Tutorial on Shunt Capacitor Banks Design, Application and Protection Considerations

Presenter: Pratap Mysore, HDR

Minnesota Power Systems Conference
November 12, 2015
Topics Covered

- Power system Considerations, Capacitor Benefits
- Capacitor Ratings, Capabilities and Service Conditions
- Capacitor Unit Construction and failure mode
- Bank Design, Connections and Configuration
- Sizing of Capacitor Banks
  - MVAR sizing
  - Voltage Rating
  - Insulation requirement
Topics Covered

- Switching Transients
  - Single Bank Switching
  - Back to Back Switching
  - Voltage Magnification
- Resonance Issues
- Use of Current Limiting Reactor
  - Sizing
  - Switching Issues
Topics Covered

- Switching Devices
  - Circuit Breaker
  - Circuit Switcher
- Bank Protection
  - System Protection VS Bank Protection
  - Unbalance Protection Methods
Tutorial Reference Materials

- PES-TR16*; Technical Report, “Transient Limiting Inductor Applications in Shunt Capacitor Banks”
  * Document developed under Capacitor Subcommittee of Transmission and Distribution Committee

- C37.99 2012# – IEEE guide for the Protection of Shunt capacitor Banks
  # Document developed under IEEE Power Systems Relaying Committee (Will soon be Power Systems Relaying and Control Committee)
IEEE Reference Documents

- This standard provides a basis for uniformity in design, manufacturing and testing of shunt power capacitors.
- The revision included portions of NEMA CP1 document. The ratings and capabilities remain the same as 2002 version.
IEEE Reference Documents

- Provides guidelines for the application, protection, and ratings of equipment for the safe and reliable utilization of shunt power capacitors.
IEEE Reference Documents

- C37.99 -2012; IEEE Guide for the Protection of Shunt Capacitor Banks
  - Revisiting analog relays technologies for the application of digital relays technologies for the protection of externally fused, internally fused, fuseless and unfused capacitor banks.
  - Added theory and analysis of unbalance relaying methods.
  - Massive editorial changes.
  - Minimized bank grounding section directing references to IEEE 1036.
IEEE Reference Documents


As Stated in the document,

“The report was written in response to a great amount of confusion in the power industry surrounding the application of Transient limiting Inductors in shunt capacitor banks”.

Other IEEE Documents

- NEMA CP 1-2000 (R2008), Shunt Capacitors
- Portions of this document was incorporated in the Latest revision of IEEE-18.
Reactive Compensation

- Allows System voltage levels to stay within the acceptable limits
- Permits the maximum utilization of transmission circuits
Long Transmission line

- Represented as a series of inductor/Capacitor elements

\[
\begin{align*}
V(x) &= V_R \cos \beta (L-x) + jZ_0 I_R \sin \beta (L-x) \\
I(x) &= I_R \cos \beta (L-x) + j[V_R/Z_0] \sin \beta (L-x)
\end{align*}
\]
Terms used in Transmission wave equations

• $\beta = \omega \sqrt{LC} = \text{Phase constant} \text{ Typically } 2.07 \times 10^{-3} \text{ radians/mile}$

• $Z_0 = \sqrt{L/C} = \text{Surge Impedance of the line} \sim 450 \Omega \text{ for single conductor (230 kV and below) and around } \sim 280 \Omega \text{ for bundled conductor (345 and higher)}$

• Charging KVAR/Mile $\sim 900 @ 345 \text{ kV}$; $\sim 270 @ 230 \text{ kV and around } \sim 70 @ 115 \text{ kV}$

• Inductive reactance $\sim 0.5-0.8 \text{ ohms/mile}$
Receiving End Voltage of an Unloaded Line

- \( V_R = \frac{V_S}{\cos \beta L} \);
- For a 300 mile 500 kV line, the receiving end voltage = 1.0/\(\cos(2.07 \times 10^{-3} \times 300)\)
- Angle = \(2.07 \times 10^{-3} \times 300\) radians = 0.621 radians = 35.6°
- \( V_R = 1.229\text{P.U.} \). Remote end voltage is 130% of the nominal.
Line Voltage and Charging Current

\[ V_X \]

\[ I_X \]

Line Length
Surge Impedance Loading

- If the line is terminated with impedance $Z_0$, $V_R = I_R Z_0$

- $V(x) = V_R \left[ \cos \beta (L-x) + j \sin \beta (L-x) \right] = V_R e^{j(1-x)}$

- The magnitudes of voltage at any point of the line is independent of the position, $x$
Voltage Profile of a Loaded Line

$V_R = \text{controlled to 1.0 P.U.}$

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Surge Impedance $Z_0$</th>
<th>SI Loading $[V^2/Z_0]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>345 kV</td>
<td>285 Ω</td>
<td>425 MVA (711 Amps)</td>
</tr>
<tr>
<td>500 kV</td>
<td>285 Ω</td>
<td>877 MVA (1013 Amps)</td>
</tr>
</tbody>
</table>
P-V, V-Q Curves

105% $V_R$ (Stable Voltage Region)

70% $V_C$ (Unstable Voltage Region)

0.9 Lead Unity PF

Critical Point of Voltage Instability

Operating Point

$P_{critical}$

$Q$

Bus Voltage

MVAR required to keep the bus voltage at a level (ex:1.05) at specified power transfer

MIPSYCON_2015 - Shunt Capacitor Bank Tutorial
Shunt Reactor and Shunt Capacitor

• Compensate the effect of capacitive/inductive currents
• Shunt Capacitors raise the system voltage – Shunt Reactors lower the bus voltage
• During light load periods, shunt reactors are used to control the system voltage
• During heavy load periods, shunt capacitors are used to maintain the system voltage
Application of Shunt Capacitor Banks

- To provide local voltage support
  - Banks are switched when voltage falls below a set value. (15 - 20 sec)

- To provide system voltage support for higher power transfer

- To provide fast switching to prevent voltage collapse or voltage excursions—(Poor man’s SVCs) (switching time in cycles)
Shunt Capacitor Bank Function

- Var support (local Voltage Support).
- Capacitors supply the reactive power and reduce losses by reducing the current on equipment such as transmission lines.
Size and number of capacitor banks

- Maximum bank size is influenced by:
  - Change in system voltage upon capacitor bank switching
  - Switchgear continuous current limitation

- Minimum bank size is influenced by:
  - The type of capacitor bank used: externally fused, internally fused, fuseless, etc.
  - The easily available ratings of capacitor units
  - Capacitor bank unbalance considerations
  - Fuse performance and/or coordination
  - The cost of the required switchgear and protection
Size and Number of Capacitor Banks

Capacitor bank sized so that the system voltage will not change more than 3% during switching

( GE flicker curve)

\[
\Delta V = \left( \frac{I_C}{I_{sc}} \right) = \left( \frac{Q_c M \text{ var}}{S_{sc} M\text{va}} \right)
\]

It is important to know the application of Capacitor Bank

- for Local voltage support under contingencies (loss of a source)

- for System Support during through flow.
Capacitor Unit Ratings As Per IEEE Std. 18

Standard ratings

IEEE Std 18-2012 establishes ratings for the following electrical parameters:

- Voltage, rms (terminal-to-terminal)
- Reactive power
- Number of phases
- Frequency
- Terminal(s)-to-case (or ground) insulation class
Capacitor Unit Ratings

- Voltage - RMS (continuous): 110% of the rated value
  Crest Voltage: 120% of the peak value including harmonics
- Current: 135% of nominal rating including Harmonics
- VAR: -0 to +10% of the rated value ( +15% for units manufactured before the year 2000) measured at 25 deg.C
- Temperature: -40 deg. C to +40 deg. C
- Max. continuous reactive output: - 135% of the rated value
### Capacitor Unit Overvoltage Limit

Reference - NEMA CP1-2000 and IEEE 1036

<table>
<thead>
<tr>
<th>Voltage (Percentage of Rated)</th>
<th>Duration</th>
</tr>
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<tbody>
<tr>
<td>110%</td>
<td>Continuous</td>
</tr>
<tr>
<td>125%</td>
<td>30 minutes</td>
</tr>
<tr>
<td>130%</td>
<td>1 minute</td>
</tr>
<tr>
<td>140%</td>
<td>15 seconds</td>
</tr>
<tr>
<td>170%</td>
<td>1 second</td>
</tr>
<tr>
<td>200%</td>
<td>15 cycles</td>
</tr>
<tr>
<td>220%</td>
<td>6 cycles</td>
</tr>
</tbody>
</table>
Capacitor Transient overvoltage Limit

Momentary capabilities, transient peak overvoltage

Source: IEEE 1036
Effect of Geomagnetically Induced Currents

- GIC is quasi-DC (slowly varying) current
- The Capacitors offer higher impedance to lower frequency components
- Capacitor banks offer lower impedance path to higher harmonics due to Transformer saturation during GIC resulting in higher currents through the bank
Voltage Rating of a Capacitor

- The rated voltage selected not to below the maximum system operating voltage (Typically 1.05 PU up to 345 kV)
- Additional margin may be provided to account for higher currents due to GIC
- Example 345 kV can be rated at 362 kV or 380 kV (1.1 PU) to allow higher harmonic current capability during GIC event
- Flip side- Banks cost higher
Capacitor Switching Transients

- Energizing a single bank
  - Normal
  - Immediate reenergizing
  - Phase-to-phase transients
  - Voltage magnification
  - Transformers and capacitors
Capacitor Switching Transients

Energization: overvoltage and overcurrent

Typical OV levels range from 1.2 to 1.8 per unit for substation capacitor banks.
Capacitor Switching Transients

Energization: Prestrike

Prestrike may occur during the energization of a capacitor bank. When the capacitor bank is energized, an arc is established within the interrupters before the contacts physically make contact.

Energization: Inrush current

Capacitor switches must be capable of repeatedly withstanding inrush current

\[
I_{\text{max pk}} = 1000 \times V_{LL} \times \sqrt{\frac{2}{3}} \times \sqrt{\frac{C_{eq}}{L_S}}
\]

\[
I_{\text{max pk}} = \sqrt{2} \times \sqrt{I_{SC} \times I_1}
\]

- \(C_{eq}\) is the effective capacitance of the capacitor bank (in farads).
- \(L_S\) is the effective inductance of the source (in henries).
- \(I_{SC}\) is the symmetrical rms three-phase short-circuit current (A).
- \(I_1\) is the rms capacitor bank current (A).
Capacitor Switching Transients

Energization: frequency

Transient frequencies due to isolated capacitor bank switching is generally in the 300 to 1000 Hz range.

\[
f_s = \frac{1}{2\pi\sqrt{L_s C}} = f_{\text{system}} \times \sqrt{\left(\frac{S_{sc} \text{ Mva}}{Q_C \text{ Mvar}}\right)} \approx f_{\text{system}} \times \sqrt{\left(\frac{1}{\Delta V}\right)}
\]

- \(f_s\) is the switching transient frequency
- \(f_{\text{system}}\) is the system power frequency
- \(L_s\) is the source inductance of the system
- \(C\) is the capacitance of the capacitor bank
- \(S_{sc}\) is the short circuit MVA at the capacitor bus
- \(Q_C\) is the Mvar of the capacitor bank at nominal system voltage
- \(\Delta V\) is the steady state voltage rise as per unit of the nominal
Capacitor Switching Transients

Energization: back-to-back capacitor banks

- A capacitor bank energized in close proximity to a previously energized capacitor bank results in generating a high-frequency inrush currents.

\[ I_{\text{max pk}} = 1000 \times V_{LL} \times \sqrt{\frac{2}{3}} \times \sqrt{\frac{C_{eq}}{L_{eq}}} \]

\[ f_t = \frac{1000}{2\pi \times \sqrt{L_{eq} \times C_{eq}}} \]

- \( C_{eq} \) is the equivalent capacitance of the two capacitor banks in series (in farads).
- \( L_{eq} \) is the total equivalent inductance per phase between capacitor banks (in henries).
Capacitor Switching Transients

Back to Back switching current would be in kA,
Breaker Re-strike / Bank Renergization after half a cycle
Capacitor Switching Current limit

Momentary capabilities, transient overcurrent

For frequent back-to-back capacitor bank switching, peak capacitor unit current should be held to a lower value as indicated in figure below

![Capacitor Switching Current limit graph](source: IEEE 1036)
Rate of Rise of current-di/dt (ixf)

- **Frequency**
  \[ f = \frac{1}{2\pi \sqrt{L_{eq} C_1}} \]

- **Peak Current**
  \[ I_{pk} = V_0 \sqrt{\frac{C_1}{L_{eq}}} \]

\[ I_{pk} \times f = \frac{V_0}{2\pi L_{EQ}} \]

Product is independent of the capacitance value
Reducing Switching Current Magnitude and Frequency

• Use of inrush/ outrush reactors – Reduces the magnitude and frequency of inrush current
• Use of breakers with synch-close feature – the breaker poles on each phase is closed when the voltage across the breaker pole is zero
• Circuit switchers with Pre-insertion resistor and inductor
Current Limiting Reactor sizing

- C37.06-2009 – “IEEE Standard for A.C. High Voltage Circuit Breakers Rated on Symmetrical Current Basis- Preferred Ratings and Related Required Capabilities For Voltages Above 1000V” –Table 4
- C0: General Purpose breaker – no Back to back switching capability
  50kA Peak current and 2x10^7 A-HZ (ixf) product
- C1 or C2 (Formerly Definite Purpose Breaker)
  - Preferred Rating, Alternate 1 and Alternate 2

The preferred ratings and alternates 1 or 2 ratings have different values. These values are for qualification of circuit-breaker capacitance switching according to their capabilities. The preferred ratings lists the previous values indicated in ANSI C37.06-2000 and represent the standard values for circuit breakers. Alternate 1 ratings were added in particular for some ratings of vacuum and some other circuit breakers, and alternate 2 ratings represent the exceptional maximum values as seen by users and manufacturers in some world-wide applications. As of the time of the printing, only synthetic tests for alternate 2 are available in some laboratories.
### C37.06-2009 Table 4

#### Preferred capacitance current switching ratings for Class S1 circuit breakers for cable systems below 100 kV

<table>
<thead>
<tr>
<th>Line No.</th>
<th>Rated maximum voltage $U_1$, kv, rms</th>
<th>Rated continuous current A, rms</th>
<th>Back-to-back capacitor bank switching</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Col 1</td>
<td>Col 2</td>
<td>Preferred rating (6)</td>
</tr>
<tr>
<td></td>
<td>Col 7</td>
<td>Col 8</td>
<td>Alternate current (8)</td>
</tr>
<tr>
<td></td>
<td>Col 9</td>
<td>Col 10</td>
<td>Alternate 2 (8)</td>
</tr>
<tr>
<td></td>
<td>peak kA, peak kHz</td>
<td>peak kA, peak kHz</td>
<td>peak kA, peak kHz</td>
</tr>
<tr>
<td></td>
<td>Col 13</td>
<td></td>
<td>Col 12</td>
</tr>
<tr>
<td>Line No.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>4.76</td>
<td>1200</td>
<td>630</td>
</tr>
<tr>
<td>2</td>
<td>4.76</td>
<td>2000</td>
<td>1000</td>
</tr>
<tr>
<td>3</td>
<td>4.76</td>
<td>3000</td>
<td>1600</td>
</tr>
<tr>
<td>4</td>
<td>8.25</td>
<td>1200</td>
<td>630</td>
</tr>
<tr>
<td>5</td>
<td>8.25</td>
<td>2000</td>
<td>1000</td>
</tr>
<tr>
<td>6</td>
<td>8.25</td>
<td>3000</td>
<td>1600</td>
</tr>
<tr>
<td>7</td>
<td>15</td>
<td>1200</td>
<td>630</td>
</tr>
<tr>
<td>8</td>
<td>15</td>
<td>2000</td>
<td>1000</td>
</tr>
<tr>
<td>9</td>
<td>15</td>
<td>3000</td>
<td>1600</td>
</tr>
<tr>
<td>10</td>
<td>15</td>
<td>4000</td>
<td>1600</td>
</tr>
<tr>
<td>11</td>
<td>27</td>
<td>≤3000</td>
<td>250</td>
</tr>
<tr>
<td>12</td>
<td>27</td>
<td>≤3000</td>
<td>400</td>
</tr>
<tr>
<td>13</td>
<td>27</td>
<td>≤4000</td>
<td>630</td>
</tr>
<tr>
<td>14</td>
<td>38</td>
<td>≤4000</td>
<td>250</td>
</tr>
<tr>
<td>15</td>
<td>38</td>
<td>≤4000</td>
<td>630</td>
</tr>
<tr>
<td>16</td>
<td>38</td>
<td>≤4000</td>
<td>1000</td>
</tr>
<tr>
<td>17</td>
<td>72.5</td>
<td>≤4000</td>
<td>250</td>
</tr>
<tr>
<td>18</td>
<td>72.5</td>
<td>≤4000</td>
<td>630</td>
</tr>
<tr>
<td>19</td>
<td>72.5</td>
<td>≤4000</td>
<td>1000</td>
</tr>
</tbody>
</table>
Effect of Inrush/Outrush Current

- Circuit breakers have max. $I_{\text{peak}}$ and max. Frequency rating – $I_{\text{xf}} = 8.5 \times 10^7$. For SF6 Breakers this is the closing and latching capability $= 2.6 \times I_{\text{SC}}$ rating.

- Current/frequency transients cause interference.

- May damage cables, equipment in the substation.

- Outrush current – capacitor discharge current into close in faults with similar magnitude and frequency as inrush.

(9) For Class C1 and C2 circuit breakers exposed to transient inrush currents from nearby capacitor banks during fault conditions, the capacitance transient inrush peak current shall not exceed the close and latch (peak withstand) capability of the circuit breaker. This is considered an infrequent event, and therefore the circuit breaker should be expected to handle this duty twice in the life time of the circuit breaker without requiring maintenance of the contacts.
Technical Report PES-TR16

- Reactors were named Transient Limiting Inductors
- Energy of the capacitor banks were never considered in determining di/dt in C37.06 standard
- There is no need to use reactors for outrush for SF6 breakers as long as it is less than 2.6*\(I_{SC}\)
- Report suggests ixf of \(2.5 \times 10^9\)A-Hz for SF6 which is much higher than the specified.
- Also addresses effects of these transients on CT secondary suggesting the use of protectors to prevent failures.
Drawbacks of Installing TLIs

- High Rate of rise of recovery voltage for faults between reactor and capacitor
- TRV delay capacitors are suggested to reduce the rate of rise – could be phase to ground or across the reactor
Capacitor Switching Transients

- **Energization: Phase-to-phase insulation**
- On transformers terminated at the end of the lines from Station with capacitor bank
  - Surges generated by the energization of the capacitor bank would travel down the line towards the transformer and double at that point.
  - It would be possible to get a +2.0 per unit surge on one phase and a –2.0 per unit on another. This would result in 4.0 per unit across two phases.
Voltage Magnification

- Interaction between two capacitor banks at different voltages

\[ L_S \cdot C_{HV} = L_{TR} \cdot C_{LV} \]
Capacitor Bank Configuration

**Delta**

**Grounded Wye**

**Ungrounded Wye**
Capacitor Bank Configuration

Ungrounded Double Wye

Grounded Double Wye

H configuration
Capacitor Unit – Construction

Voltage Rating: Standardized according to NEMA CP1 Standard.

Range – 2.4 kV – 24.9 kV; up to 800 KVAR

Terminology:
Unit – New name for a “Can”
Element (Pack) – small capacitor within an element

Filled with insulating fluid
Discharge Resistor

The residual voltage across the terminals should reduce to 50V DC or less within 5 minutes after disconnection from the voltage source.
Capacitor Element

Film is rolled together with aluminum foils (Electrodes)

Typical rating: Around 2 kV

Older units had Kraft Paper

Plastic (Polypropylene) film
Capacitor Element Failure Mode

The film punctures and creates a short circuit (two foils weld together)
Failure is always due to voltage stress

Failure Mode – Always failure of insulation between aluminum foils resulting is a short circuit
Capacitor Bank Types

- Externally fused
- Fuseless
- Internally fused
- Unfused (only mentioned in C37.99 – These are banks with fuses removed and jumpered)
Externally Fused Capacitor Bank
Capacitor Unit - Externally Fused

- Single Bushing Unit
- Rated as high as 24.9 kV
- Case is connected to one end of the capacitor stack
Externally Fused Bank

- Used to be the most common design in North America.
- Capacitor units individually fused by expulsion or current limiting fuses.
- Fuses are replaceable and are mounted external to the capacitor unit.
Externally Capacitor Bank

Schematic of an externally fused capacitor bank, single wye, 11 capacitors per series group, 4 series groups per phase.

Source: C37.99 -2012
Externally Fused Bank (Contd.)

- The capacitor bank is made of groups of parallel units connected in series.
- Failure of an element causes overvoltage on remaining series group; Cascade failures within a unit shorts out many elements within the capacitor unit.
- Other capacitor units connected in parallel discharge into the failed unit to force fuse operation.
In case of a blown fuse, replace both the unit and the fuse even if the capacitance is OK.
Internally Fused Capacitor Unit

- Each Element is fused inside the unit
- Always a double Bushing Unit
- Voltage rating is less than the externally fused unit due to terminal to case insulation
Fuseless Capacitor Bank
Fuseless Bank Arrangement

- Capacitor units arranged in “series strings” connected between the phase terminals and neutral but, there are no parallel connections in-between.

- Internal elements fail as a solid metallic short and continue to conduct current. The current is limited to less than 50 - 75 A. This prevents overheating and opening of the short.

- Sensitive unbalance detection relaying removes bank from service when sufficient elements have failed.
Fuseless Capacitor Bank Configuration
Fuseless Capacitor Bank
Capacitor Unit - Fuseless

- Always a double Bushing Unit
- Rated voltage less than externally fused (Case is not connected to Capacitor stack)
- Terminal to case insulation around 2PU at 60Hz
- This will be increased to around 7 or 8 PU
Fuseless Capacitor Bank

Strings

LV Units, 825V, 167kVAR each
Capacitor Bank Grounding

Advantages of the grounded-wye compared to the ungrounded Bank:

- Initial cost of the capacitor bank may be lower since the neutral does not have to be insulated from ground,
- Capacitor switch recovery voltages are reduced,
- Mechanical duties (e.g., seismic) may be less severe for the structure

Ungrounded Bank:

- Ungrounded wye banks do not permit zero sequence currents, third harmonic currents, or large capacitor discharge currents during system ground faults.
- The neutral, however, should be insulated for full-line voltage, since it is momentarily at phase potential when the bank is switched on.
- Capacitor Switch TRV requirement is higher
Capacitor Bank Grounding

Disadvantages of the grounded-wye compared to the ungrounded wye:

- High inrush currents may occur in station grounds and structures, which may cause instrumentation problems.
- Grounded neutral may draw zero-sequence harmonic currents and cause telephone interference.
- A fault short circuiting one phase of the capacitor bank results in a system line to ground fault.
- In capacitor banks with one series group, the grounded-wye arrangement may make current-limiting fuses necessary because of the line-to-ground fault magnitudes.
Capacitor Bank Grounding

Substation ground grids

Two methods of neutral grounding have been successfully used; single point grounding and peninsula type grounding.

![Diagram of Single Point Grounding](image)
Capacitor Bank Grounding

Substation ground grids

The peninsula ground grid connects to main station ground grid under buswork at the edge of the capacitor area.

The shaded area shows the location of the peninsula ground grid.

Peninsula type grounding

Capacitor bank grounds (for grounded capacitor banks)
Protection considerations

- System protection
- Bank Protection
System Protection

- to protect the capacitor bank from stresses which may be caused by the system,

- to protect the substation and system from stresses which may be caused by the operation of the capacitor bank
## Capacitor Unit Overvoltage Limit

Reference - NEMA CP1-2000 and IEEE 1036

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Bank Protection

• Faulty Capacitor Unit or shorted elements
• Continuous overvoltage on capacitor elements or units due to faulted elements or fuse operations within the bank.
• External arcing may cause case ruptures or other damage to capacitor units and may blow fuses.
System and Bank Protection

Internally Fused Capacitor Bank - Many bushings blown off
System and Bank Protection
Externally Fused Capacitor Bank - Many fuses blown
System and Bank Protection

External arcing (Rack to rack flashovers)

- External arcing may cause case ruptures or other damage to capacitor units and may blow fuses.
- The overcurrent protection is not normally sensitive to arcing within a capacitor bank - unbalance protection required.

Bank Overvoltage Protection

- If the system voltage exceeds the capacitors capability with the capacitor bank, the bank should be removed with minimum delay
- Overvoltage relay 59B are used, and set according to the capabilities provided by IEEE Std 1036-2010 or manufacture.
- Overvoltage protection based on current measurements can be used as well.
System and Bank Protection

Impedance-based Protection

Major bank faults as well as problems with capacitor elements can be detected as changes in the directly measured impedance of the capacitor bank.

\[
Xc
\]

\[
-jXc
\]

ALARM

TRIP

MIPSYCON_2015 - Shunt Capacitor Bank Tutorial
System and Bank Protection

Loss of bus voltage

In some cases, it may be necessary to trip a shunt capacitor bank if the supply bus voltage is lost.

- Re-energizing a bank with a trapped charge.
- Energizing a capacitor bank without parallel load through a previously de-energized transformer

Undervoltage relay, device 27B, will detect loss of system voltage and trip the capacitor bank after a sufficient time delay.

The 27B relay should be set so that the relay will not operate for voltages that require the capacitor bank to remain in service.
System and Bank Protection

sample scheme for large EHV capacitor bank

Legend*:

- Breaker
- Overcurrent Relay
- Neutral overcurrent - Relay
- Bus overvoltage Relay
- Bus undervoltage Relay
- Voltage Differential Relay
- Neutral Unbalance Relay

* See IEEE C37.2-2008 for definitions
System and Bank Protection

Unbalance relaying normally applied to

a) Trip the bank promptly if an unbalance indicates the possible presence of external arcing or a cascading fault within the capacitor bank.

b) Provide early unbalance alarm signal(s) to indicate the operation of fuses or failure of capacitor elements.

c) Trip the bank for unbalances that are large enough to indicate that continuing operation may result in

1) Damage to remaining healthy capacitor units or elements from overvoltage.

2) Fuse malfunction (blown fuse of healthy units/elements).

3) Undesirable filter operation
System and Bank Protection

Unbalance relaying methods: Voltage Differential

\[ V_{OP} = \left| V_{TAP} - k \cdot V_{BUS} \right| \]
System and Bank Protection

Unbalance relaying methods: Neutral Voltage Unbalance

\[ V_{OP} = \left| 3 \cdot V_0 - 3 \cdot V_N + V_{UNB} \right| \]

\[ V_{UNB} = k_{AB} \cdot (V_B - V_N) + k_{AC} \cdot (V_C - V_N) \]
System and Bank Protection

Unbalance relaying methods: Banks Grounded Through a Capacitor

\[ V_{OP} = \left| 3 \cdot V_0 - \left(3 + \frac{X_A}{X_N}\right) \cdot V_N \right| \]
System and Bank Protection

Unbalance relaying methods: Bank Grounded Through a CT with Resistive Burden

\[ V_{OP} = \left| 3 \cdot V_0 + j \cdot \frac{X}{R} \cdot V_R \right| \]
System and Bank Protection

Unbalance relaying methods: Phase Current Unbalance

\[ I_{OP} = \left| I_{DIF} - k_1 \cdot I_{BANK} \right| \]

\[ I_{BANK} = \frac{V_{BANK}}{-j\cdot X_1} + \frac{V_{BANK}}{-j\cdot X_2} \]
System and Bank Protection

Unbalance relaying methods: Neutral Current Unbalance

\[ I_{OP} = |I_{DIFN}| \]

\[ I_{OP} = |I_{DIFN} - (k_A \cdot I_A + k_B \cdot I_B + k_C \cdot I_C)| \]
Overcurrent Relays

- Provides protection against major faults.

- Time overcurrent - P.U.: 135% of nominal phase current for grounded wye banks or 125% for ungrounded banks. Extremely inverse characteristic is used.

- Instantaneous - set at three to four times the nominal phase current to override back to back inrush during switching.
Overvoltage Protection

• The capacitor bank is disconnected (tripped) if the system voltage exceeds 110% of the capacitor bank rated voltage. This prevents failure of capacitor bank.

• If the 110% value higher than the max. System voltage (121 kV for 115 kV, 72.5 kV for 69 kV system), then the capacitor bank is also tripped if the system voltage exceeds the max. Permissible system voltage. This protects other equipment in the substation.
Bank Lockout Operation

- Capacitor bank is locked out only for faults within the bank – Short circuit or unbalance protection.
- The capacitor breaker is opened if the voltage of the system exceeds either the max. operating voltage limit or 110% of the capacitor bank voltage rating.
Bank Breaker Failure Protection

Phase Current Pick up: 50% of the capacitor bank normal rated current.
Protection of Grounded – Y Capacitor Banks – Neutral Unbalance Relay

Capacitor Bank – Fuseless or externally fused
- 59N – Simple overvoltage relay or unbalance/ capacitor control relay
- Additional PT and a switching device (circuit breaker) are required if capacitors are switched in and out for voltage control.
Neutral Unbalance Protection

• From the previous example [80 MVAR, 118 kV capacitor bank], Loss of one capacitor unit will create an unbalance current of 6.02 A.
• Typical Neutral CT ratio 25:5 =5.
• Voltage across the resistor (assume 1.5 ohm) = 1.204 volts.
• Voltage across resistor with loss of three units = 5.76 V; [unbalance primary current =19.22A].
• The relay is set to pick up at 5.4 V.
• The operating time is set high for slow relay operation.
Protecting Relay Against Transients

- To avoid excessive voltage across the relay, MOVs are installed.
- Lockout relay contact is used across the CT to short the secondary after the relay operates.
- Protection gap (0.064”) across primary of aux. CT, protects wound CT against high switching currents.
QUESTIONS?