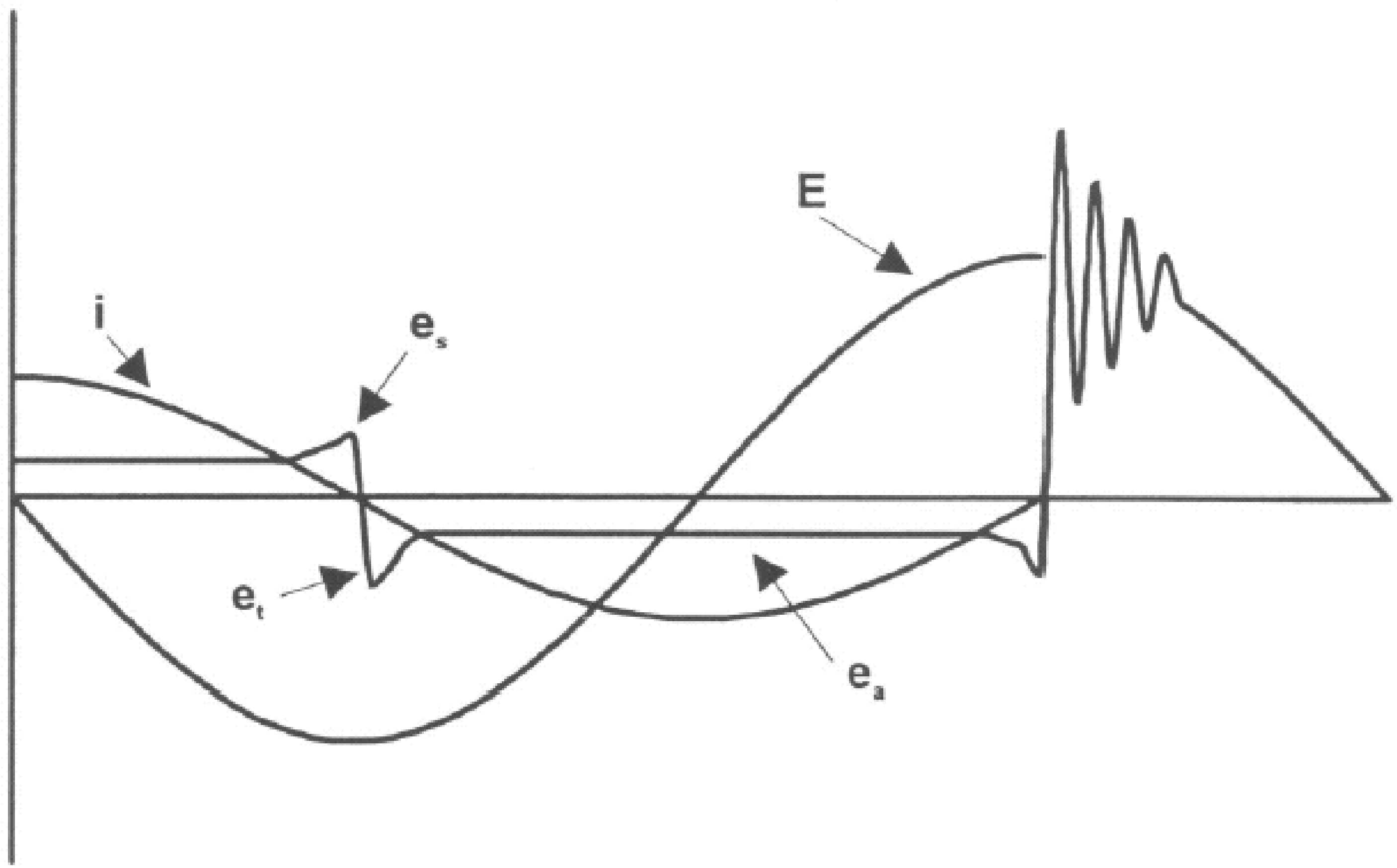


Figure 1.7 Current and voltage characteristics during interruption of an inductive circuit.

Capacitive Circuit Interruption

Capacitive Circuits - Fig 1.8

- **I leads V by 90 degrees**
- **Recovery voltage rise is slow**
  - **½ cycle of power frequency to Vp**
  - **takes 8 to 10 milliseconds**
  - **Slower than a resistive or inductive circuit**
- **Recovery voltage is high**
  - **Vp $\geq$ 2 x Vpeak of system voltage**
  - **Higher Vp than a resistive or inductive circuit**

Capacitive Circuit Interruption

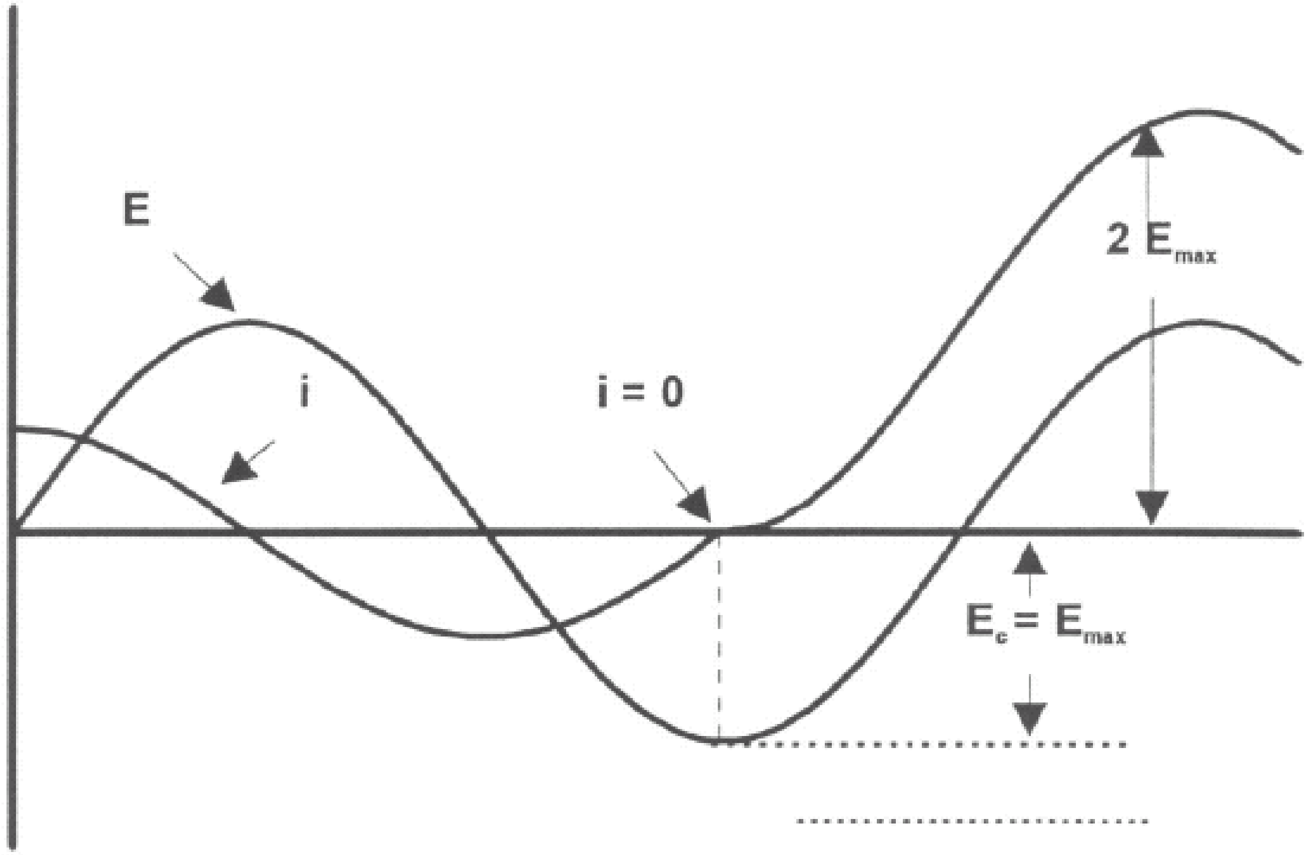
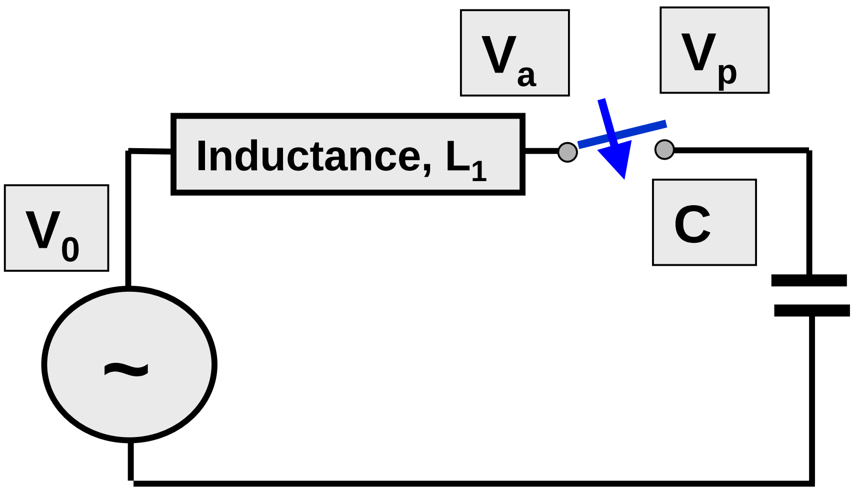


Figure 1.8 Voltage and current characteristics during the interruption of a capacitive circuit

Capacitor Switching Topics

- **Energizing a single capacitor bank**
- **Energizing back to back capacitor banks (capacitor banks in parallel)**
- **De-energizing capacitor banks**
- **Cable switching & line dropping**

Energizing a Single Capacitor Bank



$$I(inrush) = (V_0/Z)\sin\omega_1 t$$

$$\omega_1 = [1/L_1C]^{0.5}$$

I(inrush) = few kA, ω_1 = few 100's Hz

When the switch closes, the inrush current flows from the source to charge the capacitance

The inrush current affects the whole system from the power source to the capacitor bank, and especially the local bus voltage which initially is depressed to zero.

Energizing a Single Capacitor Bank

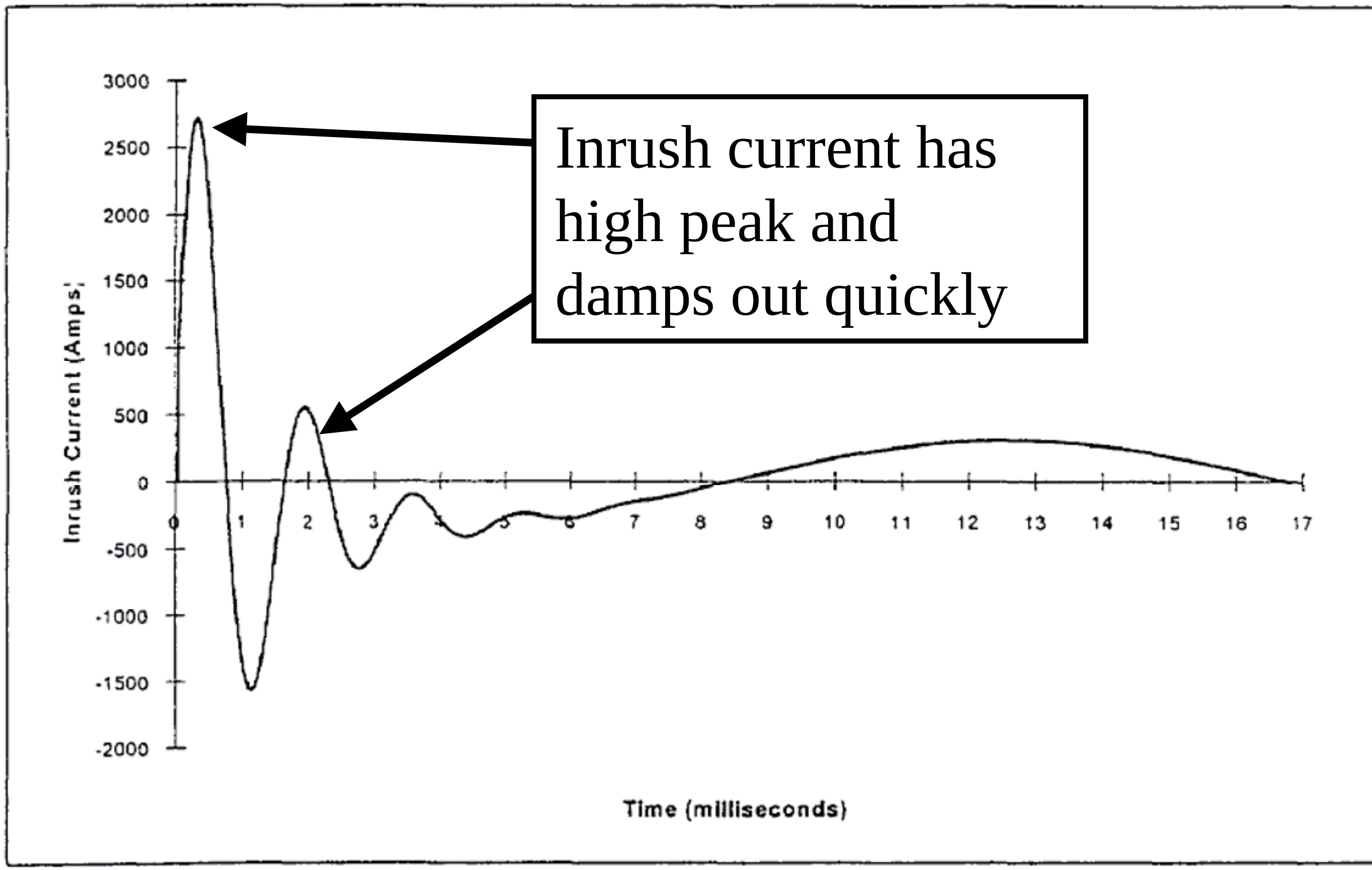


Figure 6. Courant d'appel lors de la mise sous tension d'un banc unique de condensateurs shunt à la tension de crête [13].

Figure 6. Inrush current when energizing a single shunt capacitor bank at peak voltage [13].

Energizing a Single Capacitor Bank

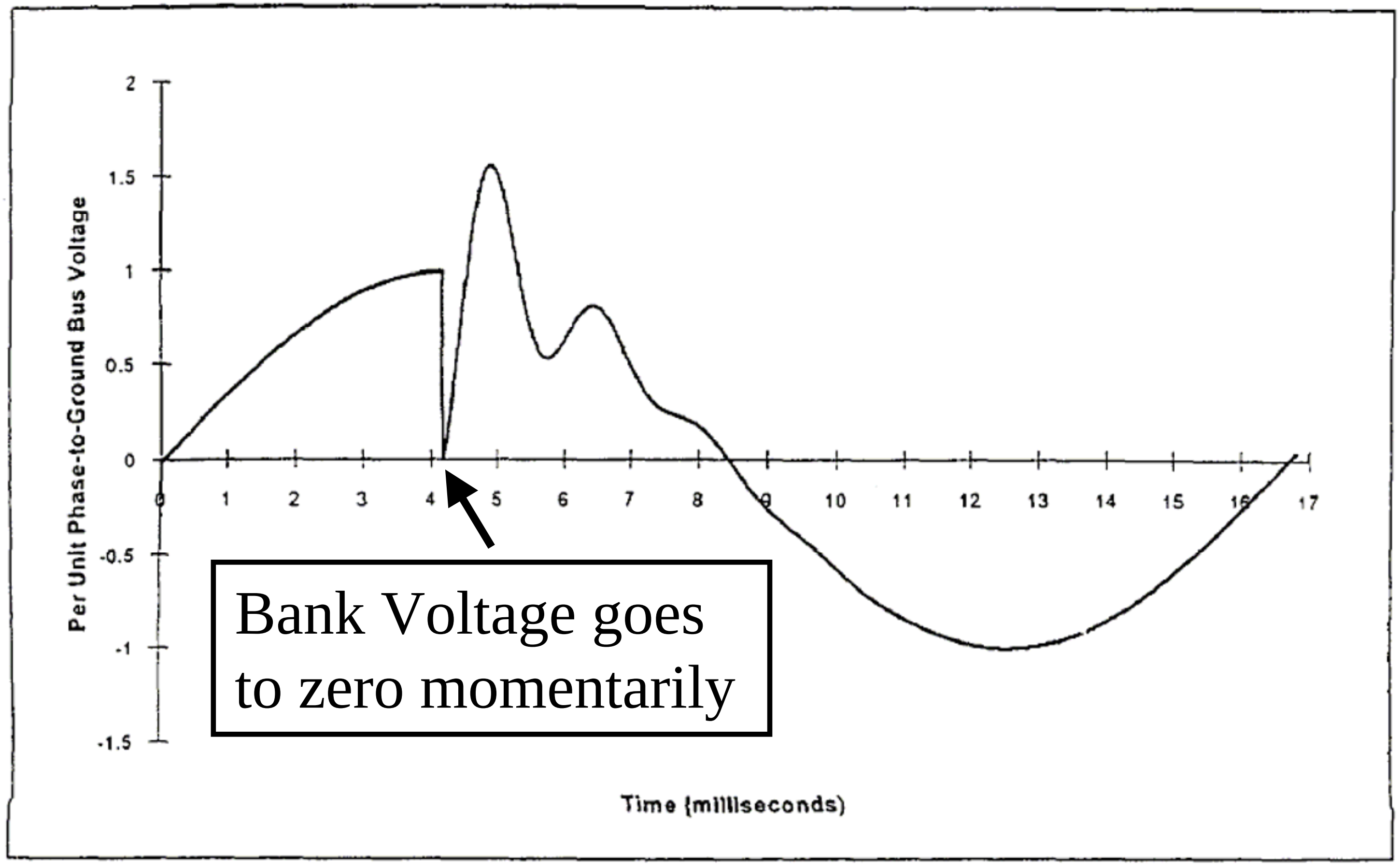


Figure 2. Surtension sur le jeu de barres raccordé à un banc de condensateurs shunt lors de la manœuvre de mise sous tension de ce banc [13].

Figure 2. Switched capacitor bank bus overvoltage when energizing a shunt capacitor bank [13].

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Energizing a Single Capacitor Bank

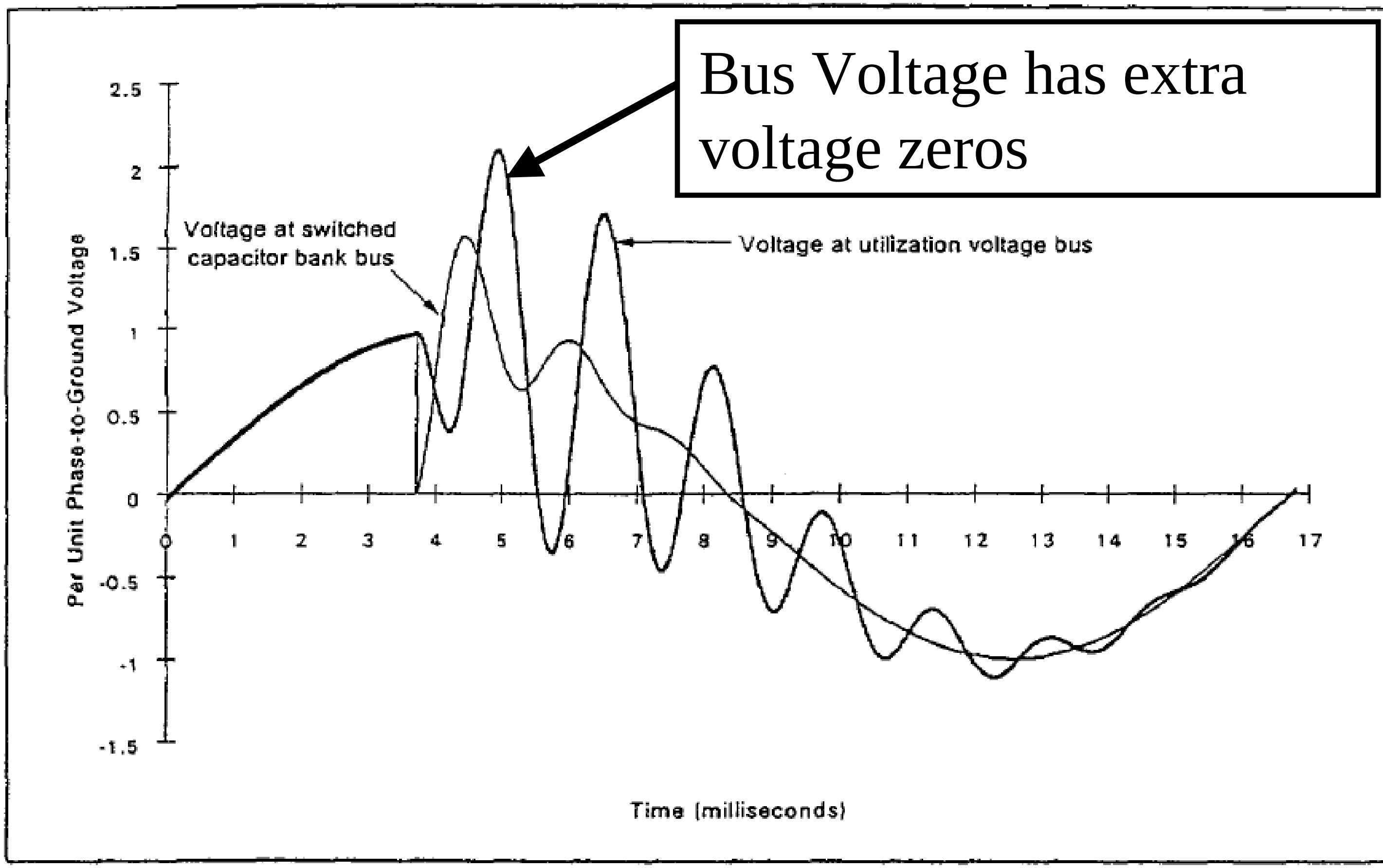

Figure 3. Surtensions entre phase et terre sur le jeu de barres raccordé à un banc de condensateurs et sur le jeu de barres à la tension d'utilisation, illustrant l'amplification de la tension [13].

Figure 3. Phase-to-earth overvoltages at the switched capacitor bank bus and at the utilization voltage bus, illustrating voltage magnification [13].

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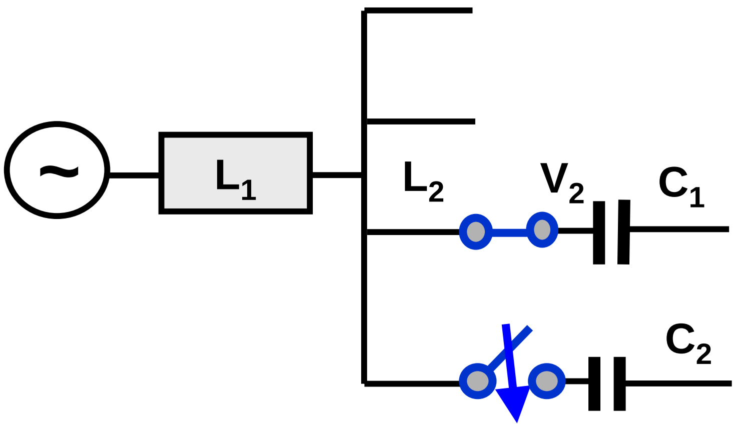
Energizing Back to Back Capacitor Banks



When the switch closes to insert the second capacitor bank, the inrush current affects mainly the local parallel capacitor bank circuits and bus voltage.

I(inrush) = $(V_2/Z_2)\sin\omega_2 t$

I(inrush) = few 10's kA at ω_2 = few kHz

The peak inrush current should be limited for

Low probability re-strike performance

Energizing Back to Back Capacitor Banks

Back to back inrush current

-Much higher peak

-Much higher Frequency

-Damps out more quickly

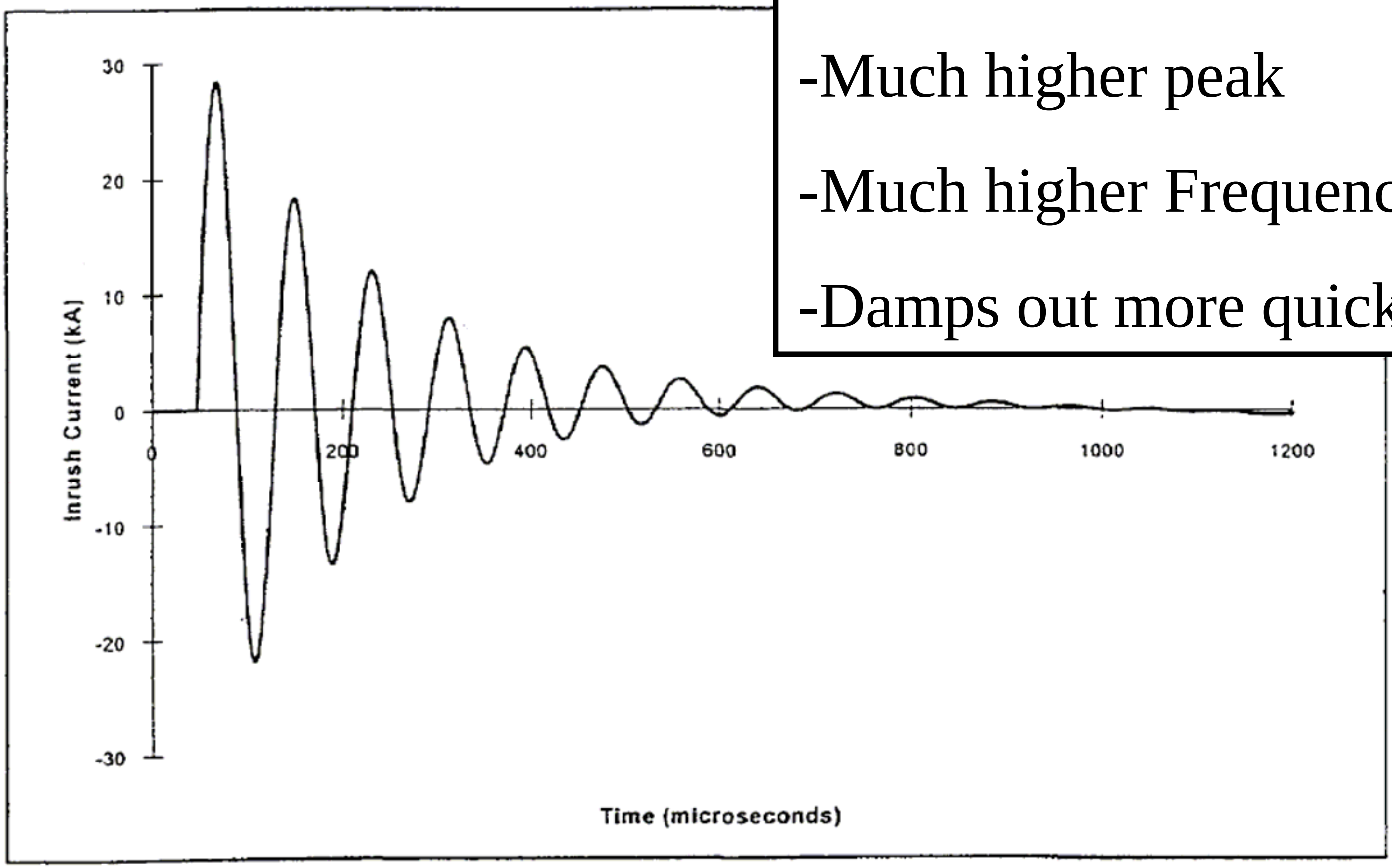


Figure 7. Courant d'appel lors de la mise sous tension de bancs de condensateurs shunt dos à dos [13].

Figure 7. Inrush current when energizing back-to-back shunt capacitor banks [13].

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Examples of Inrush Currents

Larry Smith, IEEE 1995

- **Three capacitor banks on one bus**
  - **$V_{l\text{-}l}$ = 145 kV, $E_{l\text{-}l}$ = 138 kV**
  - **$C_1 = C_2 = C_3$ = 10 Mvar, grounded wye**
  - **Fs = 60 Hz**
  - **Ls = 50,000 μH, system inductance**
  - **$L_1 = L_2 = L_3$ = 23 μH, bank L**
  - **$L_{B1} = L_{B2}$ = 13 μH, bus L**

Examples of Inrush Currents

Larry Smith, IEEE 1995

- **Energize the first bank**
- **Single or isolated bank**
- **Inrush current**
  - $\mathbf{I_{inrush\ peak}}$ **= 0.67 kA, peak**
  - $\mathbf{I_{inrush\ frequency}}$ **= 535 Hz**

Examples of Inrush Currents

Larry Smith, IEEE 1995

- **Energize the second bank**
- **Back-to-back banks**
- **Inrush current**
  - $I_{\text{inrush peak}}$ **= 14.1 kA, peak**
  - $I_{\text{inrush frequency}}$ **= 22.4 kHz**
- **Inrush current - Back-to-back banks**
  - **Peak and frequency much higher**

Examples of Inrush Currents

Larry Smith, IEEE 1995

- **Energize the third & fourth banks**
- **Inrush current, third bank**
  - $I_{inrush\ peak}$ **= 15.5 kA, peak**
  - $I_{inrush\ frequency}$ **= 18.4 kHz**
- **Inrush current, fourth bank**
  - $I_{inrush\ peak}$ **= 16.1 kA, peak**
  - $I_{inrush\ frequency}$ **= 17.1 kHz**

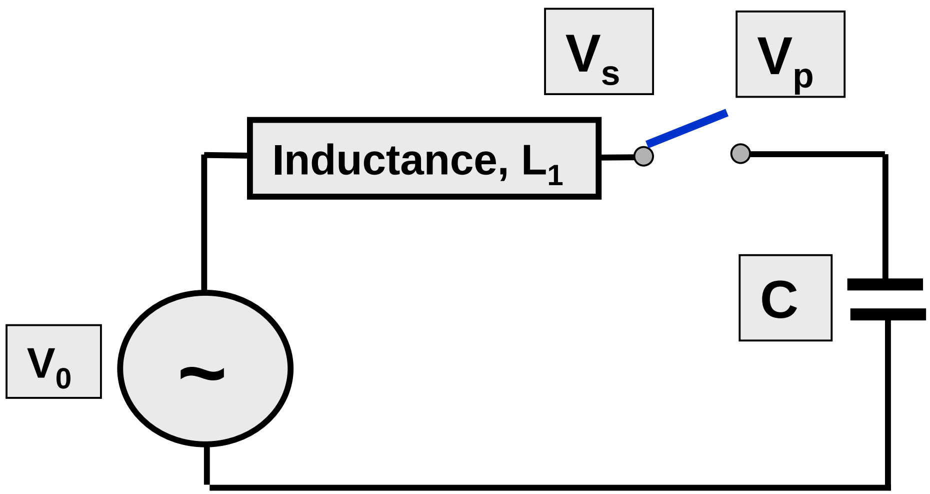
Effects of Inrush Currents

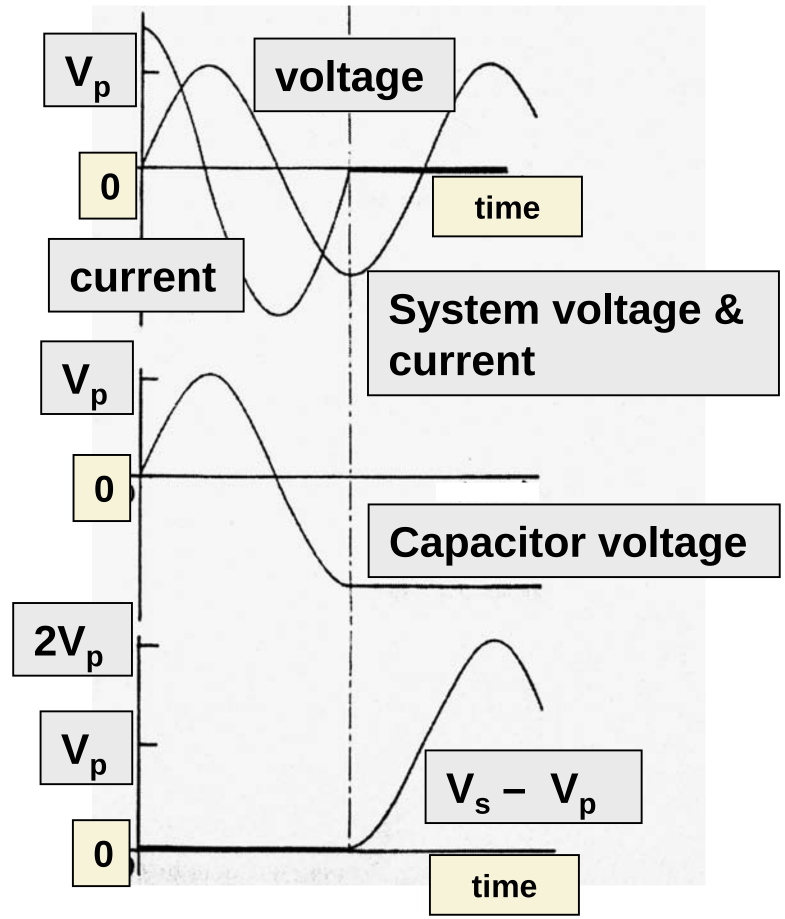
- **Inrush current - Back-to-back banks**
  - **Peak and frequency much higher**
- **First part of inrush during prestrike arcing affects contact surfaces**
  - **More on this later**
- **High di/dt can couple to nearby instrumentation & control circuits**
  - **Some example**

Effects of Inrush Currents

- **Examples of di/dt coupling**
  - **$I_{peak\ inrush}$ = 25 kA,pk – 6400 Hz**
  - **Linear Coupler 1000 : 5 ratio**
    - **E secondary = E_s**
    - **E_s = 6400 / 60 x 5 / 1000 x 25000 = 13,300 V**
  - **Current Transformer 1000 : 5 ratio**
    - **E secondary = E_s**
    - **E_s = 6400 / 60 x 5 / 1000 x 25000 x 0.3 = 4000 V**
  - **Lower inrush f and I can lower effect**

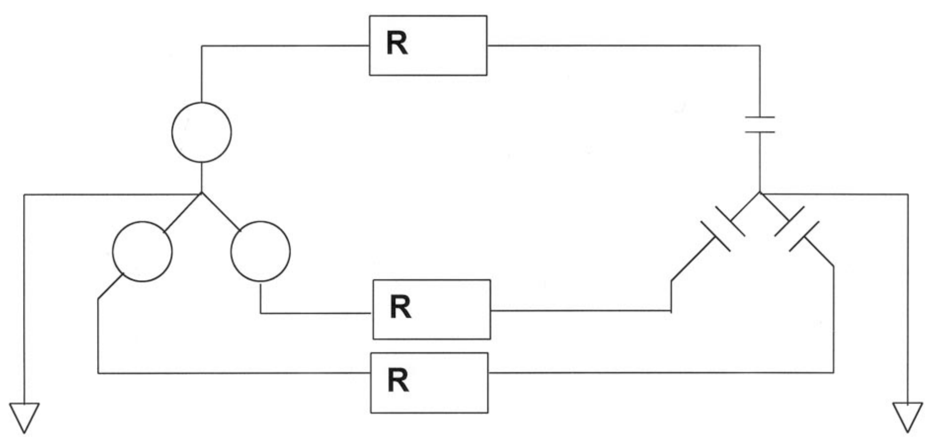
De-energizing Capacitor Banks
Single-phase bank





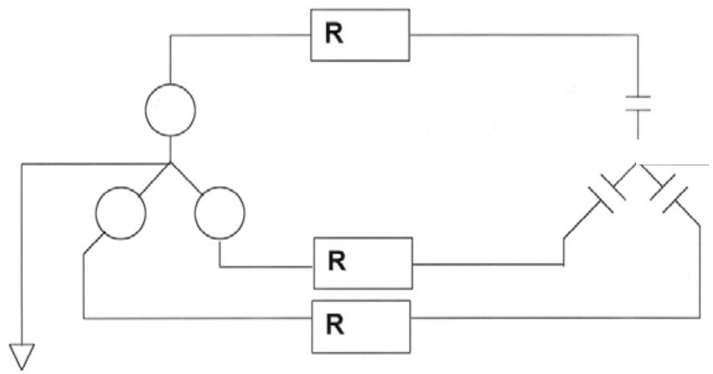
De-energizing Capacitor Banks Three-phase banks

- **Grounded source and bank neutrals**
- **Behaves like 3 single-phase banks**
  - **Vp = 2 x Vpeak of system voltage**



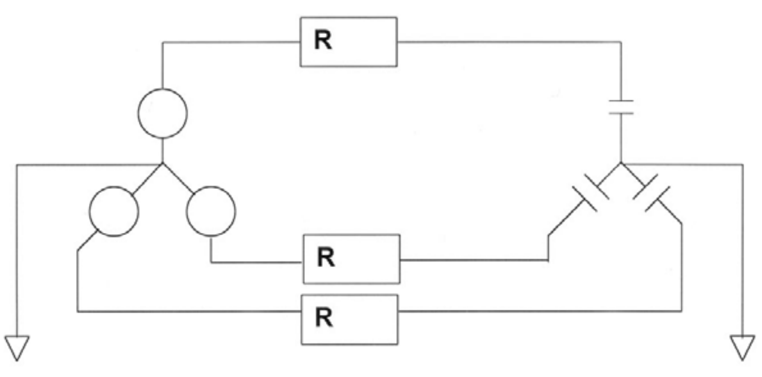
De-energizing Capacitor Banks Three-phase banks

- **Grounded source neutral**
- **Ungrounded bank neutral**
- **First phase gets higher Vp**
  - **Vp = 2.5 x Vpeak of system voltage**

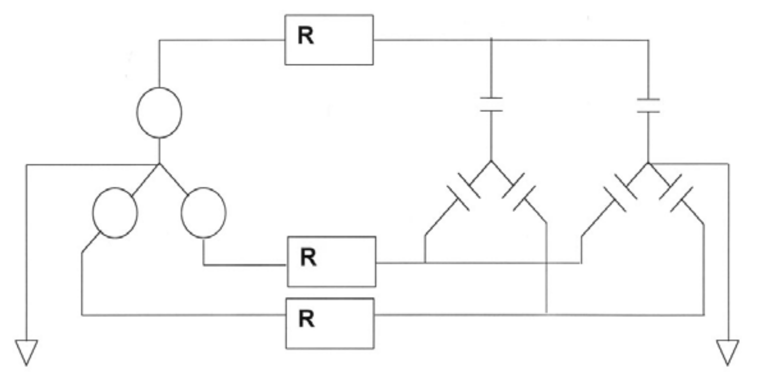


DISCONNECTING BELTED CABLES & OVERHEAD LINES

- **Cables with individual grounded sheaths = similar to grounded banks**
- **Belted cables & overhead lines are similar**
  - **V_{max} From 2.2 V_p to 2.3 V_p**
- **When testing belted cables & overhead lines, use a 2 bank circuit**



Test Circuit for Cables with individual grounded sheaths



Test Circuit for Belted Cables and Overhead Lines

De-energizing Capacitor Banks; the Maximum Voltage

$V = V_p(1 - \cos \omega t)$

$V_p = [V(system) \times \sqrt{2}]$

a) **Grounded capacitor banks:**

$V_{max} = 2 V_p$

b) **Cables with individual grounded sheathes:**

$V_{max} = 2 V_p$

c) **Cables with 3 conductors & 1 ground sheath or overhead lines:**

$V_{max} = 2.2$ to $2.3 V_p$

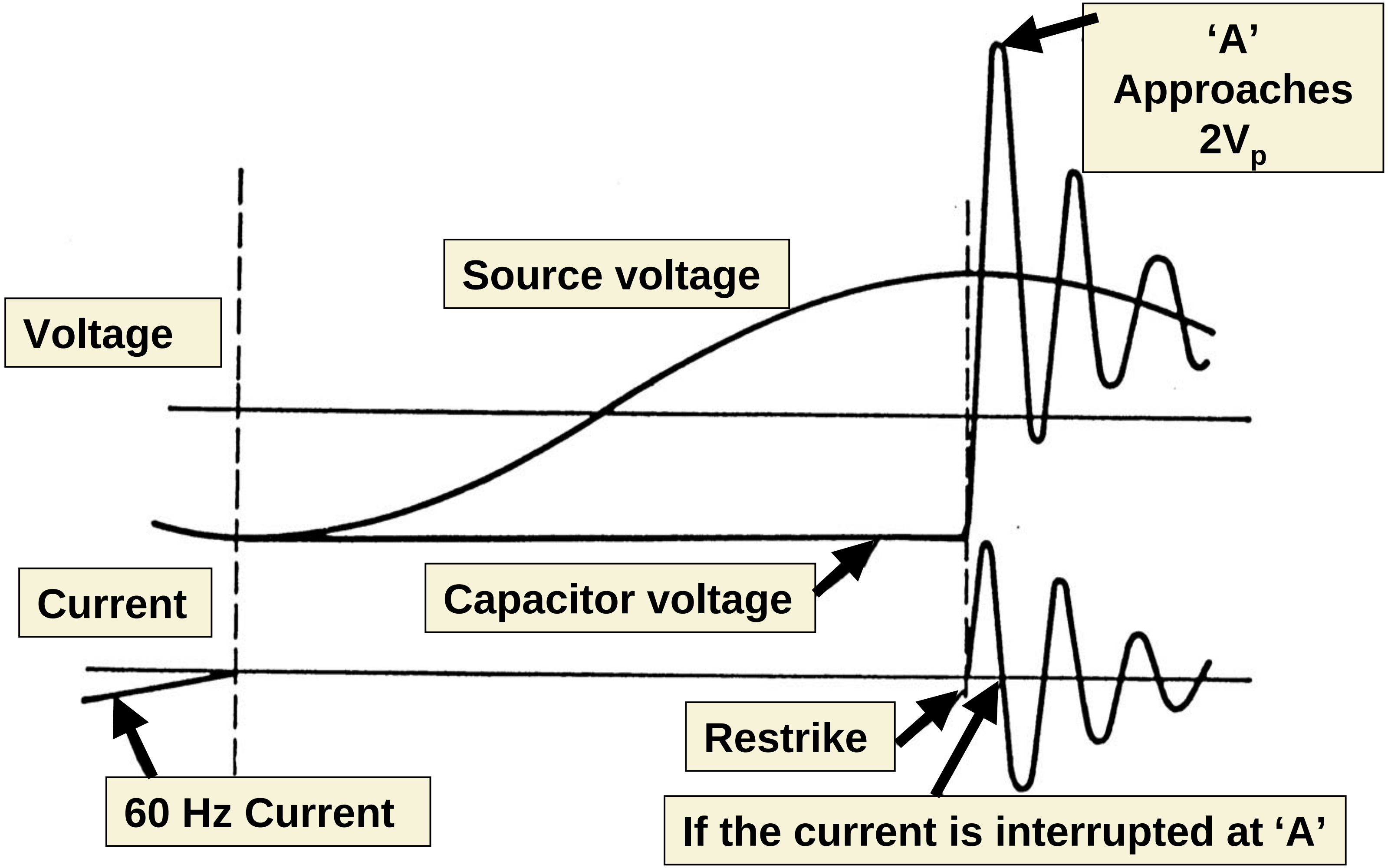
d) **Ungrounded capacitor banks:**

$V_{max} = 2.5 V_p$

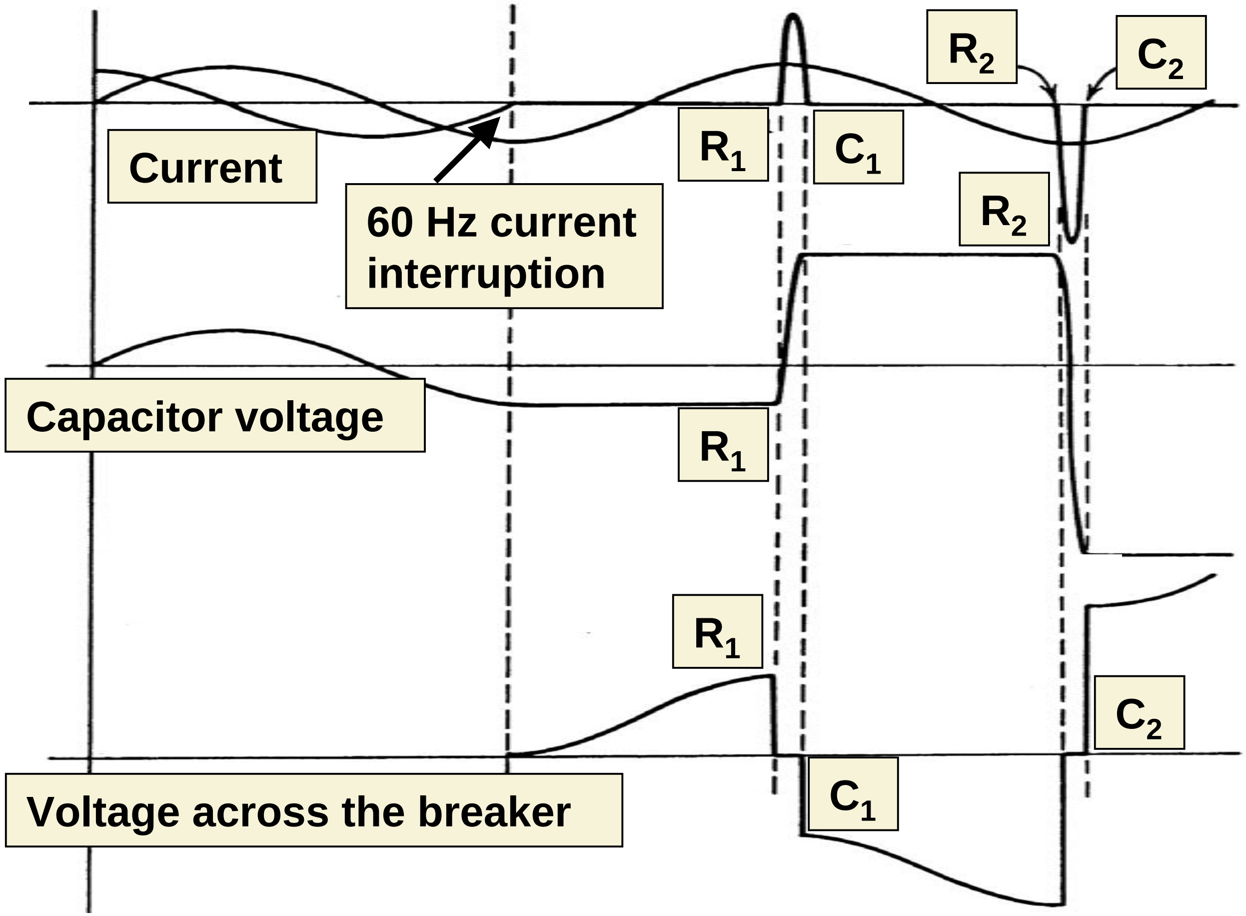
e) **Non simultaneous 3 phase switching:**

V_{max} can range from $2.5 V_p$ (<90º) to $4.1 V_p$ (>210º)

De-energizing Capacitor Banks the Effect of a Restrike



De-energizing Capacitor Banks the Effect of Multiple Restrikes



What would cause a Restrike when Switching Capacitors?

1) During opening if the Electric Field between the contacts

$$E = \beta V_{max}/d > E_c$$

Solution: Open the contacts faster so that $E \ll E_c$

2) Typical Vmax < design voltages

Circuit Voltage	V_{max} for 3ϕ grounded cct.	V_{peak} for 1 minute withstand	BIL
12 – 15 kV	24.5 kV	71	110
24 – 27 kV	44 kV	84	150
16 – 38 kV	62 kV	113	200

3) Possible Causes: particles & microdischarges will result in an NSDD or a full breakdown

4) As switching progresses surface gas on contact eliminated and rougher contact surface shields particles

Inrush Current and Restrikes when Switching Capacitors

1) **During closing, the Electric Field between the contacts increases as the contacts come closer together**
   1) **Contact gap d becomes smaller**
   2) **$E = \beta V_{max}/d$ becomes larger**
   3) **Gap breaks down before the contacts touch**
2) **Gap at breakdown is around 1 to 2 mm**
3) **Closing speeds typically 1 mm/millisecond**
4) **Time before contacts touch 1 to 2 milliseconds**
5) **An arc forms once the gap breaks down**
6) **Inrush current passes through and arc**

Inrush Current and Restrikes when Switching Capacitors

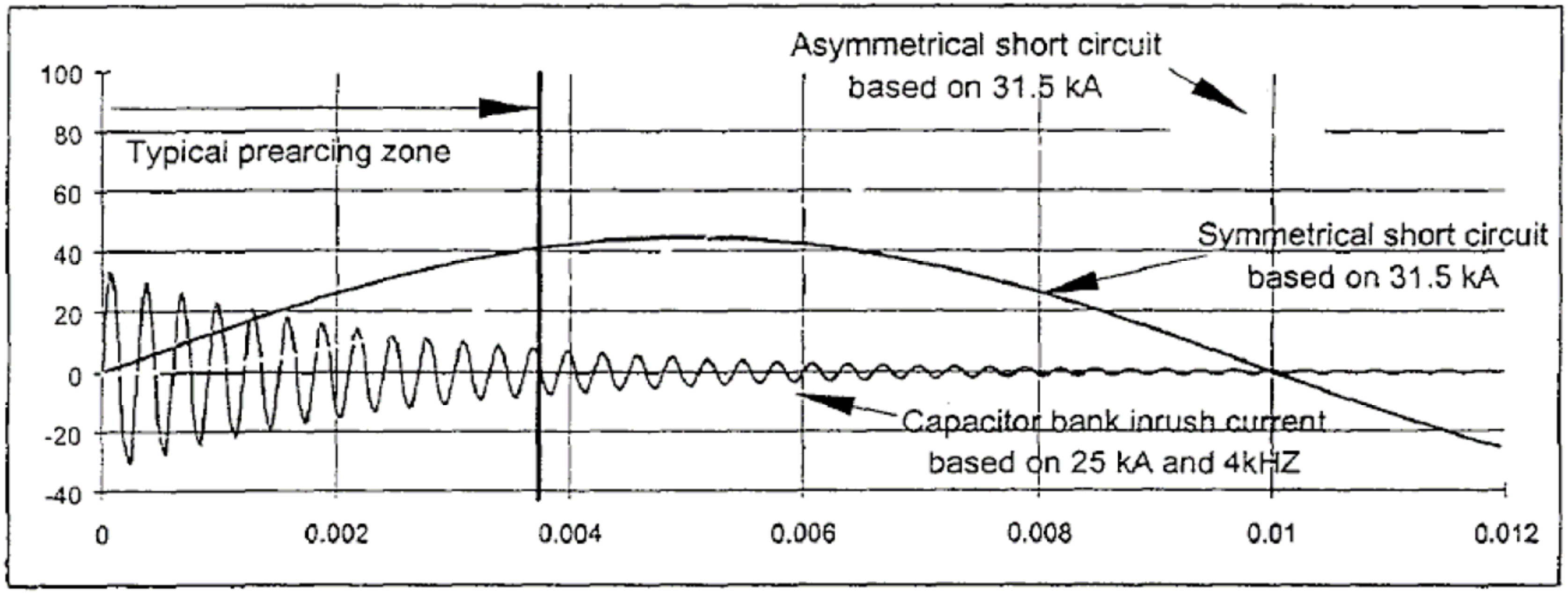


Figure 8. Comparaison entre le courant d'appel d'un banc de condensateurs et les courants de défaut.

Figure 8. Comparison of Capacitor-Bank Inrush-Current and Fault Currents.

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Inrush Current and Restrikes when Switching Capacitors

1) **A high inrush current produces a large arc and the melting of contact material**
2) **The contacts are pressed together with high force and the melted material solidifies and forms a small weld**
3) **When the contacts are opened, the weld is broken and the resulting contact surface is rough**
4) **Rough contact surface increases β**
    1) **$E = \beta V_{max}/d$ = higher E stress as contacts open**
    2) **Increased probability of restrikes**
    3) **<u>High inrush current increases the probability of restrikes</u>**

Inrush Current and Restrikes when Switching Capacitors

1) **Decreasing the inrush current reduces the probability of restrikes**

2) **Limit the peak inrush current to 6 kA or less to achieve low or very low probability of re-strikes**

De-energizing Capacitor Banks

- **Re-strikes can result in system over-voltages**
- **Finite probability of re-strikes with ALL switch technologies**
- **Standards requirements**
  - **Classes of capacitor switching versus probability of re-strikes**
  - **C1 - Low probability of re-strikes**
    - **About 1 in 50 operations**
  - **C2 - Very Low probability of re-strikes**
    - **About 1 in 500 operations**
- **Certification tests on new VIs are the most severe duty, more so than actual operation in service**
- **Protect capacitor banks from all over-voltage events**
  - **Restrikes can happen while de-energizing the capacitor bank and cause overvoltages but is a low probability event**
  - **Overvoltages from other sources; Lightning surges, other circuit switching surges**
- **IEEE C37.012 - application of circuit breakers to capacitor switching**

De-energizing Capacitor Banks with vacuum circuit breakers

- **Vacuum Circuit Breakers have successfully performed capacitor switching for over 30 years**

- **Requires good high voltage vacuum interrupter design**

- **Limit the peak inrush current to 6 kA or less to achieve low or very low probability of re-strikes**

Capacitor Switching using a Load Break Vacuum Interrupter

- **The load break vacuum interrupter uses a low erosion, high voltage, contact material – W-Cu**
- **It is a shaped butt contact for high voltage**
- **W-Cu generally better than Cr-Cu for capacitor switching**
- **Load break switches used for special duty capacitor switches have no fault interrupting duty**

Capacitor Switching using a Load Break Vacuum Interrupter

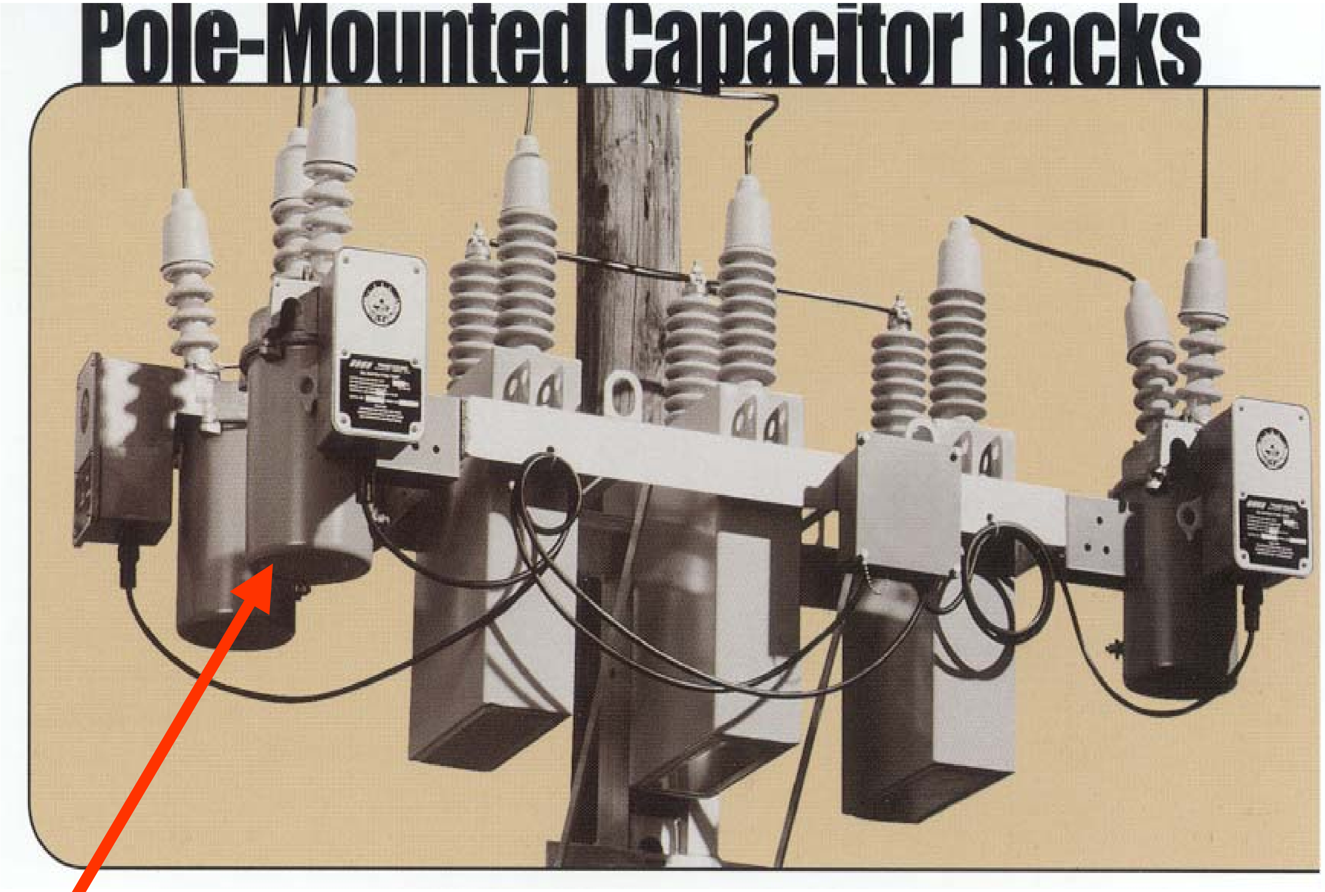
ANSI C37.66 Certification test for capacitor switches

- **Dielectric Tests**
- **Inrush Current Tests e.g. @**
  - **15 kV; 200A circuit: 6kA, 6 kHz;**
  - **400A circuit: 13.5 kA, 4.2 kHz or 600A circuit: 24kA, 3.4 kHz;**
- **Operating Duty: random opening**

Operations	% of Rated Current
1 – 400	90 – 100
401 – 800	45 – 55
801 – 1200	15 – 20

- **Maximum over-voltage allowed 2.5 x Peak Line to Ground**

Vacuum Capacitor Switch



Oil Insulated Switch

Vacuum Capacitor Switch

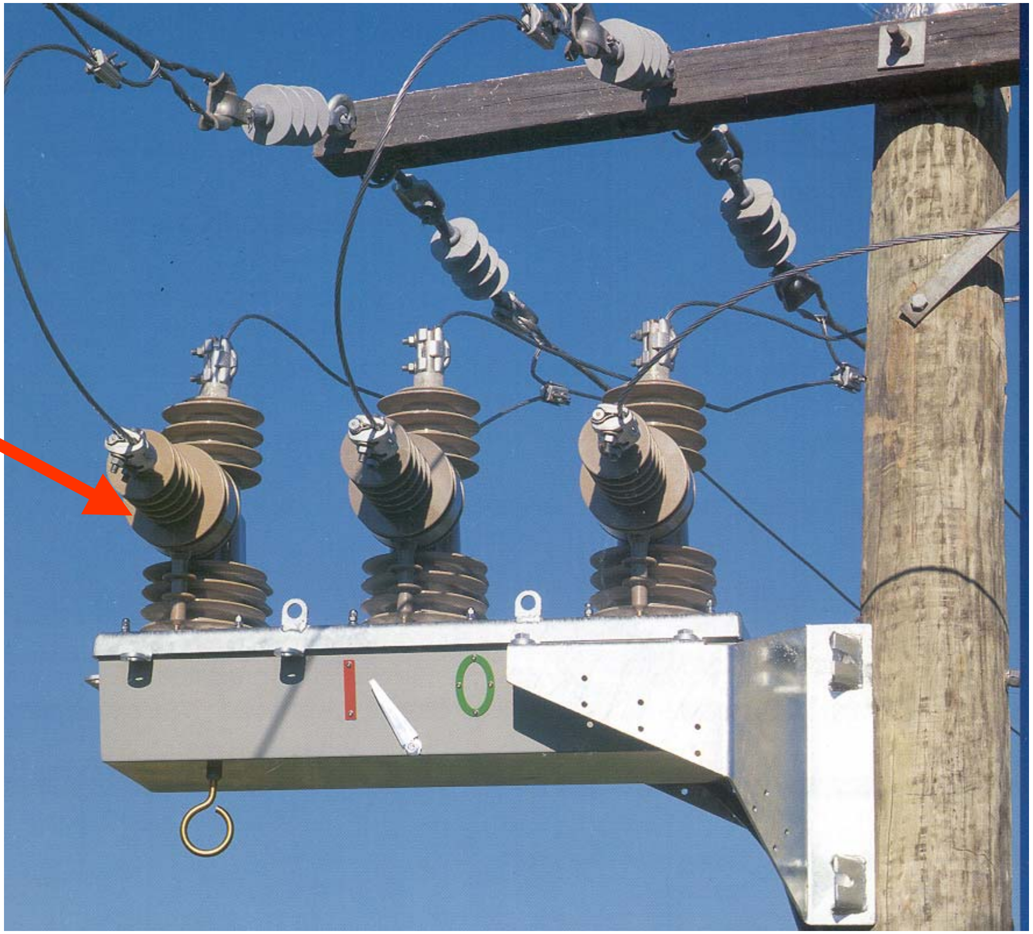
Solid Insulated

Pole Unit

Recloser

or

Capacitor Switch



References on Capacitor Switching

- High Voltage Circuit Breakers
  - Ruben Garzon
- Electrical Transients in Power Systems
  - Allan Greenwood
- Vacuum Switchgear
  - Allan Greenwood
- Numerous technical papers in IEEE and IEC and CIGRE publications

References on Capacitor Switching

- Solver - Capacitor switching - State of Art - Electra 155 - Aug 1994
- Bonfanti - Shunt Capacitor Bank Switching Stresses & Tests Part 1 - ELECTRA-182 – 1999
- Bonfanti - Shunt Capacitor Bank Switching Stresses & Tests Part 2 - ELECTRA-183 - 1999

References on Capacitor Switching

- IEEE Circuit Breaker Standards
  – C37.04a, C37.06 and C37.09a
- IEC Circuit Breaker Standards
  – IEC 62271-100
- IEEE Capacitor Switch Standard
  – C37.66
- IEEE Load Interrupter Switch Standard
  – IEEE 1247
- IEC HV Switch Standards
  – IEC 60265

Review – Cap Switching

1. **Some degree of capacitor switching is a normal part of the duty of many switching devices**
   - **True or False**
2. **The switching of capacitor banks isolated from other banks or closely coupled banks in back-to-back applications are considered to be special capacitor switching duties.**
   - **True or False**

Review – Cap Switching

3. In which of the following the capacitor switching applications does the <u>highest</u> peak recovery voltage occurs.

- **Circle one: A. B. C.**

A. **A three-phase system with both the source neutral and the neutral of the wye- connected capacitor bank are grounded**

B. **A three-phase system with the source neutral is grounded and the neutral of the wye- connected capacitor bank is ungrounded**

C. **A three-phase system with a cable load where the cable consists of three conductors, surrounded by a single ground shield**

Review – Cap Switching

4. In which of the following the capacitor switching applications does the lowest peak recovery voltage occurs.

- **Circle one: A. B. C.**

A. **A three-phase system with both the source neutral and the neutral of the wye- connected capacitor bank are grounded**

B. **A three-phase system with the source neutral is grounded and the neutral of the wye- connected capacitor bank is ungrounded**

C. **A three-phase system with a cable load where the cable consists of three conductors, surrounded by a single ground shield**

Review – Cap Switching

5. The magnitude of the peak inrush current when energizing a bank is an important parameter to <u>limit</u> to reduce the stress on the interrupter and to minimize the probability of restrikes.

- **True or False**