Physics and Numerical Modeling of Electric Arcs in Circuit Breakers

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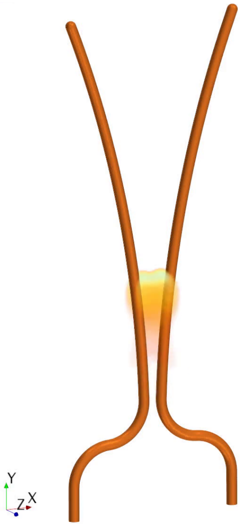
About me

Roman Fuchs, Dr. sc. ETH
born in 1987, 2 kids

- Bachelor in Mathematics (2006-2009)
  University of Bern.
- Master in Computational Science and Engineering (2009-2012)
  ETH Zürich. Focus in CFD.
- Doctoral Studies (2014-2021)
  ETH Zürich.
  "Numerical Modeling and Simulation of Electric Arcs"
  `https://doi.org/10.3929/ethz-b-000489867`
- Lecturer, Researcher at OST



About me

Since 2012 at OST, Institute for Energy Technology.
`www.ost.ch/iet`

- Electrical power Engineering
- Building technology (heat pumps, zerp/plus energy buildings)
- Scientific Computing & Engineering
- Wind Energy Innovation
- Power-to-X / -H2 / -Methane / ...

We are open for Master Thesis!

Abstract

Circuit breakers are engineered to safely interrupt currents and isolate faulty sections of the electrical power network and prevent damage caused by overcurrents or short circuits under normal or fault conditions; hence, they contribute reliable operation of the power system.
When a circuit breaker is triggered to open, an electric arc may form due to the high voltage and current. We will discuss fundamental physics from an applied perspective. We discuss the Cassie-Mayr model as a zero-dimensional representation of arcs. We then consider 3D-simulations of electric arcs which requires a coupled solution of compressible fluid dynamics, electromagnetism, radiative heat transfer and advanced physics modeling. Subsequently, we build on these fundamental aspects and discuss the working principle of High Voltage Circuit Breakers in AC and DC power networks. We conclude with aspects of Low Voltage Circuit Breakers, and their use in Electric Vehicles.

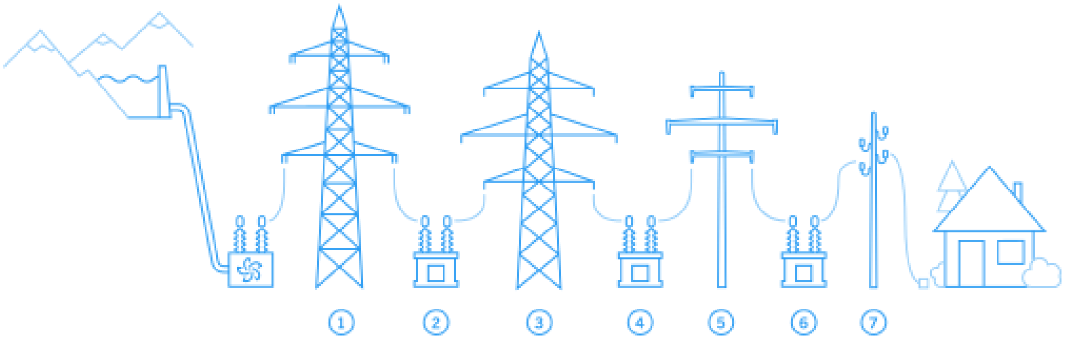
Outline

Learning objectives:

You are able to:

- sketch and explain the layout of an electric power grid.
- state grid components of a power substation.

Electric Power Grid



- Extra-high voltage (220 kV, 380 kV)
- High voltage (36 kV - 150 kV)
- Medium voltage (1 kV - 36 kV)
- Low voltage (< 1 kV)

Source: `https://www.swissgrid.ch/en/home/operation/power-grid/grid-levels.html`

European Transmission Grid

https://www.entsoe.eu/data/map/

- red: 380 kV Transmission line
- green: 220 kV Transmission line
- purple: DC line

CH:

- 4 nuclear plants, hydro power (pumped storage & river-flow)
- EU-Swiss Institutional Framework Agreement, Electricity agreement

see also https://nfp-energie.ch/en/projects/1024/

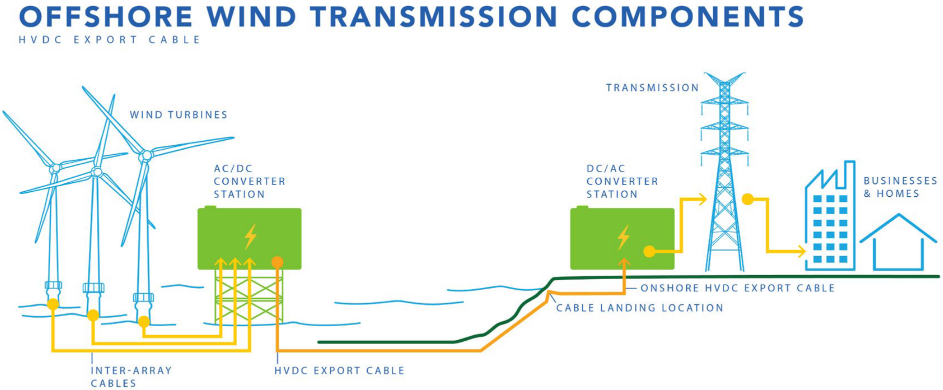


Figure: Offshore wind park connected to power grid.

https://www.energy.gov/sites/default/files/2023-09/Atlantic-Offshore-Wind-Transmission-Plan-Report_September-2023.pdf, Fig. 6.

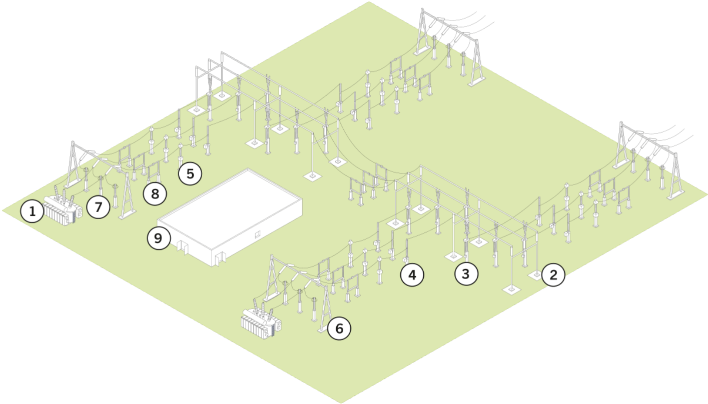


Figure: Substation components. 1 - transformer, 3 - disconnecting switch, 4 - circuit breaker, 7 - lightning arrester.

https://www.swissgrid.ch/en/home/operation/power-grid/technologies.html

What is their main functionality?

Transformer

Disconnecting switch

Circuit breaker

Lightning arrester

Outline

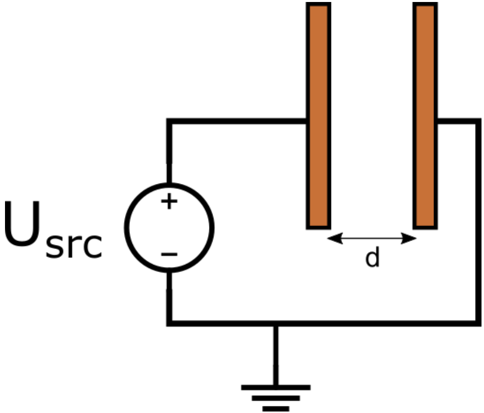
Motivation

Consider two parallel plates with insulating air gap d and electric potential difference $\Delta\phi = U_{src}$.

What happens if:

1. $d = 2\,\text{mm},\ U_{src} = 230\,\text{V}$
2. $d = 2\,\text{mm},\ U_{src} = 1\,\text{kV}$
3. $d = 2\,\text{mm},\ U_{src} = 10\,\text{kV}$

You should argue with electric field.



Electric Arc

Continuous, high-density electric current between two separated conductors in a gas or vapour with a relatively low potential difference, or voltage, across the conductors.

- Circuit breakers
- Electric arc furnaces
- Metal-arc welding

Figure: Gas Metal Arc Welding.

Encyclopedia Britannica, https://www.britannica.com/science/electric-arc, Image:
https://www.rsi.edu/blog/skilled-trades/what-is-gas-metal-arc-welding/

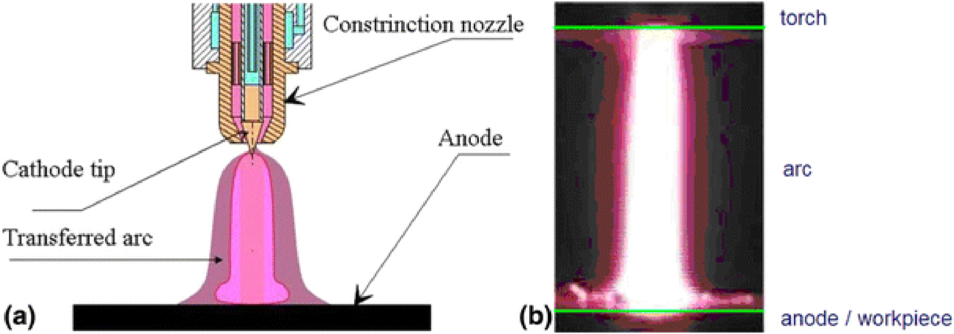


Figure: Electric arc formed by a transferred arc plasma torch and typical picture. [1]

Task: Estimate current density, electric field, and power density in arc column. Operation conditions: 250 A to 1000 A, 30 V to 100 V, arc diameter 1 mm, arc length 5 mm.

- Video: High-voltage disconnect-switch arcing.
  `https://youtu.be/GMbN9nb3qyk?feature=shared`
- Explanation:
  `https://capturedlightning.com/frames/longarc.html#500_kV_Switch`

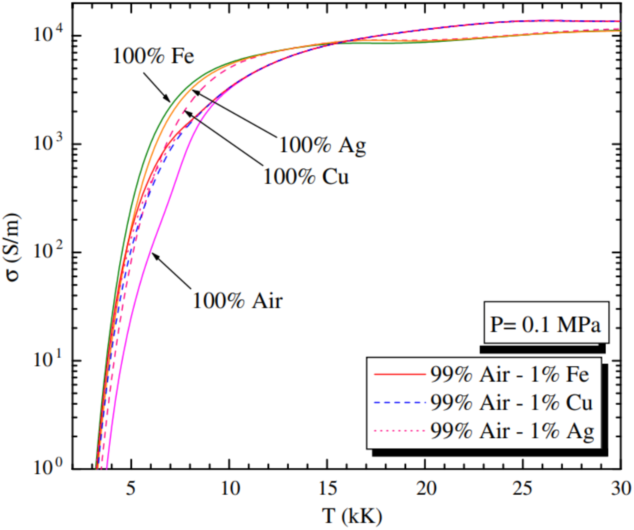


Figure: Electrical conductivity. [2]

Definition (Plasma)

any ionized gas consisting of free electrons, ions and neutral particles (atoms and/or molecules), electrically neutral on a macroscopic scale and electrically conductive.
Source: IEC Electropedia, ref. 841-31-01

Kinetic gas theory:

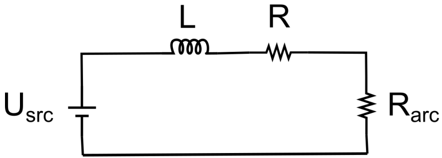
- Collisions of electrons and heavy particles, momentum exchange.
- Temperature = mean kinetic energy of gas particles that follow a Maxwellian velocity distribution.

Basic assumption: local thermodynamic equilibrium (LTE).
In essence,

- all species share an identical temperature ($T_e = T_h$)
- collision rate is sufficiently
- spatial variations are sufficiently small

see, e.g., [3]
Thermal arc plasma: high current density (10^8 A m^{-2}) at ambient pressure.

Cassie-Mayr model



Effective model for arc resistance in terms of Ohmic heating and Heat losses:

$$\frac{dR_{arc}}{dt} = \frac{R_{arc}}{\tau}\left(1 - \frac{R_{arc} I^2}{P}\right)$$

τ timescale, P heat losses from arc.
Mayr: $P = P_0$, Cassie: $P = P_0 R^{-1}$

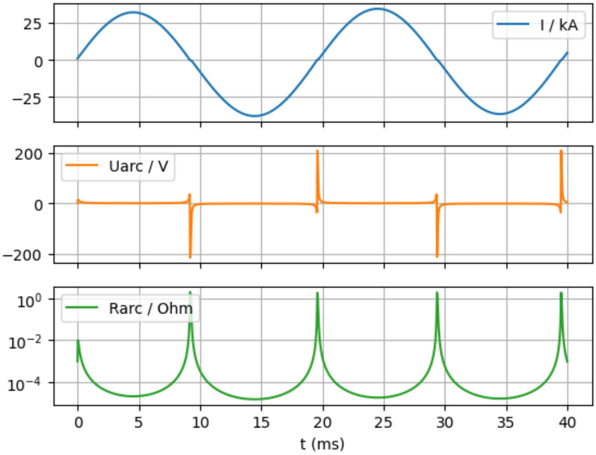
- A. M. Cassie, "Arc rupture and circuit severity", Conseil International des Grands Reseaux Electriques a haute tension (CIGRE), Paris, France, Report No. 102 (1939).
- O. Mayr, "Beiträge zur Theorie des statischen und dynamischen Lichtbogens", Archiv fur Elektrotechnik 37 (12), 588 (1943).

Task: Consider a cylindrical arc with radius r and length L at temperature T.

- Find the arc resistance R in terms of r and L.
- Find the surface power loss from a cylinder with radius r and length L at temperature T, and show that $P = P_0 R^{-1/2}$.
- Then assume that power loss is proportional to cylinder volume, and show that $P = P_0 R^{-1}$.

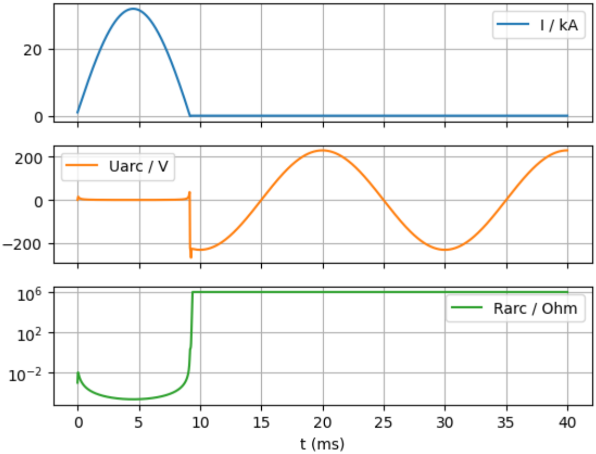
Reference: see, e.g., [4]

Example: failed



$R = 1\,\text{m}\Omega,\ L = 20\,\mu\text{H},\ U_{src} = 230\,\text{V},\ 50\,\text{Hz},\ I_0 = 1\,\text{kA},\ R_{arc,0} = 1\,\text{m}\Omega.$
$P_0 = 2.2 \times 10^4\,\text{W},\ \alpha = 0.9,\ \tau = 10\,\mu\text{s}.$

Example: success



$R = 1\,\mathrm{m\Omega},\ L = 20\,\mu\mathrm{H},\ U_{src} = 230\,\mathrm{V},\ 50\,\mathrm{Hz},\ I_0 = 1\,\mathrm{kA},\ R_{arc,0} = 1\,\mathrm{m\Omega}.$
$P_0 = 2.3 \times 10^4\,\mathrm{W},\ \alpha = 0.9,\ \tau = 10\,\mu\mathrm{s}.$

Outline

Learning objectives:

You should be able to:

- state the extended Navier-Stokes equations, Maxwell's equations, and Radiative Transfer Equation
- identify key parameters in the fundamental equations

Reference: [1]

Magneto-Hydro-Dynamics (MHD)

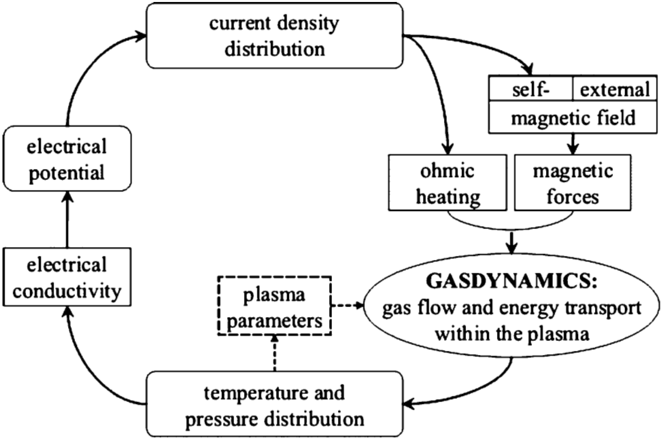


Figure: Interaction of processes in arc column. [5, Fig. 1]

see also: [6]

Navier-Stokes Equations

$$\partial_t(\rho) + \nabla \cdot (\rho u) = \Gamma$$
$$\partial_t(\rho u) + \nabla \cdot (\rho u u) = -\nabla p + \nabla \cdot \tau + J \times B$$
$$\partial_t(\rho e_{tot}) + \nabla \cdot (\rho h_{tot} u) = \nabla \cdot (\tau \cdot u) + \nabla \cdot (\lambda \nabla T) + \sigma E^2 - \nabla \cdot q_{rad}$$

p pressure
T temperature

ρ mass density
Γ species source

σ electrical conductivity

λ thermal conductivity
q_{rad} radiative heat flux

τ viscous stress tensor
h_{tot} total enthalpy
e_{tot} specific total energy

u velocity

E electric field
B magnetic flux density
$J = \sigma E$ electric current density (Ohm's law)

Maxwell's equations

$$\partial_t B + \nabla \times E = 0 \qquad \nabla \cdot B = 0 \qquad B = \mu H$$
$$\partial_t D - \nabla \times H = -J \qquad \nabla \cdot D = q_{el} \qquad D = \varepsilon_0 E$$

Potential formulation: $B = \nabla \times A$ and $E = -\nabla\phi - \partial_t A$.
$\leadsto$ Magnetic Gauss' law ✓, Faraday's law ✓

Ampère's law in low-frequency approximation ($J \gg \partial_t D$)
Current conservation

$$\nabla \times \left(\frac{1}{\mu}\nabla \times A\right) = -\sigma\nabla\phi$$
$$-\nabla \cdot (\sigma\nabla\phi) = 0$$

FE-based solver required if permeability (μ) is discontinuous (e.g., steel)

Radiative heat transfer

Total net radiative heat flux

$$\nabla \cdot q = \int \nabla \cdot q_\nu \, \mathrm{d}\nu$$

based on radiative transfer equation (RTE) including emission and absorption

$$s \cdot \nabla I_\nu(x, s) = \kappa_\nu (B_\nu - I_\nu)$$

(w/o transient term, scattering, refraction)
B_ν blackbody radiance, Planck function ($\mathrm{W\,sr^{-1}\,m^{-2}\,Hz^{-1}}$)
I_ν spectral radiative intensity ($\mathrm{W\,sr^{-1}\,m^{-2}\,Hz^{-1}}$)

- spectral absorption coefficient κ_ν ($\mathrm{m^{-1}}$)
- Optical depth ($L \gg 1$: opaque, $L \ll 1$: transparent)

$$L = \int \kappa_\nu s \, \mathrm{d}s$$

Spectral absorption coefficient

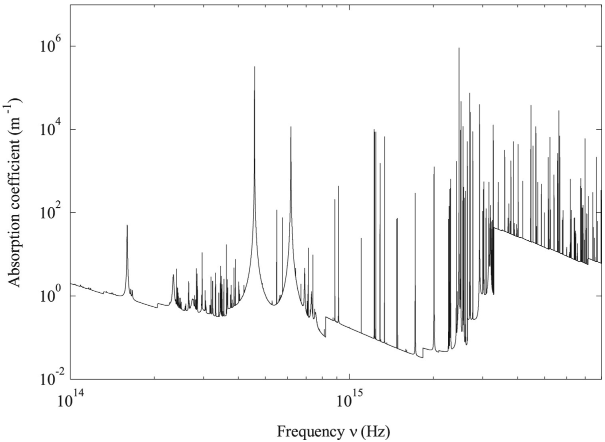
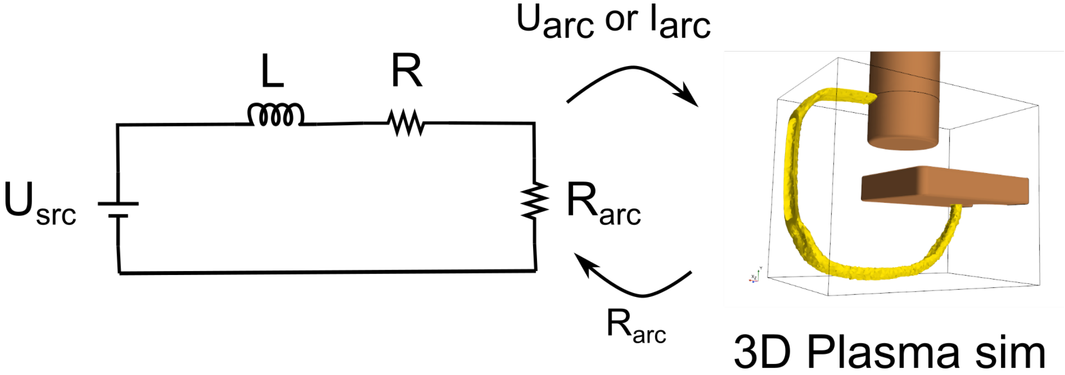


Figure: Absorption spectrum for a mixture of 50% silver, 25% air and 25% hydrogen at 16,300 K and 1 atm. [7]. Visible light in 0.4 - 0.8 $\times 10^{15}$ Hz

External Circuit, Multiphysics



Multiphysics:

- MHD: Navier-Stokes, Maxwell, Radiative heat transfer
- Rigid body motion (grid deformation, remeshing)
- Chemical reactions
- Electrode erosion, wall ablation
- Non-LTE

Wall-stabilized arc

1D model: arc as an axisymmetric cylinder, radial profile $T(r)$

$$\nabla \cdot (-\lambda \nabla T) = \sigma E^2 - \nabla \cdot q_{rad}$$

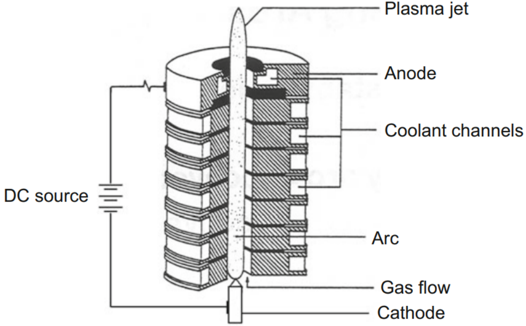


Figure: Wall-stabilized arc. [8]

Outline

Learning objectives:

You should be able to:

- describe the working principle of a gas-blast high voltage circuit breaker in AC and DC grids.
- explain why SF6 has been banned in EU and name alternative gases or technologies to them.

References: [9], [10]

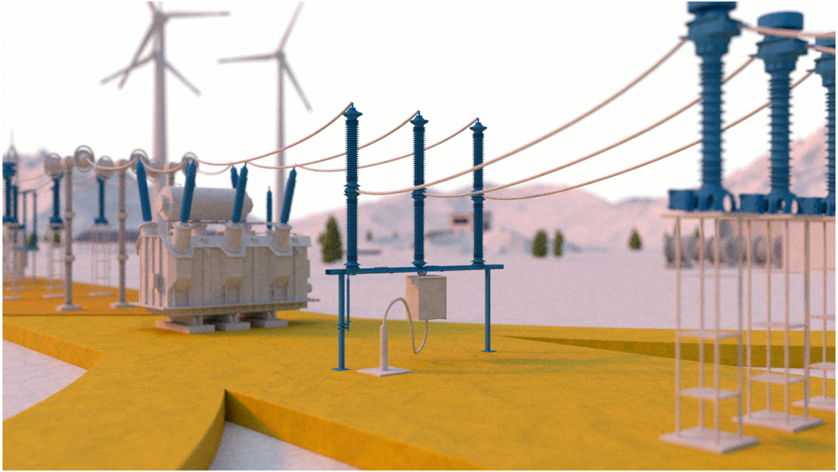


Figure: High voltage circuit breaker.

https://www.pfiffner-group.com/products-solutions/details/
circuit-breaker-with-natural-origin-gas-insulation

History

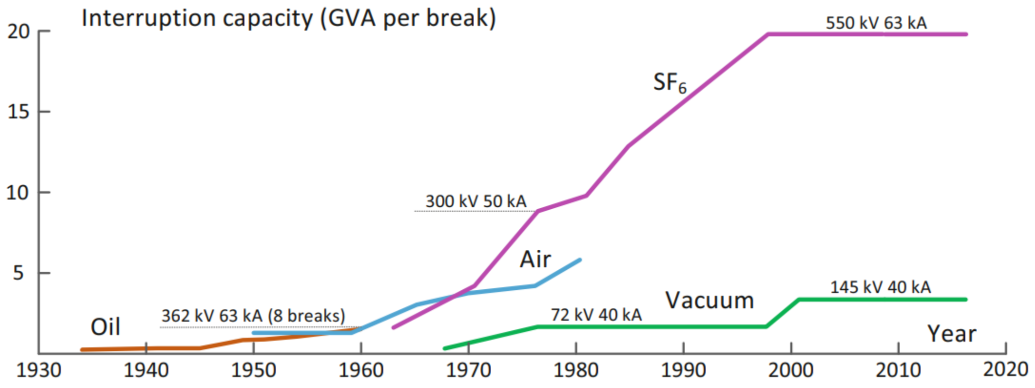


Fig. 1.2 Development of interruption capacity per break for different circuit breakers

Figure: HVCB Interruption Capacities. [11]

HVAC Circuit Breakers

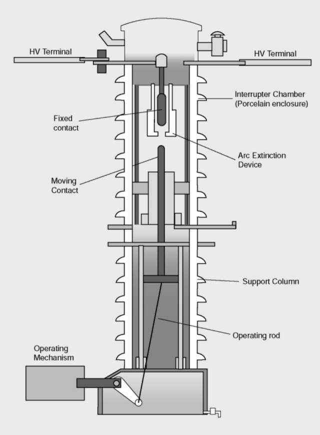


Figure: Components of a HVCB. [12]

Design characteristics:

- high voltage, i.e., 35 to 100 kV
- a few kA of load current
- Short circuit currents, 10 to 100 kA
- 30 years lifetime
- temperature ranges: -50 to 60 °C

Gas-blast Circuit Breaker

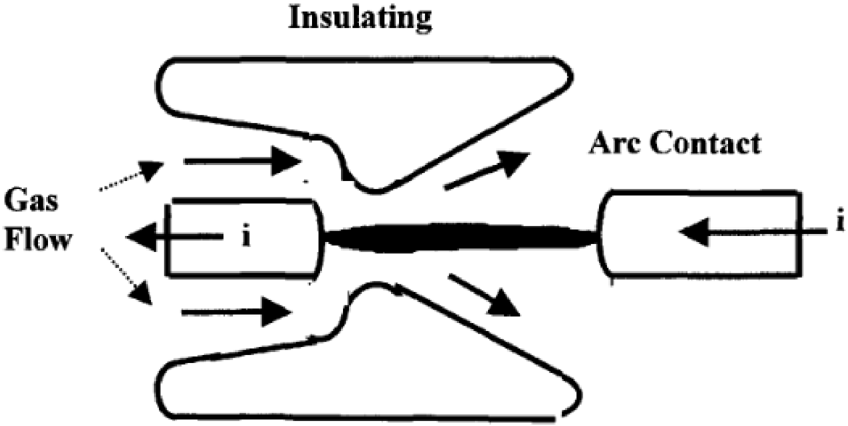


Figure: Axial gas-blast circuit breaker. [9, Fig. 5.13.]

Gas-blast circuit breaker

Video: explanation of self-compression principle.
Starts at 0:39.
https://www.siemens-energy.com/global/en/home/products-services/product-offerings/circuit-breakers.html

Normal current interrupt process

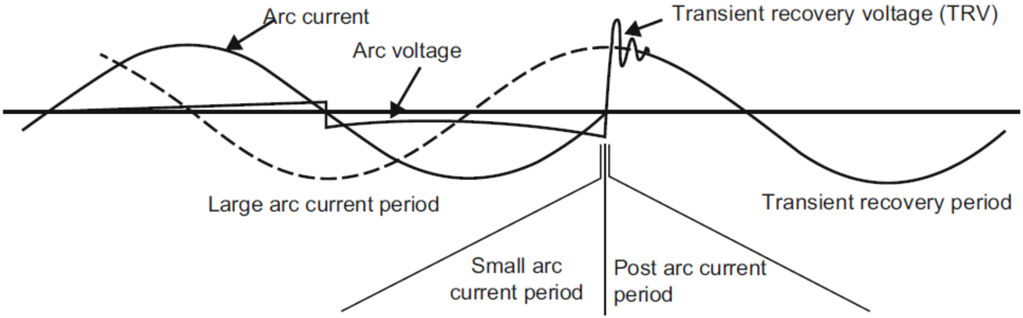


Figure: Current interruption process. [13, Fig. 3.8]

Thermal failure

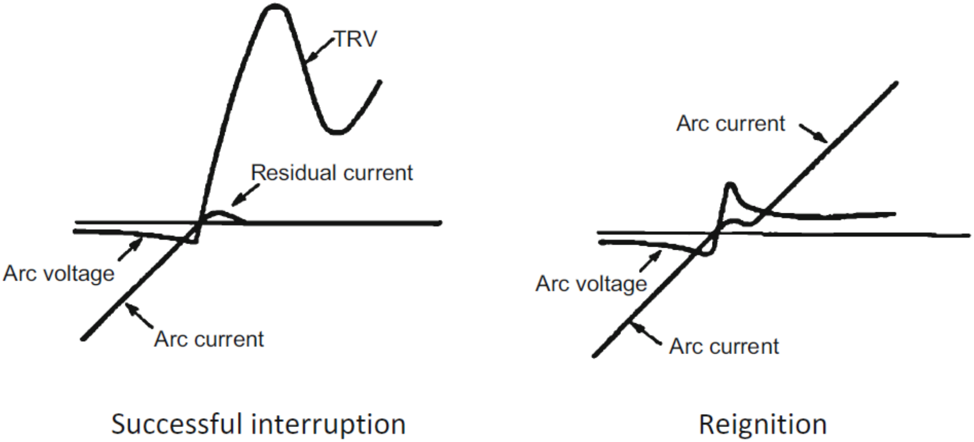


Figure: Success and failure during the thermal interrupting process. [13, Fig. 3.10]

Dielectric failure

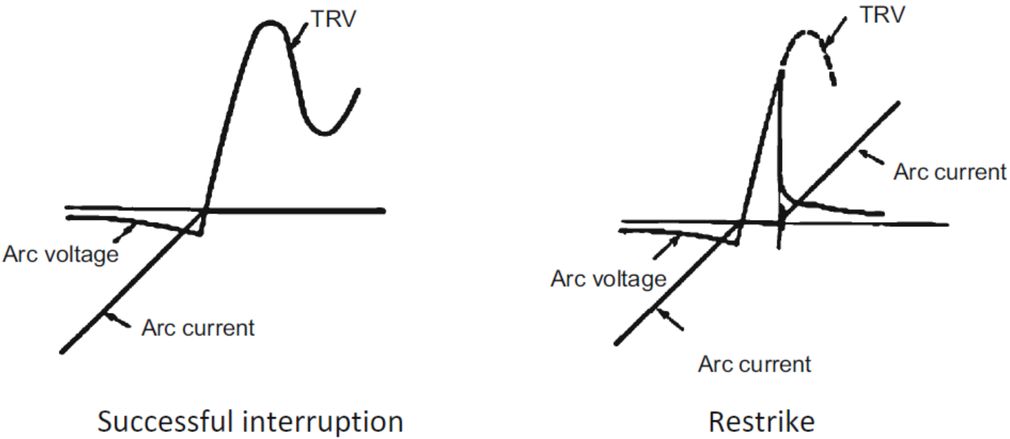


Figure: Success and failure during the dielectric interrupting process. [13, Fig. 3.11]

From SF6 to GWP-neutral gases

- Air was used in 1940s - 1990s.
- SF6 has superior dielectric properties (1920s), used anywhere in HV
  - 1st SF6 CB by Westinghouse: 230 kV, 25 kA (1959)
  - dielectric strength, heat transfer, e-negative, low dissociation temperature, high dissociative energy, almost total recombination, non-reactive
  - most potent Greenhouse gas: GWP 24000, 3200 year lifetime
- Alternative gases: N2, CO2, H2
- Additives: C4-Fluorinitriles, C5-Fluoroketones
- Alternative technologies (vacuum CB, . . .)

Referenes: [14], [15], [16], [17]
See also: EU F-gas regulation (next slide)

EU F-gas legislation

F-gas Regulation (EU) 2024/573, Article 13: Control of use.

Par. 7:

From 1 January 2035, the use of SF6 for the maintenance or servicing of electrical switchgear equipment shall be prohibited unless it is reclaimed or recycled, except if (...)

This paragraph shall not apply to military equipment.

Par. 9: Prohibited to put into operation switchgear using (...) fluorinated greenhouse gases:

- 2026: MV switchgear $\leq 24\,\mathrm{kV}$
- 2028: HV switchgear $\leq 145\,\mathrm{kV}$ and $\leq 50\,\mathrm{kA}$ short circuit current, with GWP ≥ 1.
- 2030: MV swtichgear $\leq 52\,\mathrm{kV}$
- 2032: HV switchgear $\geq 145\,\mathrm{kV}$ or $\geq 50\,\mathrm{kA}$ short circuit current, with GWP ≥ 1.

HVDC Circuit breakers

Task: derive a circuit equation. Which condition must be satisfied to decrease a fault current to zero?

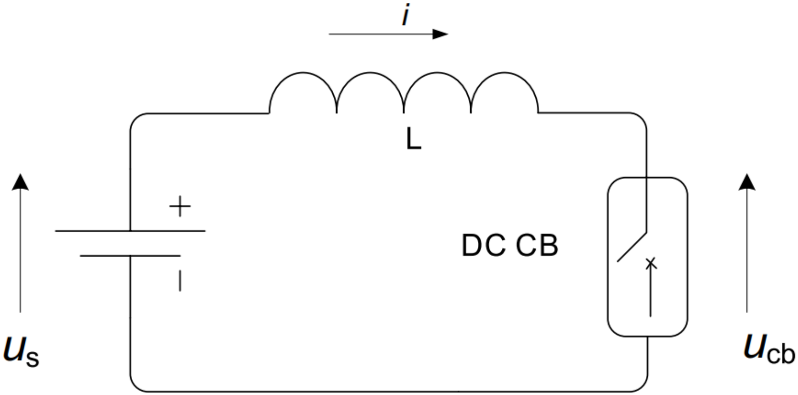


Figure: DC circuit diagram. Source: [18]

Challenges in DC fault current interruption:

1. There is no natural current zero in DC systems, and they must absorb magnetic energy ($\frac{1}{2}LI^2$).
2. Fault current in HVDC systems rises rapidly to a peak value limited only by the resistance in the current path. That is, DC breakers must clear 10x faster than AC breakers.
3. HVDC circuit breakers need to quickly generate and sustain counter voltage exceeding the system voltage.

Mechanical Passive DC CB design

HVDC breaker create a CZ using a resonant circuit.

main branch low-resistance AC interrupter

current injection path LC resonant circuit

energy absorption branch single/multiple surge arrestors

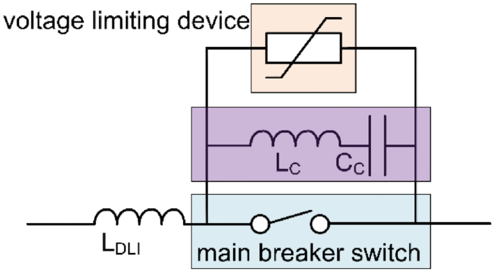


Figure: Mechanical switch - passive resonance. [19]

HVDC CB Designs

- The discussed design has considerable limitations in the maximum interruptible current.
- Applicable up to 550 kV and 4 kA.
- More complex designs allow for higher power ratings.

Reference: [20]

Outline

Motivation: Low voltage circuit breakers

- Why do we install LVCB? What is their purpose?
- How do LVCB work?

Figure: Miniature Circuit Breaker. [21]

Learning objectives:
You should be able to:

- identify key components in a low voltage circuit breaker and state their functionality.
- describe the arc quenching process in LVCB in own words.
- explain why splitter plates are used in LVCB.
- explain how a pyro-fuse is used in EV DC system.

References: [9, Sec. 5.2], [22]
Low voltage: $< 1\,\mathrm{kV}$ AC.

Low voltage circuit breaker

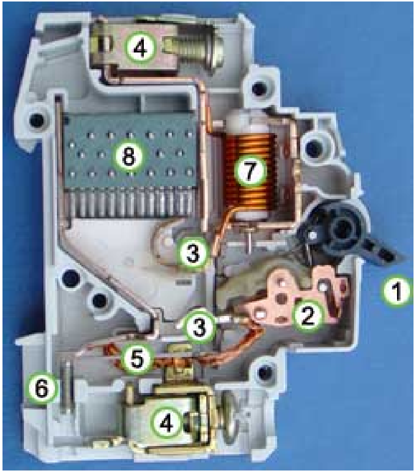


Figure: Low voltage circuit breaker diagram. [23]

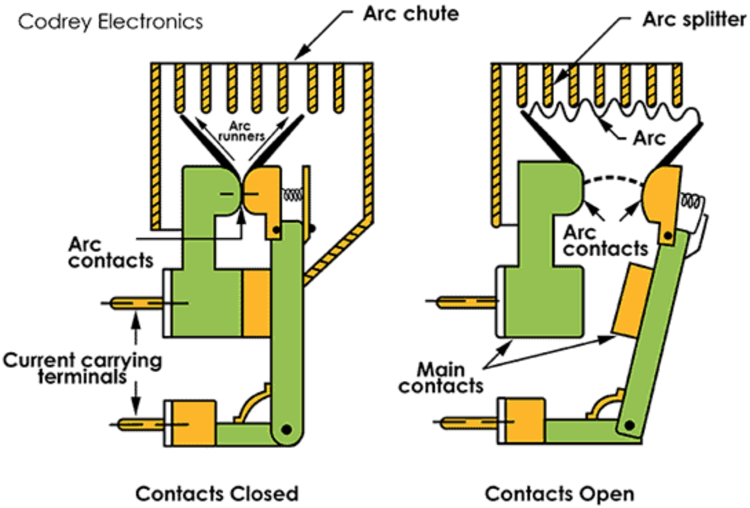


Figure: Air circuit breaker diagram. [24]

- Contact opening, arc formation
- Arc moves away from contacts by Lorentz force, pressure gradient
- Arc splitting
- Arc cooling, prevent restriking

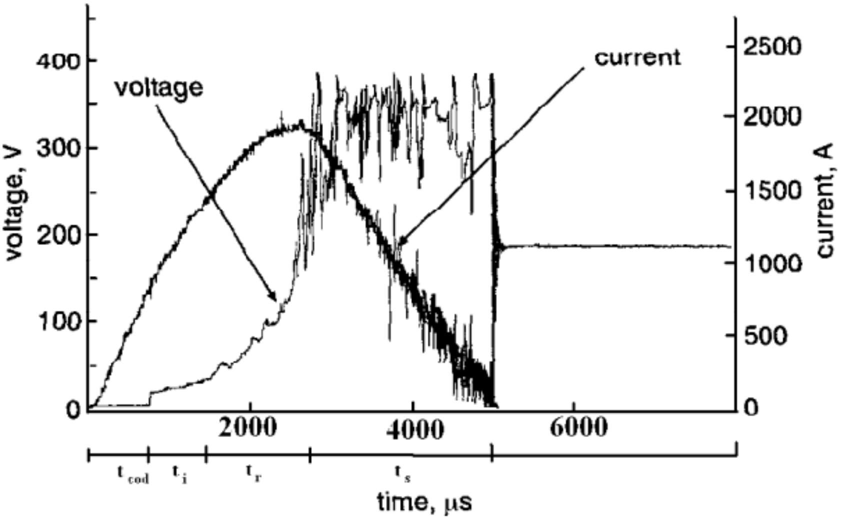


Figure: Current and Voltage in LVCB. [22]

Arc root voltage

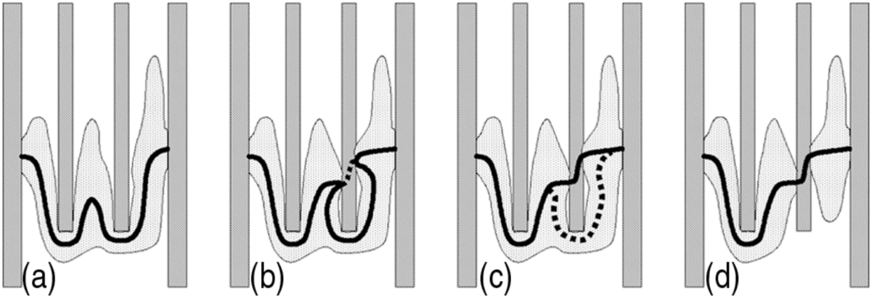


Figure: Principle of arc splitting by metal plates. [5]

Note: each pair of arc roots incurs 20 V additionally.
Task: Consider a 5mm thick and 10mm long electric arc in air. Estimate arc resistance. How much current is required to reach 230 V? What does it mean w.r.t. product safety of a circuit breaker? What if the arc is split into 10 sections?

Arc root voltage model

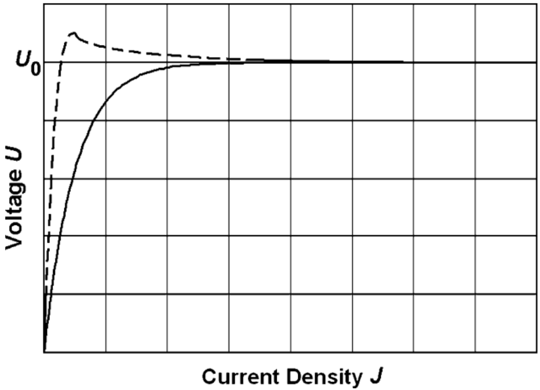


Figure: Voltage-current characteristics for modeling the formation of an arc spot. [5, Fig. 8]

Further modeling

- Arc root voltage drop: add surface heat term to Plasma
- Electrode erosion: evaporation model (add Cu (g) to Plasma, heat sink)
- Wall ablation: evaporation model (add cold gas, heat sink)
- Rigid body motion: include Lorentz force in electrodes
- Chemical reactions
- Radiative heat transfer
- etc.

Circuit breakers in Electric Vehicles

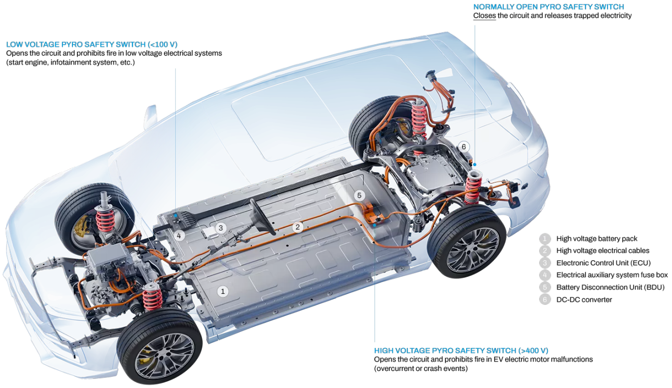


Figure: Electric vehicle.

Source:

https://www.autoliv.com/safety-solutions/electrical-safety-solutions/pyro-safety-switches

Circuit breakers in Electric Vehicles

- Volt-Breaker by DAISI (Pyro-Fuse)
  https://youtu.be/78YvpWDAhuA?feature=shared
- Astotec (Austria): CB 500-2
  Pyrotechnic circuit breaker for high-voltage applications in electric vehicle.
  500 V DC, 12.5 kA, 12.5 µH
  https://www.astotec.com/wp-content/uploads/2022/09/CB500-2_web.pdf

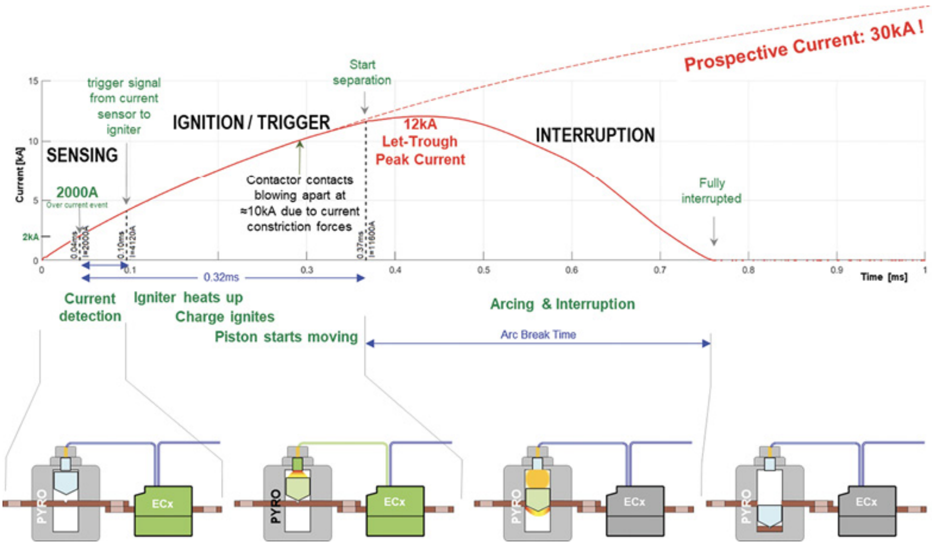


Figure: Response of a pyro switch and current sensor. [25]

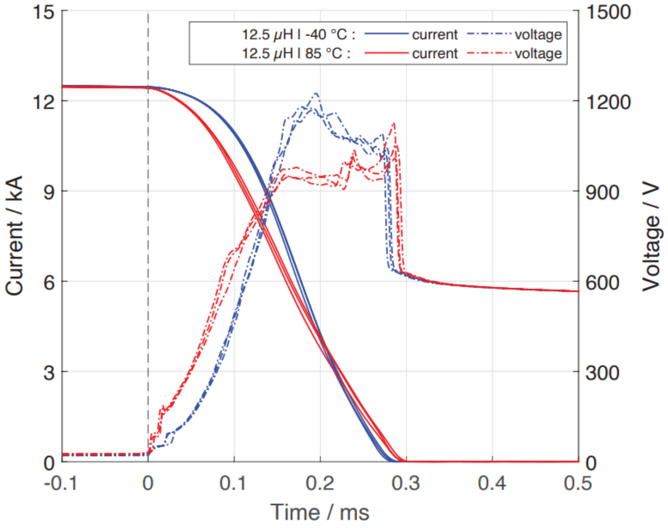


Figure: Typical current and voltage curves. [26]

Outline

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