FINITE ELEMENT SIMULATION OF
IMPULSE ARC DISCHARGE
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OUTLINE:

- Problem statement
- Description of the physical model
- Numerical implementation
- Validation
- Preliminary results
- Conclusions
Lightning protection of overhead lines
Lightning protection of overhead lines
Lightning protection of overhead lines

A line with bare conductor
Arc is moving

A line with covered conductor
Conductor burn down
Insulator flashover
Lightning protection of overhead lines
MULTI-CHAMBER ARRESTERS

Lightning protection of overhead power lines up to 35 kV

20 kV

35 kV
Finite element simulation of impulse arc discharge

1 – silicone rubber length;
2 – intermediate electrodes;
3 – arc quenching chamber;
4 – discharge channel.

Lightning overvoltage imposed
Investigation of impulse arc quenching in multi-chamber systems.

**QUENCHING TEST SCHEME**

- **8/50 µs**
- \( I_m = 3\div30 \text{ kA} \)
- \( f = 50 \text{ Hz} \)
- \( U_{ch} = 2\div30 \text{ kV} \)
- \( I_f = 1\div10 \text{ kA} \)

**LIGHTNING IMPULSE GENERATOR**

**POWER LINE VOLTAGE GENERATOR**
MULTI-CHAMBER ARRESTERS
MULTI-CHAMBER ARRESTERS
Finite element simulation of impulse arc discharge

- discharge slot
- inner electrode
- outer electrode
- silicone rubber arc cavity
- fiber-glass plastic sleeve
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3 kA
Finite element simulation of impulse arc discharge

10 kA

Current, kA

\( t, \mu s \)

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20 kA
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Finite element simulation of impulse arc discharge

Type #1

Optimal geometry?

Type #2
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ARC DISCHARGE MODEL

Magnetohydrodynamics equations (MHD)

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot \{ \rho \mathbf{v} \} = 0 \]

\[ \frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot \{ \rho \mathbf{v} \otimes \mathbf{v} \} = -\nabla p + \nabla \cdot \mathbf{T} + \mathbf{j} \times \mathbf{B} \]

\[ \frac{\partial (\rho H)}{\partial t} + \nabla \cdot \{ \rho Hv - \lambda \nabla T \} = \frac{\partial p}{\partial t} + \nabla \cdot (\mathbf{T} \cdot \mathbf{v}) + \mathbf{j} \cdot \mathbf{E} - \nabla \cdot \mathbf{F} \]

\[ \mathbf{j} = \sigma (\mathbf{E} + \mathbf{v} \times \mathbf{B}) \]

\[ \nabla \times \mathbf{B} = \mu_0 \mathbf{j} \]

\[ \partial_t \mathbf{B} + \nabla \times \mathbf{E} = 0 \]
ARC DISCHARGE MODEL

- CFD
  - High Mach Number Flow, Laminar ($hmnf$)
- Electrodynamics
  - Electric Currents ($ec$)
- Radiation Transport
  - Radiation in Participating Media ($rpm$)
Finite element simulation of impulse arc discharge

ARC DISCHARGE MODEL

Outlet

Heat source
Joule Heat + Radiation

Preheated channel (~10 kK)

High Mach Number Flow, Laminar (hmnf)
- Fluid 1
- Initial Values 1
- Wall 1
- Thermal Insulation 1
- Symmetry 1
- Outlet 1
- Heat Source 1
- Initial Values 2

General source
- $Q_0$ User defined
- $ec.Qrh+rpm.Qr+rpm2.Qr$ W/m$^3$
ARC DISCHARGE MODEL

- CFD
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Finite element simulation of impulse arc discharge

**ARC DISCHARGE MODEL**

Electrodynamics

Electric Currents (ec)
- Current Conservation 1
- Electric Insulation 1
- Initial Values 1
- Terminal 1
- Ground 1

Terminal type:
- Current

Current: $I_0 \text{ CurrentPulse}(t)$ A

Terminal

Ground

8/50 $\mu$s

$I_m = 3\div30$ kA
Finite element simulation of impulse arc discharge

ARC DISCHARGE MODEL

- CFD
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  - Electric Currents ($ec$)
- Radiation Transport
  - Radiation in Participating Media ($rpm$)
Radiation transport

\[ s \cdot \nabla I_{\nu}(r, s) = \kappa_{\nu} [I_{\nu}^{b}(T) - I_{\nu}(r, s)] \]

\[ I_{\nu}^{b}(T) = \frac{2h}{c^2} \frac{\nu^3}{e^{\frac{h\nu}{k_B T}} - 1} \]

\[ G_{\nu}(r, s) = \int_{4\pi} I_{\nu}(r, s) d\Omega \]

\[ \nabla \cdot \left( \frac{1}{\kappa_{\nu}} \nabla G_{\nu} \right) = 3\kappa_{\nu} (G_{\nu} - 4\pi I_{b\nu}) \]

**Radiation in Participating Media (rpm)**
- Radiation in Participating Media 1
- Opaque Surface 1
- Incident Intensity 1

**Equation**

Equation form:
- Study controlled

Show equation assuming:
- Study 1, Time Dependent

\[ Q_r = \kappa (G - 4\pi I_b) \]

\[ \nabla \cdot (D_{\nu} \nabla G) + \kappa (G - 4\pi I_b) = 0 \]

**Participating Media Settings**

Radiation discretization method:
- P1 approximation
Radiation transport

Two-band model

from zero up to $\lambda = 120$ nm

$\alpha = 2000 \text{ m}^{-1}$

from $\lambda = 120$ nm up to $\lambda = 1$ mm

$\alpha = 50 \text{ m}^{-1}$
ARC DISCHARGE MODEL

Material properties

- High Mach Number Flow, Laminar (hmnf)
- Electric Currents (ec)
- Radiation in Participating Media (rpm)
- Radiation in Participating Media 2 (rpm2)

Materials

- Air (mat1)
  - Basic (def)
    - Interpolation 1 (rho)
    - Interpolation 2 (cp)
    - Interpolation 3 (mu)
    - Interpolation 4 (k)
    - Interpolation 5 (sigma)
  - Radiation heat transfer (RadiationHeatTransfer)
    - Interpolation 1 (Qrad)
  - Ideal gas (idealGas)
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ARC DISCHARGE MODEL

Material properties

\[ \sigma(p, T) \]

\[ \rho(p, T) \]

Electric Conductivity

Specific Heat

[Graphs showing electric conductivity and specific heat as functions of temperature for different pressures.]
ARC DISCHARGE MODEL
ARC MODEL VALIDATION

Open spark gap

Steel electrodes
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ARC MODEL VALIDATION
ARC MODEL VALIDATION

Finite element simulation of impulse arc discharge

- High Mach Number Flow, Laminar (hmnf)
- Electric Currents (ec)
- Radiation in Participating Media (rpm)
- Radiation in Participating Media 2 (rpm2)

8/50 μs

$I_m = 3\div30$ kA

Electrodes
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SIMULATION RESULTS

30 kA

Temperature, K

Current, kA

$\times10^4$

2.5

2

1.5

1

0.5
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SIMULATION RESULTS

30 kA

Pressure, Pa

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SIMULATION RESULTS

3 kA
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SIMULATION RESULTS

10 kA
SIMULATION RESULTS

20 kA
SIMULATION RESULTS

30 kA
SIMULATION RESULTS

Fast-imaging record of plasma jet
Finite element simulation of impulse arc discharge

SIMULATION RESULTS

3 kA
SIMULATION RESULTS

Finite element simulation of impulse arc discharge

10 kA
Finite element simulation of impulse arc discharge

SIMULATION RESULTS

20 kA
SIMULATION RESULTS

30 kA
SIMULACIÓN RESULTS
SIMULATION RESULTS: PRESSURE

Finite element simulation of impulse arc discharge.
SIMULATION RESULTS: DENSITY

Finite element simulation of impulse arc discharge
SIMULATION RESULTS: TEMPERATURE

Finite element simulation of impulse arc discharge
SIMULATION RESULTS: VELOCITY

Finite element simulation of impulse arc discharge
Type #1 is better than Type #2

$R_1^t=200\mu s < R_2^t=200\mu s$
CONCLUSIONS:

- Conventional approach to thermal plasma modeling based on MHD is applicable for the case of impulse arcs caused by lightning overvoltage to some certain extent.

- However current model is lacking some important physics.

- It could be electrode erosion, chamber geometry deformation, Lorentz force influence, something else.

- Still numerical simulation is considered as a promising tool for development of future lightning protection devices.
Thank you for your attention!