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Shunt Capacitor Bank Switching Transients:
A Tutorial and Case Study

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Capacitor Bank Switching

- Overview of recent installations at NSP
- Observations and trends
- Study work that must be done
- Tutorial on capacitor bank switching
- Brief overview of 115-kV case study
- Comments
### MMTU Phase I

*Increased Power Transmission*

<table>
<thead>
<tr>
<th>Station</th>
<th>Voltage</th>
<th>MVAR</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red Rock</td>
<td>115 kV</td>
<td>240</td>
<td>3 x 80</td>
</tr>
<tr>
<td>Kohlman Lake</td>
<td>115 kV</td>
<td>240</td>
<td>3 x 80</td>
</tr>
</tbody>
</table>

### MMTU Phase II

*Increased Power Transmission*

<table>
<thead>
<tr>
<th>Station</th>
<th>Voltage</th>
<th>MVAR</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forbes</td>
<td>500 kV</td>
<td>600</td>
<td>2 x 300</td>
</tr>
</tbody>
</table>

400 MVAR Thyristor Switched
### MMTU Phase III

**(Increased Power Transmission)**

<table>
<thead>
<tr>
<th>Station</th>
<th>Voltage</th>
<th>MVAR</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prairie</td>
<td>115 kV</td>
<td>480</td>
<td>12 x 40 MVAR</td>
</tr>
<tr>
<td>Little Fork</td>
<td>230 kV</td>
<td>240</td>
<td>6 x 40 MVAR</td>
</tr>
<tr>
<td>Sheyenne</td>
<td>115 kV</td>
<td>200</td>
<td>5 x 40 MVAR</td>
</tr>
<tr>
<td>Roseau</td>
<td>230 kV</td>
<td>80</td>
<td>2 x 40 MVAR</td>
</tr>
</tbody>
</table>

### Others

**(Voltage/VAR Support)**

<table>
<thead>
<tr>
<th>Station</th>
<th>Voltage</th>
<th>MVAR</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eau Claire</td>
<td>161 kV</td>
<td>320</td>
<td>4 x 80 MVAR</td>
</tr>
<tr>
<td>Parkers Lake</td>
<td>115 kV</td>
<td>240</td>
<td>3 x 80 MVAR</td>
</tr>
<tr>
<td>Aldrich</td>
<td>115 kV</td>
<td>240</td>
<td>2 x 120 MVAR</td>
</tr>
<tr>
<td>Elm Creek</td>
<td>115 kV</td>
<td>120</td>
<td>1 x 120 MVAR</td>
</tr>
<tr>
<td>Elliot Park</td>
<td>115 kV</td>
<td>80</td>
<td>1 x 80 MVAR</td>
</tr>
<tr>
<td>Rogers Lake</td>
<td>115 kV</td>
<td>240</td>
<td>3 x 80 MVAR</td>
</tr>
</tbody>
</table>
Others, Cont’d
(Voltage/VAR Support)

<table>
<thead>
<tr>
<th>Station</th>
<th>Voltage</th>
<th>MVAR</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Koch Refinery</td>
<td>161 kV</td>
<td>80</td>
<td>1 x 80 MVAR</td>
</tr>
<tr>
<td>Split Rock</td>
<td>115 kV</td>
<td>160</td>
<td>2 x 80 MVAR</td>
</tr>
<tr>
<td>Cherry Creek</td>
<td>115 kV</td>
<td>40</td>
<td>1 x 40 MVAR</td>
</tr>
<tr>
<td>Lk Yankton</td>
<td>115 kV</td>
<td>40</td>
<td>1 x 40 MVAR</td>
</tr>
<tr>
<td>Buffalo Ridge</td>
<td>34.5 kV</td>
<td>80</td>
<td>Total Dist.</td>
</tr>
<tr>
<td>Traverse</td>
<td>69 kV</td>
<td>14</td>
<td>1 x 14 MVAR</td>
</tr>
</tbody>
</table>

Trends

• At least 4 GVAR installed in NSP system in recent years.

• Most installed at 115-kV and above

• **LOTS** of stored energy in cap banks

• Higher X/R ratio means less damping than is observed at lower voltage levels.

• More concern about switching transients
Types of Studies Needed

- Inrush/Outrush Current
- Transient Overvoltage (TRV)
- Voltage Magnification (Interaction with capacitors on nearby distribution system)
- Existing Equipment Ratings
  - Breakers
  - Surge Arresters
- New Equipment Ratings
  - Breakers
  - Surge Arresters
  - Inrush/Outrush Current-Limiting Reactors
- Current Transformer High Secondary Voltage

Getting Started -

Useful Reference Information

- A. Greenwood, Electrical Transients in Power Systems
- IEEE Std. C37.012-1979
- IEEE Standards Collection on Power Capacitors
- IEEE Tutorial - Application of Power Circuit Breakers
- IEEE Special Publication - Modeling and Analysis of System Transients using Digital Programs
- Other misc. papers
Learning the Basic Concepts of Capacitor Bank Switching

34.5-kV Per-Phase System

1 - Energization Inrush

CB1 and CB4 Closed, Close Switch S1.
Energization Inrush - First Bank $C_1$

$$ i(t) = \frac{V(0)}{Z_0} \sin \omega_0 t $$
$$ Z_0 = \sqrt{\frac{L}{C_1}} $$
$$ \omega_0 = \frac{1}{\sqrt{LC_1}} $$

Peak Current = 3041 Amps, Natural Frequency = 500 Hz

Energization Inrush - First Bank $C_1$

Bus Voltage: Peak Voltage = 1.87 per unit
2 - Back-to-Back Energization

CB1, CB4, S1 Closed. Close Switch S2.

Peak Current = 1400 Amps, Natural Frequency = 9.4 KHz
Back-to-Back Energization

\[ i(t) = \frac{V(0)}{Z_{01}} \sin \omega_{01} t \]

\[ Z_{01} = \frac{L_b}{\sqrt{C_{EQ}}} \]

\[ \omega_{01} = \frac{1}{\sqrt{L_b C_{EQ}}} \]

\[ C_{EQ} = \frac{C_1 C_2}{C_1 + C_2} \]

Peak Bus Voltage = 1400 Amps

3 - Outrush Transient

\[ i(t) = \frac{V(0)}{Z_{02}} \sin \omega_{02} t \]

\[ Z_{02} = \frac{L_F}{\sqrt{C_1}} \]

\[ \omega_{02} = \frac{1}{\sqrt{L_F C_1}} \]

CB1, CB3, CB4, S1 Closed. Fault on Feeder or Bus.
4 - Voltage Magnification

CB1, CB2, CB4 Closed. Close Switch S1 or S2.

Peak Distribution Bus Voltage = 1.76 per unit.
5 - Transient Recovery Voltage

CB1 Closed, Fault on Bus. Open CB1 to Clear Fault.

Transient Recovery Voltage

Oscillation between Circuit Breaker Bushing Capacitance and Source Inductance.

Peak Bus Voltage = 1.4 per unit, Frequency = 5 KHz.
Split Rock - A Case Study

2 - 80 MVAR 115-kV Banks

The Study Zone

- Multi-Port 60-Hz Thevenin Equivalent to model surrounding system
- Transformers - coupled R-L with core saturation and bushing capacitances
- Transmission Lines: distributed parameter for long lines. Coupled-Pi for very short sections
- Capacitors with parallel dissipation resistors
- RLC Coupled-Pi for Buswork
Single Bank Energization

Inrush Reactor Sizing
Back-to-Back Energization

Capacitor Outrush Current
Outrush Reactor Sizing

Voltage Magnification Summary:
Peak Distribution Bus Voltages
Other Concerns

- Statistical studies of peak currents and voltages in synchronous closing schemes
- Failure of synchronous closing scheme
- Time delay required to discharge banks in cases where reclosing is applied. Nonlinear voltage ringdown in cases when discharged through voltage transformers.
- Unintentional re-energization of bank before it has discharged. Worst case: energize when source voltage is opposite the polarity of the trapped charge.
- Changes in frequency response of system due to addition of capacitor banks.

CLOSING COMMENTS

- Studies performed over last 10 years and equipment specified seem to be correct.
- Ferroresonance involving the banks and regulator transformers has been observed for short periods of time. Nonlinearity of transformer makes it hard to predict. Some work in this area may be in order.
- Simulation results are only as good as the model. Transmission line and transformer models must be continually improved.
- Gathering equipment parameters can be most time-consuming part of simulation. Ask for complete equipment parameters when writing new equipment specifications.
COMMENTS?

QUESTIONS?