Guide to the conversion of existing AC lines to DC operation

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SC B2

22 August 2016
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### SECTION 1:

Guide to the conversion of existing AC lines to DC operation: TB583

- Special characteristics of DC overhead lines
  - DC line configuration
  - DC losses analysis
  - DC insulation coordination
- Special considerations for AC to DC conversion
  - Corrosion effects of AC/DC hybrid configurations
  - DC insulator dimensioning
  - Conversion issues and costs

*TB = Cigre Technical Brochure

### SECTION 2:

**TUTORIAL**

**AC to DC conversion opportunities**

<table>
<thead>
<tr>
<th>Current uprating AC voltage</th>
<th>Upgrading</th>
<th>Conversion to DC</th>
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</table>

**SECTION 2:**

TB 425 (2010): Capacity increase vs. cost for different line uprating – conversion options
SECTION 2:
Power capacity gain from conversion to DC

Max. voltage level:
\[ U_{DC_{\text{peak}}} \quad \text{(corona & field effects, insulator pollution)} \]
\[ U_{DC_{\text{max}}} \quad \text{(corona effects, switching overvoltage)} \]

Max. current level:
\[ I_{DC} = I_{\text{thermal rating of conductors}} \]

SECTION 2:
Conversion applications

- DC embedded in AC systems (TB 536)
  - Control of voltage and power flow
- DC for segmentation of AC systems
  - Control of power flow between AC grid segments
- DC grids (TB 533)
  - Meshed DC networks using DC breakers

SECTION 3
TUTORIAL
Conversion configuration options
SECTION 3:
DC line configurations after conversion

- **Monopole**
  - Utilizes all three conductors
  - Requires earth return

- ** Bipole**
  - Only two conductors utilized in operation
  - Provides neutral conductor

- **Tripole**
  - Utilizes all three conductors

- **AC/DC hybrid**
  - Requires considerations regarding hybrid corona, field effects etc.

SECTION 3:
Alternative DC line configurations

SECTION 4
TUTORIAL
Corona and field effects of converted lines
SECTION 4:
Limiting criteria for DC voltage level

- DC corona effects
- Audible noise in dry conditions
- Electric field and ion currents at ground level
- Annoying microshocks
- Insulator pollution performance
  - Required insulator length in polluted areas may be in conflict with available tower top clearances & required conductor clearance to ground level

- DC corona effects: audible noise
  - Caused by high electric field on the positive conductor
  - Highest in dry conditions, lower in rain due to space charge limitation
  - Calculated by empirical methods (TB 61)
  - Recommended limit is 40-45 dBA at edge of ROW*
  - AN is an important design issue, that has to be checked for each particular case

- DC corona effects: radio interference
  - Caused by high electric field on the positive conductor
  - Highest in dry conditions, lower in rain due to space charge limitation
  - Calculated by empirical methods (TB 61)
  - Importance depends on broadcast technology
SECTION 4: DC corona effects; corona losses

- Caused by high electric fields on positive & negative conductors
- Increases in risk, but not to the same extent as with AC
- Usually small compared to joule losses, but can be > 25% in some cases
- Cause environmental impact through ion currents & intensified electric field at ground level

SECTION 4: DC field effects

- Electric field at ground level (TB 473):
  - Nominal (geometric) electric field is enhanced 2-3 times by the effect of ion currents caused by corona discharges on the conductors
  - No induction effects as with AC, but annoying microshocks may occur caused by the electric field in combination with ion currents
  - Recommended limits are 20-30 kV/m and 100 nA/m²
  - Enhanced field can be estimated by analytical calculation methods
- Magnetic field at ground level: static field has similar magnitude to the earth's field

Perception and annoyance

Averaged head-hair sensation level as a function of DC electric field for AC electric fields of 1, 2, 5, 10, and 15 kV/m

1. Averaged head-hair sensation level as a function of DC electric field for AC electric fields of 1, 2, 5, 10, and 15 kV/m
SECTION 4: Hybrid AC/DC corona & field effects

![Electric field on conductor surface](image)

**Electric field on AC conductors in a DC field**

**Electric field on DC conductors in an AC field**

SECTION 5: TUTORIAL

**Insulation coordination aspects**

SECTION 5: DC insulator dimensioning

- Normally, existing AC insulators have to be replaced with insulators intended for DC.
- Ceramic & glass insulators for DC have special corrosion protection & electrical characteristics.
- Composite long-rod insulators made of Hydrophobicity Transfer Materials (HTM) have generally better pollution performance in comparison with ceramic or glass insulators of the same length.
- The limited space available on the existing line necessitates optimized dimensioning of the DC insulators.
  - Simplified dimensioning approach (TB 518)
  - Statistical dimensioning approach
SECTION 5: DC insulation coordination

- Temporary overvoltages
  - Depending on converter configuration
  - Normally < 1.8-2.0 p.u.
- Slow-front overvoltages
  - Occur on healthy pole for single pole-to-ground faults
  - Normally < 1.7-1.8 p.u.
- Fast-front overvoltages
  - Occur when lightning strikes conductors or shieldwires
  - Slightly higher stress on the insulation than with AC due to high and constant conductor voltage
  - Positive pole vulnerable to backflashover
  - Negative pole vulnerable to shielding failure

- Neutral conductor (if present)
  - Slow-front overvoltages in the range of a few hundred kilovolts are induced on the neutral conductor during pole-to-ground faults
  - High-fast-front overvoltages occur across the neutral insulation upon lightning strikes to the line
  - Both events may cause flashovers of the neutral insulation
  - Arcing horns with sufficient V-I characteristics are needed in order to extinguish the arc

- Overvoltage withstand of air clearance
  - Transients are superimposed on the DC voltage
  - Overvoltage withstand of air gaps is only marginally affected by the presence of DC bias (use total peak)
- Safety clearances to ground level
  - Governed by national codes & regulations (for AC)
  - Usually based on coordination between the flashover voltage of insulators & the flashover voltage of the safety clearance by applying appropriate gap factors
  - Fast-front overvoltages are decisive for determination of safety clearances on DC lines
SECTIONS 6: Issues and Costs of Line Conversion

- Check of conductors & connectors
- Operation close to thermal limit after conversion?
- Check of structures & foundations
  - Changing mechanical loads & points of application?
- Outages before & after conversion
  - Replacement of insulators
  - Live line replacement minimizes the outage time
  - Re-routing of the line to the new converter station
  - Testing & commissioning of the HVDC equipment

SECTIONS 6: Issues of Line Conversion

- Insulator replacement & rearrangement
- Check DC compatibility of existing AC insulation (i.e., regarding creepage distance)
- Optional insulator rearrangement to allow longer insulation (with longer creepage) without decreasing the safety clearance to ground level
SECTION 6: Identification of costs components:
- Insulator replacement
- Conductor and/or connector replacement
- Structure & foundation modifications
- Power losses
  - Operation closer to thermal limit
- Operation & maintenance
- Protection of external installations
  - Pipelines, telecommunication lines, railway systems

SECTION 6: Costs for line conversion

SECTION 6: Cost for total capacity vs. incremental capacity gain

SECTION 7 TUTORIAL
Case studies
SECTION 7:
Case study no. 1
Conversion of 380 kV line to DC:
- Effect on power capacity by constraints on conductor surface gradient at high altitude
  - Corresponding maximum gradient: 17.5, 20 & 25 kV/cm
- Effect of number of subconductors

SECTION 7:
Case study no. 2
Conversion double-circuit 380 kV line to hybrid line:
- Repositioning of subconductors to create a triple-conductor DC bipole from a twin-conductor AC circuit
- Statistical dimensioning of DC composite insulators
- Audible noise & electric fields in hybrid configuration allow ±450 kV DC
- Power capacity gain $P_{DC}/P_{AC} > 2$

SECTION 7:
Case study no. 3
Conversion of two parallel 287 kV lines to DC:
- The capacity of the 287 kV line is limited to 560 MW
- DC voltage limited by audible noise (gradient <24 kV/cm)
- Optimal configuration is two split bipoles ±245 kV DC
- Center phase reconducted with HTLS conductor to double the current rating
- DC power capacity is 1762 MW
SECTION 7:
Case study no. 4

Conversion of 275 kV line to ± 270 or ± 500 kV DC:
- Extensive system studies performed to optimize DC current ratings with regard to AC & DC system losses
- Cost estimation & optimization of line interventions
- Optimal option includes tower top reconfiguration & reconductoring for ±500 kV DC

SECTION 8:
TUTORIAL
Further investigations

Further investigations: Aspects of insulation coordination for DC links using hybrid lines

Simulation results using PSCAD

<table>
<thead>
<tr>
<th>Slow front overvoltages at converter terminals caused by earth fault</th>
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</thead>
<tbody>
<tr>
<td>Simulated scenario conditions</td>
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<tr>
<td>Symmetrical standard</td>
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<td>Slow front overvoltage at converter terminals</td>
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<td>SFO in pu at fault location caused by earth faults at different fault locations</td>
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</tbody>
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SECTION 8: Further investigations: Aspects of insulation coordination for DC links using hybrid lines

FFO in pu at fault location, converter terminal and GIL-OHL interface caused by lightning:

<table>
<thead>
<tr>
<th>FFO in pu at</th>
<th>Transmission line</th>
<th>2-level VSC</th>
<th>3-level VSC</th>
<th>MMC</th>
<th>Insulator string</th>
<th>Shortest path</th>
<th>Insulator string</th>
<th>Shortest path</th>
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</thead>
<tbody>
<tr>
<td>Fault location</td>
<td>DC service voltage</td>
<td>Dff [m]</td>
<td>D sf [m]</td>
<td>D [m]</td>
<td>DC</td>
<td>VSC</td>
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<td>OHL</td>
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FFO = 2.1 pu to be considered for IC ensuring adequate arrester ratings. Simulation result using PSCAD®

SECTION 8: Further investigations: Ohmic coupling between AC and DC circuits on hybrid overhead lines

- Idea of “Ultranet” by Amprion GmbH, Germany
SECTION 8:
Further investigations: Ohmic coupling between AC and DC circuits on hybrid overhead lines

- Results of the tests done in 2013: monopole configuration
- Highest ion currents in the nearest conductor
- Lower impact in bipole arrangement
- Strong dependency on rain intensity (ratio between fair and rainy weather conditions up to 10)
- Increase of ion currents by 20% to 30% due to adjacent AC conductors

SECTION 9
TUTORIAL

Conclusion
SECTION 9: Conclusion

- Conversion from AC to DC operation is possible
- Electric fields of hybrid lines, especially DC lines, cause annoying effects
- Increased neutral insulation level significantly improves the chances of spontaneous extinction of DC arcs
- Conversion must achieve a very large boost in capability before the effective cost becomes reasonable compared with the avoided cost of new line
- Insulation coordination for hybrid lines is feasible
- Special focus on different coupling phenomena is necessary
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References

- Cigre Technical Brochure 583
