HVDC systems

Rectifier

Transmission line

Inverter
Types of HVDC

Monopolar
- Older/smaller systems
- Subsea cable
- Ground electrode
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- Older/smaller systems
- Subsea cable
- Ground electrode

Bipolar/UHVDC
- Newer/higher power
- Overhead lines
- Ground electrode or dedicated metallic return (DMR)

(Solar farms)
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Corrosion threat
Types of HVDC systems

Monopolar
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- Subsea cable
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Bipolar/UHVDC
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(Solar farms)

Corrosion threat

Safety threat
Most common systems

<table>
<thead>
<tr>
<th></th>
<th>Africa</th>
<th>Australia &amp; Oceania</th>
<th>Asia</th>
<th>Europe</th>
<th>North America</th>
<th>South America</th>
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<tbody>
<tr>
<td>Operational</td>
<td>3</td>
<td>5</td>
<td>54</td>
<td>53</td>
<td>17</td>
<td>3</td>
</tr>
<tr>
<td>Planned (&lt;2020)</td>
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<td>0</td>
<td>1</td>
<td>9</td>
<td>4</td>
<td>0</td>
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<tr>
<td>Total in 2020</td>
<td>3</td>
<td>5</td>
<td>55</td>
<td>62</td>
<td>21</td>
<td>3</td>
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</table>
### Corrosion threats

#### Rectifier
- Current discharge by HVDC
- Current pick-up by pipe
- Mainly risks of overprotection (coating disbondment, H₂-cracking)

#### Inverter
- Current pick-up by HVDC
- Current discharge by pipe
- Mainly risks of corrosion
Impact of HVDC electrode

\[ V_r = \frac{\rho I}{2\pi r} \]

4V

0.1km 100km

2.5mV/m

0.1km 100km

References:
- Stryge (Ref 10 table 2)
- Gisborne (Ref 7 fig. 4)
- Nan Giao (Ref 7 fig. 3)
- Sarâ (Ref. 12 fig. 5)
- Rioh (Ref. 10 fig. 4)
- Leona
- Canegyndra
- Edo kia Iku (Ref 6 fig. 7)
- São Paulo (Ref 6 fig. 7)
- Lisbon (Ref. 9 fig. 7)
- Des Cartons (Ref. 10 fig. 4)
- Gaia
- Faimo-Sára Arcola (Ref 10 fig. 4)
- Odessa

The curves are mainly calculated from surface potential data given in the references. The calculations are carried out assuming an even potential distribution between the distances where the surface potentials are known. Therefore, the curves may not correspond exactly to the values given on page 6 in ref. [10].

07 June 2022
Pipe protection criteria

- Protective measures must be applied if the pipe leakage current density is more than 1 μA/cm² (10mA/m²) or the cumulative corrosion amount (thickness) affects the safe operation.
- DC interference exists if the pipe-to-soil potential is higher than 20 mV positive shift to the pipe natural potential or the DC soil potential gradient near the pipe is greater than 0.5 mV/m.
- For a new pipeline, if a pipeline route is in the zones where the DC soil potential gradient is greater than 2.5 mV/m, the pipeline may be subject to DC interference and therefore must be evaluated.
- For CP protected pipeline the CP criteria shall be met.
Mitigation strategies

Insulation joints

Sacrificial anodes

- Resistance-to-earth < internal pipe R
- Anodic side: $J < 1 \text{ A/m}^2$
- Cathodic side: $J < 0.3 \text{ A/m}^2$
- Not so effective -> only small stray current

Automated CP system (w/ drainage)

Line current compensation:

- Current control based on voltage gradient
- Difficult (long cables)
Bipolar HVDC
- 500MV nom. power
- 400KV nom. Voltage
- electrode resistance of 0.11 Ω
- 710 km long

Pipeline
- 24” FBE coated
- 20 – 50 Ωm
- 487 km long

Clearance
- rectifier – 431 km
- inverter – 32 km
Corrosion threat at inverter

PSP ON – as-found with no interference

PSP ON – 1375 Amps monopolar operation mode
Corrosion threats at inverter

Computed ground potential rise around HVDC electrode
- -228V@electrode
- -12@pipeline

PSP ON – 1375 Amps monopolar operation mode
Corrosion prevention

Mitigation system

- Voltage controlled rectifier (50V/40A) with deep ground anode bed of 2.74 Ω

- Grounding system of 920 m length in 22 cm backfill having a resistance-to-earth of 0.42 Ω

- Anode potential must compensate the GPR of -12 V
Safety threats
HVDC fault currents

UHVDC with DMR

- 800kVA/6000A nominal
- Rectifier feeds the fault current
- Transient signal
- Higher amplitude than DC (1 p.u.)
- Different phase and frequency in conductors/DMR
- Longer clearing time than AC systems
- Total charge accumulated in body during fault event

$\text{Imax} = 6000 \text{ A}$

![Current vs Time Graph](image)
Fibrillation risks

\[ I_{crms} = \sqrt{\int_0^T \frac{1}{T} i_b^2(t) dt} \]

\[ I_{B,50} = \frac{0.116}{\sqrt{t_s}} \quad I_{B,70} = \frac{0.157}{\sqrt{t_s}} \]

\[ F_q = I_{crms,T} \times \Delta T \quad \text{with } \Delta T = 4ms \]
Induced pipeline voltage

Back flashover

1.8K coating

Shielding failure

1.8K coating

22.5 K coating

22.5 K coating
Case study

HVDC bipolar system
- 250kV, 500MW (2000A)

Pipeline
- 36” FBE coated
- Coating resistance of 78 kΩm2
- 100 mi parallelism

Clearance
- Tower – pipe of 25m
Fault currents

Fault during bipolar mode

Fault during monopolar mode
Induced pipeline voltage

Fault during bipolar mode

Fault during monopolar mode
## Fibrillation risks

### Fault during bipolar mode

<table>
<thead>
<tr>
<th>Reference location</th>
<th>Event waveform duration [ms]</th>
<th>Total event current [A$_{rms}$]</th>
<th>Path/Heart current factor</th>
<th>Specific fibrillation charge (4 ms) [mC]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Calculated</td>
<td>Safe limit</td>
<td>Calculated</td>
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<tr>
<td>L3E0397</td>
<td>23.9</td>
<td>1.695</td>
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<td>Hand-to-feet, F = 1.0</td>
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<td>39.6</td>
<td>1.037</td>
<td>0.583</td>
<td>Hand-to-feet, F = 1.0</td>
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</tbody>
</table>

### Fault during monopolar mode

<table>
<thead>
<tr>
<th>Reference location</th>
<th>Event waveform duration [ms]</th>
<th>Total event current [A$_{rms}$]</th>
<th>Path/Heart current factor</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Calculated</td>
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<td>Calculated</td>
</tr>
<tr>
<td>L3E0397</td>
<td>49.5</td>
<td>1.621</td>
<td>0.521</td>
<td>Hand-to-feet, F = 1.0</td>
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<td>Hand-to-feet, F = 1.0</td>
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<td>L3E0611</td>
<td>44.75</td>
<td>1.037</td>
<td>0.548</td>
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</tbody>
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Conclusions & recommendations

Corrosion risks

• Monopolar, bipolar and solar systems with ground return through HVDC electrode
• Stray currents < 2000 Amps under continuous operation (monopolar & bipolar)
• Clearance between pipeline and HVDC electrode < 100 km
• Location near HVDC inverter is most critical
• Criteria of -4V for GPR and 2.5mV/m for electrical field gradient
• Corrosion prevention with grounding systems and potential-controlled rectifiers
• Risk prediction and mitigation design through computational modeling
Conclusions & recommendations

Safety risks

- Bipolar (U)HVDC with overhead lines
- Monopolar and bipolar operation differs
- Clearance from towers <100m
- Location near HVDC rectifier is most critical
- Criteria of 5kV for coating stress and 2mC (4ms) <0.5A (95%) for heart fibrillation
- Safety prevention with conventional grounding systems for reducing induced voltage
- Risk prediction and mitigation design through computational modeling
Thank you for your attention.