RRRV Issues associated with breakers on Capacitor banks with reactors

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IEEE/IAS Chapter – Augusta, Maine
August 12, 2014
Shunt Capacitor Bank

Provides Reactive Power

• Local voltage support
• System VAR support
Switching Transients

• Inrush Current
• Outrush Current
• Back to Back Switching currents
Capacitor Inrush Currents

Frequency  \[ \frac{1}{2\pi\sqrt{LsC1}} \]

\[ I_{\text{peak}} = \sqrt{2} \frac{V_s}{\sqrt{L_s/C1}} \]
Inrush- Current and Frequency

Example: 161 kV, 60 MVAR capacitor bank;
System MVA_{SC} = 1000 MVA

\[ C_1 = \frac{10^6 \ast \text{MVAR}}{\omega(KV)^2} \mu F; \quad C_1 = 6.1 \mu F \]
\[ L_S = \frac{10^3 \ast (kV)^2}{\omega\text{MVA}_{SC}} \text{mH}; \quad L_S = 68.8 \text{mH} \]
\[ I_{\text{peak}} = 1242A; \quad \text{Frequency} = 245 \text{HZ} \]

Frequency and peak current can also be calculated using the following formula:

\[ \text{Frequency, HZ} = 60 \ast \sqrt{\frac{\text{MVA}_{SC}}{\text{MVAR}}} \]
\[ I_{\text{peak, KA}} = \frac{\sqrt{\left( \text{MVA}_{SC} \ast \text{MVAR} \ast 2/3 \right)}}{\text{KV}} \]

On 10,000 MVA system:

\[ f = 775 \text{ HZ}; \quad I_{\text{peak}} = 3927 \text{ Amps} \]

With 100 MVAR bank, \( f = 600\text{HZ}; \quad I_{\text{peak}} = 5071 \text{ A} \)
Inrush Waveform

161 kV, 60 MVAR Bank Inrush (MVA_{SC} -1000 MVA)
Outrush (Back to Back) Current

\[ I_{\text{peak}} = \sqrt{2} \frac{V_s}{\sqrt{L_B / C_{eq}}} \]

\[ \text{Frequency} = \frac{1}{2 \sqrt{L_B C_{eq}}} \]

\[ C_a = \frac{(C_1 \cdot C_2)}{(C_1 + C_2)} \]
Outrush – Current and Frequency

Example:
• Back to Back switching:
  Switching a second 60 MVAR bank
  \( C_{eq} = 3.07 \, \mu F; \, L = 26.1 \, \mu H; \)
  \( I_{peak} = 45kA; \, Frequency = 17.8KHz \)
• Outrush for external close in faults:
  \( C_{eq} = 12\mu F \) Assuming 300 ft of bus, \( L = 78 \, \mu H \)
  Freq: 5.2 kHz ; \( I_{outrush} = 51 \, kA. \)
Back to Back Switching

Back-Back switching – Two 161 kV, 60 MVAR banks
Breaker Capabilities

- C37.06-2009, ANSI/IEEE standard lists circuit breaker inrush current magnitude and frequency capabilities (Table – 14)
- Example: 161 kV system would use 170 kV rated breakers.
- $I_{\text{peak}} = 20 \text{ kA}$ and Frequency $= 4.3 \text{ KHZ}$ (Definite Purpose breaker example)
- If current is less than the specified value, then $I_{\text{peak}} \times f$ product (rate of rise) should not exceed $20 \times 4300 \times 10^3 = 8.6 \times 10^7 \text{ A/sec.}$ (General purpose breaker limit is $2 \times 10^7$)

- Without any current limiting devices, back to back switching or closing into a fault results in exceeding the breaker capability.
Solutions to limit Inrush /Outrush currents or its effects

- Pre-insertion resistors – Works well for inrush or back to back switching. For reclosing onto a close-in external fault or switching into a faulted line, high frequency current magnitudes exceed ANSI ratings.
- Controlled Closing (Synchronous closing) – Each phase (pole) of the breaker is closed voltage zero crossing. Has same issues as pre-insertion resistors.
- Current limiting reactors (CLR) – Always in the circuit to limit inrush/outrush current frequency and magnitudes.
- CT secondary protectors – To prevent flashover/failures in CT secondary circuits due to high frequency, high magnitude currents
Typical Capacitor Bank Installation

Photo: Xcel Energy Inc.
Current Limiting reactor Arrangement
Sizing of Current Limiting Reactors (CLR)

- CLR reduces peak current and frequency – Reduces the I x f (Rate of rise of current)
- \( I_{\text{peak}} = \frac{V_{\text{Peak}}}{\sqrt{(L/C)}} \); \( f = \frac{1}{2\pi\sqrt{(LC)}} \)
- \( I_{\text{Peak}} \times f = \frac{V_{\text{Peak}}}{2\pi L} \) – Not dependent on C
- Ex: At Max. system voltage of 170 kV, Minimum CLR size to limit ixf to 8.6x10^7 is 160\( \mu \)H.
- Size increases if there are parallel banks
- Depends on the type of the breaker (Definite C1,C2 Vs. General purpose, C0)
Problems with Current Limiting reactors

• Reported Failures of Capacitor bank breakers clearing internal faults.
• NERC sent out an advisory after Hydro- one Bank breaker failure (Jan. 2008 report).
• Cause of the failure was attributed to excessive rate of rise of transient recovery voltage (RRRV) for faults in between the reactor and the capacitor bank.
Reported Failures of Breakers Clearing faults on capacitor banks

- Failure of a 2000A 138 kV breaker protecting two 57.6 MVAR banks
  Com Ed’s (Excelon) Silver Lake Substation in Sept 1999.
  - Reactor size – 1 ohm (2.65 mH)
  - Fault current - 21kA
Silver Lake

Figure 1. Simplified one-line diagram of 138-kV circuit in ComEd’s Silver Lake Substation.
Hydro One

- Jan 30, 2007 – Two breakers failed clearing three phase fault on 230 kV, 400 MVAR ungrounded bank. Reactor size unknown
Analysis

- Ungrounded Double-Y
- Preliminary Investigations by Hydro One

Preliminary analysis by Hydro One determined that the Transient Recovery Voltage (TRV) that occurred as a result of the fault at Richview exceeded the design values of the 230 kV capacitor breakers SC22A and SC22SC. The rapid rising voltage is a result of the current limiting reactor at Richview interacting with stray capacitances at its terminals.

In the event of the TRV capability of a breaker being exceeded there is a possibility of arc re-ignition. When arc re-ignition occurs the fault current is interrupted, but for only microseconds, and the arc is sustained across the breaker contacts.
Rate of Rise of Recovery Voltage @ Richview

<table>
<thead>
<tr>
<th></th>
<th>SC22A TRV (kV/µs)</th>
<th>SC22SC TRV (kV/µs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>3.6</td>
<td>3.6</td>
</tr>
<tr>
<td>Three-phase to neutral fault*</td>
<td>21.5</td>
<td>10.5</td>
</tr>
</tbody>
</table>

- Calculated using average stray capacitances values and with the conservative assumptions that both breakers open simultaneously.
- This slide is from the Presentation of Ajay Garg of Hydro One at NERC
Regional action

- On February 9th, 2007 the IESO declared all 230 kV capacitors with current limiting reactors connected to the Ontario Bulk Power System unavailable for service, even for reliability concerns. All 115 kV capacitors with current limiting reactors were deemed available for emergency operation only to be used as a last resort before load shedding.
- Temporarily bypassing the current limiting reactors on at least one capacitor bank at a station. At stations that require both capacitors available, reactors on both units were bypassed and the bus will be split for operation. In some installations it may also be necessary to remove lines from service to limit fault current.
- At some stations the reactors were installed with the expectation of a second capacitor being installed in the future. Seven of the 32 installations where the second capacitor has yet to be installed will have the reactors removed or bypassed following analysis by Hydro One and the IESO. Capacitors at six stations are currently out of service and will remain that way until a long term solution is implemented.
Industry Advisory
January 15, 2008

To Whom It May Concern:

You have received this message because you are listed as the designated contact for your organization on the North American Electric Reliability Corporation's compliance registry. The Advisory Alert below is being sent to all entities classified as Transmission Owners and Operators on the compliance registry as an informational item. Please forward this Advisory to the appropriate personnel within your organization.

This Advisory is not the same as a reliability standard, and your organization will not be subject to penalties for a failure to address this Advisory. NERC is making this information available for such use as your organization deems appropriate; no particular response is necessary.

Please contact me should you have any questions regarding this Advisory.

Sincerely,

Robert Cummings
NERC Advisory

Status: Informational Only
Distribution: Transmission Owners & Operators
Background: On January 30 2007, a fault on a 400 Mvar capacitor bank in Hydro One's 230 kV system caused excessive rate of rise of transient recovery voltage (RRRV) across the main and backup capacitor bank breakers (above the breaker contact ratings), which prevented the breakers from clearing the fault. The main and backup breakers then failed as a single contingency.

More detail >>

Observation: Transmission owners should be aware that capacitor bank installations using series reactors to control back-to-back capacitor bank switching transients are potentially subject to capacitor terminal faults as well as faults between the capacitor bank and its series reactor that may be problematic to clear due to excessive RRRV. Electromagnetic transient studies can be performed to evaluate the RRRV at the breaker terminals. Surge capacitors may be needed to "slow down" the voltage transients across the breaker contacts and reduce the risk of breaker failure.

Primary Interest Groups:

System Protection Engineers
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Director of Event Analysis & Information Exchange
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bob.cummings@nerc.net
A-2008-01-15-01
Other Failures

- First Energy 115 kV capacitor bank
  - Solution - Installed CCVT to reduce the RRRV.
- TVA 161 kV capacitor bank breaker failure(?)
Breaker TRV ratings

• Transient Recovery Voltage (TRV) is the voltage across the breaker contact immediately after the breaker successfully interrupts the fault current.
• For successful interruption, the Rate of Rise of TRV (RRRV) cannot exceed 2.0 kV/μs (1.8 kV/μs for older breakers) as per industry standards, C37.04 and C37.06.
• Interpretation of TRV or RRRV capability is a convoluted process.
Recovery Transients seen after fault Interruption
Transient Voltages

Voltage on the source Side of the breaker

Current & Voltage waveforms
Source side Voltage

Source – Transformer fed fault or Transformer + lines
Source side capacitance is of the order of 50nf.
Faults close to the breaker
Transients on the line/reactor side

Typical capacitance – 100pf - 300 pf.
Voltage across the breaker
Transients on line side of the Transmission line breaker

- Short line faults – Kilometric fault (0.5-0.6 mile away from the breaker) result in higher rate of rise- Saw-toothed Waveform
Transient Recovery Voltage

• Voltage across the breaker contact stressing the insulation.

• Restrike Voltage – used outside USA.

• IEC/IEEE standards specify terminal ungrounded three phase faults and single line to ground short line fault testing.
IEEE –IEC Harmonization

A.2 Figures explaining the symbols

Figure A.1—Graphic showing the two parameters recovery voltage ($t_3$, $u_c$) used for voltages below 100 kV and a delay line with the delay time $t_d$.
IEC-IEEE Harmonization

Figure A.2—Correspondence between the new two-parameter method representing the recovery voltage for voltages below 100 kV and the old method listed in IEEE Std C37.04-1999.
Ratings for breakers above 100 kV

Figure B.1—Four-parameters recovery voltage \((t_1, u_1, t_2, u_c)\) used for voltages 100 kV and above and a delay line with the delay time \(t_d\) and the two defining parameters \(u'\) and \(t'\)

\[\text{RRRV} = \frac{U_1}{t_1}; \quad U_1 = 0.75 \times k_{pp} \times \frac{2}{3} \times U_{\text{rated}}; \quad K_{pp} = 1.5 \text{ first pole to open factor for ungrounded three phase fault.}\]
Voltage Across CLR

Figure: Typical capacitor installation with CLR.

\[ V_L = I_{sc} \times \omega L \]

where:

- \( V_L \) = peak CLR voltage, kV,
- \( I_{sc} \) = peak short circuit current, kA, and
- \( L \) = inductance of current-limiting reactor.
Voltage across the CLR for a fault on the capacitor side of the reactor

- The voltage across the reactor depends on the system short circuit strength.
- The voltage drop increases with fault current and also with the increase in the reactor size.
- Multiple bank stations with high fault currents will have higher voltage drops across CLR
TRV calculation

- For a fault on the capacitor side of the reactor, the voltage on the breaker terminals will be the reduced voltage equal to the voltage across the current limiting reactor.
- Rate of rise of voltages on both sides of the breaker is calculated after breaker interrupts the fault current.
Voltage Recovery

• The system side of the breaker recovers to the nominal value with oscillations dictated by the system impedance and the total connected capacitance.

• The reactor side of the breaker oscillates at a frequency dictated by the reactance and the bus capacitance.
Voltage drop Calculations

<table>
<thead>
<tr>
<th>Fault Current (RMS) KA (MVA)</th>
<th>Peak Voltage across 300 ( \mu )H Reactor, ( V_L )</th>
<th>Voltage as a percentage of the system ( V_{\text{nom}} ) rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>5kA (1394 MVA)</td>
<td>0.8 kV</td>
<td>0.61%</td>
</tr>
<tr>
<td>15kA (4183 MVA)</td>
<td>2.4 kV</td>
<td>1.8%</td>
</tr>
<tr>
<td>25 kA (6972 MVA)</td>
<td>4 kV</td>
<td>3%</td>
</tr>
<tr>
<td>40kA (11,154 MVA)</td>
<td>6.4 kV</td>
<td>4.9%</td>
</tr>
<tr>
<td>50kA (13,943 MVA)</td>
<td>8 kV</td>
<td>6.1%</td>
</tr>
</tbody>
</table>

- Assumptions: 161 kV system with single reactor (300 \( \mu \)H) bank assumed.
- For the fault location considered, the fault current is assumed to be same as the System Short circuit current. Actual fault current will be lower than these values.
System model for the reactor side of the breaker

Reactor side system model

(Typical values shown)

Other capacitance (Bus, breaker Bushing, ...)

Capacitor

If

V_L

5 pf

30 pf

30 pf
Reactor side capacitance

- Bus capacitance could be around 3-4 pf per foot.
- Assuming 15ft - 50ft of bus $C_{bus} = \sim 45 - 200$ pf.
- Breaker bushing capacitance - $\sim 100 - 150$ pf
- Reactor - $\sim 30$ pf
- Total capacitance – $\sim 200 - 400$ pf
- C37.011 provides typical values
Frequency of Oscillation on the Reactor side

- Frequency, $f = 1/[2\pi \sqrt{(300 \times 10^{-6} \times C_{pf} \times 10^{-12})}]$
- $f = 650$ kHz with 200 pf capacitance
- $f = 460$ kHz with 400 pf capacitance
Rate of rise of voltage on the reactor side of the breaker

- The rate of rise of the voltage on the reactor side of the breaker is dependant on the voltage drop across the reactor during fault and the frequency of oscillations.

- Slope is maximum around voltage zero crossing.

- Time taken from -0.5 to +0.5 of the voltage peak is 1/6\textsuperscript{th} of the total period.

- Time = 1/(6*f)

- Rate of rise = V_{PEAK} \times 6*f
## Rate of rise calculations on the reactor side of the breaker

<table>
<thead>
<tr>
<th>Fault Current KA (MVA)</th>
<th>Peak Voltage across 300 µH Reactor, $V_L$</th>
<th>Rate of rise of voltage (KV/µs) $V_L<em>6</em>f*10^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5kA (1394 MVA)</td>
<td>0.8 kV</td>
<td>0.96 kV/ µs, 2.9 kV/ µs</td>
</tr>
<tr>
<td>15kA (4183MVA)</td>
<td>2.4 kV</td>
<td>2.9 kV/ µs, 8.7 kV/ µs</td>
</tr>
<tr>
<td>25 kA (6972MVA)</td>
<td>4 kV</td>
<td>4.8 kV/ µs, 14.4 kV/ µs</td>
</tr>
<tr>
<td>40kA (11,154 MVA)</td>
<td>6.4 kV</td>
<td>7.7 kV/ µs, 23 kV/ µs</td>
</tr>
<tr>
<td>50kA (13,943 MVA)</td>
<td>8 kV</td>
<td>9.6 kV/ µs, 28.8 kV/ µs</td>
</tr>
</tbody>
</table>
Simplification of RRRV calculation for Capacitor Breakers

- It assumed that the RRRV is mainly dictated by the rate of rise on the reactor side of the breaker.
- If the rate of rise on the reactor side exceeds 2.0 kV/μs (1.8 kV/μs for older breakers), additional capacitance is needed to reduce the frequency of oscillations.
- At currents lower than the rated interrupting currents, RRRV would be higher as listed in C37.011.
- The frequency of oscillations has to be reduced to keep rate of rise below 2 kV/μs or below the specified RRRV.
Mitigation Techniques

- Add capacitance to reduce the frequency of oscillation to meet RRRV requirement
- Two methods of surge capacitor connection
  a. At circuit breaker terminals
  b. Across CLR terminals

**Figure**: Typical application of surge capacitor
Surge Capacitance Connection

- Phase to Ground connection – must be rated to system max. voltage; Expensive
- Across the reactor – voltage rating selected to be above the maximum voltage drop across the reactor (Max. 8 kV in our example). It requires additional protection (surge arrestor) across the capacitor terminals to limit the voltage during back-to-back or outrush conditions
Need for Surge Arrester

- Outrush and Back-Back energization transients.
- Selected to limit the peak transient voltage to 2 p.u. on surge capacitor voltage rating.

\[ V_{peak} = \frac{EC_1}{C_1 + C_{Surge}} \]

where:
\[ V_{peak} = \text{First peak of voltage imposed on the surge capacitance and reactor combination.} \]
\[ E = \text{System phase peak voltage.} \]
\[ L = \text{Current limiting reactor inductance.} \]
\[ C_1 = \text{Capacitor Bank Capacitance.} \]
\[ C_{Surge} = \text{Surge Capacitance.} \]
Field Installation
Questions ?