Capacitor Switching in Power Distribution Systems

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# 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. 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:**
  - $12\text{kV}$, 1 MVar – 48A; 10 MVar – 481A
  - $24\text{kV}$, 10 Mvar – 242A; 40 Mvar – 1157A
  - $36\text{kV}$, 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, $I_p$
  - Rate $di/dt$ approaching Current Zero

- **Voltage stress**
  - Magnitude of voltage peak, $V_p$
  - 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
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
  • $V_p \geq 2 \times V_{\text{peak}}$ of system voltage
  • Higher $V_p$ 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

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.

\[
I(\text{inrush}) = \left(\frac{V_0}{Z}\right)\sin\omega_1 t
\]

\[
\omega_1 = \left[\frac{1}{L_1 C}\right]^{0.5}
\]

\[
I(\text{inrush}) = \text{few kA, } \omega_1 = \text{few 100’s Hz}
\]
Energizing a Single Capacitor Bank

Inrush current has high peak and damps out quickly

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

Bank Voltage goes to zero momentarily

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

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Energizing a Single Capacitor Bank

Bus Voltage has extra voltage zeros

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].
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.

\[ I(\text{inrush}) = \frac{V_2}{Z_2} \sin \omega_2 t \]

\[ I(\text{inrush}) = \text{few } 10\text{'s kA at } \omega_2 = \text{few kHz} \]

The peak inrush current should be limited for Low probability re-strike performance
Energizing Back to Back Capacitor Banks

- Much higher peak
- Much higher Frequency
- Damps out more quickly

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
  - \( V_{\text{in}} = 145 \text{ kV}, E_{\text{in}} = 138 \text{ kV} \)
  - \( C_1 = C_2 = C_3 = 10 \text{ Mvar}, \text{ grounded wye} \)
  - \( F_s = 60 \text{ Hz} \)
  - \( L_s = 50,000 \mu\text{H}, \text{ system inductance} \)
  - \( L_1 = L_2 = L_3 = 23 \mu\text{H}, \text{ bank L} \)
  - \( L_{B1} = L_{B2} = 13 \mu\text{H}, \text{ bus L} \)
Examples of Inrush Currents
Larry Smith, IEEE 1995

- Energize the first bank
- Single or isolated bank
- Inrush current
  - $I_{\text{inrush peak}} = 0.67 \text{ kA, peak}$
  - $I_{\text{inrush frequency}} = 535 \text{ Hz}$
Examples of Inrush Currents
Larry Smith, IEEE 1995

- Energize the second bank
- Back-to-back banks
- Inrush current
  - $I_{\text{inrush peak}} = 14.1 \text{ kA, peak}$
  - $I_{\text{inrush frequency}} = 22.4 \text{ kHz}$
- 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
  - $I_{\text{inrush peak}} = 15.5$ kA, peak
  - $I_{\text{inrush frequency}} = 18.4$ kHz
- Inrush current, fourth bank
  - $I_{\text{inrush peak}} = 16.1$ kA, peak
  - $I_{\text{inrush frequency}} = 17.1$ kHz
Effects of Inrush Currents

- Inrush current - Back-to-back banks
  - Peak and frequency much higher
- First part of inrush during prestrike arc ing 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
  - $I_{\text{peak inrush}} = 25 \text{ kA, pk} - 6400 \text{ Hz}$
  - Linear Coupler 1000 : 5 ratio
    - $E_{\text{secondary}} = E_s$
    - $E_s = \frac{6400}{60 \times 5} \times \frac{1000}{1000} \times 25000 = 13,300 \text{ V}$
  - Current Transformer 1000 : 5 ratio
    - $E_{\text{secondary}} = E_s$
    - $E_s = \frac{6400}{60 \times 5} \times \frac{1000}{1000} \times 25000 \times 0.3 = 4000 \text{ V}$
  - Lower inrush f and I can lower effect
De-energizing Capacitor Banks
Single-phase bank

\[ V_s - V_p \]

System voltage & current

Capacitor voltage

\[ 2V_p \]

\[ V_p \]

\[ 0 \]

\[ V_s \]

\[ V_p \]

\[ 0 \]

\[ V_p \]

\[ 0 \]

\[ 0 \]
De-energizing Capacitor Banks
Three-phase banks

- Grounded source and bank neutrals
- Behaves like 3 single-phase banks
  - $V_p = 2 \times V_{peak}$ of system voltage
De-energizing Capacitor Banks

Three-phase banks

- Grounded source neutral
- Ungrounded bank neutral
- First phase gets higher $V_p$
  
  $V_p = 2.5 \times V_{peak}$ of system voltage
DISCONNECTING BELTED CABLES & OVERHEAD LINES

- Cables with individual grounded sheaths = similar to grounded banks
- Belted cables & overhead lines are similar
  - $V_{\text{max}}$ 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

\[ V = V_p(1 - \cos \omega t) \]
\[ V_p = [V(\text{system}) \times \sqrt{2}] \]

a) Grounded capacitor banks:
   \[ V_{\text{max}} = 2 \ V_p \]

b) Cables with individual grounded sheathes:
   \[ V_{\text{max}} = 2 \ V_p \]

c) Cables with 3 conductors & 1 ground sheath or overhead lines:
   \[ V_{\text{max}} = 2.2 \text{ to } 2.3 \ V_p \]

d) Ungrounded capacitor banks:
   \[ V_{\text{max}} = 2.5 \ V_p \]

e) Non simultaneous 3 phase switching:
   \[ V_{\text{max}} \text{ can range from } 2.5 \ V_p \ (\leq 90^\circ) \text{ to } 4.1 \ V_p \ (\geq 210^\circ) \]
De-energizing Capacitor Banks the Effect of a Restrike

If the current is interrupted at ‘A’

Source voltage
Capacitor voltage
60 Hz Current
Current
Voltage

‘A’ Approaches $2V_p$
De-energizing Capacitor Banks
the Effect of Multiple Restrikes

Current
Capacitor voltage
Voltage across the breaker

60 Hz current interruption
What would cause a Restrike when Switching Capacitors?

1) During opening if the Electric Field between the contacts
   \[ E = \beta V_{\text{max}} / d > E_c \]
   Solution: Open the contacts faster so that \( E < E_c \)

2) Typical \( V_{\text{max}} < \) design voltages

<table>
<thead>
<tr>
<th>Circuit Voltage</th>
<th>( V_{\max} ) for 3φ grounded cct.</th>
<th>( V_{\text{peak}} ) for 1 minute withstand</th>
<th>BIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 – 15 kV</td>
<td>24.5 kV</td>
<td>71</td>
<td>110</td>
</tr>
<tr>
<td>24 – 27 kV</td>
<td>44 kV</td>
<td>84</td>
<td>150</td>
</tr>
<tr>
<td>16 – 38 kV</td>
<td>62 kV</td>
<td>113</td>
<td>200</td>
</tr>
</tbody>
</table>

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) $E = \beta V_{\text{max}}/d$ 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. 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 $\beta$
   1) $E = \beta V_{\text{max}}/d = \text{higher E stress as contacts open}$
   2) Increased probability of restrikes
   3) **High inrush current increases the probability of restrikes**
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

<table>
<thead>
<tr>
<th>Operations</th>
<th>% of Rated Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 – 400</td>
<td>90 – 100</td>
</tr>
<tr>
<td>401 – 800</td>
<td>45 – 55</td>
</tr>
<tr>
<td>801 – 1200</td>
<td>15 – 20</td>
</tr>
</tbody>
</table>

- Maximum over-voltage allowed 2.5 x Peak Line to Ground
Vacuum Capacitor Switch

Pole-Mounted Capacitor Racks

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

- 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 highest peak recovery voltage occurs.

   o 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 limit to reduce the stress on the interrupter and to minimize the probability of restrikes.

○ True or False