EMTP-RV
ElectroMagnetic Transients Program

TRAINING DUBROVNIK, CROATIA - APRIL, 27 - 29 2009
SIMULATION & ANALYSIS OF POWER SYSTEM TRANSIENTS WITH EMTP-RV

Modeling of Transmission Line and Substation for Insulation Coordination Studies

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OUTLINE OF PRESENTATION

- INTRODUCTION
- MODELING GUIDELINES
- LIGHTNING MODEL
- TOWER
- INSULATOR
- FOOTING RESISTANCE
- LINE, CONDUCTORS AND EARTH WIRES
- BOUNDARY CONDITIONS
- SUBSTATION MODEL
- SURGE ARRESTER
- EXAMPLE

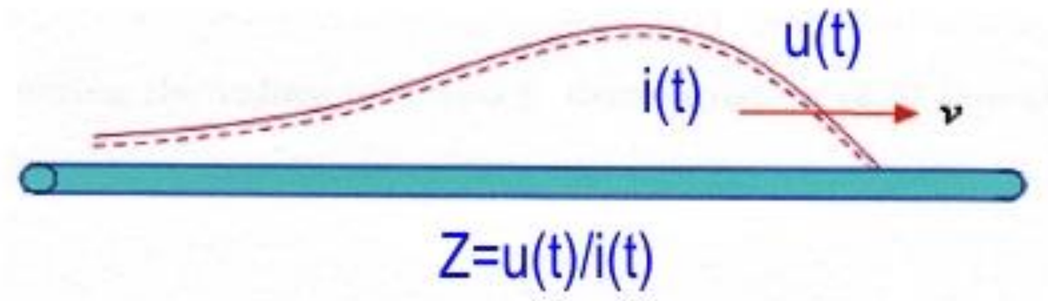
INTRODUCTION

- Computer modeling of transmission lines and substation helps engineers understand how protection systems behave during disturbances and faults.

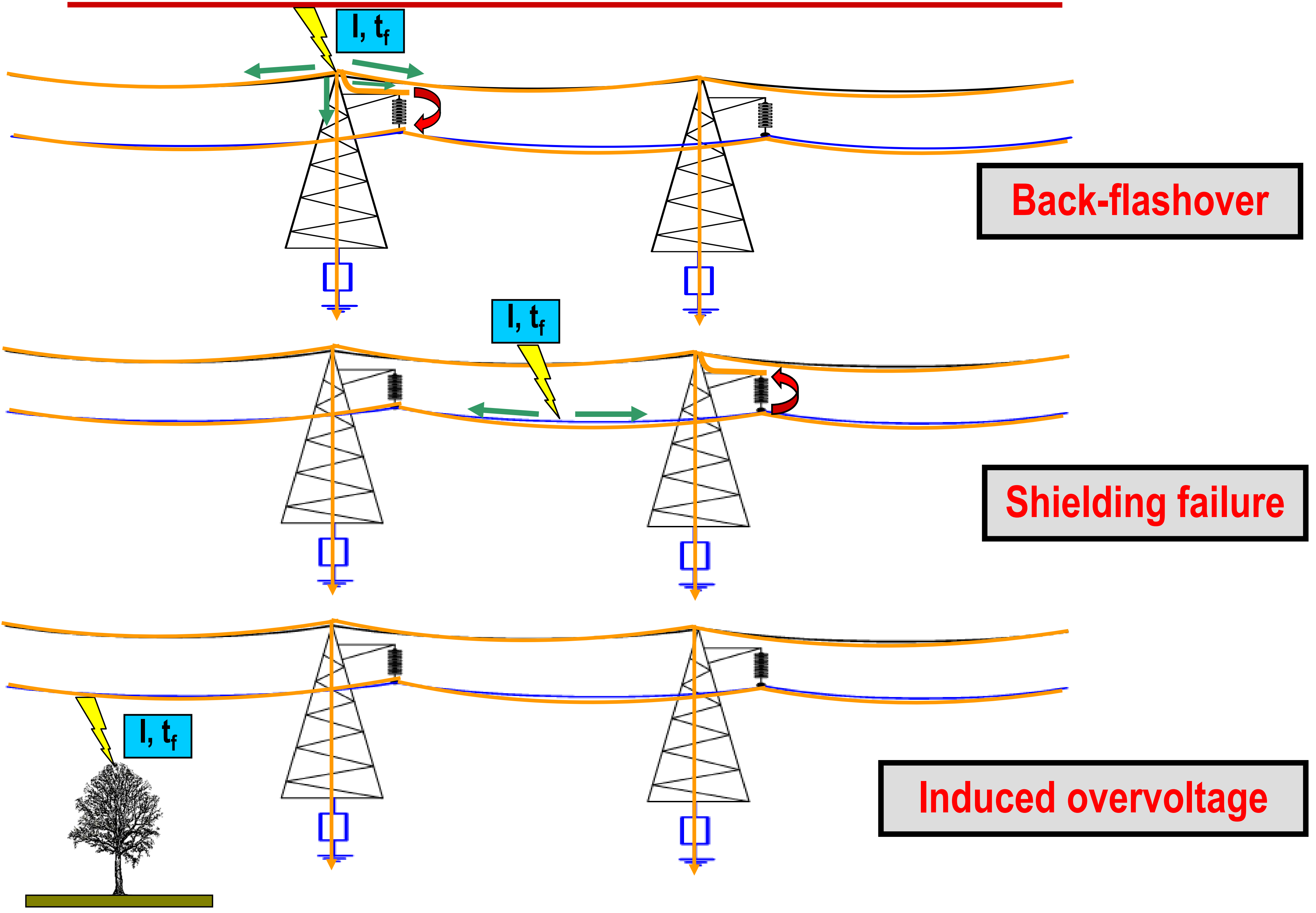
- Any transient disturbance, such as lightning stroke terminating on a phase conductor can be analyzed by use of traveling wave.

- A lightning stroke to a conductor or the closing of a circuit breaker produces traveling waves of voltage *u(t)* and current *i(t)* that are related by a surge impedance Z equal to *formula* that travels along the conductor at the speed of light *c*.

$$Z = \frac{u(t)}{i(t)}$$



INTRODUCTION (Lightning overvoltages on HV transmission lines)



INTRODUCTION

Definitions of insulation coordination:

- Insulation coordination is the selection of the insulation strength.

- Insulation coordination is the "selection of the dielectric strength of the equipment in relation to the voltages which can appear on the system for which equipment is intended and taking into account the service environment and the characteristics of the available protective devices (*) ".

- Line insulation coordination; transmission and distribution lines.

- Substation insulation coordination; generation, transmission and distribution substation.

(*) IEC 60071-1-1993-12: Insulation coordination – Part 1: Definitions, principles and rules.

MODELLING GUIDELINES

- ❑ There are various modeling strategies for lightning transient studies have been presented elsewhere.

- ❑The summary of modeling guidelines that had been adapted:

  - IEC/TR 60071-4 Edition 1.0 (2004-06): Insulation co-ordination - Part 4: Computational guide to insulation co-ordination and modeling of electrical networks;

  - IEEE PES Task Force on Data for Modeling System Transients of IEEE PES Working Group on Modeling and Analysis of System Transients Using Digital Simulation: Parameter Determination for Modeling System Transients, IEEE Transactions on Power Delivery, Vol. 20, No. 3, July 2005.

MODELLING GUIDELINES

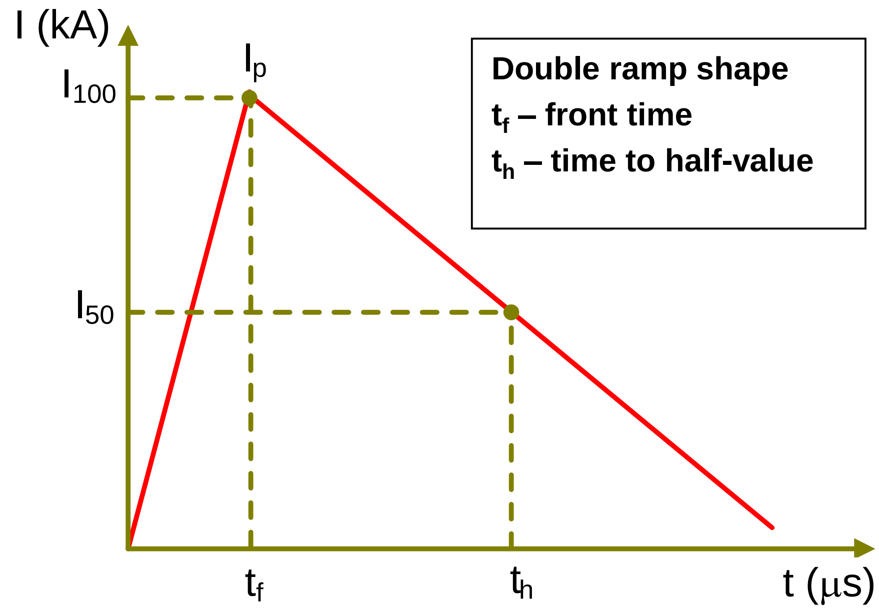
- CIGRE, Working Group 01 of Study Committee 33: Guide to Procedures for Estimating the Lightning Performance of Transmission lines, Paris, October 1991.

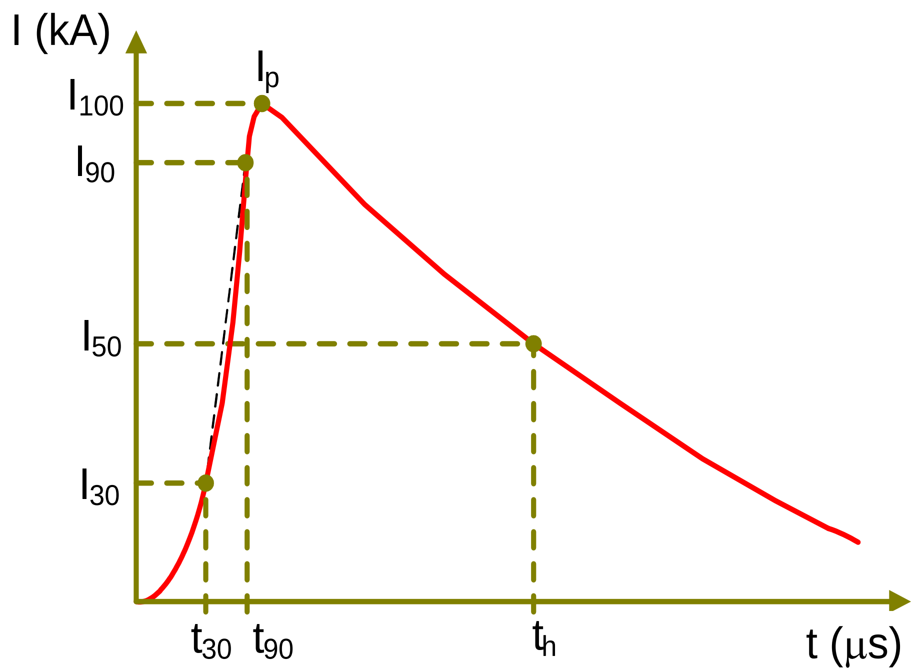
- IEEE Working Group 15.08.09: Modeling and Analysis of System Transients Using Digital Programs, 1998.

- IEEE Working Group: A Simplified Method for Estimating Lightning Performance of Transmission Lines, IEEE Transactions on Power Apparatus and System, Vol. 104, No. 4, April 1985.

LIGHTNING MODEL

- Lightning stroke is represented as a current source with magnitudes between a few kA to over 200 kA.
- Peak current magnitude and tail time are important when observing energy stresses of SA (simplest representation is double ramp).
- Current wavefront is an important parameter with regard to insulator flashover.
- CIGRE model describes well the concave wavefront of a lightning current.





LIGHTNING MODEL

- A statistical approach considering the ground flash density at the location is used for the determination of lightning parameters such as:

– crest value;

– front time;

– maximum current steepness;

– duration.

- The probability that a certain peak current will be equal or greater than a current *I* can be determined by Anderson's distribution:

$$P = \frac{1}{1 + \left(\frac{I}{31}\right)^{2.6}}$$

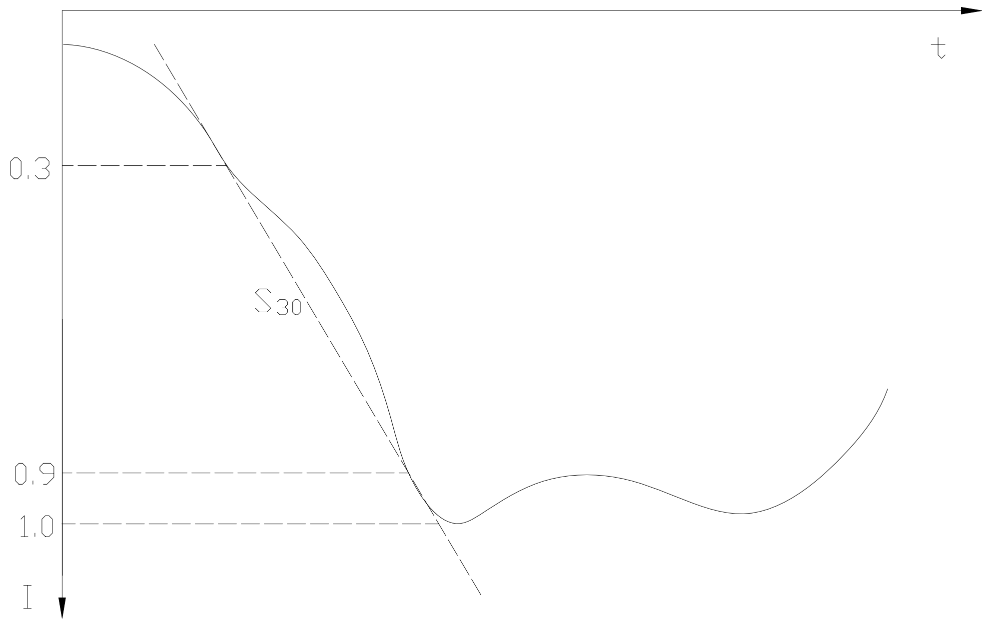
Where:

P(I) = the probability that the peak current in any stroke will exceed *I*

I = the specified crest current of the stroke in kA.

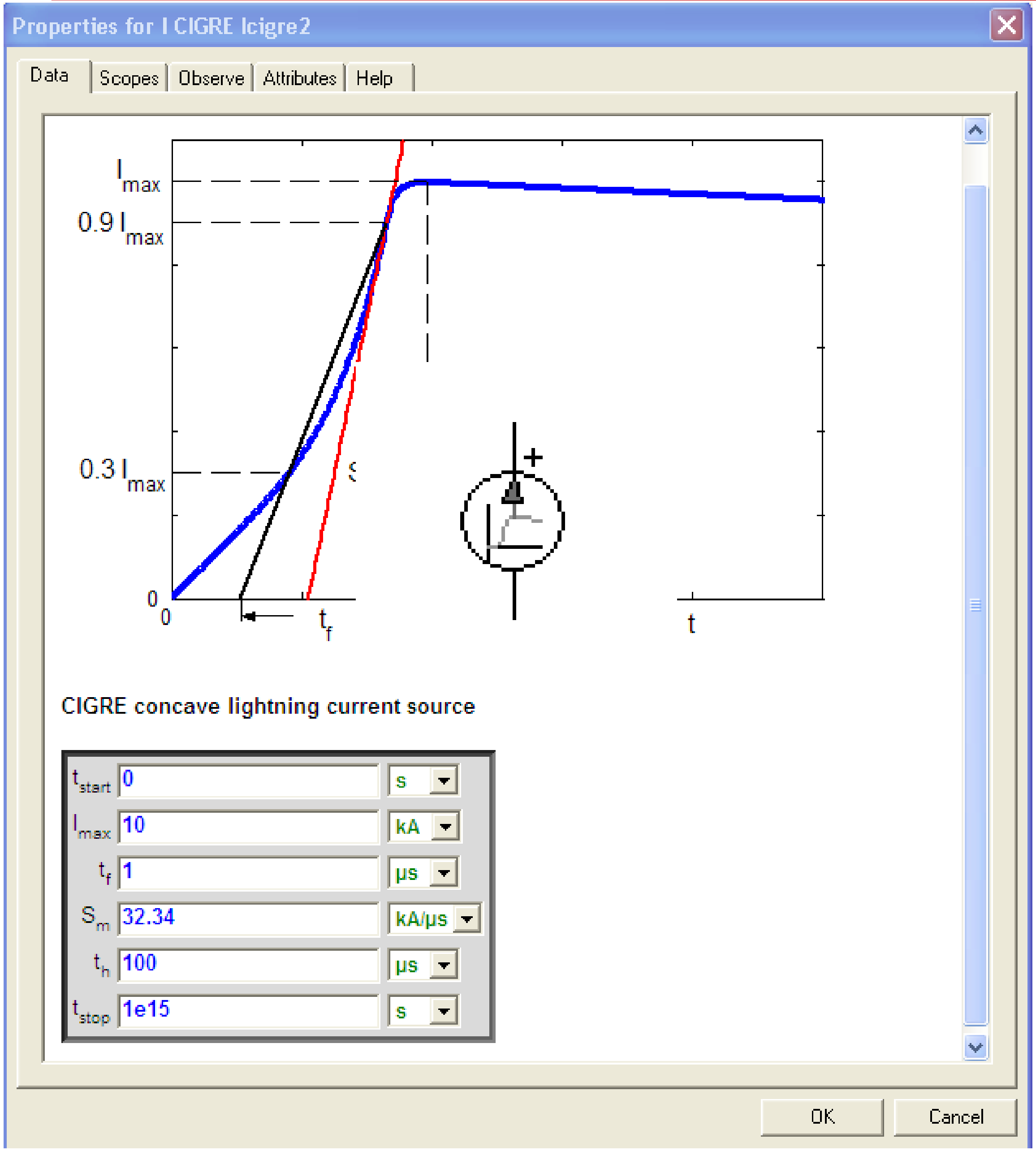
LIGHTNING MODEL

Steepness can be determined as: $S = \alpha \cdot I^{\beta}$



Coefficients	α	β
First stroke		
S_{30}	3.2	0.25
S_m	3.9	0.55
Subsequent stroke		
S_{30}	6.9	0.42
S_m	3.8	0.93

LIGHTNING MODEL – CIGRE model in EMTP RV



The model parameters are:

t_{start} - start time, if $t < t_{start}$ the source is an open-circuit;

I_{max} - maximum current;

t_f - from time;

S_m - maximum steepness;

t_h - time to half value;

t_{stop} - stop time, if $t > t_{stop}$ the source is an open-circuit. The stop time must be greater than the start time.

TOWER

- Extensive research has been performed on the response of vertical towers to lightning strokes, and research is still continuing.

- The response of a tower is an electromagnetic problem, although its study often relies on the circuit approach and models that are simple to apply in transient simulations:
  - simple distributed line model,
  - multistory tower model.

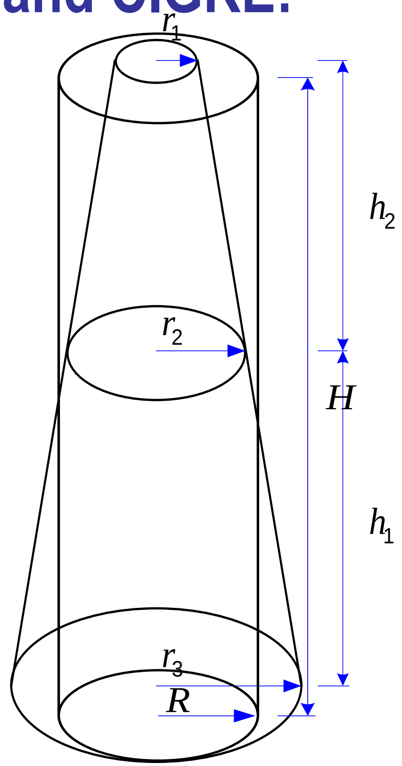
- Simple distributed line model provides a constant value of surge impedance and the constant velocity of travel along the tower.

- Different formulas are applied for various tower types.

TOWER - Simple Distributed Line Model

- The tower surge impedance depends on the direction of wave propagation and the shape of a lightning current.
- The average surge impedance recommended by IEEE and CIGRE:

$$Z = 60\ln\left(\cot\left(\frac{\Theta}{2}\right)\right) = 60\ln\left(\cot\left(\frac{1}{2}\tan^{-1}\left(\frac{R}{H}\right)\right)\right)$$



- *Θ* – half-angle of cone,
- *H* – tower height [m],
- *R* – tower base radius [m].

- Radius *R* is calculated by dividing the tower into upper and lower truncated cones:

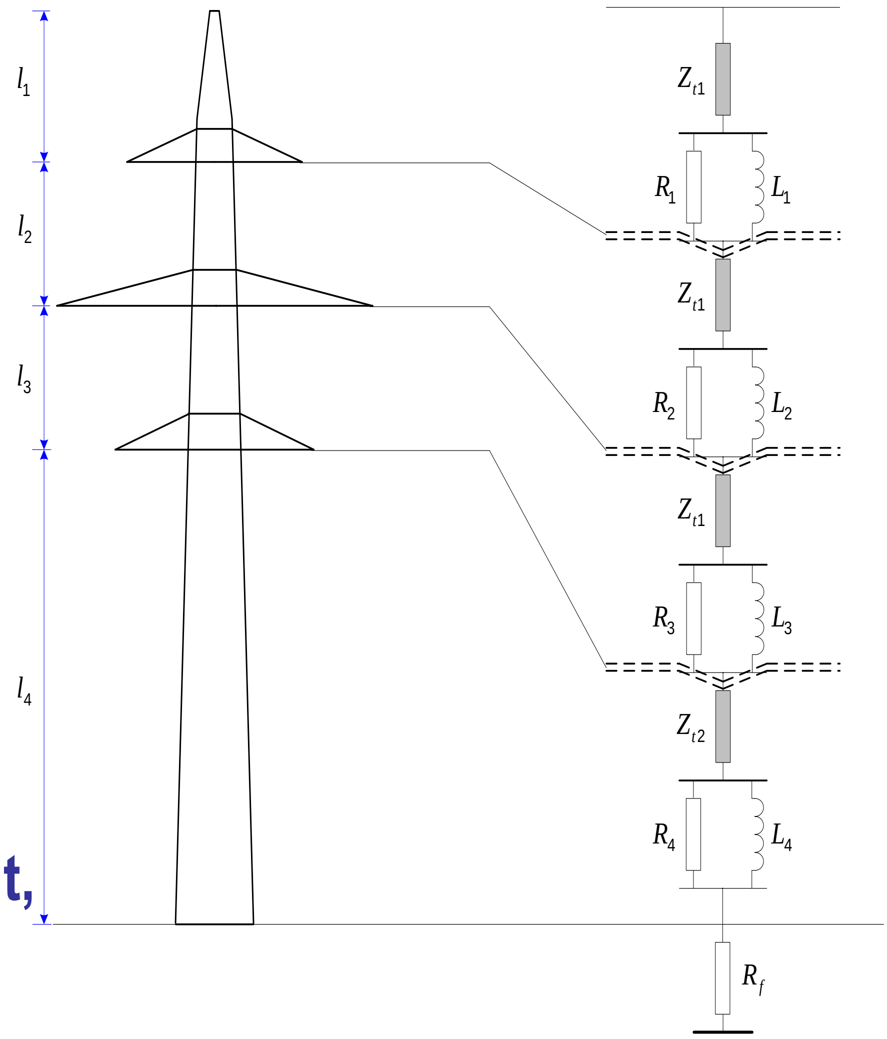
$$R = \frac{(r_1 h_2 + r_2 H + r_3 h_1)}{H}$$

- An approximation of surge impedance equation is determined by equivalently replacing the tower with a cylinder.

$$Z = 60\left[\ln\left(\frac{H}{R}\right) - 1\right] \qquad R << H$$

TOWER - Multistory Tower Model

- Multistory tower model is developed for representing towers of UHV transmission lines (*). Its parameters were revised according to the results of experimental studies (**).
- The model is composed of four sections representing the tower sections between cross-arms.
- Each section consists of a lossless line in series with a parallel R-L circuit, included for attenuation of the traveling waves.

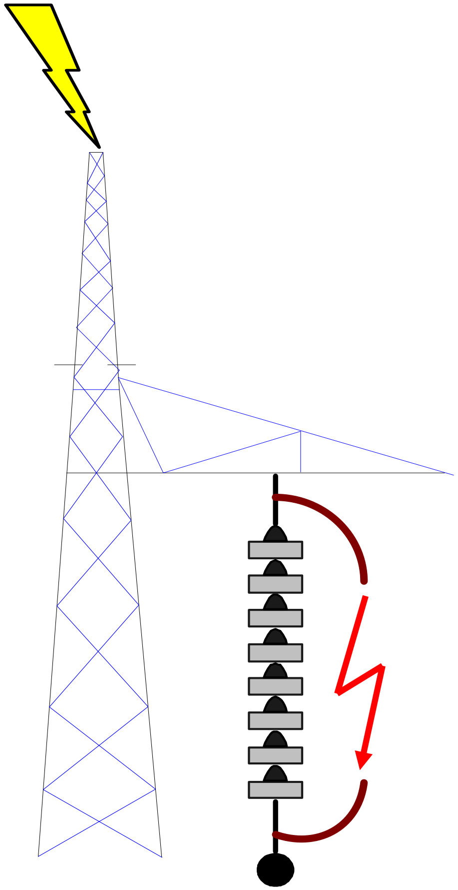


(*) M. Ishii, T. Kawamura, T. Kouno, E. Ohsaki, K. Shiokawa, K. Murotani, and T. Higuchi, "Multistory transmission tower model for lightning surge analysis," IEEE Trans. Power Delivery, vol. 6, July 1991, pp. 1327–1335

(**) Yamada, T.; Mochizuki, A.; Sawada, J.; Zaima, E.; Kawamura, T.; Ametani, A.; Ishii, M.; Kato, S.; „Experimental evaluation of a UHV tower model for lightning surge analysis" IEEE Trans. Power Delivery, Vol. 10, No. 1, Jan. 1995 pp 393 – 402

INSULATOR

- The critical flashover voltage (CFO) is the impulse voltage level at which the probability of flashover of the insulator is 50%.



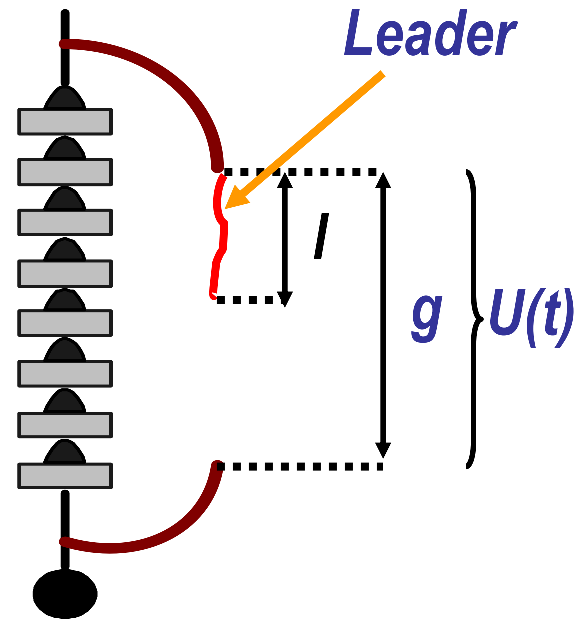
- Flashover should not happen when the line arrester is installed in parallel with the insulator since the residual voltages developed across surge arrester are much lower than the dielectric strength of insulators, even for the highest stroke currents.

- Flashover voltage of line insulators should be randomly varied according to the statistical distribution laws with the appropriate standard deviation.

INSULATOR Flashover - Leader Propagation Model

- The leader progression model is used to represent line insulation flashovers:

$$v = \frac{dl}{dt} = k_l U(t)\left[\frac{U(t)}{g-l} - E_{10}\right]$$

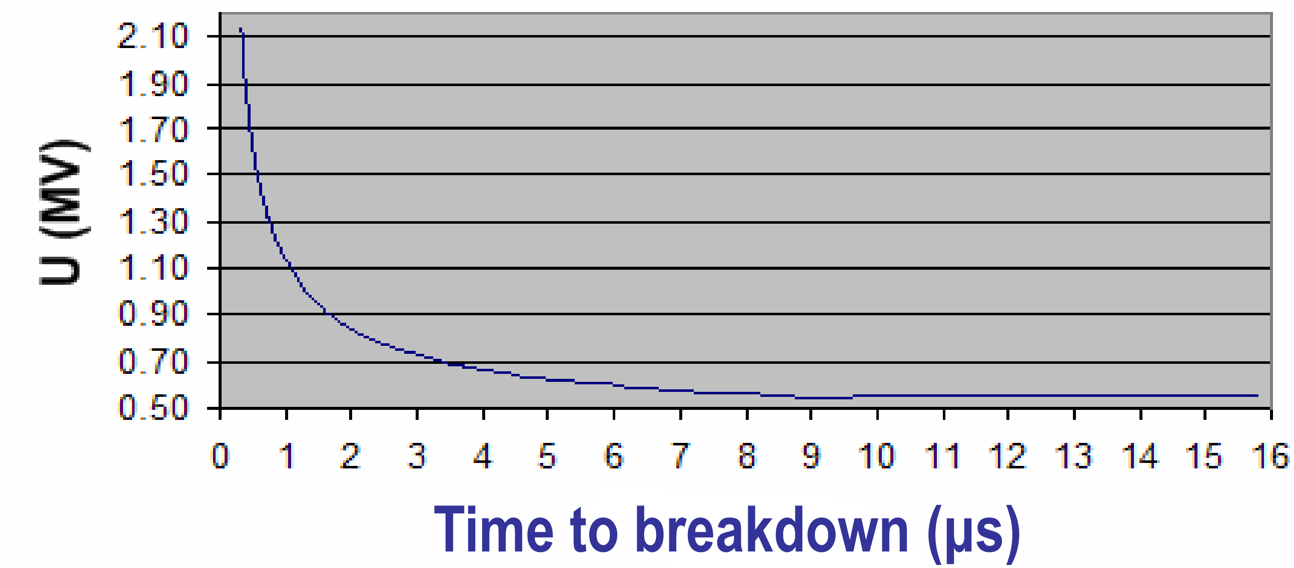


- v – leader velocity (m/s)
- $U(t)$ - voltage across the gap (kV)
- g - gap length (m)
- l - leader length (m)
- E_{10} - critical leader inception gradient (kV/m)
- k_l - leader coefficient ($m^2V^{-2}s^{-1}$)

- The leader propagation stops if the gradient in the unbridged part of the gap falls below E_{10}.

INSULATOR Flashover - Volt-time Characteristic

- The flashover voltage characteristic of the insulator string is time dependent.



- The experimental volt-time characteristic is only adequate for relating the peak of the standard impulse voltage to the time of flashover.

- An open switch connected to insulator string terminals can control the flashover voltage characteristic.

INSULATOR Flashover - Area Criterion Model

- The method allows the applied nonstandard waveform to be taken into account.
- It involves determining the instant of breakdown using a formula:

$$\int_{T_0}^{t} (|V_{gap}(t)| - V_0)^k \, dt \geq D$$

$V_{gap}(t)$ - voltage applied at the time t, to the terminals of the air gap,

V_0 - minimum voltage to be exceeded before any breakdown process can start or continue,

T_0 - time from which $V_{gap}(t) > V_0$,

k, V_0, D - constants corresponding to an air gap configuration and overvoltage polarity (*).

- Flashover occurs when the integral becomes greater or equal to D. The parameters V_0, k and D are determined by using the voltage-time curve.

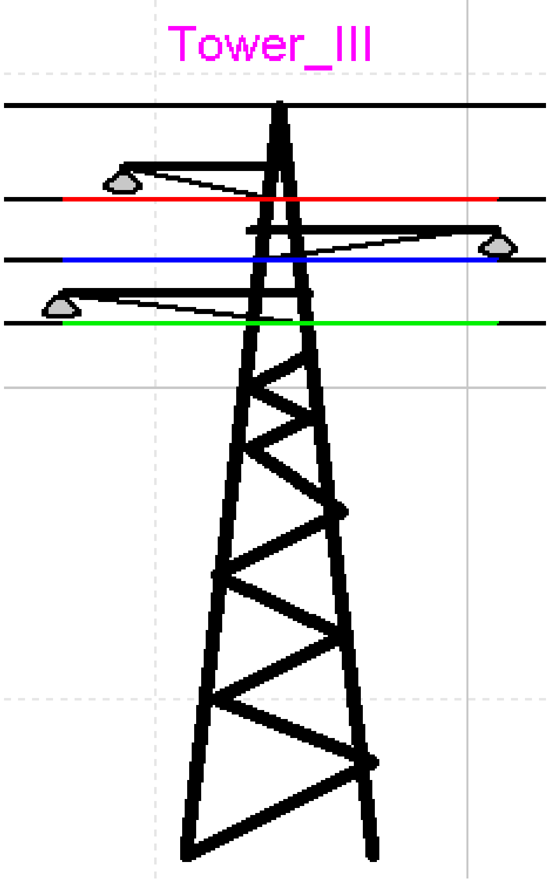
(*) IEC 60071-4: Insulation co-ordination – Part 4: Computational guide to insulation co-ordination and modeling of electrical networks, 2004.

TOWER - Example

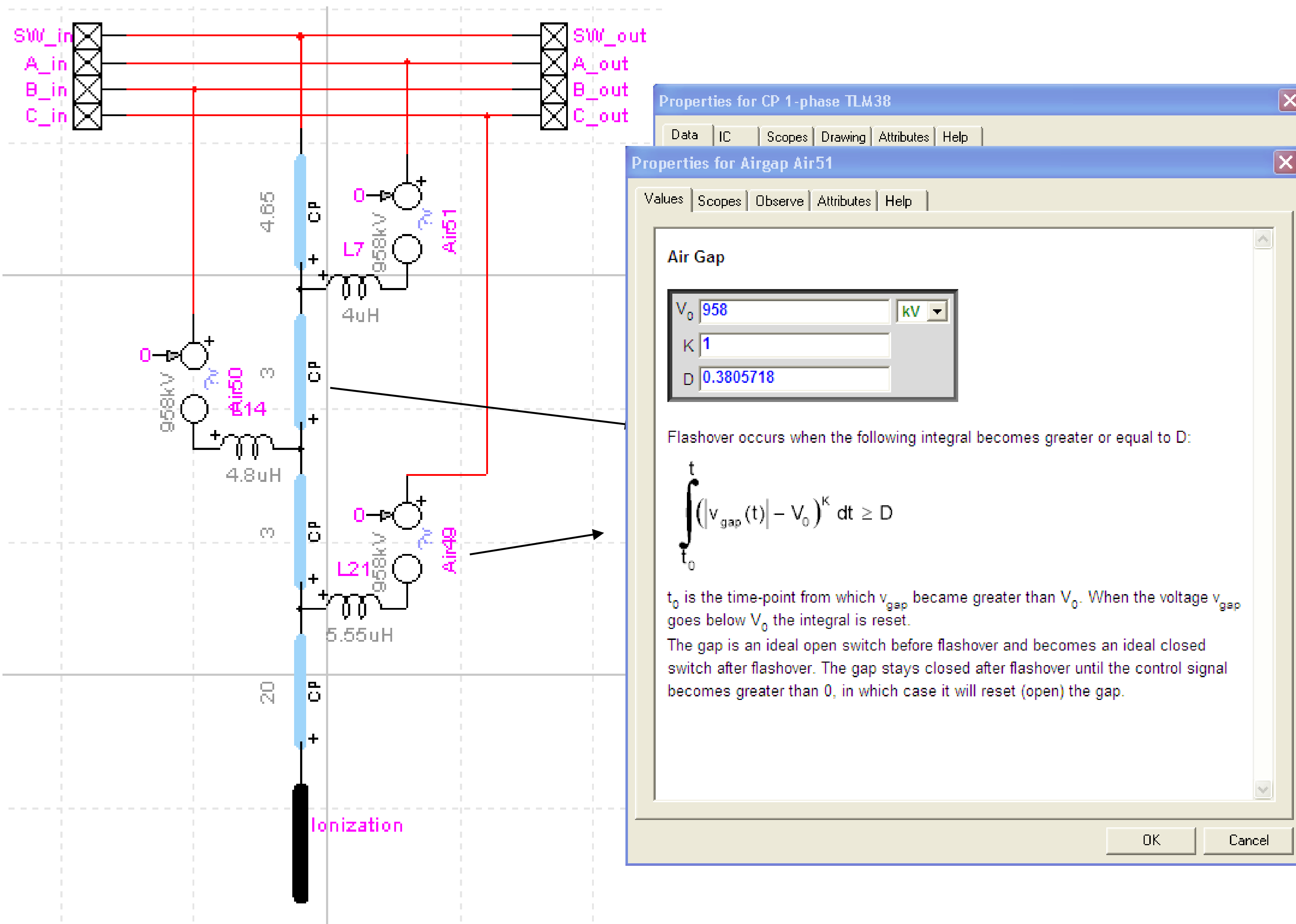
- Tower surge impedances are calculated using equation:

$$Z = 60 \cdot \left\{ \ln\left(\frac{H}{R}\right) - 1 \right\} \qquad (R << H)$$

- Each tower is divided in four parts. First part is from tower top to upper arm, second one from upper arm to middle arm, third part from middle arm to lower arm and the last part from lower arm to ground. On this way it is possible to calculate transient voltages of tower arms.

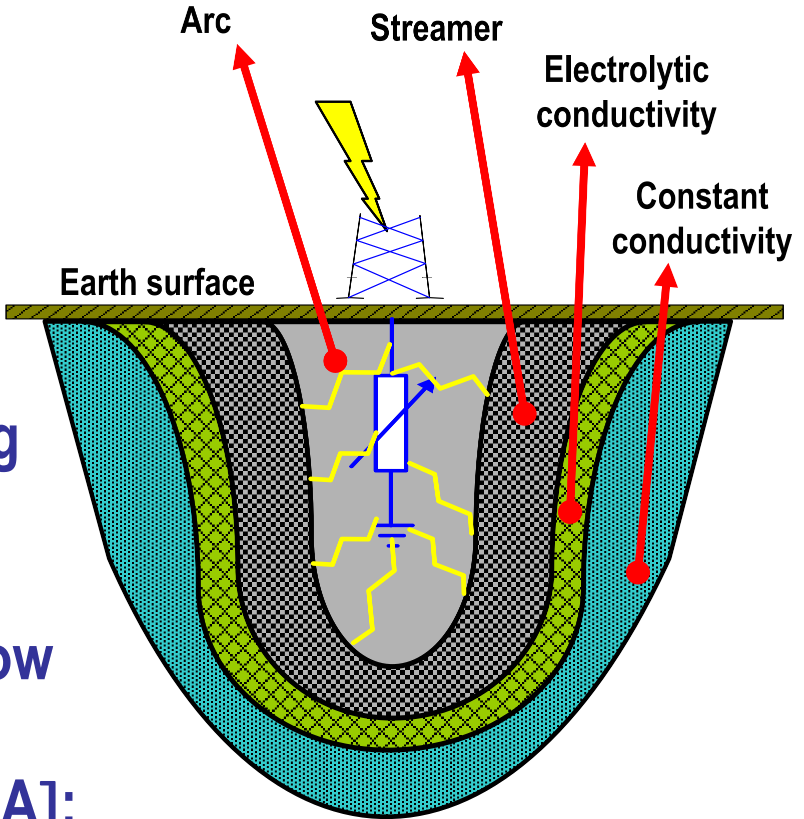


TOWER


SW_in
A_in
B_in
C_in
SW_out
A_out
B_out
C_out
4.65
CP
3
CP
3
CP
20
CP
0
L7
958kV
Air51
4uH
0
958kV
Air50
L14
4.8uH
0
L21
958kV
Air49
5.55uH
Ionization
Properties for CP 1-phase TLM38
Data
IC
Scopes
Drawing
Attributes
Help
Properties for Airgap Air51
Values
Scopes
Observe
Attributes
Help
Air Gap
V0 958 kV
K 1
D 0.3805718
Flashover occurs when the following integral becomes greater or equal to D:
$\int_{t_0}^{t} \left(\left| v_{gap}(t) \right| - V_0 \right)^K dt \geq D$
t_0 is the time-point from which v_{gap} became greater than V_0. When the voltage v_{gap} goes below V_0 the integral is reset.
The gap is an ideal open switch before flashover and becomes an ideal closed switch after flashover. The gap stays closed after flashover until the control signal becomes greater than 0, in which case it will reset (open) the gap.
OK
Cancel

FOOTING RESISTANCE

- It can be represented as:
  - constant resistor (conservative approach),
  - current and frequency dependable resistor.
- The ionization model takes into account the soil ionization caused by the lightning currents.
- Tower grounding non-linear resistor should be represented as:



$$R_i = \frac{R_o}{\sqrt{1+\left(\frac{I}{I_g}\right)}}$$

R_o - footing resistance at low current and low frequency, i.e. 50 or 60 Hz [Ω];

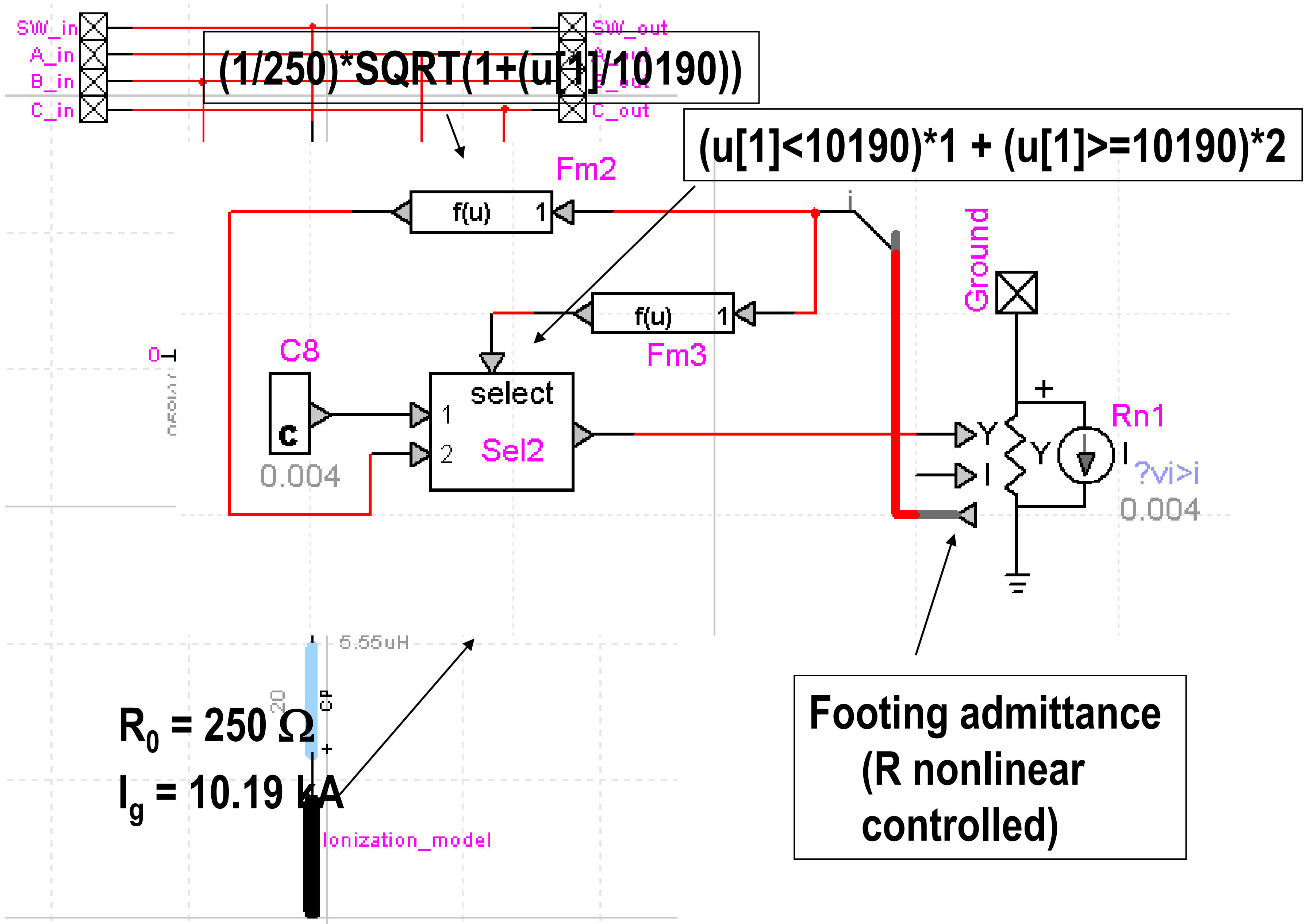
I - stroke current through the resistance [kA];

$$I_g = \frac{\rho \cdot E_0}{2 \cdot \pi \cdot R_o^2}$$ - limiting current to initiate sufficient soil ionization [kA].

ρ - soil resistivity [Ωm];

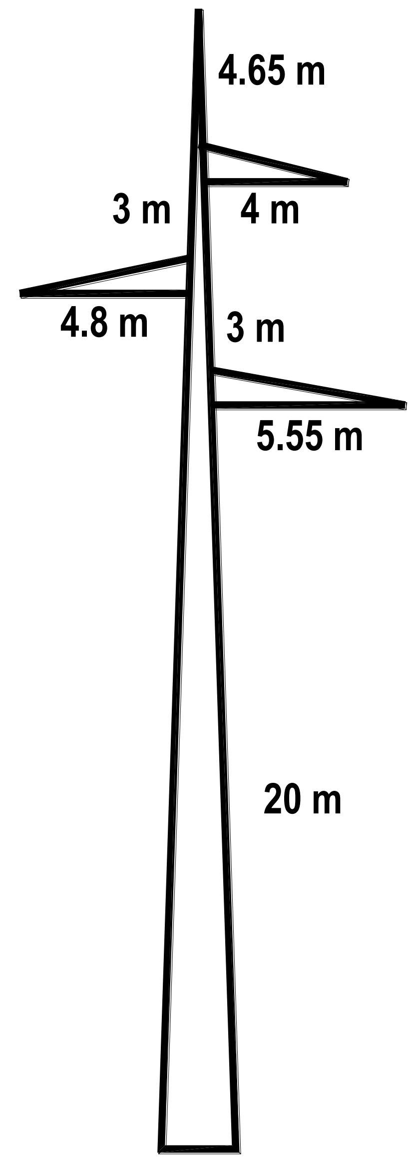
E_0 - is the soil ionization gradient, recommended value: 400 [kV/m].

FOOTING RESISTANCE

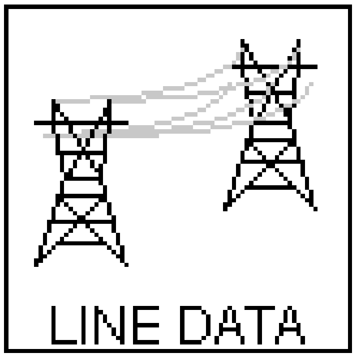


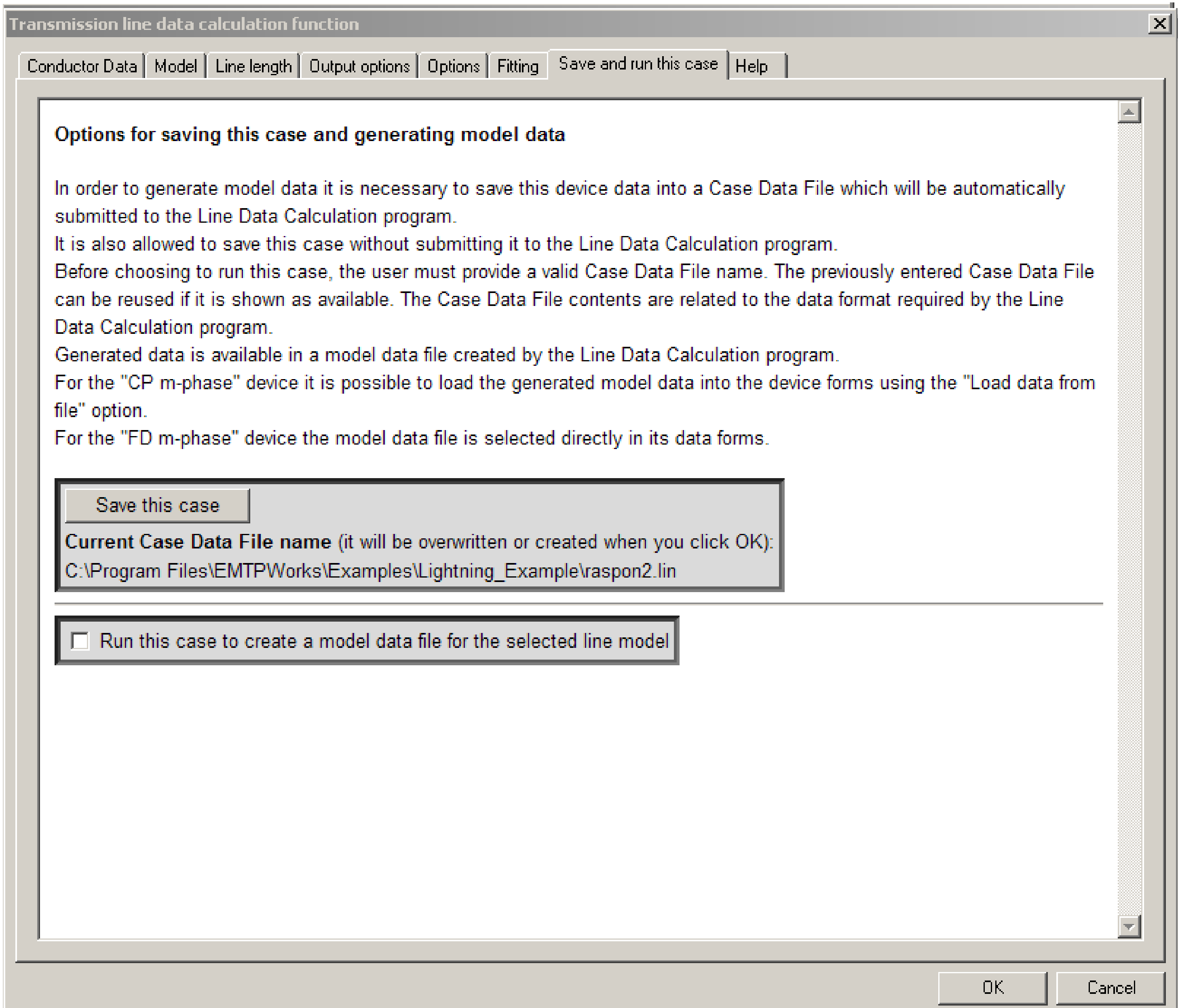
LINE, CONDUCTORS AND EARTH WIRES

- The transmission line, conductors and earth wire have to be represented by frequency-dependent parameters of multi-phase untransposed distributed line.
- A line termination should be connected on the modeled line to prevent reflections that could affect the simulated overvoltages.
- Several line spans in front of substation should be modeled when observing the overvoltages in substation.

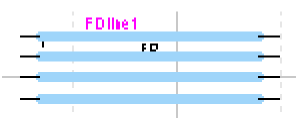


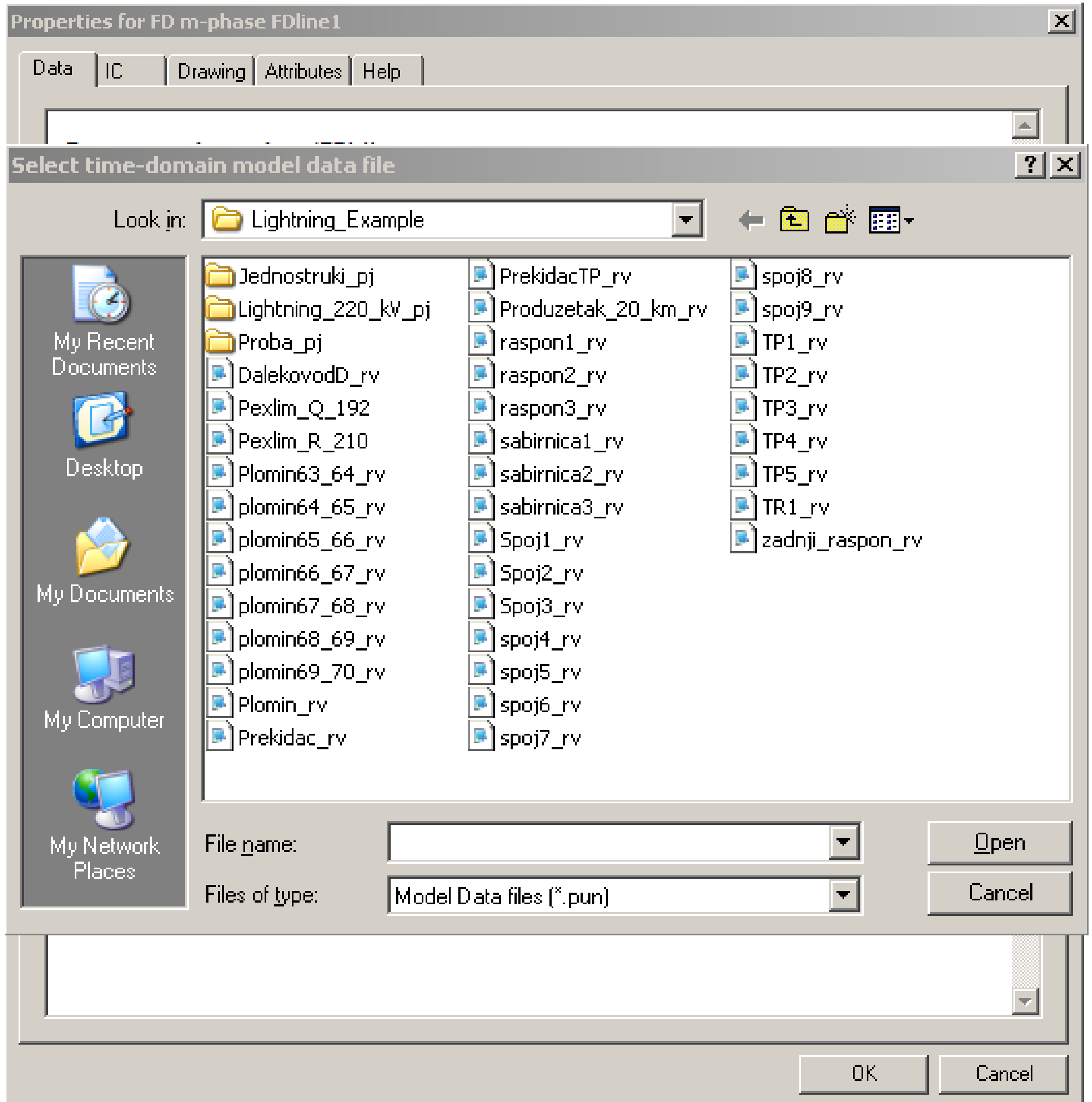
LINE, CONDUCTORS AND EARTH WIRES





LINE, CONDUCTORS AND EARTH WIRES





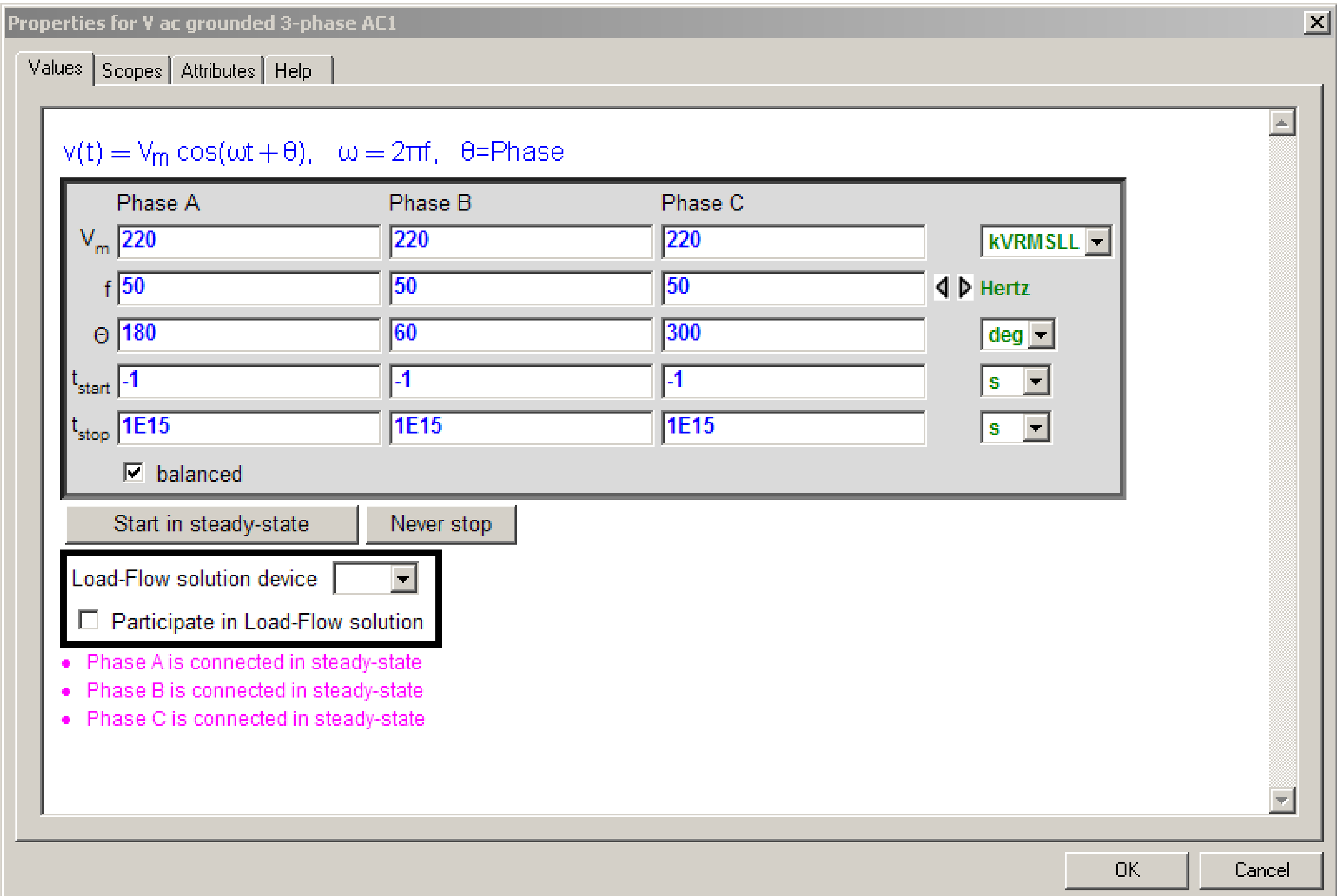
BOUNDARY CONDITIONS

- Phase voltages at the instant at which a lightning stroke impacts the line must be included.

- The largest voltage difference across insulator terminals occurs during the peak value of phase voltage, which has the opposite polarity of the lightning surge.

- For statistical calculations, phase voltages can be deduced by randomly determining the phase voltage reference angle and considering a uniform distribution between 0^0 and 360^0.

BOUNDARY CONDITIONS



SUBSTATION MODEL

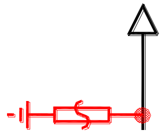
In a study of lightning overvoltage protection crucial elements are:

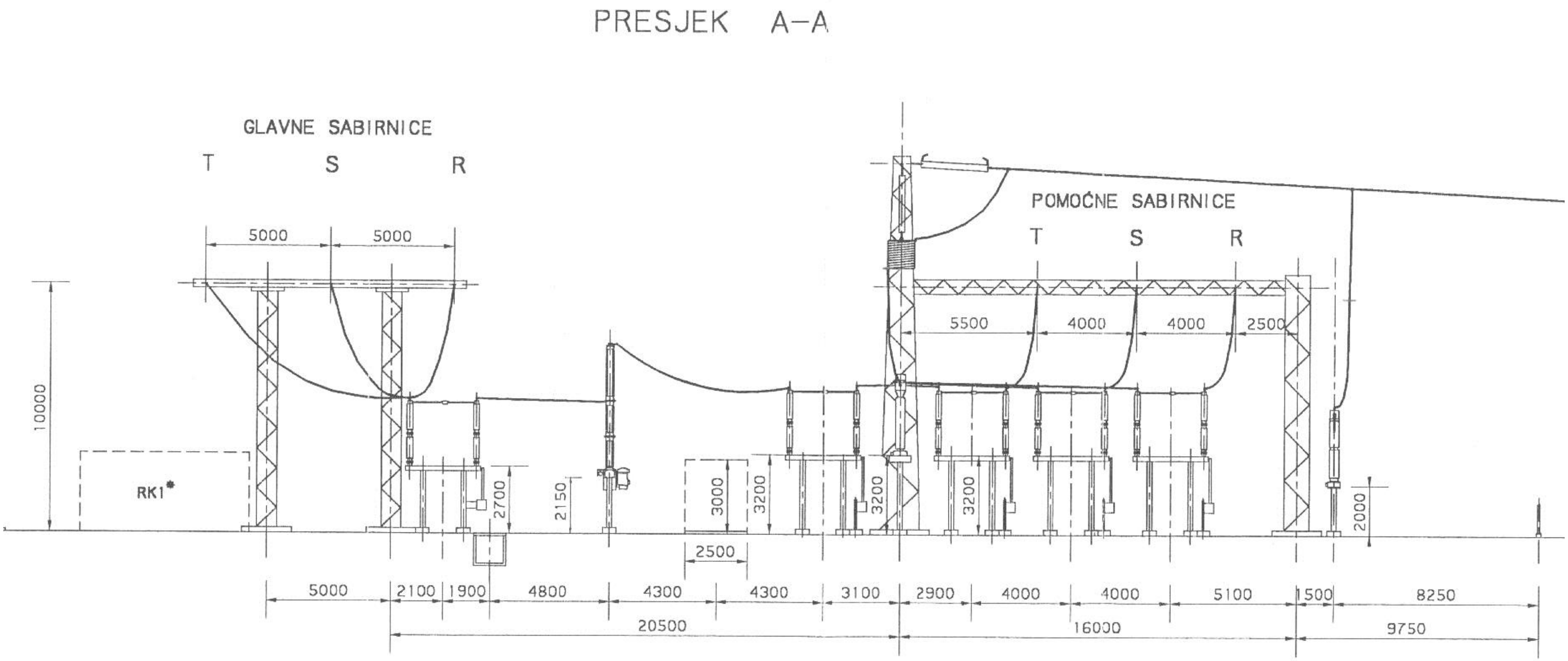
- Busbars and connective conductors
- Circuit breakers (CB) - (2x50 pF)*
- Capacitive voltage transformers (CVT) - (~4400 pF)
- Current transformers (CT) – (200 – 800) pF*
- Power transformer (1-6) nF*
- Metal-oxide surge arresters (MO SA)

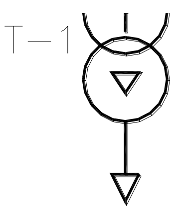
Also another elements (supporting insulators etc.) could be modeled by means of surge capacitance.

(*) Andrew R. Hileman: Insulation Coordination for Power Systems, Marcel Dekker, 1999.

SUBSTATION MODEL

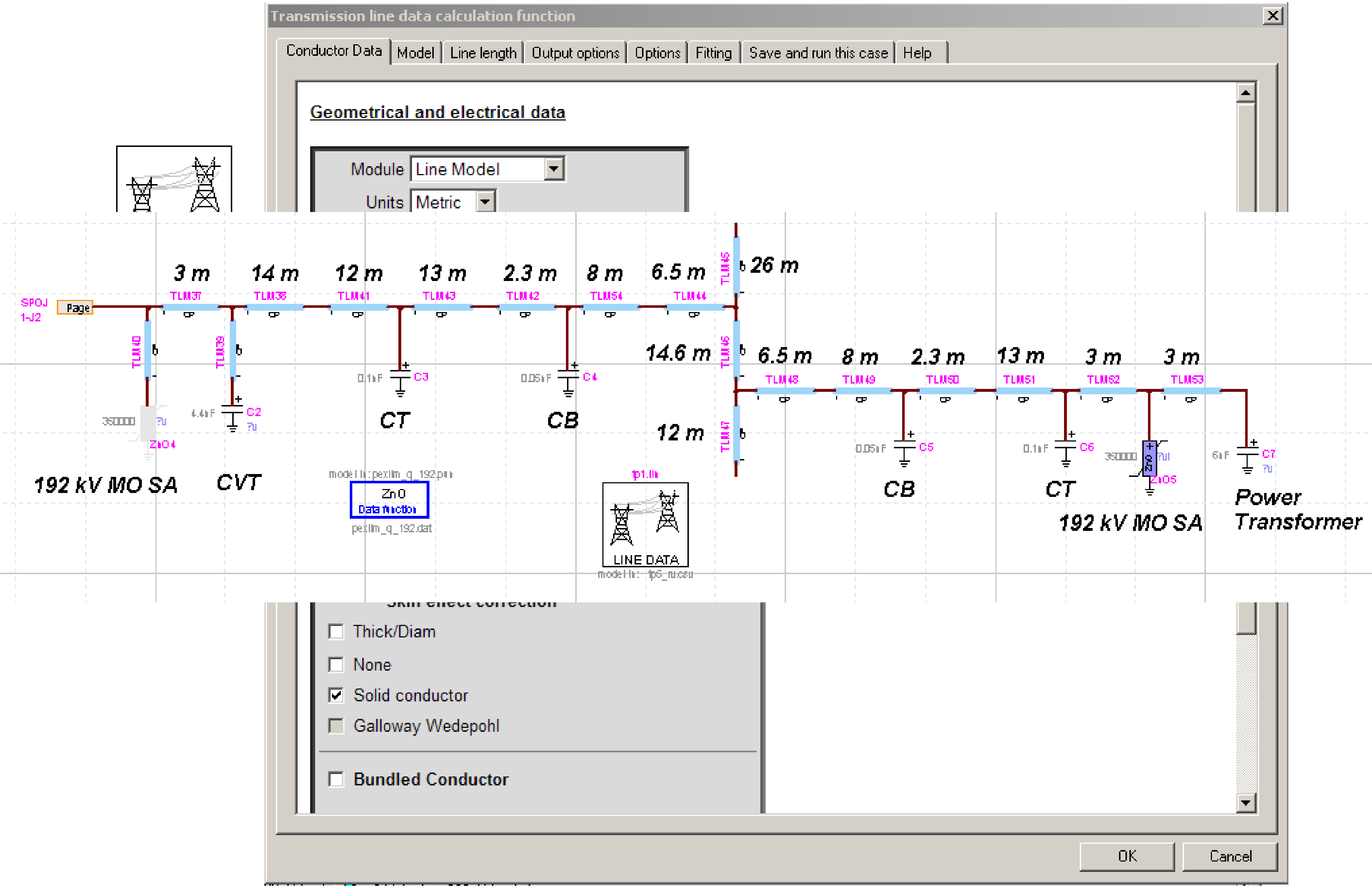






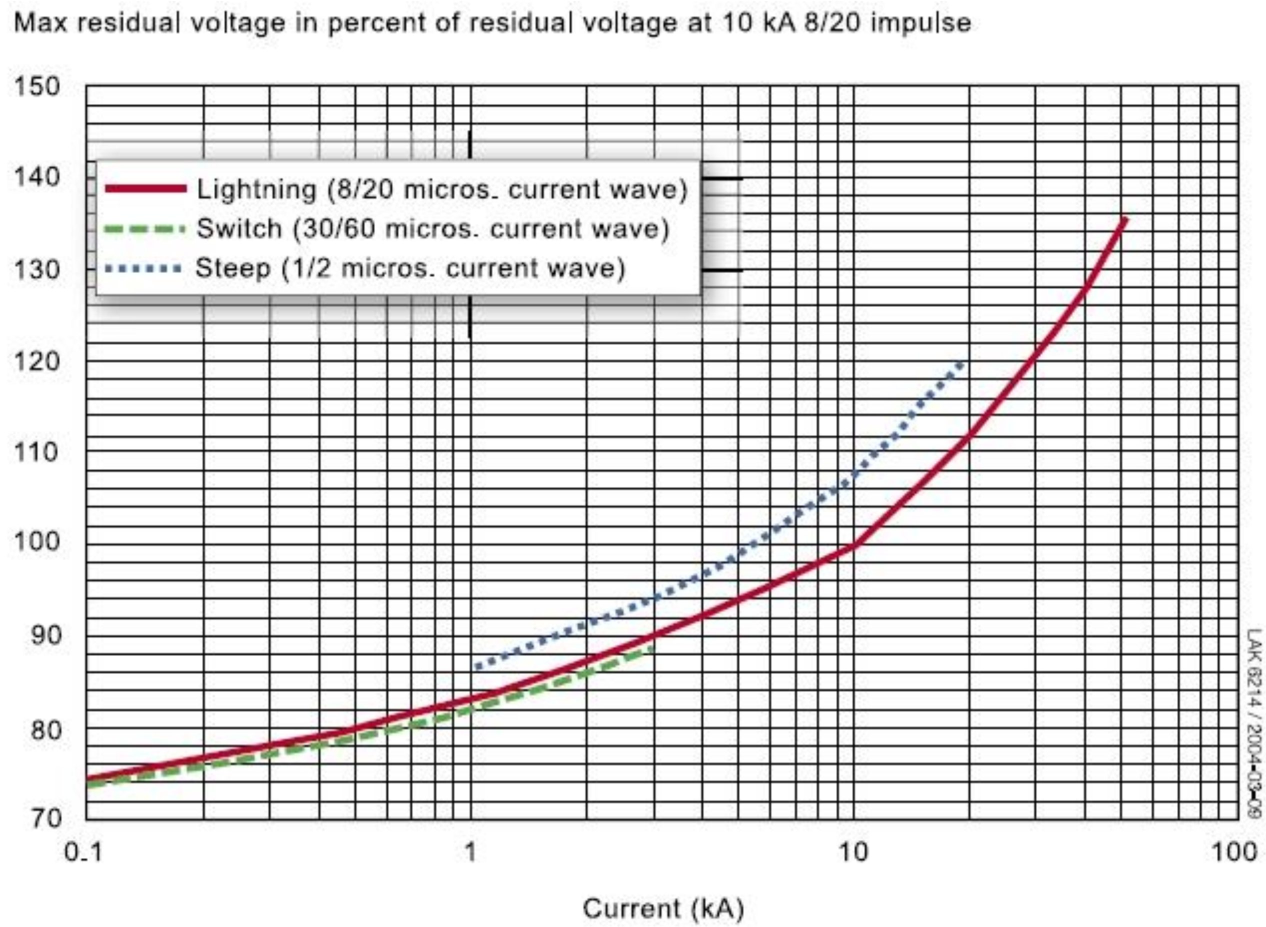
Drawing of HV substation

SUBSTATION MODEL



SURGE ARRESTER - Gapless Type

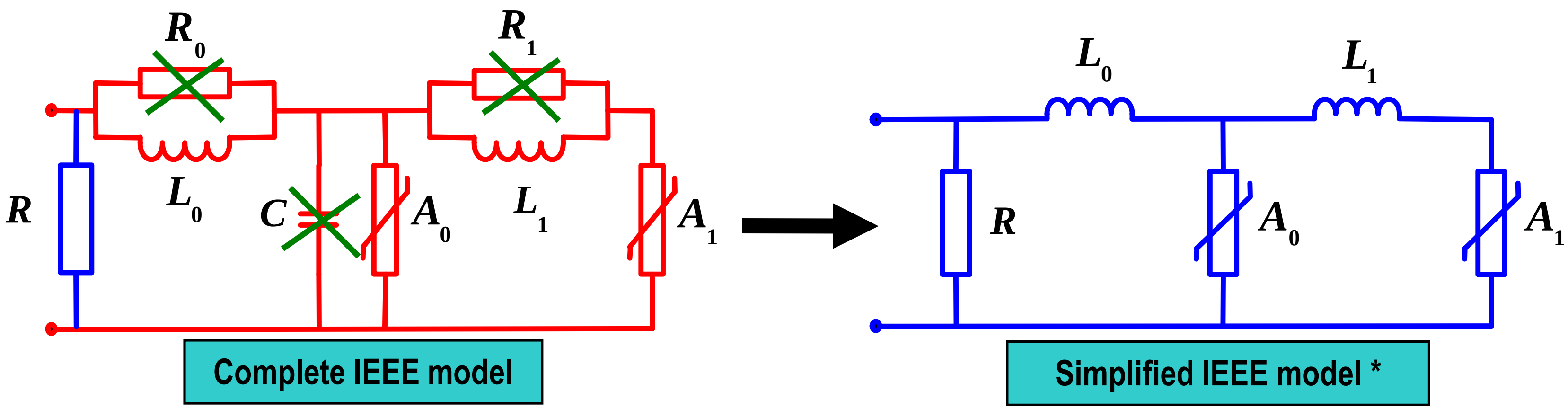
- The non-linear behaviour is represented by the U-I characteristic.



- The arrester leads can be modeled as conductors whose lumped parameter inductances have a value of approximately 1 µH/m.

SURGE ARRESTER - Gapless Type

- The frequency-dependent arrester model proposed by IEEE WG takes into account its dynamic behaviour.

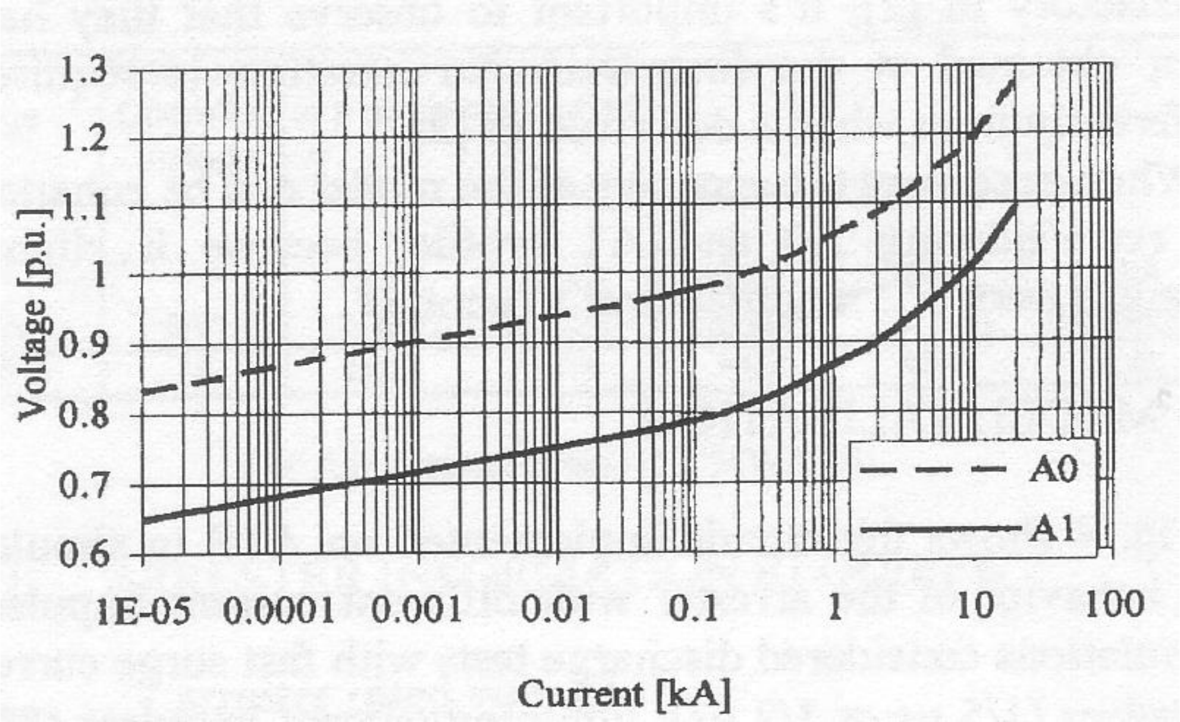


- IEEE model needs iterative procedure for identification of parameters.
- Simplified IEEE model uses data reported on manufacturers' datasheets.
- Capacitance is eliminated and the two resistances in parallel with the inductances are replaced by one resistance R.

*P. Pinceti, M. Giannettoni, "A simplified model for zinc oxide surge arrester", IEEE Trans. Power Delivery, Vol. 14, No. 2, April 1999, pp 545 – 550

SURGE ARRESTER – Simplified Model

- The parameters of simplified IEEE model can be defined by adopting the following rules:
  - the definition of non-linear resistor characteristics (A0 and A1) is based on the curve shown in Figure.
  - These curves are referred to the peak value of the residual voltage measured during a discharge test with a 10 kA lightning current impulse ($U_{r8/20}$).



SURGE ARRESTER – Simplified Model

- The following equations can be used to define the inductances (values are in μH):

$$L_1 = \frac{1}{4}\frac{U_{r1/T_2} - U_{r8/20}}{U_{r8/20}}U_r \qquad L_0 = \frac{1}{12}\frac{U_{r1/T_2} - U_{r8/20}}{U_{r8/20}}U_r$$

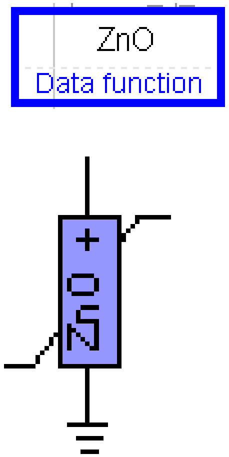
where:

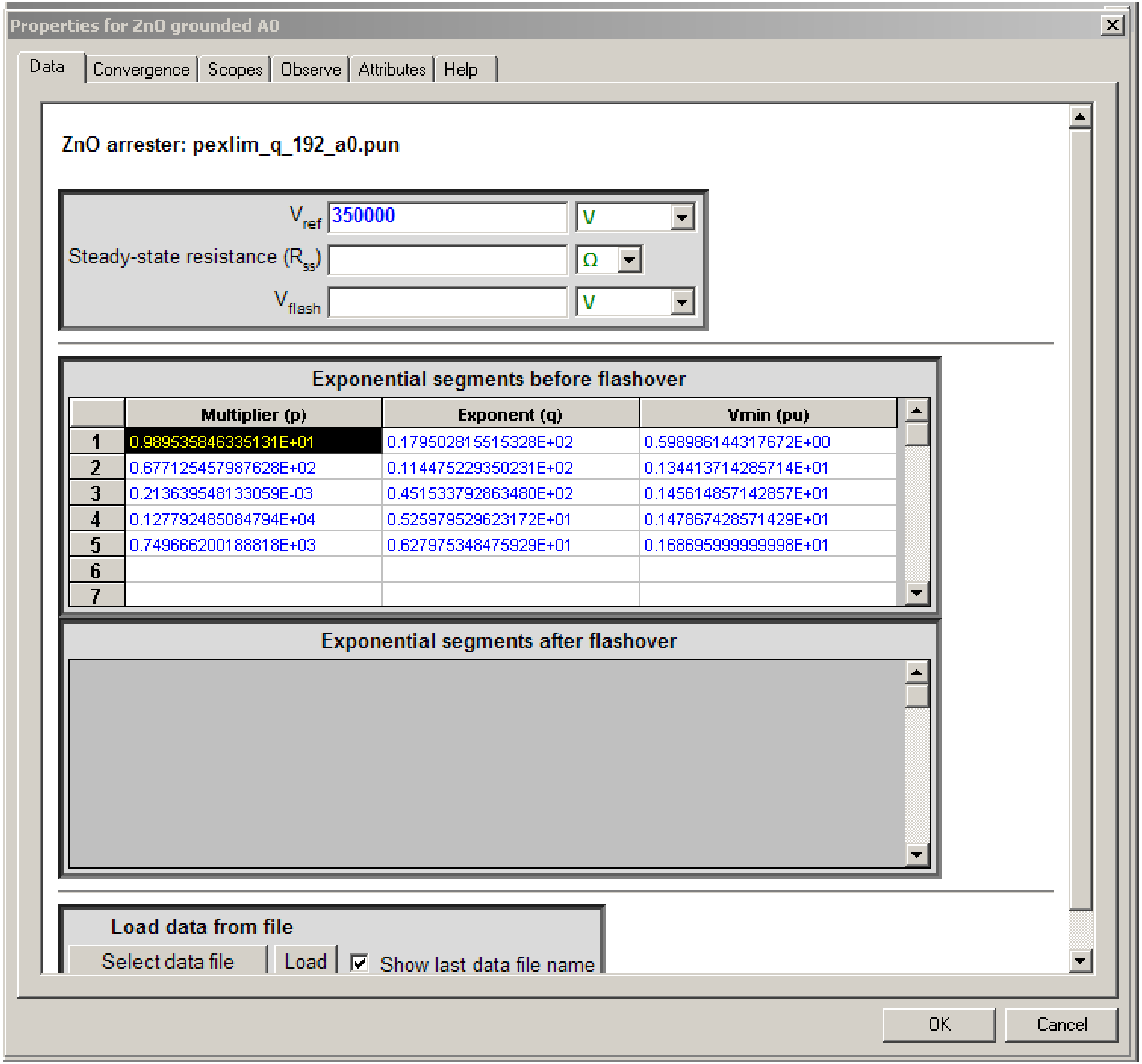
U_r is the arrester rated voltage,

$U_{r1/T2}$ is the residual voltage at 10 kA fast-front current surge ($1/T_2$ μs). The decrease time T_2 may have different values, which don't have any influence, since the peak value of the residual voltage appears on the rising front of the impulse,

$U_{r8/20}$ residual voltage at 10 kA current surge with 8/20 μs shape.

SURGE ARRESTER



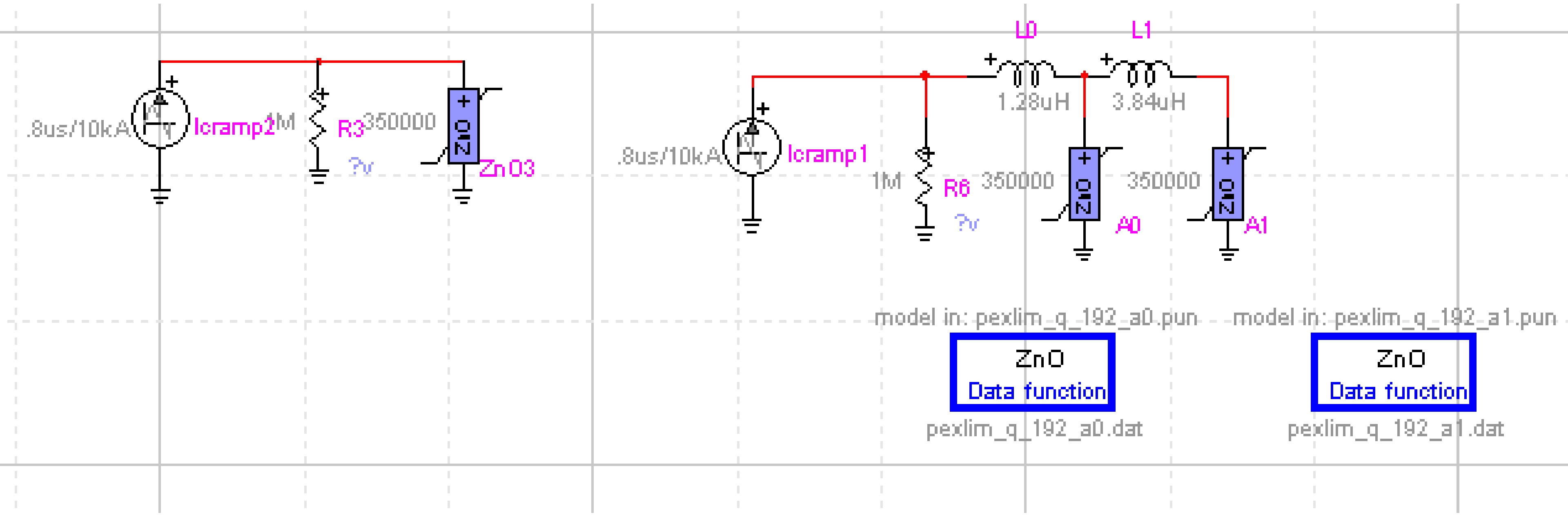


SURGE ARRESTER - Example

Residual voltage for MOSA of U_r=192 kV

Current (A)	Voltage (V)
1000	419100
2000	435600
5000	471900
10000	479200
20000	546700
40000	610500

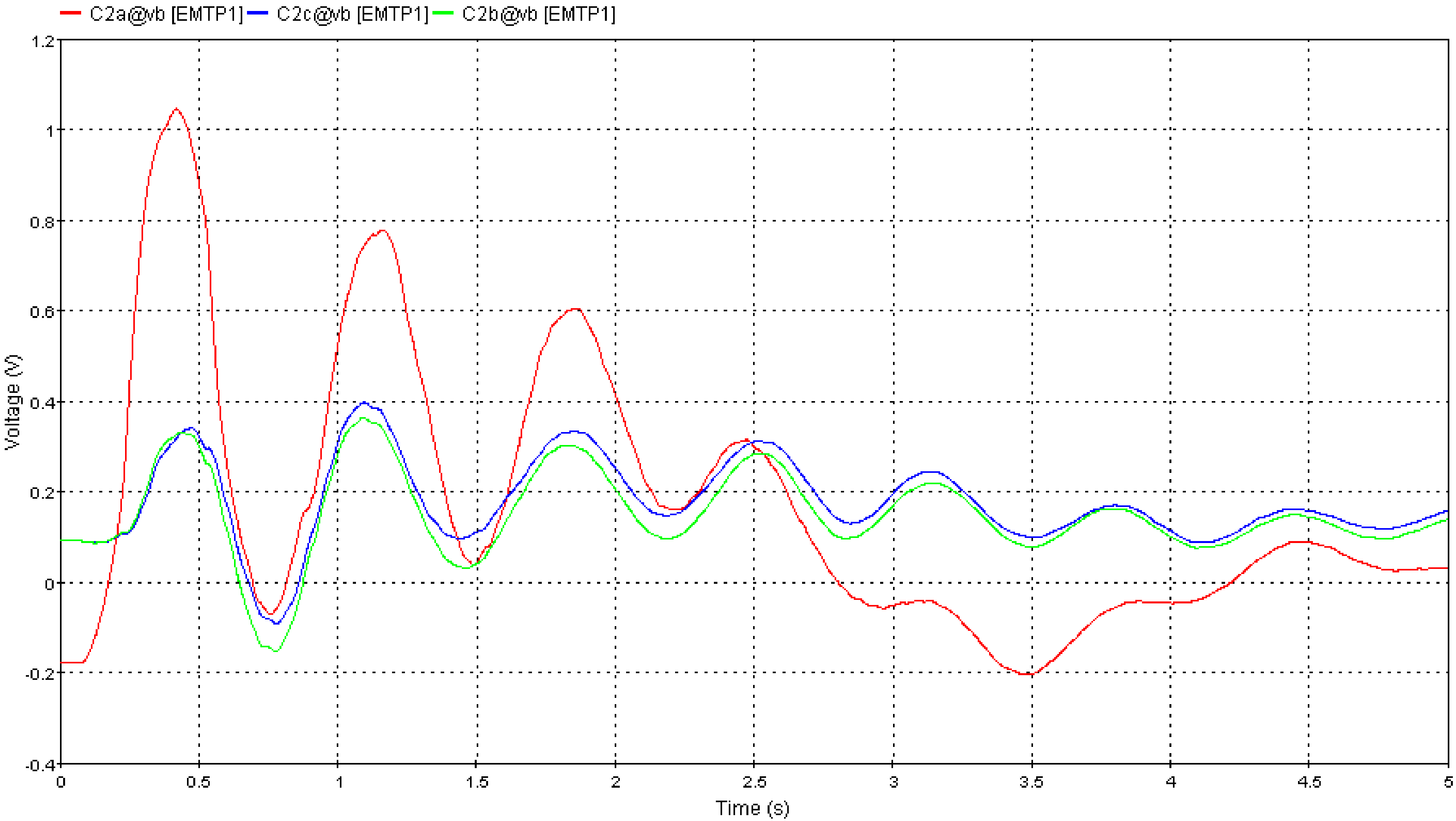
SURGE ARRESTER - Example



Comparison of MOSA models

EXAMPLE – Shielding failure case

- Stroke 10 kA, 32.34 kA/μs,
- CVT voltage without MO SA in line bay.



EXAMPLE – Shielding failure case

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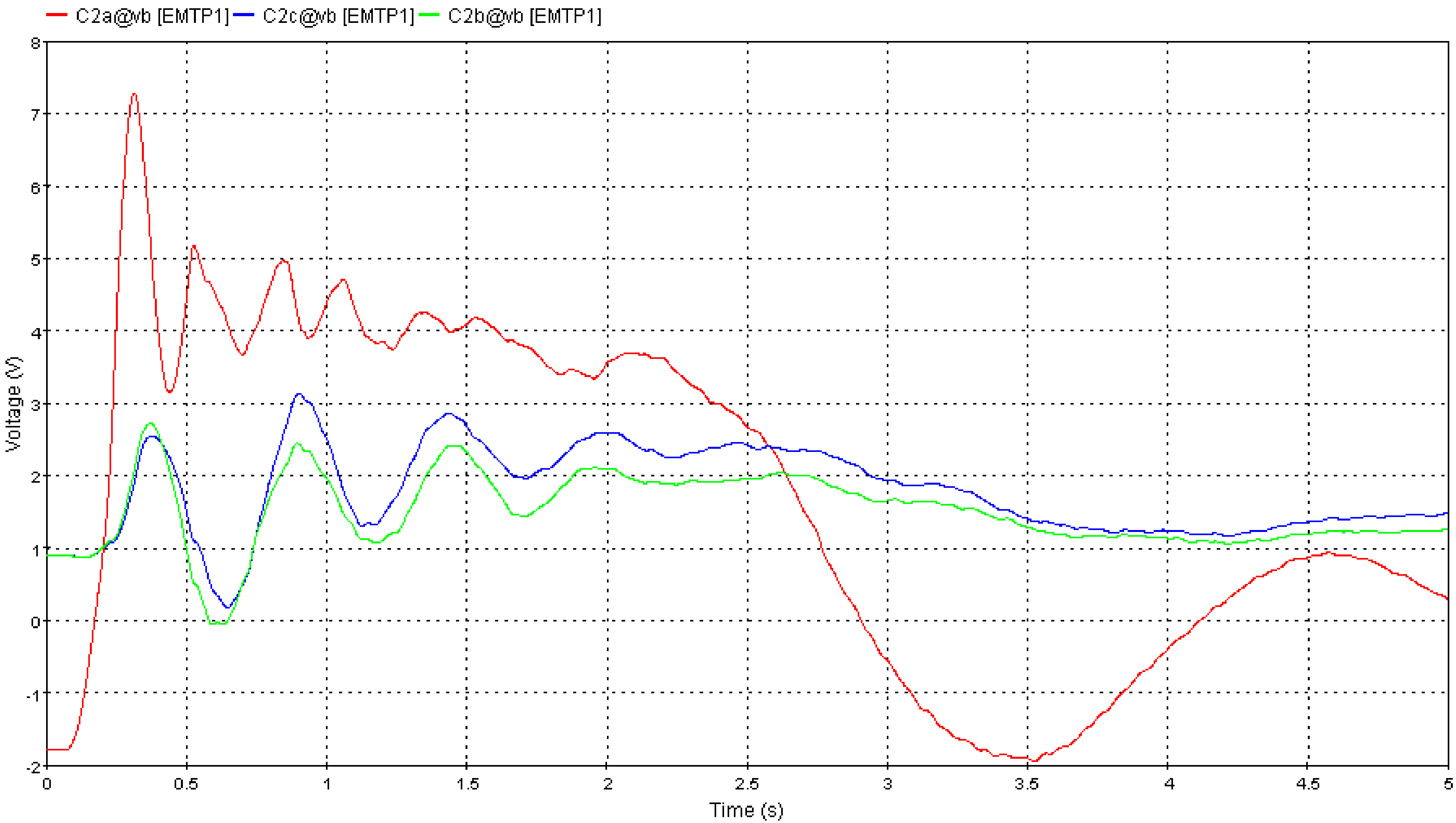

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