Operation and Protection of HV Cable Systems in TEPCO

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Contents

1. Introduction of TEPCO’s Cable Network
2. Operation of HV Cable Systems
3. Protection of HV Cable Systems
Bulk Power Transmission Network

East-West Route
240km [1999]

Minami-Iwaki

Kashiwazaki-Kariwa

Higashi-Gunma

North-South Route
190km [1993]

Shin-Imaichi

Higashi-Yamanashi

Tokyo

Large demand area

UHV designed tower

GS
SS
SW
550kV line
UHV designed line
## Percentages of Cable Types

<table>
<thead>
<tr>
<th>Cable Type</th>
<th>500kV</th>
<th>79km</th>
<th>all XLPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>275kV</td>
<td>1006km</td>
<td>XXLP</td>
<td>262km (26%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SCFF</td>
<td>513km (51%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HPFF</td>
<td>231km (23%)</td>
</tr>
<tr>
<td>154kV</td>
<td>788km</td>
<td>XXLP</td>
<td>156km (20%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SCFF</td>
<td>614km (78%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HPFF</td>
<td>18km (2%)</td>
</tr>
<tr>
<td>66kV</td>
<td>5,977km</td>
<td>XXLP</td>
<td>5,114km (86%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SCFF</td>
<td>863km (14%)</td>
</tr>
<tr>
<td>Duct</td>
<td></td>
<td></td>
<td>2,430km</td>
</tr>
<tr>
<td>Tunnel</td>
<td></td>
<td></td>
<td>483km</td>
</tr>
<tr>
<td>Multi-Utility Tunnel</td>
<td></td>
<td></td>
<td>280km</td>
</tr>
</tbody>
</table>
500 kV Underground Cable Project

Aluminum covered XLPE (CAZVI) 2,500 mm², 39.5 km, 2 circuits

Shin-Toyosu S/S
Shin-Toyosu T/L
Shin-Keiyo S/S
Underground 500kV Substation (Shin-Toyosu)
Contents

1. Introduction of TEPCO’s Cable Network

2. Operation of HV Cable Systems
   • Tunnel and Cooling System
   • Reactive Power Compensation
   • System Studies

3. Protection of HV Cable Systems
Design of Underground Cables

- Cable Alignment
- Transmission Capacity
- Cable Type Selection
- Environment
- Shortest Length
- Future Planning
- Coordination with Other Utilities

Cable Accommodation

- Direct Burial
- Duct
- Open Cut Tunnel
- Shield Tunnel

Route Selection

- XLPE
- OF
- POF
- GIL

Cable Type Selection

- Bicycle Burial
- Duct
- Open Cut Tunnel
- Shield Tunnel

Transmission Capacity
Cable Alignment Design

Cable Alignment

Share tunnel space with other utilities (Multi-Utility Tunnel)

LV and HV Cables

EHV Cables

Water Cooling

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Water Cooling Design

Lower Cost by Water Cooling

- Reference (228MW)
- With Water Cooling (456MW)
- Without Water Cooling (456MW)

- No Additional Tunnel and Cable Cost
- Additional Cooling Cost

• Additional Tunnel Cost
• Additional Cable Cost

Water Cooling Design

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Cooling System

Water Cooled Line 160km

30km

Water Cooled Line (Planned) 18.1km

500 kV Cable 79 kmccct
275 kV Cable 1007 kmccct
TEPCO Tunnel 483 km
Gov. Tunnel 280 km
500kV Shin-Toyosu Cable Line

Shin-Keiyo S/S  

- O7  
- O9

Shin-Toyosu S/S  

- O1  
- O3

300 MVA  

- 500 kV  
- 39.5 km

1500 MVA  

- 275 kV

Compensation Rate: \[
\frac{1200 \text{ MVar}}{1286 \text{ MVar}} \times 100 = 93.3%\]
Most shunt reactors are automatically switched at scheduled times to control system voltages.
Some cables are taken out of service in low demand days to lower system voltage, without affecting reliability.

During the new year holiday, 10 EHV cable circuits (1150MVA) were taken out of service.
System Studies for Cable Installations

1. Load Flow analysis
   • Reactive power compensation
2. Temporary overvoltage
   • Resonance overvoltage
   • Oscillatory overvoltage in an islanded system
   • Ferranti phenomenon
   • Overvoltage in sound phase in SLG faults
3. Slow-front overvoltage
   • Overvoltage in line energizations
   • Ground fault and Fault clearing overvoltage
4. Fast-front overvoltage / Very-fast-front overvoltage
   • Lightning-overvoltage
   • Restrike after opening shunt reactor
5. Zero-miss (DC offset current) phenomenon analysis
6. Leading current interruption
7. Discharge of the cable line
Series Resonance Overvoltage
Series Resonance Overvoltage

Series resonance frequency:

\[ f = \frac{1}{2\pi \sqrt{LC}} \]
Oscillatory Overvoltage caused by Islanding

Example of the system islanding
Oscillatory Overvoltage by Islanding

Oscillatory temporary overvoltage  Sustained temporary overvoltage

Example of the overvoltage caused by the system islanding
Leading (Capacitive) Current Interruption

Leading (Capacitive) Current Interruption Capability according to IEC 62271-100

<table>
<thead>
<tr>
<th>Rated Voltage</th>
<th>Rated Capacitive Switching Currents* (Cable)</th>
</tr>
</thead>
<tbody>
<tr>
<td>420 kV</td>
<td>400 A</td>
</tr>
<tr>
<td>550 kV</td>
<td>500 A</td>
</tr>
</tbody>
</table>

*: Preferred values, voltage factor: 1.4 pu

420 kV, 400 A $\rightarrow$ 290 MVar, 0.2 uF/km $\rightarrow$ 26 km

For long lines, it is necessary to consider leading current interruption capability. It may be useful to review the level of the overvoltage.
Contents

1. Introduction of TEPCO’s Cable Network
2. Operation of HV Cable Systems
3. Protection of HV Cable Systems
   - Charging current compensation
   - LR numerical distance relay
   - Zero-miss phenomenon
   - Point-on-wave open timing controller
Charging Current Compensation

Current differential relay

Obtain \( I_c \) by software computation and use \( I_d \) instead of \( (I_a + I_b) \)

\[
\dot{I}_d = I_a + I_b - I_c
\]

\[
\dot{I}_c = j \begin{bmatrix}
\omega(Caa + Cab + Cac), & -\omega Cab, & -\omega Cac \\
-\omega Cab, & \omega(Cbb + Bbc + Cba), & -\omega Cbc \\
-\omega Cac, & -\omega Cbc, & \omega(Ccc + Cca + Ccb)
\end{bmatrix} \cdot \dot{V}
\]
Impedance Calculation in Distance Relays

Obtain inductance $L$ from a set of power system differential equations by digital computation. Accurate impedance measurement is realized by this relay, even when low order harmonics are contained.

\[
\begin{align*}
    v(t) &= L \cdot \frac{di(t)}{dt} + R \cdot i(t) \\
    v(t-\tau) &= L \cdot \frac{di(t-\tau)}{dt} + R \cdot i(t-\tau)
\end{align*}
\]

\[
L = \frac{v(t) \cdot i(t-\tau) - v(t-\tau) \cdot i(t)}{\frac{di(t)}{dt} \cdot i(t-\tau) - \frac{di(t-\tau)}{dt} \cdot i(t)}
\]
Impedance Calculation in Distance Relays

In recent distance relays, the following set of equations are used, instead of the set of differential equations in the previous slide.

\[
\begin{align*}
\int_{t_0}^{t} v \, dt &= L i + R \int_{t_0}^{t} i \, dt \\
\int_{t_0}^{t-\tau} v \, dt &= L i + R \int_{t_0}^{t-\tau} i \, dt \\
\end{align*}
\]

Simpson’s rule for numerical integration is used to calculate the integrals.

\[
\int f \, dt = \frac{h}{3} \left[ f(a) + f(a + nh) + 4 \sum_{i=1}^{n/2} f(a + (2i-1)h) + 2 \sum_{i=1}^{n/2-1} f(a + 2ih) \right]
\]

\[n = (b - a) / h\]
Zero-miss Phenomenon

Close C under a no load condition with a shunt reactor

Current on C has dc-component for several seconds.

If a fault occurs during this periods, circuit breaker cannot interrupt fault current.
Zero-miss Phenomenon

Zero-miss phenomenon with a single line to ground fault on phase B
Sequential Control of Line-CB and Shunt Reactor-CB

Fault clearance

Substation A

87L

Trip Order

One Phase Fault

Substation B

87L

Source side

Load side

ShR

ShR
Sequential Control of Line-CB and Shunt Reactor-CB

ShR CB open

Source side

Load side
Sequential Control of Line-CB and Shunt Reactor-CB

Healthy Phases of Line CB at Load Side Open

Substation A

Substation B

Trip Order

87L

Source side

Load side

ShR

ShR
Sequential Control of Line-CB and Shunt Reactor-CB

Healthy Phases of Line CB at Source Side Open

Substation A

Trip Order

Source side

Substation B

Load side

ShR

87L
Sequential Control of Line-CB and Shunt Reactor-CB

- Open shunt reactors
- Open CB of Phase B
## Countermeasures

<table>
<thead>
<tr>
<th>Countermeasure</th>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sequential switching</td>
<td>• established technology</td>
<td>• requires higher leading current interruption capability</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• requires single phase CB and current differential relay</td>
</tr>
<tr>
<td>Point-on-wave switching</td>
<td>• basically established technology</td>
<td>• causes higher switching overvoltage</td>
</tr>
<tr>
<td>CB with pre-insertion resistor</td>
<td></td>
<td>• has to develop a new CB (expensive)</td>
</tr>
<tr>
<td>Reactor with lower X/R</td>
<td>• no disadvantages described above</td>
<td>• causes higher loss</td>
</tr>
<tr>
<td>Energise reactor after the cable</td>
<td></td>
<td>• causes higher overvoltage</td>
</tr>
</tbody>
</table>
Very-fast-front Overvoltage

Example of Restrike Overvoltage Analysis

- Restrike
- Chopping of ShR current
- Power Frequency
- Slow-front Overvoltage
- Overvoltage due to Restrike
Overvoltage Caused by the Restrike

Point-on-wave Open Timing Controller

- Minimum arching time: $T_4 = 9.5\text{ms}$
- Setting time: $T_2 = 11.0\text{ms}$
- GCB pole opening time: $T_1 = 13.4\text{ms}$
- Scattering time: $T_3 = \pm 1.5\text{ms}$

Order point to open CB pole

Pole separating point

Alternating current
Thank you for your attention.