CIGRE
SESSION 2016

TUTORIAL

Guide to the conversion of existing AC lines to DC operation

Presented by Stefan Steevens

SC B2

22 August 2016

INTERNATIONAL COUNCIL
ON LARGE ELECTRIC SYSTEMS

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Introduction

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SECTION 1:

Background TB 583

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WG B2.41

Members

Main authors:

J. Lundquist, **Convener** (SE), L.O. Barthold (US), A. Beutel (ZA), A.C. Britten (ZA), D.A. Douglass (US), J. Iglesias (ES), V. Jankov (CA), J.A. Jardini (BR), D. Muftic (ZA), S. Steevens (GE)

Contributions have been made by:

R. Adapa (US), E. Brocard (FR), R. Iravani (CA), R. Lake (NZ), D.I. Lee (KR), J.F. Nolasco (BR), T. Papazoglou (GR), G. Ruiz (ES), A. Singh (ZA), P. Stevenin (FR), A. Useros (ES)

SECTION 1:

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

- **Special characteristics of DC overhead lines**
  - DC line configuration
  - DC corona effect
  - DC insulation coordination
- **Special considerations for AC to DC conversion**
  - Corona effects of AC/DC hybrid configurations
  - DC insulator dimensioning
  - Conversion issues and costs

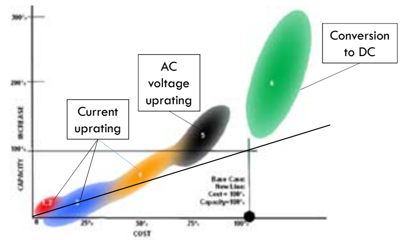
** TB = Cirgré Technical Brochure*

SECTION 2
TUTORIAL

AC to DC conversion opportunities

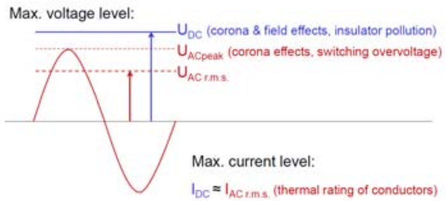
SECTION 2:

TB 425 (2010): Capacity increase vs. cost for different line uprating - conversion options



SECTION 2:

Power capacity gain from conversion to DC



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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

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SECTION 3 TUTORIAL

Conversion configuration options

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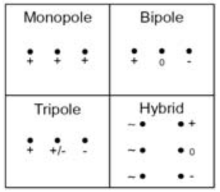
SECTION 3:

DC line configurations after conversion

- **Monopole**
  - Utilizies 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.



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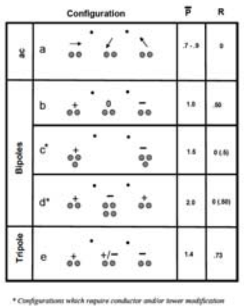
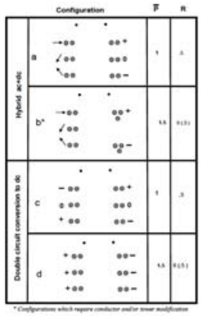
SECTION 3:

Alternative DC line configurations





SECTION 4
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Corona and field effects of converted lines

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SECTION 4:

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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

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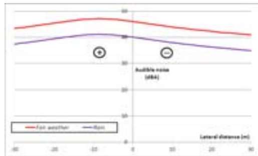
DC corona effects: audible noise

- 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



* *ROW = right of way (servitude)*

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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 in broadcast technology

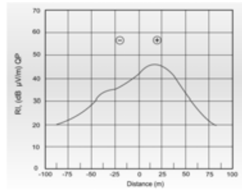

Figure from Eskom Power Series book, referenced in TB

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DC corona effects: corona losses

- Caused by high electric fields on positive & negative conductors
- Increases in rain, but not to the same extent as with AC
- Mainly of economical interest (dry conditions)
- 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

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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 25-30 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**

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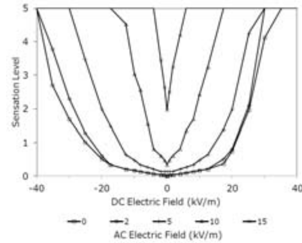
Perception and annoyance



- 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

SECTION 4:

Hybrid AC/DC corona & field effects

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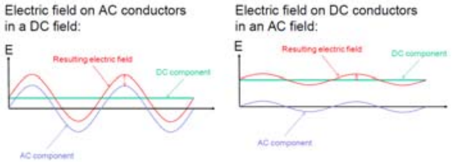
Electric field on conductor surface



SECTION 5 TUTORIAL

Insulation coordination aspects

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SECTION 5:

DC insulator dimensioning

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- **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 insulator 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

SECTION 5:
DC insulation coordination

- **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 clearance 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

SECTION 5:
DC insulation coordination

- **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

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Issues and costs of line conversion

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SECTION 6:

Issues 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 stations
  - Testing & commissioning of the HVDC equipment

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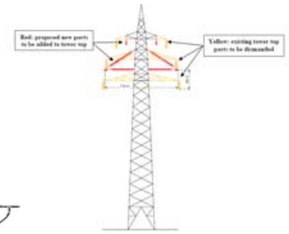
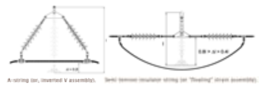
SECTION 6:

Issues of line conversion

- **Insulator replacement & rearrangement**
  - Check DC compatibility of existing AC insulators (i.e. regarding creepage distance)
  - Optional insulator rearrangement to allow longer insulators (with longer creepage) without decreasing the safety clearance to ground level





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SECTION 6:

Costs for line conversion

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

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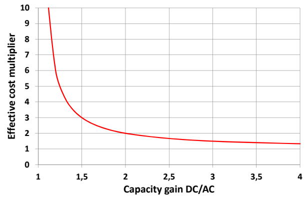
SECTION 6:

Costs for line conversion

Cost for total capacity vs. incremental capacity gain



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Case studies

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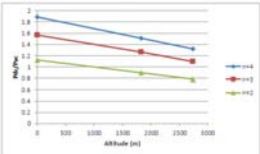
SECTION 7:

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

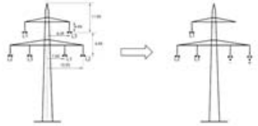


SECTION 7:

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 $P_{DC}/P_{AC} > 2$

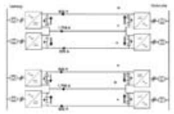


SECTION 7:

Case study no. 3

Conversion of two parallel 287 kV lines to DC:

- The capacity of the 287 kV lines 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 reconductored 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

SECTION 8:

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

SFO in pu at fault location caused by earth faults at different fault locations

SFO at line to earth faults		Bipol								symmetrical monopol, C_{DC} = 100 µF	
		2-level VSC, C_{DC} = 100 µF			MMC			LCC[1)]			
fault location		fault location	conv. term.	GIL-OHL	fault location	conv. term.	GIL-OHL	fault location	conv. term.	fault location	conv. term.
mid	without arresters	2,2	1,5	1,5	1,8	1,2	1,2	1,5	1,2	2,2	2,5
	limited by arresters										1,7
1/8	without arresters	1,7			1,7			1,1	1,1		2,3
	limited by arresters										1,7

Slow front overvoltages at converter terminals caused by earth fault

SFO at converter faults		Bipol		symmetrical monopol
Overvoltage at converter terminals		2-level VSC, C_{DC} = 100 µF	MMC	
		Overvoltage at converter terminals [pu]		
DC side	without arresters	1,8	1,2	2,3
	limited by arresters	1,6		1,8…2,0
AC side	without arresters		2,5	2,1
	limited by arresters		1,9	1,6…1,8

SFO ≈ 2 pu to be considered for IC

Simulation results using PSCAD®

SECTION 8:

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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

FFO at llightning strokes to transmission line		Bipol						symmetrical monopol C_{DC} = 1 µF	
		2-level VSC, C_{DC} = 25 µF		2-level VSC, C_{DC} = 1 µF		MMC			
		conv. term.	GIL-OHL	conv. term.	GIL-OHL	conv. term.	GIL-OHL	conv. term.	GIL-OHL
OHL	without arresters	1,15		3,8		16,1		3,8	
	limited by arresters			2,1		2,1		2,1	
OHL/GIL	without arresters	1,15	4,0	3,8	4,0	5,2	5,2	3,8	4,0
	limited by arresters		2,1	2,1	2,1	1,9	2,0	2,1	2,1

FFO ≈ 2.1 pu to be considered for IC assuming adequate arrester ratings

Simulation results using PSCAD®

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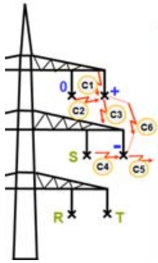
Further investigations: Aspects of insulation coordination for DC links using hybrid lines



DC service voltage		D_{ff} [m]	D_{sf} [m]	D [m]
400	C1		2.30	2.30
	C3	3.37	1.90	3.37
	C5	3.25	2.15	3.25
	C2	3.11	2.07	3.11
	C4	3.67	3.18	3.67
	C6	3.77	3.24	3.77
500	C1		3.34	3.34
	C3	4.36	2.76	4.36
	C5	4.27	3.12	4.27
	C2	4.10	3.01	4.10
	C4	4.64	3.52	4.64
	C6	4.88	4.70	4.88

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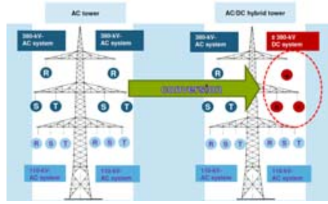
Further investigations: Ohmic coupling between AC and DC circuits on hybrid overhead lines

- Idea of "Ultranet" by Amprion GmbH, Germany



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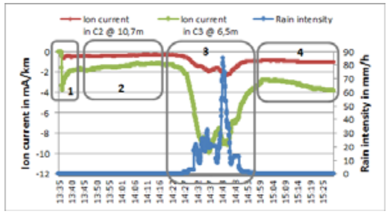
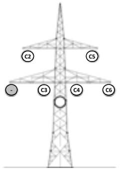
Further investigations: Ohmic coupling between AC and DC circuits on hybrid overhead lines

- Results of the tests done in 2013: monopole configuration





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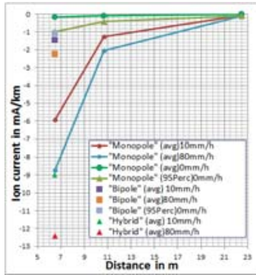
Further investigations: Ohmic coupling between AC and DC circuits on hybrid overhead lines

- 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
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Conclusion

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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 phenomenas is necessary

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References

- Cigre Technical Broschure 583
- C. Neumann, A. Wasserrab, G. Balzer, B. Rusek, S. Steevens, K. Kleinekorte, „Aspects of insulation coordination for DC links using hybrid lines“,Cigre-IEC Colloquium, Montreal, 2016
- B. Rusek, C. Neumann, S. Steevens, U. Sundermann, K. Kleinekorte, J. Wulff, F. Jenau, and K. H. Weck, “Ohmic coupling between AC and DC circuits on hybrid overhead lines,”, Cigre Symposium, Auckland, 2013