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Environmental & Interference Effects of HVDC Converters & Lines

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Presentation to IEEE HVDC & FACTS Subcommittee
July 30, 2014

What are Electrical Effects

- **Electric Fields**
- **Magnetic Fields**
- **Power Loss from Corona**
- **Audible Noise**
- **Radio/TV Interference**
- **Ozone Production**

- **Human Sensations**
- **Space Charge**
- **Ion Current To Ground**
- **Charged Aerosols**

} **More relevant for to DC**

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EPRI HVDC Transmission (Program 162)
2014 Structure

PS162A	HVDC Technology Assessment and Evaluation
• 162.003	HVDC Technology Surveillance and Reference
• 162.004	Applications of HVDC Technology and New Developments
• 162.009	Integrating HVDC into an AC Grid
PS162B	HVDC Performance and Effects
• 162.005	HVDC System Performance and Component Testing
• 162.006	Electrical Effects of HVDC

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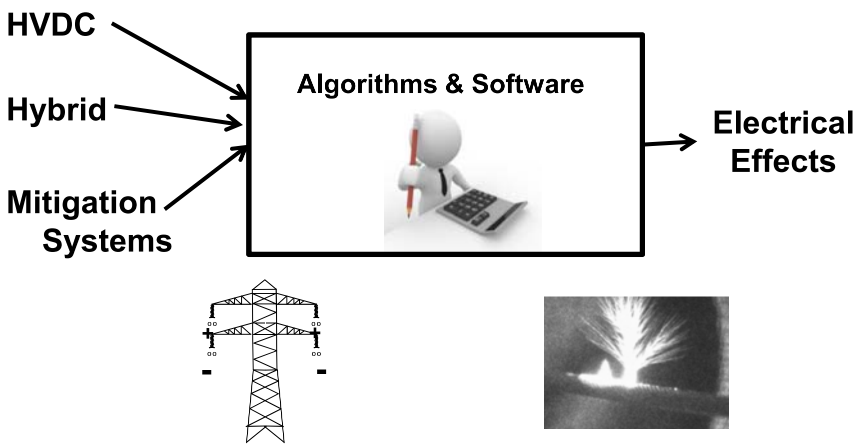
P162.006
Electrical Effects of HVDC

Algorithms & Software



Cigre – 473: Some Key Points Concerning Fields and Ions

- Data from operating lines are inadequate to fully characterize performance or validate calculations
- No scientific or regulatory bodies suggest any health risk – although perceptions are recognized
- ICNIRP (International Commission on Non-Ionizing Radiation Protection) of WHO (World Health Organization) makes no recommendations for limits
- Cigre recommends consideration, particularly during design phase
- Cigre considered only monopolar and bipolar-horizontal lines (not vertical, hybrid, converted lines, shield wires, etc.)

Deliverables

2013

- Electrical Effects of HVDC Transmission Lines: Technical Update (3002000860)

- HVDC Electrical Effects Software – Version 1.0 version
  - PID: 3002000859, Key: 4465200

Deliverables

2014

- HVDC Electrical Effects: Tests, Measurements, and Software Validation

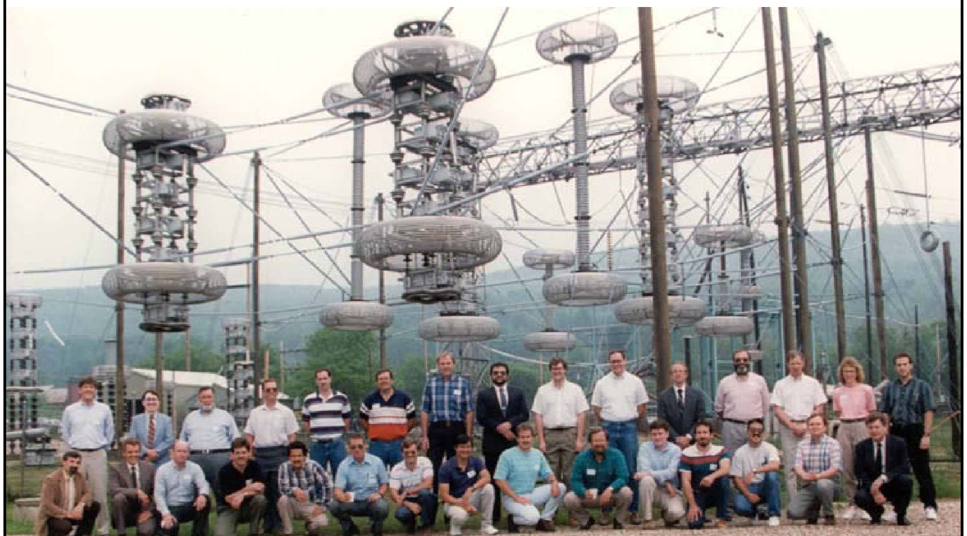
- HVDC Electrical Effects Software – Version 2.0

2014 Main Points of Study

- Critical comparisons of calculation methods
- Updated algorithm development and implementation
- Corona source study – paper
- Instrumentation procurement and fabrication
- Workshop

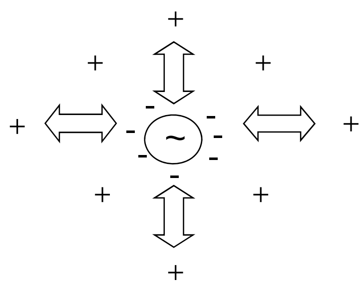
Technical Discussion: EPRI Lenox High Voltage Laboratory

Lenox +/- 750 kVDC HVDC Power Supply



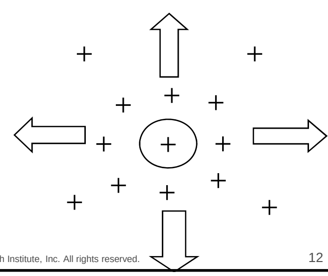
Technical Discussion: Corona, E, J, ρ

AC



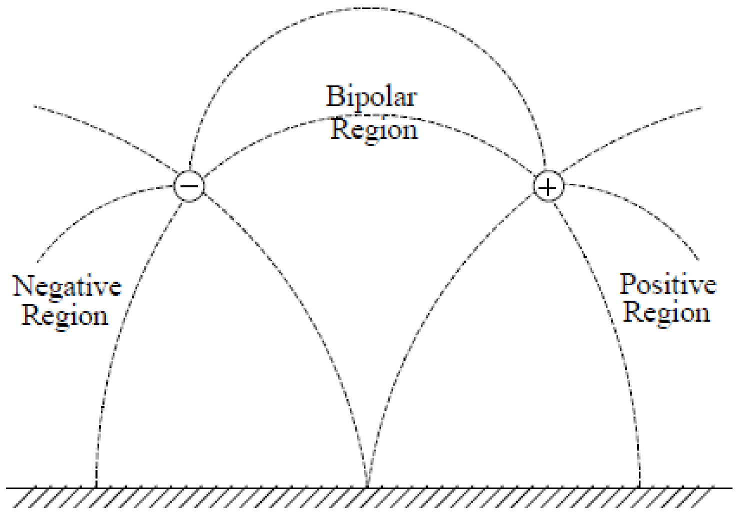
Cyclic motion of space charge.
No net charge produced.

DC



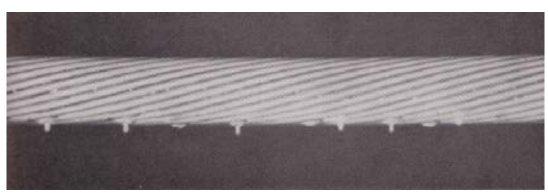
Single polarity charge.
Produces Space charge, Ion currents, charged aerosols, human sensations.

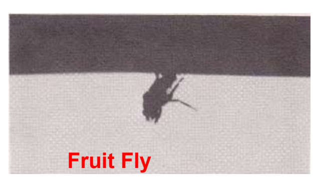
HVDC: E, J, ρ



Sources of Corona

- Water drops
- Insects
- Pollen
- Material blown by the wind
- Nicks, scratches, popped strands
- Snowflakes
- Icicles
- Hoar frost





Calculation Methods

- **Townsend/Popkov**
  - Monopolar only
- **Maruvada & Janiscewskyj**
  - Deutsch assumption
  - G remains at Go
- **Gela & Janiscewskyj**
  - FEM
  - Monopolar only
- **BPA Method**
- **EPRI Method**
  - Deutsch assumption
  - Degree of saturation approach

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EPRI's Approach to Quantifying Fields and Ions

- **DC Electric Field and Ion levels vary over wide range of values due to wide range of possible corona levels**
- **There is a well-known minimum (zero corona)**
  - E = electrostatic field (easy and accurately calculated)
  - J = 0
- **There is a theoretical maximum of E and J(saturated)**
  - Is quantified analytically (Deutsch assumption) or empirically (from model tests)
- **The actual levels are characterized by the "Degree of Saturation"**
  - This is a concept conceived by EPRI
  - Gives approximate, but reliable, results

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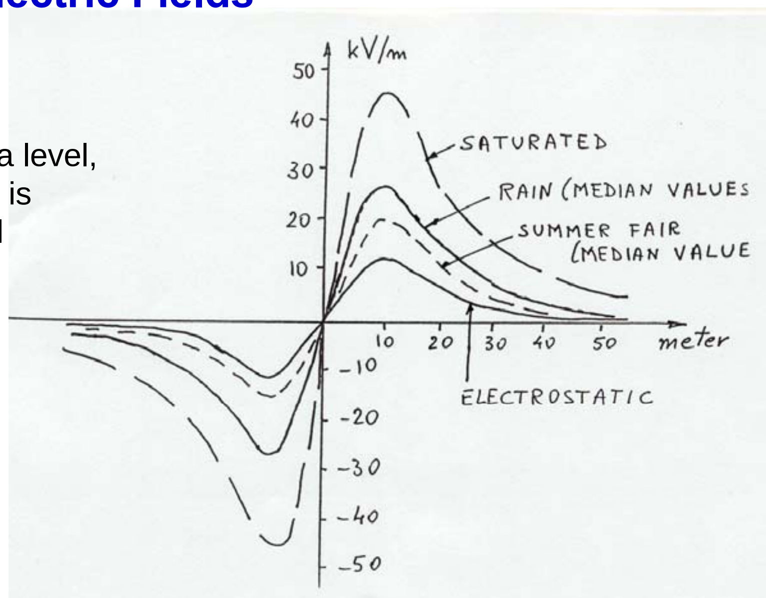
DC Electric Fields

- Depends on corona level, therefore is statistical



Example of Variability

Pacific Intertie at 500 kV, ion current density at a fixed location measured for one year was:

- **Zero for 10% of the time,**
- **> 29 nA/m^2 for 50% of time,**
- **115 nA/m^2 for 5% of the time,**
- **Values as high as 250 nA/m^2 were measured.**

Technical Discussion: Human Sensations

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Technical Discussion: Human Sensations

- Body currents
- Spark discharge (shocks)
- Surface tingling (fields)
- Hair stimulation (field/current)
  - Head hair
  - Hand hair

Estimates of sensation levels are made by comparison to database

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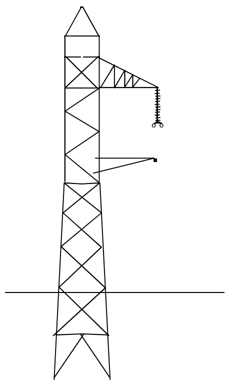
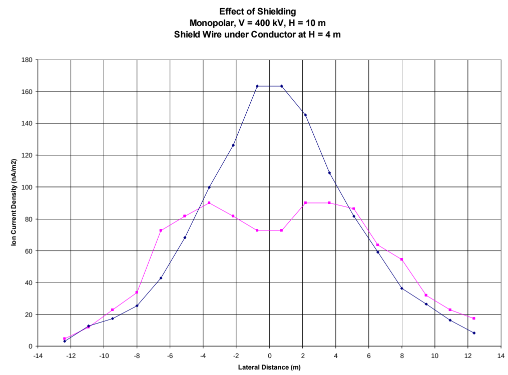
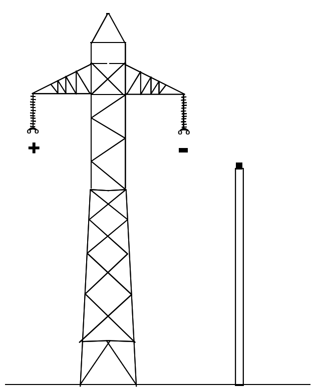
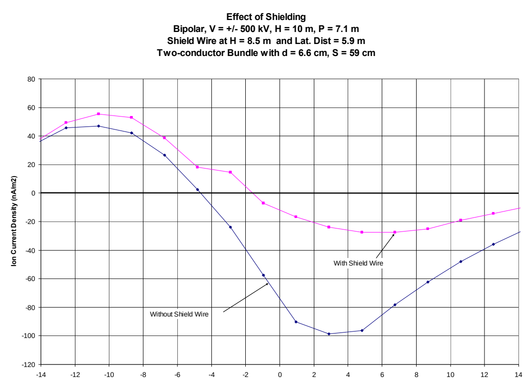
Technical Discussion: Mitigation
Shielding, Monopolar 400 kV



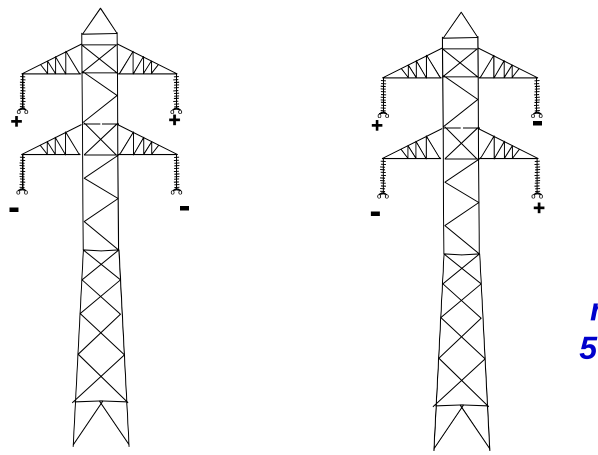


SHIELDING: *Bipolar, V = +/- 400 kV*





Tests Demonstrating Mitigation through Design



Bottom Poles
with same polarity

Bottom Poles
at different polarity

E and J reduced by 50% or more

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Research on Shielding

- **Very promising**
- **Develop Algorithms and Design Rules for Application to EPRI software**
- **Full Scale Line Tests to Validate Algorithms**

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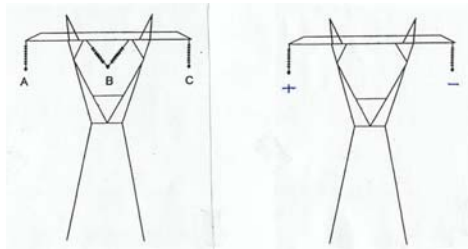
Technical Discussion: Hybrid Corridors & Structures



Interaction of AC & DC E-Fields in a Hybrid Corridor

- AC ripple imposed on DC surface gradient.
- AC Current induced on DC line.
- DC bias imposed on AC surface gradient.
- DC current injected into AC line
- Human sensations increased significantly.

Technical Discussion: *Audible Noise*

PREDICTION METHODS

•Empirical equations of the form:

AN = f(number of subconductors, diameter of subconductors, surface gradient, distance from measuring point, pole spacing)

•Empirical equations developed by:

BPA
Quebec Hydro (IREQ)
EPRI (Lenox)
Japanese (CRIEPI)

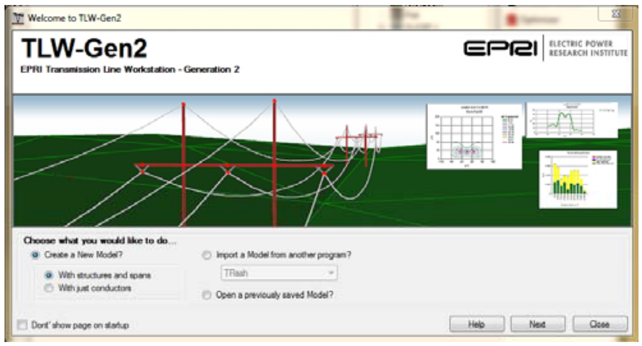
•Empirical equations compared with results from 21 operating or test lines. Best match is obtained by the Japanese equation (standard deviation = 1.4 dB)

Does AN Constrain Line Design?

- **Studies continue**
- **It is likely that conductors designed on the basis of minimizing cost (construction plus losses) will satisfy audible noise requirements**
- **Audible Noise probably would not be a constraint on HVDC line design**

Technical Discussion: Software

- HVDC/Hybrid Capability is in TLW
- Special challenges exist, being addressed



EPRI Report On Radio Interference (1984)

PRI
ic Power
rch Institute

Topics:
HVDC converter stations
Radio-frequency interference
Converter station design
Harmonics
Electromagnetic fields

EPRI EL-3712
Project 1769-1
Final Report
October 1984

**Radio Interference
From HVDC Converter Stations**

Prepared by
International Engineering Company, Inc.
San Francisco, California

EPRI Report On Radio Interference (1984): Table of Contents

Report Summary

Radio Interference From HVDC Converter Stations

Electromagnetic waves emitted from high-voltage direct current (HVDC) converter stations may interfere with electronic equipment operating nearby. A scale model HVDC converter station showed how utilities can measure the effects of such interference during the station design stage, saving them from expensive changes after construction.

BACKGROUND HVDC converter/inverter stations, which change transmission alternating current to direct current—or the reverse—generate electromagnetic (EM) fields. Historically known as radio interference, these EM fields may affect the performance of nearby electronic equipment. Once a station is built, however, it is impractical and expensive to reconfigure it to minimize EM interference. Therefore, planned increases in the use of HVDC for power transmission make it important for utilities to measure and control the effects of EM fields during the station design stage.

OBJECTIVES To design and test the effectiveness of a scale model HVDC converter station for use in station electromagnetic interference studies.

APPROACH Researchers designed and built a 1:40-scale model of the Dickinson converter/inverter station (Minneapolis), which is on the joint United Power Association and Cooperative Power Association system. The model has a frequency range of 4 to 200 MHz, corresponding to the 0.1- to 5-MHz range of the actual station, and is designed to reproduce EM effects for study under laboratory conditions. To investigate various methods for mitigating EM interference, researchers incorporated equivalent circuits that represented actual thyristors, filters, transformers, reactors, and other station components. They mapped the electric and magnetic fields in and around the model station and compared them directly with those of the Dickinson station and indirectly with those of the Arrowhead (Duluth) and Sylmar (Los Angeles) stations.

RESULTS The model accurately scaled the EM effects of the Dickinson station; the amplitudinal variations of the model electromagnetic spectra followed those of the actual electric and magnetic fields within 6 dB. Analyses of the various techniques for mitigating EM interference indicated that screening of

Report Summary

	the valve hall is an effective way of containing EM waves, but some EM energy is carried to the station exterior on conductors that exit the building wall. The magnitude of this conducted EM noise can be lessened by reducing the generation of EM waves within the station or by filtering the waves.
EPRI PERSPECTIVE	This study shows that physical modeling is a practical and cost-effective means of predicting EM effects in proposed inverter/converter stations. Using this technique, utilities can determine the EM energy conducted or radiated from stations in advance of construction and can incorporate design changes—determined by modeling—at a time when they can be made with minimal delay and cost. This report, which includes a comprehensive bibliography that covers converter station noise generation, measurement, and mitigation, will be of special value to converter station designers and operators.
PROJECT	RP1769-1 EPRI Project Manager: William E. Blair Electrical Systems Division Contractor: International Engineering Company, Inc.

For further information on EPRI research programs, call EPRI Technical Information Specialists (415) 855-2411.

ORDERING INFORMATION	EPRI EL-3712, Final Report, October 1984, 348 pages.
EPRI Members	If this report is not available from your company libraries or your

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Major Communication Facilities and Their Frequency Range

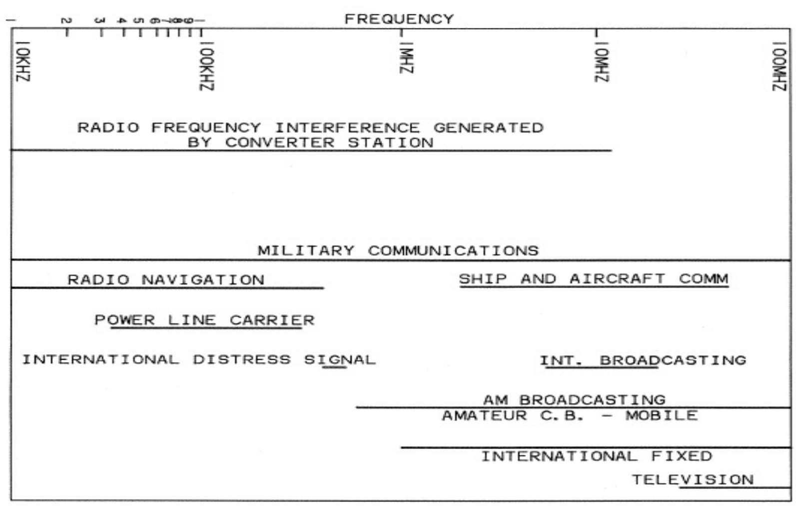

Figure 1-1 Major Communication Facilities and Their Frequency Range

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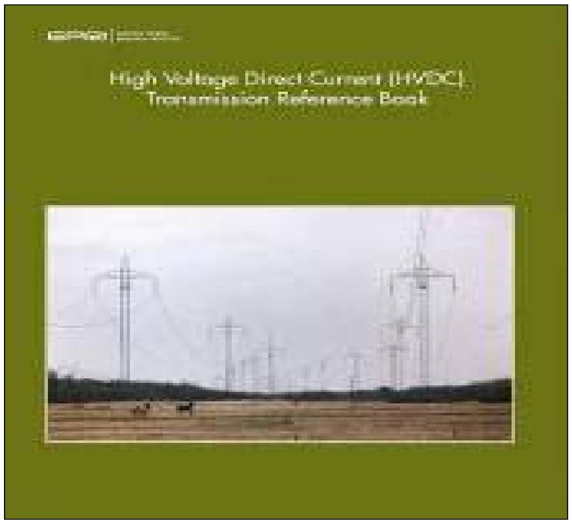
EPRI HVDC Reference Book (Olive Book) 2013
Chap 10 - Interference Effects from Converter Operation



EPRI HVDC Reference Book(2013):
Chap 10 –Interference Effects from Converters
Table of Contents

Electric and Magnetic Fields in Converter Terminals

- DC electric and magnetic fields in the converter terminal and yard are due to the energized buswork.
- Distances to ground in the terminal and yard are less than those found for transmission lines since transmission lines have to allow for large vehicles to pass beneath them.
- Table 10-4 can be used to evaluate the distances from ground to energized buswork in the converter terminal. These distances may result in a conservative design but provide an initial estimate of distances

Table 10-4 Valve Hall Clearances to Ground

- Voltage Level — Clearance to Ground in Meters
- 300 kV & 400 kV — 4 m
- 500 kV — 5 m
- 600 kV — 6 m

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Measured Ground Level Fields & Ion Currents

Table 10-5

Measured Median Fair Weather Ground-Level Field and Ion Levels of HVDC Lines

HVDC Line	Conductor Bundle (n x cm)	Line Height (m)	Line Spacing (m)	Electric Field (kV/m)		Current Density (nA/m^2)		Ion Density (ions/cm^3)	
				+pole	-pole	+pole	-pole	+pole	-pole
								+ions	-ions
Square Butte (+/- 250 kV [13]	1 x 5.04	10.7	7.6	8	-6	8	-5	54,300	34,700
CPA-UPA (+/- 400 kV [15]									
Minnesota	2 x 3.82	15.2	12.2	13	-9	10	-5	41,800	23,100
North Dakota	2 x 3.82	10.7	12.2	23	-16	46	-19	108,700	49,500
Pacific Intertie (+/-500kV) [34]	2 x 4.58	12.2	12.2	20	-16	36	-20	97,800	52,100
Nelson River (+/- 450kV) [14]	2 x 4.07	15.3	13.4	12	-12	15	-9	67,900	31,300
Quebec-New England I (+/-450 kV [18]	3 x 5.04	12.2	16.0	18	-11	25	-9	75,500	34,100

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Typical Electric Field and Ion Densities

Table 10-6
Typical Electric Field and Ion Densities

Conditions	Electric Field
Fair weather, outdoor open space	100 to 500 V/m
Storm fronts, over land	+/-3 kV to +/-10 kV/m
Storm fronts, over water	+/-10 kV/m to +/-40 kV/m
Static electric field of clothing	100 kV/m
Typical HVDC lines at peak of lateral profile	
During fair weather	+/-15 kV/m
During rain or high-corona conditions	+/-30 kV/m
Conditions	**Ion Density (both ion polarities)**
Fair weather, outdoor open spaces	700 to 1000 ions/cm^3
Family room	400 to 800 ions/cm^3
Family room, candle lit (9 candles)	Up to 27,600 ions/cm^3
12 inches above burning candle	200,000 to 300,000 ions/cm^3
200 feet from small waterfall	1500 to 2000 ions/com^3
20 feet from highway (30 vehicles/minute)*	6900 to 15,000 ions/cm^3
5 feet downwind of car exhaust	34,500 to 69,000 ions/cm^3
Downtown large urban area*	Up to 80,000 ions/cm^3

*Mobility range includes small and intermediate ions, and may include some highlyu charged small particles.

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Tolerability Criteria

- The interaction of the dc electric field and ion current with persons and objects can lead to sometimes perceivable proximity effects.
- The effects can include hair stimulation and spark discharges. Because of the lower current flux under dc lines and the differences between ac and dc field and currents, these effects are less pronounced than analogous effects under high voltage ac lines.
- The magnetic fields of dc lines produce no perceivable effects. The dc line magnetic fields are in the same range or less than that of the Earth's natural magnetic field. No state has guidelines specifically limiting the magnetic fields of HVDC transmission lines.

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Existing Electric Field Guidelines

Existing Guidelines

Two states have what could be considered guidelines on the, allowable electric field levels of dc lines. The states are Minnesota and North Dakota and the levels are shown in Table 10-8. The levels are specific to the ±400 kV "CU" (Cooperative Power Association- United Power Association) dc line that runs between those states and are written into the licensing permit of each state for the line [46]

Table 10-8 State Licensing Levels of DC Electric Field for +/-400 kV DC Line

State	Field	Field Definition
Minnesota	12 kV/m	Electrostatic Field
North Dakota	33 kV/m	Total Field

Electric Field and Ion Specifications

Table 10-9
Electric Field and Ion Specifications

Case	Peak within ROW		Beyond ROW
Severe Specifications	Ion Flux	20 nA/m^2	1 nA/m^2
	Ion Density	2 x 104 ions/cm^3	0.5 x 104 ions/cm^3
	Electric Field	20 kV/m	5 kV/m
Base Case Specifications	Ion Flux	100 nA/m^2	5 nA/m^2
	Ion Density	105 ions/cm^3	2 x 104 ions/cm^3
	Electric Field	40 kV/m	10 kV/m
No Specifications	No electric field or ion restrictions; line height and ROW determined by other considerations.		

Audible Noise Levels of HVDC Lines

Table 10-11
Audible Noise Levels of HVDC Lines

HVDC Line	Conductor Bundle (n x cm)	Line Height (m)	Line Spacing (m)	Audible Noise Median Level (dB-A)	Distance from Conductor (m)
Pacific Intertie +/-500 kV [33]	2 x 4.58	12.2	12.2	36	12
Nelson River +/-450 kV [14]	2 x 4.07	15.3	13.4	40	34
Quebec-New England I +/- 450 kV [18]	3 x 5.04	12.2	16.0	34	13

Summary of State Noise Regulations

SUMMARY OF STATE NOISE REGULATIONS

State		Maximum Noise Allowed Day	Night[1]	Comments
Colorado		55	50	
Illinois[2]		55	45	Class A noise source[3]
		55	45	Class B noise source[3]
		61	51	Class C noise source[3]
New Jersey		65	50	
Oregon[4]	L_1	60	55	All private property
	L_{10}	55	50	All private property
	L_{50}	50	45	All private property

Notes:

1. Nighttime is normally defined as 10 pm to 7 am except in Colorado where it is 7 pm to 7 am.
2. Regulation specifies octave band levels; dB(A) values in table are estimated from octave band levels.
3. Classes A, B, and C are roughly equivalent to residential, commercial, and industrial. Transmission line right-of-ways are included in class C land use.
4. Levels are statistical levels, L_x, which may be exceeded only x% of the time in quiet areas.

Summary of EPA Noise Guidelines

Table 10-13 Summary of EPA Noise Guidelines

SUMMARY OF EPA NOISE GUIDELINES

OUTDOOR ACTIVITY INTERFERENCE AND ANNOYANCE

Level	Area
$L_{dn} \leq 55$ dB(A)	Residential areas, farms, and other areas where people spend widely varying amounts of time and other places where quiet is a basis for use
$L_{eq(24)} < 55$ dB(A)	Areas where people spend limited amounts of time such as school yards and playgrounds

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RI Levels Along Operating Lines

Table 10-14 RI Levels Along Operating Lines and Other Situation

Situation	RI Level dB (1μV/m)
Pacific NW-SW Intertie [13.60]	
Surface Gradient 20.9 kV/cm	51 dB
(19m from conductor)	
Dalles Test Line [13.60]	
Surface Gradient 25.5 kV/cm	64 dB
Surface Gradient 28.05 kV/cm	65 dB
(18 m from conductor)	
Shiobara Test Line [13.60]	
Surface Gradient 22.5 kV/cm	52 dB
Surface Gradient 25.0 kV/cm	57 dB
(15 m from conductor)	
1m From Ignition System of Car	65 dB
Outdoor RI Level: Overcast	40 dB
Outdoor RI Level: Summer Fair Weather	32 dB

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Ground Electrode

In spite of the fact that a ground electrode is technically feasible and will work properly, it is very likely that there will be substantial opposition to a ground electrode. This can cause substantial delays to the project, increased costs and may in fact never be approved. The concerns are materials from the electrode leaching into the ground water, potential corrosion, lack of understanding and just opposition to ground inject for the fear of the unknown. The fact that there is an alternative such as the neutral return conductor while expensive will make it even harder to convince the public that a ground electrode is necessary.

There is a perception that no ground electrodes are allowed in the USA. Under The National Electric Safety Code (NESC) C2-2012, prohibits the continuous use of ground as a current carrying conductor.

For this reason, after 1993, monopolar HVDC systems built in the United States must have a metallic return. However, NESC regulations allow for the monopolar ground return mode of operation for bipolar HVDC systems for a limited period of time for maintenance or during emergencies. NESC regulations do not specify what conditions are considered as emergencies or elaborate on the limited time period available for maintenance. The application of these restrictions is evident in recent point-to-point HVDC schemes. The Neptune Cable HVDC link is a monopolar, line–commutated, converter-based system with a metallic return The Trans Bay Cable link uses Voltage Source Converter (VSC)-based technology, and the concept does not require an electrode. There are 4 existing Bipole HVDC schemes in the USA which have ground or sea electrode but these are thought to be "grandfathered".

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