06-Introduction to Transmission Lines

ECEGR 451
Power Systems

Topics

- Transmission Line Statistics
- Design Considerations
- Resistance

Transmission Line Benefits

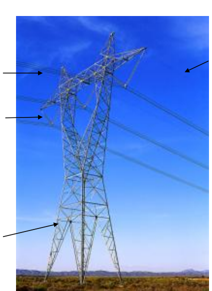
- Hedge against generation outages
- Efficient bulk power markets
- Operational flexibility
- Hedge against fuel price changes
- Low-cost access to renewable energy

Transmission Lines

- Challenges
  - capital cost
    - approx. $1000/(MWxmile)
  - economic risk
  - environmental
    - right-of-way
    - visual
    - audio
    - health
  - social resistance
    - (NIMBY)

What's wrong with this image?

Transmission Line Anatomy



Existing Transmission (U.S.)

Voltage (kilovolts)	1980	1990	1999	2000 [2]	2001 [2]	2002 [2]	2003 [2]	2004 [2]
230	NA	70,511	76,762	76,437	80,515	81,252	82,238	81,992
345	NA	47,948	49,250	51,025	53,855	54,827	54,195	55,429
500	NA	23,958	26,038	25,000	27,343	27,587	27,407	28,011
765	NA	2,428	2,453	2,426	2,518	2,560	2,560	2,560
Total	NA	144,845	154,503	154,888	164,231	166,226	166,400	167,992

Sources: EIA, Electricity Transmission Fact Sheets, http://www.eia.doe.gov/cneaf/electricity/page/fact_sheets/transmission.html; NERC, Electricity Supply and Demand Database, 2005, http://www.nerc.com/~esd/Brochure.pdf

Notes:

[1] Circuit miles of AC lines 230 kV and above.

[2] Data includes both existing and planned transmission lines

Source: EIA 2005

Note the incremental increases after Y2000

Existing Transmission (U.S.)

(Circuit Miles of Transmission)

Voltage Type	Voltage Operating (kV)	Circuit Miles FRCC	MRO	NPCC	RFC	SERC	SPP	TRE	WECC	Contigious U.S.
AC	100-199	-	-	-	-	-	-	-	-	-
AC	200-299	5,922	7,241	1,521	6,949	21,100	2,776	-	36,810	82,319
AC	300-399	-	11,468	5,064	13,610	3,538	4,934	9,500	10,301	58,415
AC	400-599	1,201	473	-	2,551	8,617	47	-	12,729	25,618
AC	600+	-	-	190	2,226	-	-	-	-	2,416
AC Total		**7,123**	**19,182**	**6,774**	**25,336**	**33,255**	**7,757**	**9,500**	**59,840**	**168,768**
DC	100-199	-	-	48	-	-	-	-	-	48
DC	200-299	-	930	-	-	-	-	-	-	930
DC	300-399	-	-	-	-	-	-	-	-	-
DC	400-499	-	872	-	-	-	-	-	-	872
DC	500-599	-	-	-	66	-	-	-	2,137	2,203
DC	600+	-	-	-	-	-	-	-	-	-
DC Total		**-**	**1,802**	**48**	**66**	**-**	**-**	**-**	**2,137**	**4,053**
Grand Total		**7,123**	**20,984**	**6,822**	**25,402**	**33,255**	**7,757**	**9,500**	**61,977**	**172,820**

Notes: • NERC region and reliability assessment area maps are provided on EIA's Electricity Reliability web page:
http://www.eia.gov/cneaf/electricity/page/eia411/eia411.html
• Circuit miles do not equal physical miles on the ground; the reference terminology for that concept is structural mile.
• Some structures were designed and then built to carry future transmission circuits in order to handle expected growth in new capability requirements.
• Lines are taken out of service for a variety of reasons including intentional changes to the right-of-way to better use available land for different levels of voltage and types of poles and towers.
Source: U.S. Energy Information Administration, Form EIA-411, "Coordinated Bulk Power Supply Program Report."

Source: EIA 2010

Proposed Transmission (U.S.)

(Circuit Miles of Transmission)

Voltage Type	Voltage Operating (kV)	Circuit Miles 2011	2012	2013	2014	2015	2016	2017	All Years
AC	100-199	1,164	1,749	932	738	466	368	214	5,630
AC	200-299	1,007	1,091	708	822	895	241	157	4,922
AC	300-399	555	1,336	4,934	1,234	699	476	1,156	10,390
AC	400-599	116	695	633	782	2,802	1,438	440	6,906
AC	600+	-	-	-	-	275	-	-	275
AC Total		**2,841**	**4,871**	**7,208**	**3,577**	**5,137**	**2,524**	**1,967**	**28,124**
DC	100-199	-	-	-	-	-	-	-	-
DC	200-299	-	-	-	-	-	-	-	-
DC	300-399	-	-	-	-	140	-	-	140
DC	400-599	-	-	-	-	60	640	-	700
DC	600+	-	-	-	-	142	-	-	142
DC Total		**-**	**-**	**-**	**-**	**342**	**640**	**-**	**982**
Grand Total		**2,841**	**4,871**	**7,208**	**3,577**	**5,479**	**3,164**	**1,967**	**29,106**
Lines taken out of service		**99**	**180**	**21**	**121**	**33**	**134**	**-**	**587**

Notes: • NERC region and reliability assessment area maps are provided on EIA's Electricity Reliability web page:
http://www.eia.gov/cneaf/electricity/page/eia411/eia411.html
• Circuit miles do not equal physical miles on the ground; the reference terminology for that concept is structural mile.
• Some structures were designed and then built to carry future transmission circuits in order to handle expected growth in new capability requirements.
• Lines are taken out of service for a variety of reasons including intentional changes to the right-of-way to better use available land for different levels of voltage and types of poles and towers.
Source: U.S. Energy Information Administration, Form EIA-411, "Coordinated Bulk Power Supply Program Report."

Source: EIA 2010

Common U.S. Voltage Levels

- Various definitions of voltage class (e.g. NEC over 600 V is high voltage)
- Transmission is generally > 69 kV

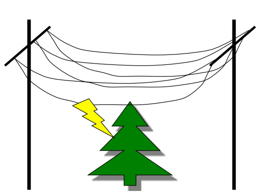
Voltage Class	Nominal Line Voltage
Low	120/240
	208
	240
	480
	600
Medium	2.4 kV
	4.16 kV
	6.9 kV
	12.47 kV
	13.8 kV
	69 kV
High	115 kV
	138 kV
	230 kV
Extra high	345 kV
	500 kV
	765 kV

Transmission Line Design

- Design considerations
  - sag
  - insulation
  - structural
  - environmental

Transmission Line Sag

- Caused by heating of conductor (I^2R)
- Dependent on several factors including:
  - conductor design
  - resistance losses (line loading)
  - wind speed
  - ambient temperature
- Limits power transfer across a line



"vegetation management" is critical

Transmission Line Design

- Insulation considerations
  - normal voltage level
  - abnormal voltage level
  - environment
    - lightning
  - Clearances
- Insulator materials
  - Porcelain
  - Glass
  - Fiberglass
  - Treated epoxy resins

source:www.transmission-line.net

Transmission Line Design

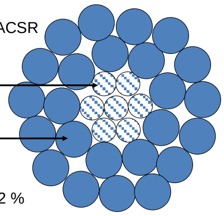
Aluminum Conductor, Steel Reinforced ACSR

7 steel (tension)

24 aluminum strands (conduction)

usually twisted, added length approx. 1-2 %

ACSR 24/7



conductor cross section

DC Resistance

- DC resistance

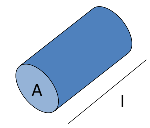
$$R_{dc} = \frac{\rho l}{A}\ \Omega$$

where

ρ : resistivity of the conductor

l : length of the conductor

A : cross-sectional area



A is usually given in circular mils (cmil):
area of circle having a diameter of 1 mil

one mil: 10^{-3} inch

Example

What is the cross sectional area of a 4/0 (212 kcmil) cable?

Note: 1kcmil = 1,000 cmils (also written as MCM, where the first M is the Roman 1000)

Example

What is the cross sectional area of a 4/0 (212 kcmil) cable?

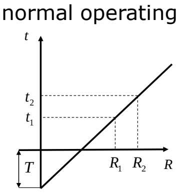
The cable has the area of 212,000 0.001-inch diameter circles:

$$212{,}000 \times \pi \times \left(\frac{0.001}{2}\right)^2 = 0.1665\ \text{in}^2$$

Resistance

- Resistance is temperature sensitive
- Approximately linear over normal operating temperatures

$$\frac{R_2}{R_1} = \frac{T + t_2}{T + t_1}$$



common T values in Celsius

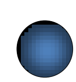
234.5	Annealed Cu, 100%
241	Hard-drawn Al, 97.3% conductivity
228	Hard-drawn Al, 61% conductivity

Resistance

- Resistance is frequency dependent
- Skin effect: interaction of magnetic flux interior to the conductor
- Results in non-uniform current distribution
  - current density increases from the interior toward the surface
- ac resistances are usually tabulated (pg. 605 – 606)

conductor cross section

dc current



ac current

Example

- *Marigold* conductor has dc resistance of 0.01558 Ohms per 1000 ft at 20° C
- spiral has increased length by 2 %
- resistivity is 17.0 (Ωxcmil/ft)
- cross section is 1,113,000 cmil
- T = 228° C
- If the ac resistance is 0.0956 Ohms/mile at 50° C, what is the percentage of resistance increase caused by the skin effect?

Example

Step 1: find the DC resistance for 1000 ft of cable and include spiraling

$$R_{dc} = \frac{\rho l}{A}\ \Omega$$

Example

Step 1: find the DC resistance for 1000 ft of cable and include spiraling

$$R_{dc} = \frac{\rho l}{A}\ \Omega$$

$$R_0 = \frac{17.0\ \ 1000}{1113\ \ 10^3}\ 1.02 = 0.01558\ \Omega$$

Note: tabulated value accounts for spiraling

Example

Step 2: find resistance at 50° C

$$\frac{R_2}{R_1} = \frac{T + t_2}{T + t_1}$$

Example

Step 2: find resistance at 50° C

$$\frac{R_2}{R_1} = \frac{T + t_2}{T + t_1}$$

$$R_1 = 0.01558\ \Omega$$

$$R_2 = 0.01558\frac{228 + 50}{228 + 20} = 0.01746\ \Omega$$

Example

Step 3: compute the ratio of resistances for one mile of conductor (hint: there are 5280 ft per mile)

Example

Step 3: compute the ratio of resistances

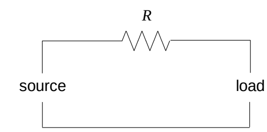
$$\frac{R}{R_2} = \frac{0.0956}{0.01746 \; 5.280} = 1.037$$

3.7 % increase

[convert to miles]

Transmission Line

- Our transmission line model so far is limited
- What other elements should we add?
  - inductance
  - capacitance



Readings for Thursday

- R2: BPA Factsheet
- R3: BPA Transmission Lines