CIRCUIT BREAKERS

The Switching Arc and Arc Modeling

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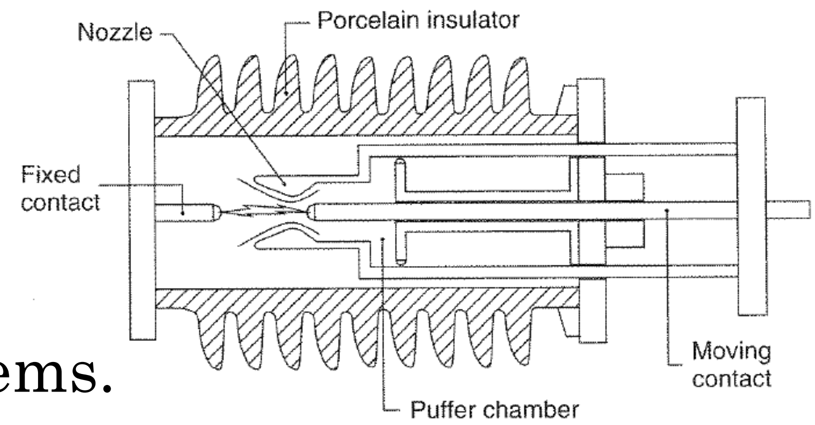
Final Exam (Presentation), Surge Phenomena in EPE

Outline

- Circuit Breakers
- The Switching Arc
- Mathematical Models of the Switching Arc
  - General Switching Arc Equations
  - Cassie Model
  - Mayr Model
- Arc-Circuit Interaction
- U.Delft's Arc Model Blockset
- Arc-Circuit Interaction Simulations
  - Cassie and Myar Models
- References

CIRCUIT BREAKERS



- Key equipment in power systems.
- Function:
  - To isolate faulted sections of a network
  - Interrupt fault currents (up to the MVA rating of the breaker)
  - Interrupt *abnormal currents:* due to nonlinear loads (arc furnace), and other load variations.

- Some history:
  - First oil circuit breaker patented by J.N. Kelman in 1907 (Two contacts in an oil tank)
  - In 1957 T.E. Browne *et al* file the first patent for SF6 breakers.

Features of a Circuit Breaker
Types of Circuit Breakers

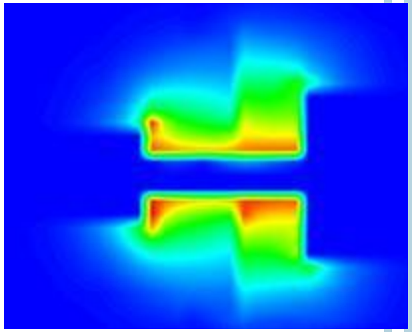
- Features:
  - Good conductor when closed
  - Good insulator when opened
  - Fast switching capabilities (change from closed to open must be very fast)
  - Doesn't cause over-voltages when operating
  - Reliable (opens when it has to!, stays closed otherwise)
- Types: categorized by their extinguishing medium
  - Oil
  - Air Blast
  - SF_6
  - Vacuum

Oil, Air Blast, SF_6 → HV Circuits (High Pressure Electric Arc)

Vacuum → MV Circuits (Low Pressure Electric Arc)

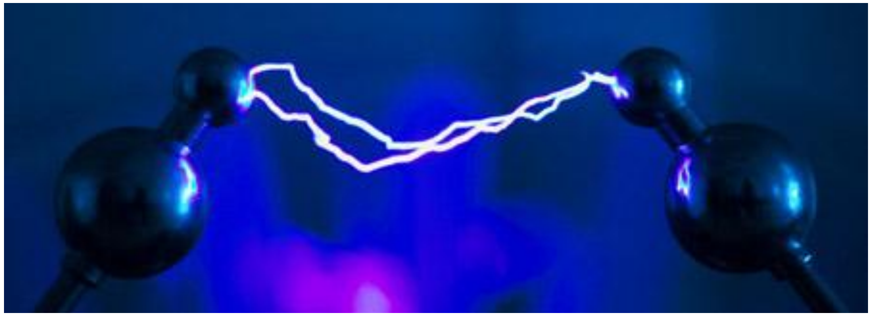
  - We will focus on SF_6 breakers →

The Electric Arc and Current Interruption Process

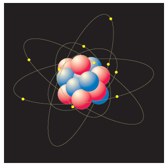


- A complex physical phenomena (not fully understood)
- Electric Arc: capable of changing from a conducting to a non conducting state very fast.
- Current Interruption (a simple description):
  1. High current is detected in the network
  2. Control circuit sends a signal to action the movable contact
  3. High-density current is established in a small contact surface
  4. As the movable contact parts, a plasma channel is established (more details are explained latter)
  5. As the movable contact continues to part, the arc is being cooled down by the medium (gaseous or liquid)
  6. When the contacts have fully separated, the arc has been extinguished by the cooling process

The Switching Arc



- Electric arc is used for interruption→ switching arc.
- What is an electric arc?
  - A <u>plasma channel</u> (the 4th state of matter) between the breaker contacts formed <u>after a gas discharge</u> in the extinguishing medium.
- How is an electric arc formed in a confined closure (circuit breaker)?
  - Before contacts separate a high current density is produced at the small surface contact area → the material of the contacts melts!
  - The melting material explodes producing a gas discharge in the extinguishing medium
  - As the breaker parts, the magnetic energy stored in the inductances of the system force current to flow
  - Plasma channel is established…



THE PLASMA STATE

Temperature Increases

Temperature Regions for SF_6

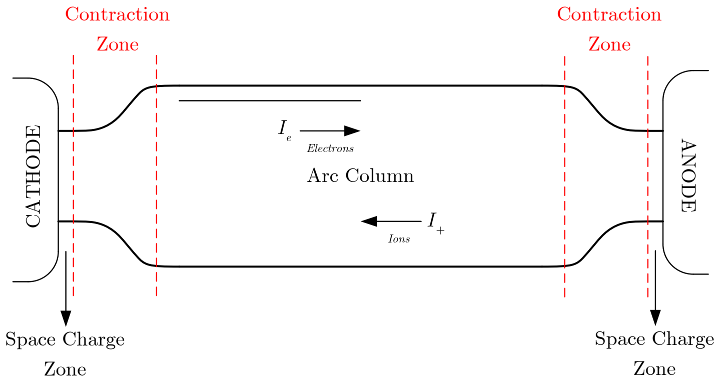
4 °K

1800 °K

5000 °K - 6000 °K

- Molecular Energy exceeds Combination Energy
  - Matter changes from SOLID → LIQUID (melting)
- Increase of Temperature → Energy is added & Var der Waals forces are overcomed
  - Matter Changes from LIQUID → GAS
- Increase of Temperature → each molecule is given more energy, so much, that the dissociate into separate atoms
- Temperature Increases Further → energy level is increased further!
  - Orbital electrons dissociate into free electros, positve ions are left

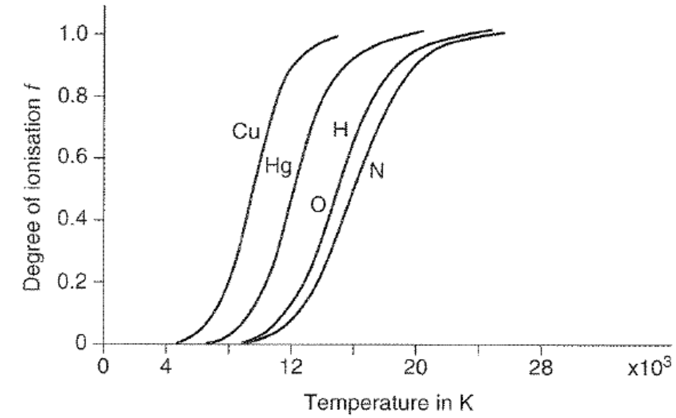
THE PLASMA STATE



- For higher temperatures the conductivity increases rapidly.
- Thermal ionization is caused by collisions between fast moving electrons and protons, the slower moving positively charged ions and the neutral atoms.
- At the same time recombination process of the positive charged electrons and positive charged ions into a neutral atom occurs
- Thermal equilibrium: rate of ionization = rate of recombination.

- *What happens after the plasma is fully established?*
  - *Free electrons and heavier positive ions in the high temperature channel make it (the plasma channel) highly conductive so current can flow freely after contact separation, until extinguished.*

Saha's Eqn. for Different Gasses



Saha's Equation

- Thermal ionization can be used to switch between a conducting state to a non conducting state.
- Relation of the pressure with the temperature and the fraction of atoms that are ionized

$$\frac{f^2}{1-f^2}P = 3.16\times10^{-7}\,T^{\frac{5}{2}}\,\varepsilon^{-e\frac{V_i}{kT}}$$

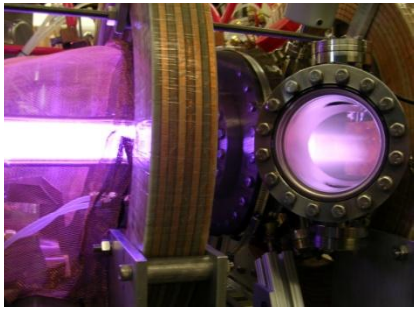
$e : 1.6\times10^{-19}$, charge of e

V_i : ionization potential of the medium

k : 1.28×10^{-23}, Boltzmann's Constant

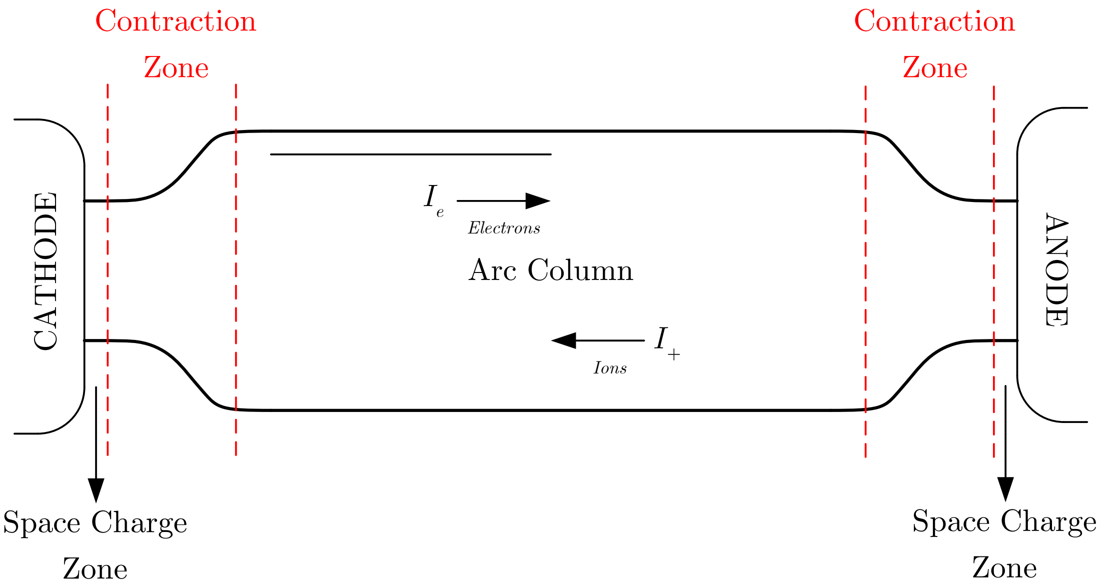
- Steep slope function of temperature → reduction of average kinetic energy level can be done by cooling with cold gas.
  - Bring the arc channel from conducting to non-conducting.

Small Time Constants



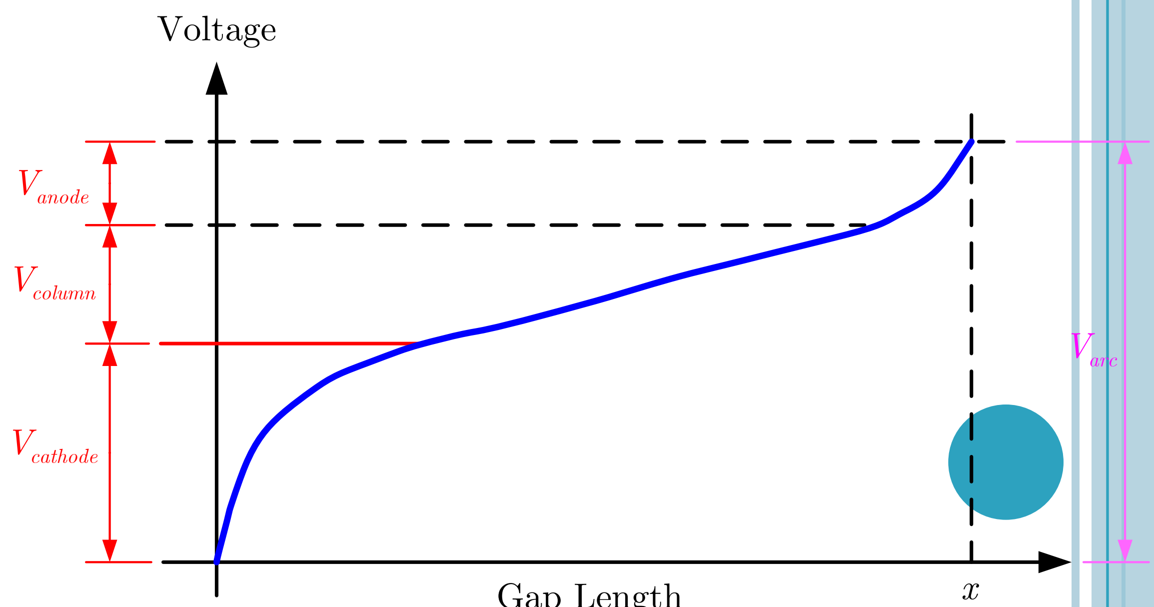
- Temperature change to interrupt current cannot be immediate, however, it can be very fast due to the characteristic of the extinguishing medium → as seen from Saha's equation.
- The time it takes to cool down the plasma channel is called *conductivity time constant,* which depends on
  - Ion-electron recombination speed $\left(10^{-8}\,\text{sec}\right)$
  - Particle-velocity distribution $\left(10^{-10}\,\text{sec}\right)$
- Consequence:
  - For the electric transient, the circuit arc is assumed to be in the thermal-ionization equilibrium

PLASMA CHANNEL



- Cathode: conducts current carrying electrons to the arc column.
- Anode: collector of electrons leaving the arc column.

- The potential gradient and the temperature distribution can be measured from the arc channel.
- Potential along the arc channel is a function of: arc current, energy exchange between plasma and medium, pressure, flow velocity, and physical properties of the medium.



Mathematical Models of the Switching Arc

- Arc Models:
  - Physical:
    - describe the physical phenomena
    - used in design
    - complex mathematics
  - Black box:
    - describe the behavior of the arc
    - used for simulation of arc-circuit interaction
    - Give the relation between the arc conductance and circuit variables
    - not used for design→ network studies
  - Parameter Models
    - more *accurate* black box models
    - parameters are obtained from complex functions and tables

General Physical Model

- Physical Models
  - Describe the entire physical process
  - *Actually used for design of breakers*
  - Based on fluid dynamics equations that obey the laws of thermodynamics in conjunction with Maxwell's equations (Large number of differential equations).
  - There are three important expressions in these models
    - Conservation of: mass, momentum, and energy
- Conservation of mass – continuity equation:
  - Arc-plasma is a chemical reaction: conservation of mass and rate equations for different chemical reactions are considered in conjunction.

$$\frac{\partial \rho}{\partial t} + div\left(\rho u\right) = 0 \quad \rho = \text{gas density} \quad u = \text{gas flow velocity}$$

  - For local thermodynamic equilibrium, rate equations become the equilibrium mass action laws – for a monotonic gas, this is Saha's equation.
  - Saha's equation describes the degree of ionisation in the gas.

General Physical Model

- Conservation of momentum (Navier-Stokes equation)

$$\rho \frac{\partial u}{\partial t} + \rho \left(u \cdot \mathrm{grad} \right) u = -\mathrm{grad} p$$

$\rho =$ gas density

$u =$ gas flow velocity

$p =$ pressure

  - Arc-plasma is electrically conducting in the momentum equation → interaction with magnetic fields from the arc or generated outside are taken into account.

- Conservation of energy:
  - Resistive heat dissipation of electric energy → calculated with Ohmn's law: volumetric heat generation term
  - Arc-plasma is strongly radiating→ radiation transport of importance for energy equation
  - A portion of the radiated energy is reabsorbed by the plasma → radiation-transfer equation or tabulated value fro the net emission coefficient.

Conservation of Energy

$$\rho\frac{\partial h}{\partial t} + u\cdot\mathrm{grad}(\rho h) - \sigma E^2 = \mathrm{div}(\rho u) + \mathrm{div}\left[K\cdot grad(T)\right] - R\left[T,r\right]$$

$p =$ pressure $h =$ enthalpy of gas $K =$ thermal conductivity

$\rho =$ gas density $E =$ electric field strength $T =$ gas temperature

$u =$ gas flow velocity $\sigma =$ electric conductivity $R =$ radiation loss

$r =$ arc radius

- Special Case: conservation equations become decoupled
  - Thermally and hydronamically fully developed and wall-constricted arc with negligible axial pressure drop, the conditions are in the z plane as follows

    $$\frac{\partial u_z}{\partial z} = 0 \quad u_r = 0 \quad \frac{\partial h}{\partial z} = 0$$

  - The energy equation becomes: $$-\left(\frac{1}{r}\right)\cdot\frac{\partial\left\{Kr\left(\frac{\partial T}{\partial r}\right)\right\}}{\partial r} + R = \sigma E^2$$

  - Used for qualitative evaluation of current increase or arc-channel diameter reduction.

Black-Box Models

- Consist on one or two differential equations.
- Arc is described by a mathematical equation relating the arc conductance with the arc voltage and arc current
- Classical models: *Cassie*, and *Myar* → solutions to the *general arc eqn.*

General Arc Equation

- Arc conductance is a function of:
  - Power supplied to the plasma channel,
  - Power transported by cooling and radiation, and
  - Time

$$g = F\left(P_{in}, P_{out}, t\right) = \frac{i_{arc}}{u_{arc}} = \frac{1}{R}$$

General Arc Equation

- The arc conductance varies with the supplied power and the transported power in the plasma channel. The stored energy in the channel is

$$Q = \int_0^t \left(P_{in} - P_{out}\right) dt$$

- The instantaneous arc conductance can be defined as

$$g = F(Q) = F\left[\int_0^t \left(P_{in} - P_{out}\right) dt\right]$$

- The rate of change of the arc conductance, divided by the instantaneous arc conductance is

$$\frac{1}{g}\frac{dg}{dt} = \frac{1}{g}\frac{dF(Q)}{dQ}\frac{d(Q)}{dt}$$

- Manipulation of the equations above gives the general arc equation

$$\frac{d\left(\ln(g)\right)}{dt} = \frac{F'(Q)}{F(Q)}\left(P_{in} - P_{out}\right)$$

- Solutions to this equation requires assumptions, black box models are solutions to the equation each with different assumptions.

Cassie Model

- **Assumptions:**
  - The arc channel has the shape of a cylinder filled with highly ionised gas *at constant temperature*.
  - The cylinder is of *variable diameter*.
- ***Consequences:***
  - Heat content and conductance are constant per unit of volume.
  - The diameter of the plasma channel varies in diameter due to cooling.
- **Model:**

$$g = F(Q) = Dg_0 = \frac{Q}{Q_0} g_0, \quad F'(Q) = \frac{g_0}{Q_0}, \quad Q = DQ_0, \quad P_{out} = DP_0 = \frac{Q}{Q_0} P_0$$

Arc Conductance | Energy | Dissipated Energy

g_0 = conductivity p.u. of vol., P_0 = loss (cooling) p.u. of vol., D = arc channel diameter,

Q_0 = energy p.u. of vol., $u_0 = \left(P_0 / g_0\right)^{1/2}$ static arc voltage

  - Substituting into the general arc equation yields

$$\frac{d\left(\ln(g)\right)}{dt} = \frac{P_0}{Q_0}\left(\frac{u_{arc}^2}{u_0^2} - 1\right), \quad \frac{d\left(\ln(g)\right)}{dt} = -\frac{P_0}{Q_0} \Rightarrow g = g_0 \varepsilon^{-t/\tau}$$

  - Time constant: time for the arc channel diameter to change.
- Applications: studying the behavior of the arc conductance in the high-current time interval at temperatures above 8000 Kelvin or more

Myard Model

- Assumptions:
  - Cylindrical arc channel with constant diameter.
  - Losses in the channel are radial heat transport
  - Temperature of the channel varies exponentially
  - Cooling (loss) of the channel is constant
- *Consequences:*
  - *Approximation of Saha's equation for the conductance* $g = F(Q) = k\varepsilon^{\frac{Q}{Q_0}}$
- Model: $$\frac{d\left(\ln(g)\right)}{dt} = \frac{\left(u_{arc} i_{arc} - P_0\right)}{Q_0}$$
  - At current zero the arc channel supply power is zero, the rate of change of the conductance is

$$\frac{dg}{dt} = -g\frac{-P_0}{Q_0} \longrightarrow \quad \tau = \frac{Q_0}{P_0}$$

  - Time constant: arc cooling without thermal input to the channel.
- Application: modeling of the arc in the vicinity of current zero at temperatures below 8000 Kelvin.

Other Models: Hybrid Models

- *Browne:* uses Cassie equation for the high current interval, and Myar for current zero.
- *Avdonin, Hochrainer, Kopplin, Schwarz,* and *Urbanek:* capable of simulating *dielectric breakdown*
- *KEMA:* based on experiments, capable of simulating dielectric breakdown of the gaseous space between the breaker contacts after current interruption.
- Hybrid models calculate the conductance of the channel with a Myar equation before current zero. During the intervals of pre-and-post current zero and thermal-and-dielectric intervals the conductance is obtained from the concentration of charged particles and their drift velocity.

Arc-circuit Interaction

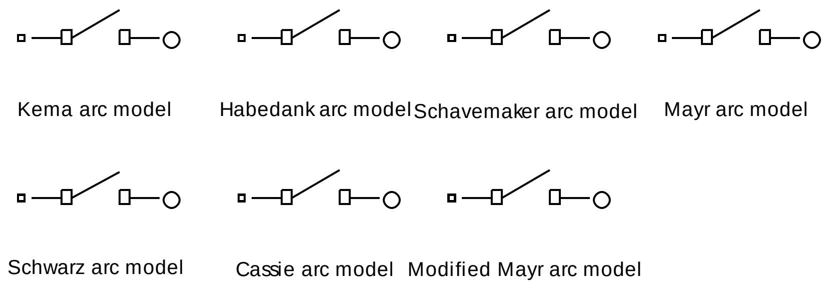
- Interruption process: strong interaction between the physical process between the contacts of the breaker and the network connected at the terminals.
- During current interruption, the arc resistance increases from zero to infinite (ideally) in microseconds
- After current interruption, the TRV (transient recovery voltage) builds up across the circuit breaker contacts. The TRV is thus formed by local oscillations and reflected voltages.
- The hot gas in the breaker does not change to an insulating state instantaneously→ the arc resistance is finite and a small current can still flow: post arc current.
- Illustrate this interaction with the ARC Model Blockset.

The Arc Model Blockset: U. Delft

- Features
  - Operates within V.2. and V.3. of the SimPowerSystems toolbox for MATLAB/Simulink.
  - Seven different arc models.
  - Ideal for arm model comparisons.
  - Highly accurate
- Current limitations:
  - The blockset complies with V.2. of SimPowerSystems, it can be updated to V.3. using the “psbupdate” command (available only in V.3.).
  - It is incompatible with V.4. (directory, graphical, and other issues). Updated not available from U. Delft as of Dec. 2007.

Arc Model Blockset

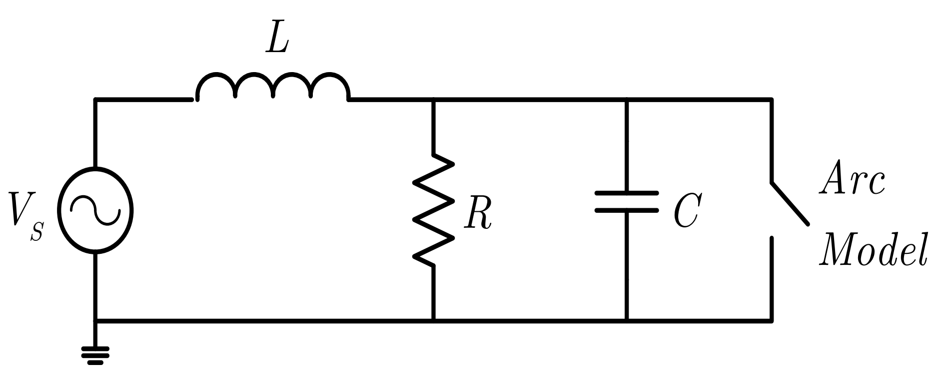
- Models in the Blockset:



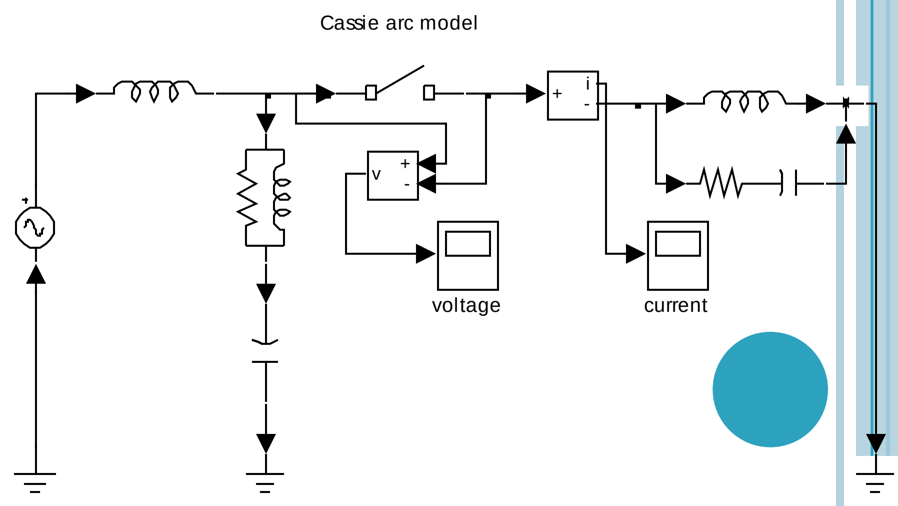
Arc Model Blockset

Electrical Power Systems
Delft University of Technology

- Simple Test Circuit Schematic

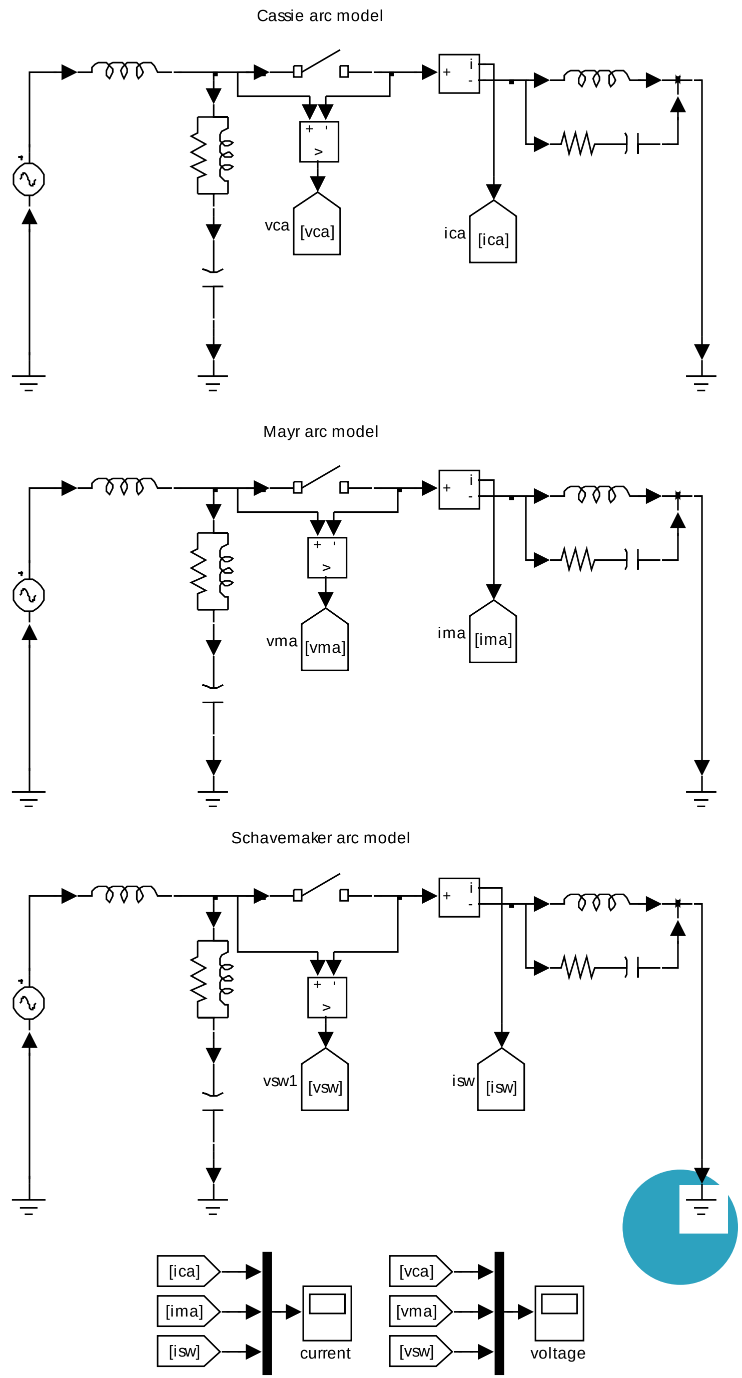


- Simple Test Circuit

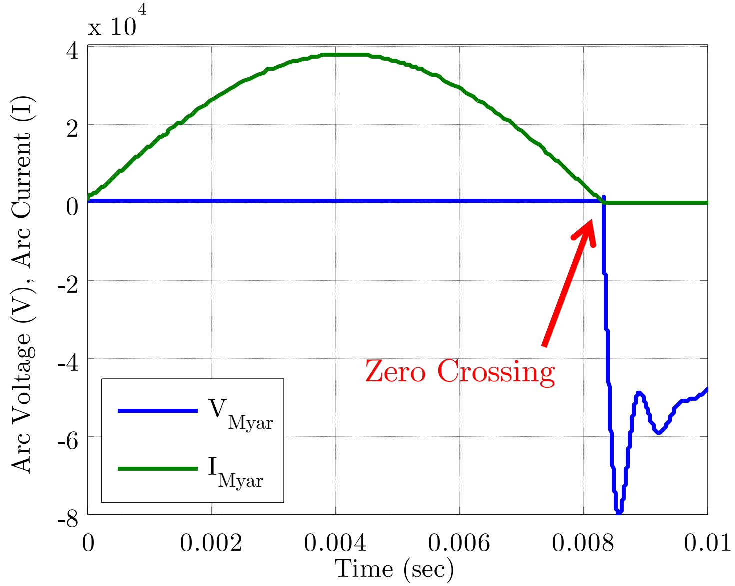


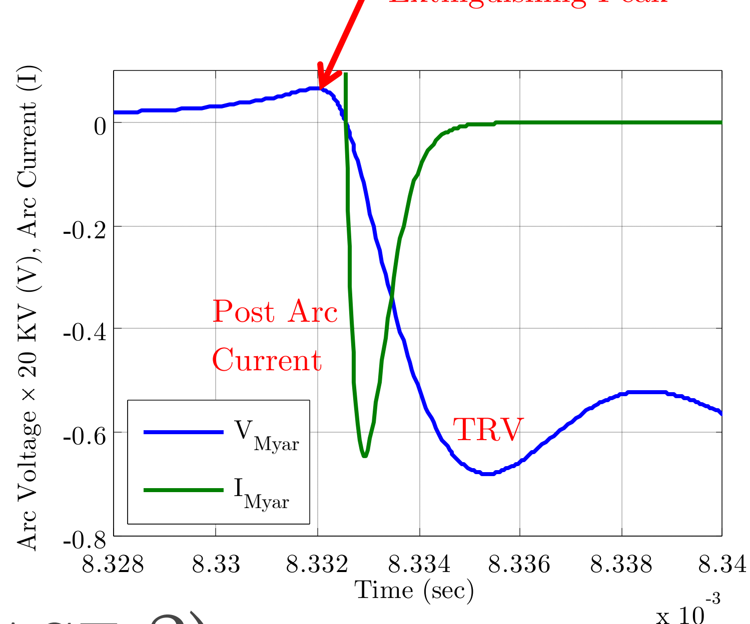
Simulations Set Up

- Two different arc models: Cassie, Myar.
- Simulate breaker interruption for two cases:
  - Case 1: Breaker opens at $t = 0$
  - Case 2: Breaker opens at $t = 9$ ms
- Observe the behavior at high current and current zero
- Compare differences with the models

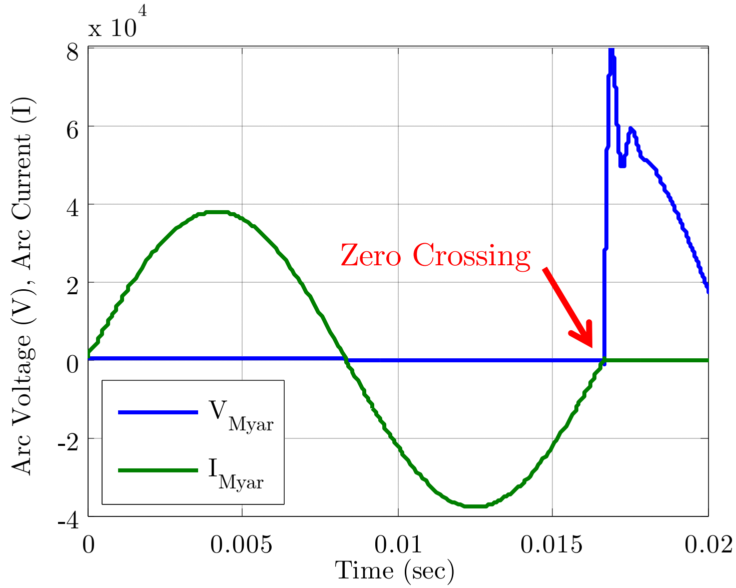


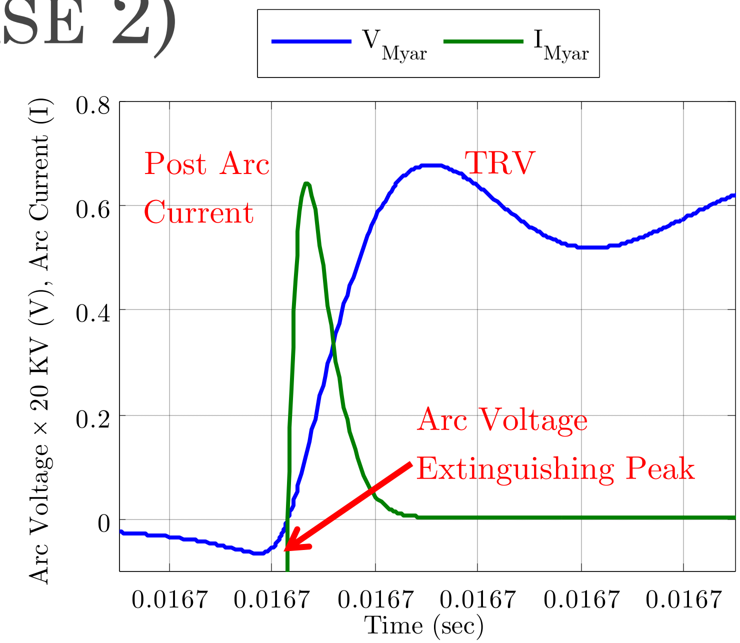
Simulation Results (Case 1)





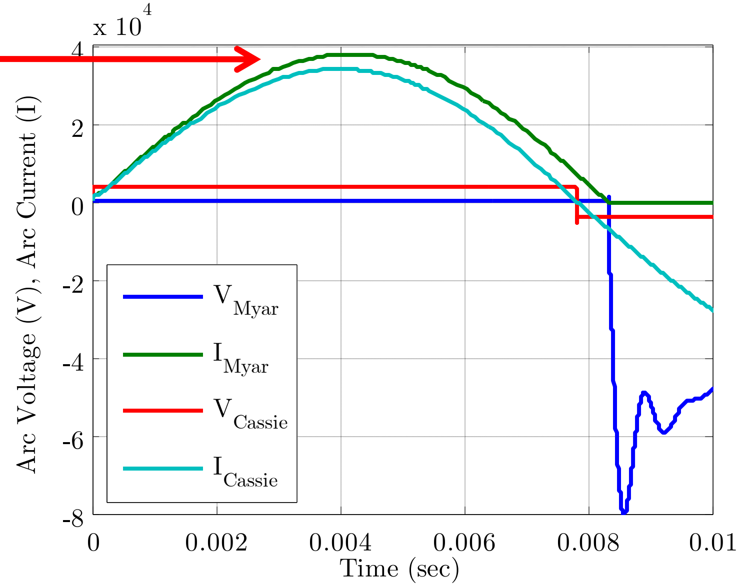
Simulation Results (Case 2)





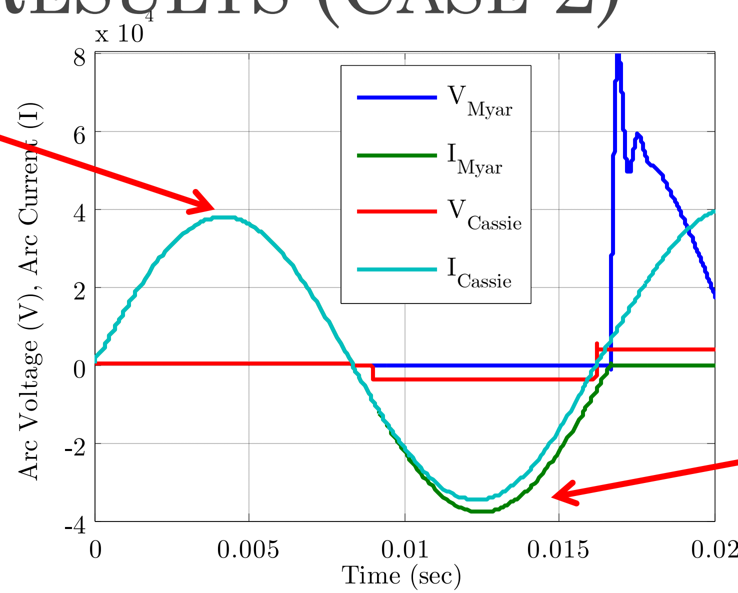
Simulation Results (Case 1)

High Current Interval



Simulation Results (Case 2)

High Current Interval



High Current Interval

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