Undergrounding power lines - the great challenge

Calculation of
1. short-circuit currents.
2. temporary overvoltages.
3. electromagnetic transients

To be revised!
Undergrounding power lines

and the capacitive current switching

Step-down transformer

Equivalent Voltage Source

n underground cables

Distribution system

Single Capacitor Bank
## Types of the capacitive switching

<table>
<thead>
<tr>
<th>Type</th>
<th>Inrush current peak</th>
<th>Inrush current rate of rise</th>
<th>Duty for CBs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switching lines/cables</td>
<td>Very low</td>
<td>high</td>
<td>Light</td>
</tr>
<tr>
<td>Switching single-step capacitor bank</td>
<td>low</td>
<td>low</td>
<td>light</td>
</tr>
<tr>
<td>Back-to-back capacitor bank</td>
<td>high</td>
<td>high</td>
<td>Very heavy</td>
</tr>
</tbody>
</table>
Switching Capacitor bank Back-to-Back to Underground Cables

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Traditional approach to switching isolated capacitor bank

![Diagram of traditional approach]

\[ V_{\text{max}} \cos(\omega t) \]

\[ I_{\text{peak}} = \frac{V_0}{\sqrt{L_S / C}} \]

\[ \frac{di}{dt} = \frac{V_0}{L_S} \]

\[ I_{\text{peak}} = 1.6 \text{ kA}, \frac{di}{dt} = 2.7 \text{ kA/ms} \]

Field tests of isolated 24 kV capacitor bank:

\[ I_{\text{peak}} = 7 \text{ kA}, \frac{di}{dt} = 3300 \text{ kA/ms} \]
Suggestion: Inrush current is a sum of current surges in the cables
Suggestion: Inrush current is a sum of current surges in the cables

\[ I(t) = \sum I_{in} \]

\[ I_{in} = \frac{V_{in}}{Z_W} \]

MV busbars

Incident current wave \( (I_{in}) \)

Feeder cable

Distance from busbars [km]
Since measured inrush currents significantly exceed the "inrush current of isolated capacitor bank", their detailed research is necessary for selection of the capacitor bank switchgear.

Main goals of the research:

1. Analytical study of the phenomenon
2. Case study of switching 24 kV capacitor banks
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Analytical study

Single phase circuit to analyze the capacitor bank inrush current
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Analytical study

Inrush current through the system impedance

Inrush current due to traveling waves in cables
Analytical study: inrush current of isolated capacitor bank

\[ i_{tr}(t) = I_{peak} e^{-\frac{R_S}{2L_S} t} \sin \beta t \]

where

\[ I_{peak} = \frac{V_0}{\sqrt{L_S / C}} \]

\[ \beta = \frac{1}{\sqrt{L_S C}} \]
Analytical study: inrush current due to the traveling waves

General case: underground cables have unequal lengths

\[ i(p) = \frac{V_0 C}{L C p^2 + Z_{CW} C p + 1} \]

Inrush current in the Laplace domain

Inrush current due to the initial current surges
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Analytical study: closed form-expressions of current waveforms

Damping reactor is not applied

\[ Z_{CW} \geq 2Z_W \]

\[ i(t) = 2Ie^{-\delta t} \sinh \alpha t \]

where

\[ I = \frac{V_0}{\sqrt{Z_{CW}^2 - 4Z_W^2}}, \quad \delta = \frac{Z_{CW}}{2L}, \quad \alpha = \frac{\sqrt{Z_{CW}^2 - 4Z_W^2}}{2L} \]

\[ Z_W = \sqrt{\frac{L}{C}} \]

Characteristic impedance of the circuit formed by inductance \( L \) and capacitance \( C \)

Damping reactor is applied

\[ Z_{CW} < 2Z_W \]

\[ i(t) = 2Ie^{-\delta t} \sin \alpha t \]

\[ Z_{CW} = \frac{Z_C}{n} \]

Equivalent surge impedance of \( n \) underground cables
Analytical study: inrush current peak

\[ I_{\text{peak}} = \frac{2I\alpha}{\sqrt{\delta^2 - \alpha^2} \left( \frac{\sqrt{\delta^2 - \alpha^2}}{\delta - \alpha} \right)^{\frac{\delta}{\alpha}}} \]

is reached when

\[ t = \frac{1}{2\alpha} \ln \frac{\delta + \alpha}{\delta - \alpha} \]

Limiting case of non-oscillatory inrush current:

\[ L \rightarrow 0 \]

\[ I_{\text{peak}} = n \frac{V_0}{Z_C} \]

Limiting case of oscillatory inrush current:

\[ \sqrt{\frac{L}{C}} \gg \frac{Z_C}{n} \]

\[ I_{\text{Peak}} = V_0 \sqrt{\frac{C}{L}} \]
Analytical study: maximum value of $\frac{di}{dt}$

$$\frac{di}{dt} = \frac{V_0}{L}$$

The maximum rate of rise of the inrush current is limited only by the equivalent inductance $L$. If $L$ includes only stray inductance (damping reactor is not applied) the maximum value of $\frac{di}{dt}$ can be extremely high.
Analytical study: inrush current due to the traveling waves

Particular case: \( n \) underground cables have equal length

Inrush current due to superposition of the initial current surges and reflected current surges

\[
i_s(p) = \frac{V_0 C}{LCp^2 + Z_{CW}Cp + 1} \times \left[ 1 - 4\delta \sum_{k=1}^{\infty} a_L^k \left[ \frac{(p + p1)(p + p2)}{(p - p1)(p - p2)} \right]^{k-1} \right]
\]
Analytical study: closed form-expression of current waveforms when the initial waves and the first 3 reflected waves are considered

\[ i_S(t) = i(t) + i_1(t_1) + i_2(t_2) + i_3(t_3) \]

\[ i(t) = 2It e^{-\delta t} \sinh \alpha t \]

\[ i_1(t_1) = 2Ie^{-\delta t_1} \left[ a_{11} \sinh(\alpha t_1) + a_{12} \alpha t_1 \sinh(\alpha t_1) - a_{12} \delta t_1 \cosh(\alpha t_1) \right] \]

\[ i_2(t_2) = 2Ie^{-\delta t_2} \left[ a_{21} \sinh(\alpha t_2) + a_{22} \delta t_2 \sinh(\alpha t_2) - a_{21} \alpha t_2 \cosh(\alpha t_2) \right. \]
\[ + a_{23} \delta^2 t_2^2 \sinh(\alpha t_2) - a_{24} \delta^2 t_2^2 \cosh(\alpha t_2) \]

\[ i_3(t_3) = 2Ie^{-\delta t_3} \left[ a_{31} \sinh(\alpha t_3) + a_{32} \delta t_3 \sinh(\alpha t_3) - a_{31} \alpha t_3 \cosh(\alpha t_3) \right. \]
\[ + a_{33} \delta^2 t_3^2 \sinh(\alpha t_3) - a_{34} \delta^2 t_3^2 \cosh(\alpha t_3) + a_{35} \delta^3 t_3^3 \sinh(\alpha t_3) \]
\[ \left. - a_{36} \delta^3 t_3^3 \cosh(\alpha t_3) \right] \]
Case study: the circuit description

Transformer of 161/24 kV,
S = 45 MVA, \( e_k = 18\% \)

Infinite busbar

Types of capacitors:
1. Isolated 9MVAR capacitor bank
2. Multi-step 3×5 MVAR capacitor bank (switching the 1st step)

\( n \) feeders

24 kV busbar

Single-core, coaxial cables, XLPE copper 300/25 cross-section

Overhead line ACSR 150/25
Case study: results of the field tests versus EMTP simulation

Switching 9 MVAR, 24 kV capacitor bank

Measured peak inrush currents

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Peak inrush currents [kA, peak]</th>
<th>$I_R$</th>
<th>$I_S$</th>
<th>$I_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>4.8</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>5.7</td>
<td>4.6</td>
<td>7.1</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>5.6</td>
<td>4.5</td>
<td>7.2</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>6.1</td>
<td>3.2</td>
<td>6.6</td>
</tr>
</tbody>
</table>

Maximum measured $di/dt = 3300 \text{ kA/ms}$
Case study: Parametric study of the inrush current peak

Dependence on the number of underground cables

\[ I_{\text{peak}} = n \frac{V_0}{Z_C} \]  
(proportional to \( n \))

\[ I_{\text{Peak}} = V_0 \sqrt{\frac{C}{L}} \]  
(practically independent of \( n \))
Case study: Parametric study of the inrush current peak

Dependence on the equivalent inductance, \( n = 8 \)

Increase of the equivalent inductance \( L \) leads to reduction of the inrush current peak \( I_{peak} \).
Parametric study of $I_{peak}$ – Concept of the minimal length of cable

Minimal length of cable $l_{min}$ as the shortest cable length among $n$ cables that makes it possible for the inrush current to reach its peak value $I_{peak}$ before the reflected wave arrives at the substation busbar.

**For the banks without damping reactor**

For the banks with damping reactor

![Graph showing minimal length of cable versus cable length](image)

- **Stray inductance [microhenry]**
- **Equivalent inductance [microhenry]**
Case study: \( n \) underground cables have equal length

Verification of the derived analytical expressions: \( Lc = 1 \text{km} \), \( Q = 9 \text{ MVAR} \), \( L = 5\mu\text{H} \), \( n = 8 \)

Very good agreement between the analytical waveforms and the EMTP waveforms enables to accept the hypothesis that the inrush currents occur due to the traveling waves in the alongside underground cables!
Case study: \( n \) underground cables have equal length

**Verification of the derived analytical expressions:** \( Ic = 5 \text{ km}, Q = 9 \text{ MVAR}, L = 5\mu\text{H}, n = 8 \)

For \( n \) identical long cables the maximum value of the inrush current is always achieved at the first peak of the current waveform.

The following crest values of the current waveform are smaller than the 1st peak because of the attenuation of the traveling waves.
Case study: Parametric study of the inrush current peak

Dependence on the cable length: $Q=9$ MVAR, $L = 5\mu H$, $n = 8$

Variation of the cable length from 0 to $l_{min}$ results in increase of the maximum current peak from zero to the inrush current peak $I_{peak}$.

The following growth of the cable length does not cause increase of the maximum current peak because of the attenuation of the traveling waves in the cables.
Switching Capacitor bank Back-to-Back to Underground Cables

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Case study: Undergrounding the distribution power lines and the inrush current

- Total inrush current
- Inrush current through the transformer
- Capacitor bank switching back-to-back to 8 underground cables
- Capacitor bank switching back-to-back to 8 overhead feeders
Switching 170 kV, 200 MVAR capacitor bank back-to-back to underground cables (damping reactor is not applied)

<table>
<thead>
<tr>
<th>Calculation method</th>
<th>$I_{peak}$ [kA, peak]</th>
<th>$di/dt$ [kA/ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>“inrush current of isolated capacitor bank”</td>
<td>6.8</td>
<td>20</td>
</tr>
<tr>
<td>Switching back-to-back to 6 underground cables</td>
<td>32</td>
<td>9000</td>
</tr>
</tbody>
</table>
Operational experience: Analysis of failures of 24 kV, minimum-oil circuit breakers used for switching isolated capacitor banks

- Handling capacitor inrush currents ($I_{peak} = 4-6$ kA, $di/dt = 1000-3000$ kA/ms)
- Quick oil deterioration; problems with CB mechanical system
- Restrikes during opening CB, Inrush currents having $I_{peak} = 8-12$ kA
- Explosions of CB breaking unit accompanied by a short circuit on the substation busbar
Conclusions

1. Since the inrush current during the capacitor bank switching back-to-back to the underground cables significantly exceeds the "inrush current of isolated capacitor bank" it should taken into account in the selection of the capacitor bank switchgear.

2. It seems that switching capacitor bank back-to-back to the underground cables should be addressed in the standards concerning the capacitive current switching