LIÈGE université
Sciences Appliquées

ELEC0014 - Introduction to electric power and energy systems

The overhead power line (and the underground power cable)
– Part 1 –

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Objectives

- Describe the main components of the overhead line
- compute the per length unit (meter) parameters[1]
- characterize the "distributed effect" of the line
- derive the equivalent circuit with lumped parameters

- describe the underground cable
- comment on its parameters

- define the thermal limits.

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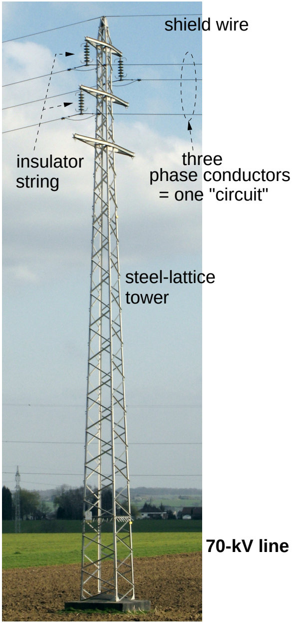
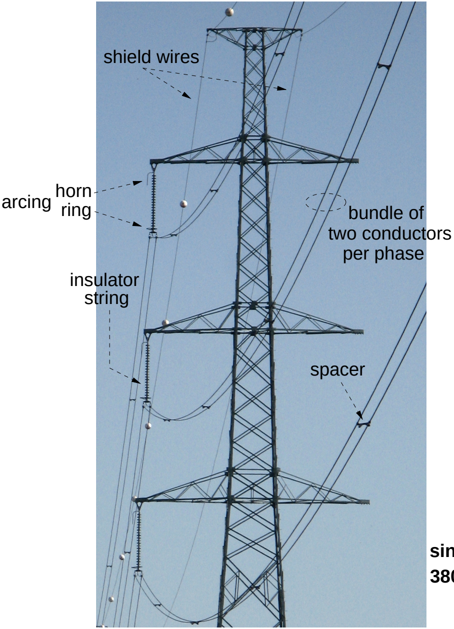
[1] parameters relative to an infinitesimal length dx, divided by dx

Layouts

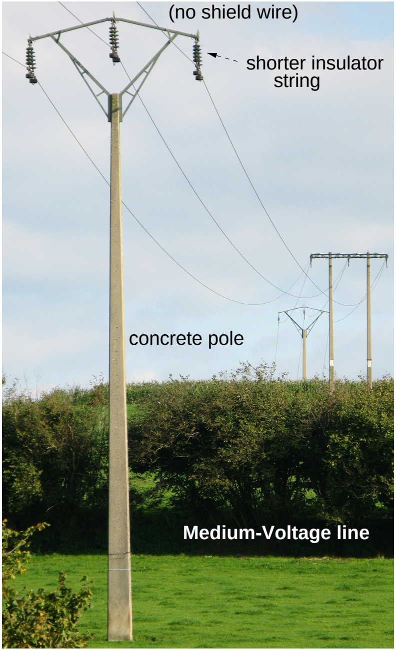


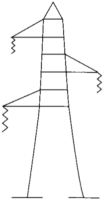
70-kV line



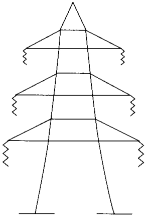
single-circuit 380-kV line

some transmission line layouts

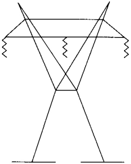




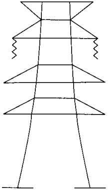
Single circuit
single earth wire



Double circuit
single earth wire



Single circuit
double earth wire



Double circuit
double earth wire

source: [1]

Interchangeable terms: *shield wires*, *ground wires*, *earth wires*, *guard wires*

Phase conductors

Low resistivity metals used to transport electrical energy:

- copper : resistivity $\rho = 18.10^{-9}\ \Omega.\text{m}$
- aluminum : resistivity $\rho = 29.10^{-9}\ \Omega.\text{m}$

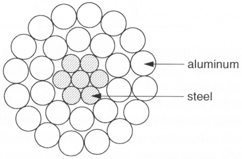
Aluminum:

- is less expensive than copper
- is lighter: density: $\delta_{Al} = 2700\ \text{kg/m}^3$ $\delta_{Cu} = 8900\ \text{kg/m}^3$
- for the same resistance, weight of Al $= \frac{29}{18} \times \frac{2700}{8900} = 0.488$ weight of Cu
- is preferred for overhead power lines: tower construction and insulator strings can be designed lighter, thus cheaper.

Aluminum has insufficient tensile strength to hold the weight of the span between towers ! Hence, aluminum conductors are replaced by:

- either *All Aluminum Alloy Conductors (AAAC)*
  - example: Aluminum Magnesium Silicon (AMS) alloy: $\rho = 32.5\ 10^{-9}\ \Omega.\text{m}$
- or *Aluminum Conductors Steel Reinforced (ACSR)*

The conductor (and the core, if any) is not manufactured in one piece, but consists of strands :



- to keep the conductor flexible enough, in order to be wound before being transported
- the strands are twisted: a spiraled strand is $\simeq 1$ - 2 % longer than the assembly (electrical resistance is also higher)
- each layer is twisted in opposite direction to the next, to avoid unwinding.

Limit on currents in phase conductors

Current in conductor ⇒ Joule losses ⇒ heating of the metal

Two important reasons to limit the current in phase conductors:

- dilatation of metal ⇒ conductor sag increases ⇒ ground clearance decreases ⇒ danger of arcing between conductor and object on ground
- beyond some temperature, annealing effect: an irreversible degradation of metal takes place, which decreases the metal elasticity.

What influences the conductor temperature ?

Heat power balance (in W/km):

$$\begin{aligned}\text{Heat generated by } RI^2 \text{ losses} = \quad & \text{heat lost by convection in wind} + \\ & + \text{heat lost by radiation} - \text{heat gained by solar radiation}\end{aligned}$$

Example of experimental law:

$$\begin{aligned} I^2 R_{20}\left[(1+\alpha(T+\theta)\right] &= 387(v_w\, d)^{0.448}\theta + \\ &+ 5.510^{-8}\pi d\, E_c\left[(T+\theta+273)^4-(T+273)^4\right]-\alpha_s S d \end{aligned}$$

where:

I	effective value of current (A)
T	ambient temperature (^{o}C)
θ	temperature difference between conductor and ambiance (^{o}C)
R_{20}	resistance of conductor at 20^o C
α	temperature coefficient of resistance at 20^o C (for ACSR: 0.00403 per ^{o}C)
v_w	wind velocity (m/s)
d	conductor diameter (mm)
E_c	emissivity of conductor; differs with conductor surface brightness (0.3 for new bright, 0.9 for black aluminum, average value: 0.6)
α_s	solar absorption coefficient (depends upon outward condition of conductor, 0.6 for new bright and shiny conductor, 0.9 for black conditions or old conductor, average value: 0.8)
S	intensity of solar radiation (W/m^2)

Typical maximum temperature of standard conductors: $T + \theta \simeq 75^o$C

Maximum admissible current I_{max} (in each phase) or *ampacity* :

- depends on the cooling conditions of ambiance: larger in winter than in summer, larger in strong wind conditions, larger by cloudy weather
- can be exceeded for some time, thanks to thermal inertia. The smaller the current, the longer this time.
- *dynamic line rating* : estimate the thermal capacity in real time
- not easy to estimate from weather data (temperature, wind speed, etc.) only

A new approach: "Ampacimon"

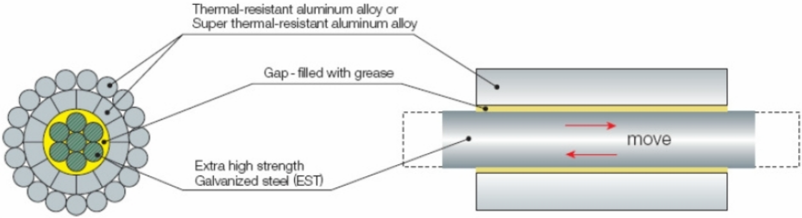
- estimates directly the conductor sag (one of the current limiting factor)
- relies on the spectral analysis of the vibration frequencies of the conductor
- ampacity is deduced using a thermal model of the conductor

invented at ULiège
developed and commercialized by AMPACIMON
a spin-off of ULg

see www.ampacimon.com

“High Temperature Low Sag” (HTLS) conductors

- core and conductors can stand much higher temperatures (up to 210^o C)
- without metal deterioration, and while elongating less than traditional metals (dilatation coefficient 3 to 6 times smaller)
- the core in steel, special alloy or composite material takes the whole mechanical effort
- I_{max} twice as large as in a conventional line
- important increase of resistance R with temperature, and hence current : 1.5 to 2 times larger at 210^o C than at 75^o C
- some transmission operators consider upgrading the conventional conductors of systematically congested lines to HTLS conductors.



Gap-type conductor G(Z)TACSR

Skin effect

- present when an alternating current flows in a conductor
- current density j decreases from its value at the surface j_s with the depth d from the surface:

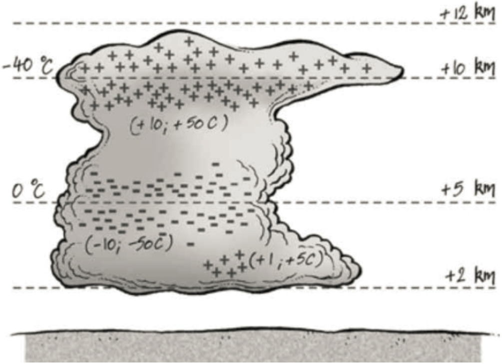
$$j(d) = j_s e^{-d/\delta}$$

- δ is the *skin depth*
    - for $d = \delta$, $j/j_s = 1/e \simeq 0.37$
    - in an AC power line $\delta \simeq 10$ mm
- resistance with Alternating Current $\simeq 10\ \%$ higher than with Direct Current:

per length unit: $r_{DC} = \dfrac{\rho}{s}$ s: cross-sectional area (m^2)

- in an ACSR conductor, the current flows mainly in the aluminum part; the steel participates very little in the total resistance, and hence in the losses.

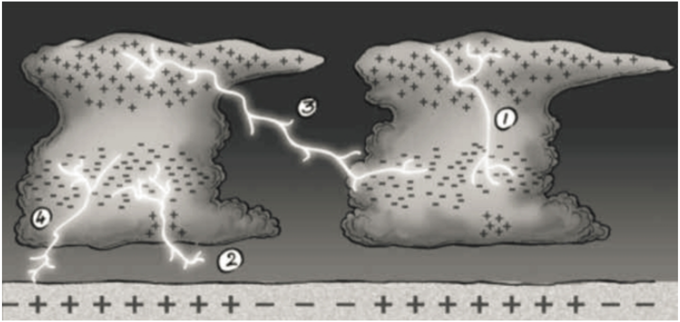
Lightning



cumulo-nimbus cloud, responsible for lightning

- separation of + and − charges inside the cloud, due to collisions between the ice crystals (+) which rise, and the water drops (-) which go down
- → electric field of high strength inside the cloud
- → electrical discharge.

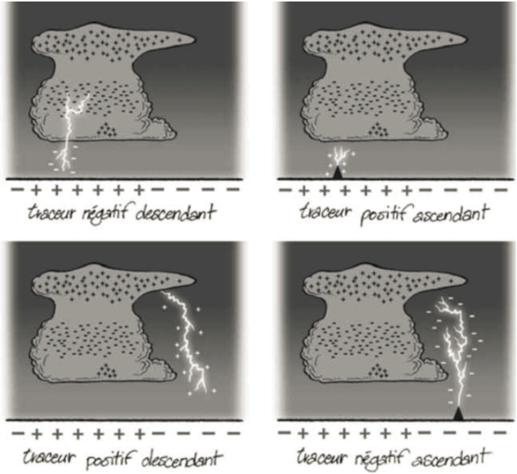
source: [3]



Four types of electrical discharges:

1. inside the cloud
2. stopping in the air
3. between two clouds
4. between one cloud and the ground

Type 4 : 90 % of the discharges between one cloud and the ground are negative (in regions of the world with a temperate climate).



Various types of electrical discharges between cloud and ground

- starts with a *stepped leader*[2]
- 90 % of cases: stepped leader is descending and negative (upper left figure)

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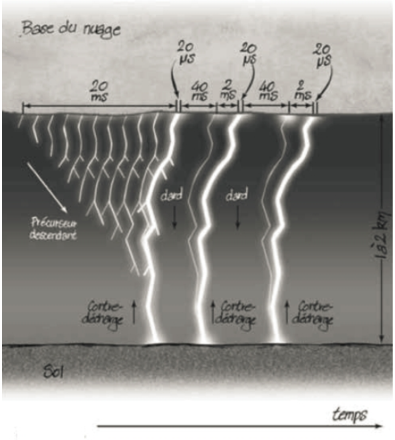
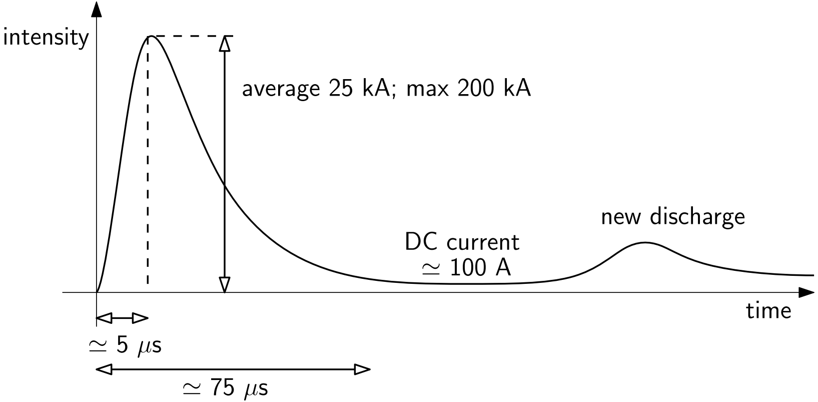
[2] en français: traceur

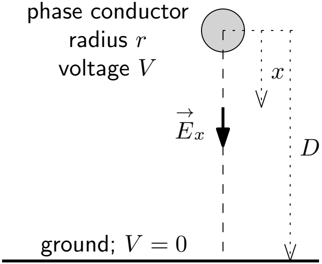


- the stepped leader jumps in steps of 10-200 m at a speed $\simeq$ 100 km/s
- when it approaches the ground, the electric field strength rises nearby
- a positive leader starts from a pointed object (electric field even larger) . . .
- . . . and meets the descending leader
- a channel is created in which the electrical charges travel ($\simeq$ 100.000 km/s)
- successive strokes in the channel (high pressure plasma, $\simeq$ 30.000^o C)

lightning current evolution with time :



Bundled conductors



Electric field intensity (V/m):

at distance x: $E_x = \frac{|V|}{x\ \ln(\frac{D}{r})}$

at the conductor surface: $E_r = \frac{|V|}{r\ \ln(\frac{D}{r})}$

The smaller r or the higher $|V|$, the higher the electric field strength.

A high strength electric field ($> 1.5 - 2$ kV/mm)[3] causes the *corona effect*:

- partial discharges due to ionization of air
- mainly for power lines with nominal voltage of 220 kV and above
- responsible for the audible noise, particularly under rainy or foggy weather conditions (amplified by the spikes formed by water drops)
- undesirable: causes significant power losses and radio interference !

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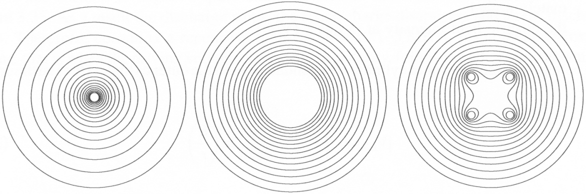
[3] field strength causing air breakdown at atmospheric pressure : 3 kV/mm

Remedy:

- use a conductor of larger radius r ?
  - too heavy !
  - metal not well used due to skin effect !
- use a bundle of several conductors, connected through *spacers*[4]



equipotential lines in the neighbourhood of respectively:
a thin conductor, a thick conductor and a bundle of four thin conductors

Other advantages of conductor bundles:

- easier to transport and to assemble
- better cooling of the conductors
- lower line reactance (will be shown later in this chapter)

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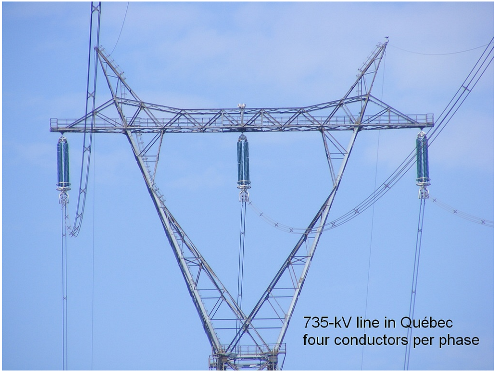
[4] necessary because the current-carrying conductors attract each other

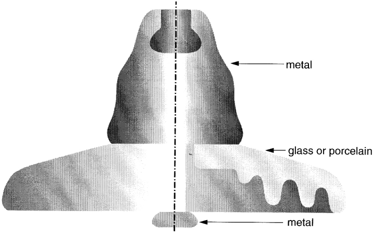

three conductors per phase


735-kV line in Québec
four conductors per phase

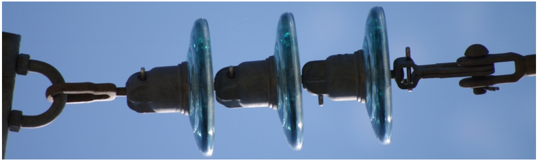
source: [2]

Insulators

- Keep the grounded tower and the phase conductor at some distance
- dimensioned to withstand not only the normal voltage but also overvoltages resulting from switching transients and lightning strokes
- rain and pollution ⇒ designed with a long *creepage path* so that the water film does not create a conducting path between the tower and the conductor



a module of *cap and pin* insulator



arcing horns :
in case of flashover
the arc takes place
at sufficient distance
from the insulators
to avoid damaging
them (arc heat !)

The terms in French

tower	pylône
pole	poteau
circuit	terne
bundle	faisceau
spacer	entretoise
insulators	isolateurs
shield wire	câble de garde
arcing	amorçage
arcing horn	corne d'amorçage (ou aussi éclateur)
tensile strength	résistance à la traction
span	portée
alloy	alliage
strand	brin

sag	flèche
ground clearance	garde au sol
annealing	recuit
corona effect	effet couronne
creepage path	chemin de fuite
cap and pin	capot et tige
flashover	claquage

“ACSR” est souvent traduit par “Alac”, pour “aluminium-acier”

References

[1] C. Bayliss and B. Hardy, *Transmission and distribution Electrical Engineering*, Elsevier, 2012, 4th edition, ISBN 978-0-08-096912-1

[2] P. Schavemaker, L. van der Sluis, *Electrical power system essentials*, John Wiley & Sons, 2008, ISBN 978-0470-51027-8

[3] C. Bouquegneau, “La foudre – Phénoménologie”, Revue de l’Electricité et de l’Electronique (REE), Vol. 3, 2017, pp. 45-51