Using of WAMS technology for transmission OHL fault location

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S e r b i a

Phasor Measurement Unit - PMU

- In 1893, Charles Proteus Steinmetz introduced a simplified mathematical description of the waveforms of alternating current - a phasor.

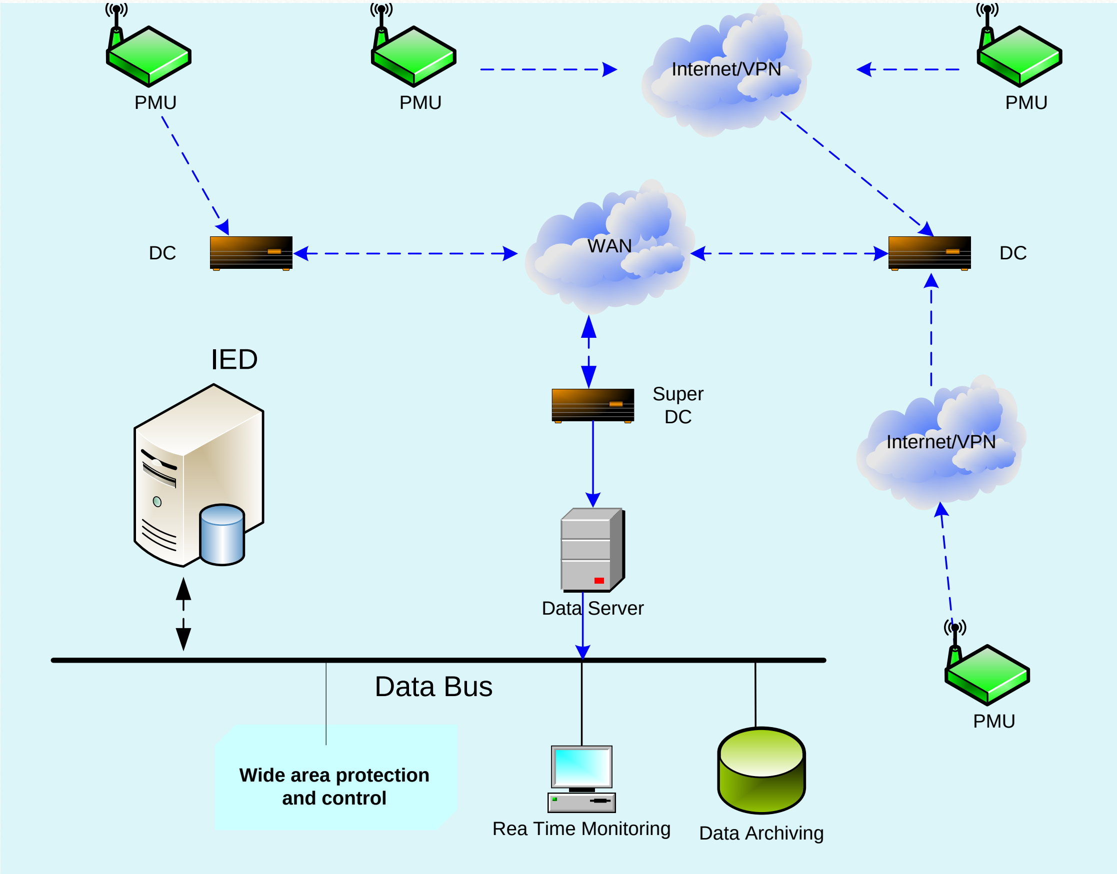
- Phasor measurement unit (PMU) was invented and early prototypes built in 1988 by Arun Phadke and James Thorp at Virginia Tech.

- Macrodyne company built the first PMU in 1992.

Source: Macrodyne

Wide Area Measurement System - WAMS

- A phasor network consists of PMUs dispersed throughout the electricity system, Data Concentrators (DC) and a Supervisory Control And Data Acquisition (SCADA) system at the central control facility. Such a network is used in Wide Area Measurement Systems (WAMS)
- The first WAMS started in 2000 by the Bonneville Power Administration.
- Real-time phasor measurements are synchronized to an absolute time reference provided by the Global Positioning System (GPS) at the accuracy of 1 µs.



Application of WAMS in Power Systems

- **Generation applications**: generator operation status monitoring and transient angle stability
- **Transmission applications**: Load flow (LF), Optimal Power Flow (OPF), Wide-Area Dynamic Monitoring and Analysis, Synchronized Disturbance Record and Replay, Online Low-Frequency Oscillation Analysis, Power Angle Stability Prediction and Alarming, PMU based State Estimation (SE), **OHL fault location and fault nature identification**
- **Substation automation**: service restoration via bus sectioning, bus voltage control, substation parallel transformer circulating current control, line drop compensation, and automatic reclosing
- **Distribution Automation**: monitor, coordinate, and operate distribution components and equipment from remote locations in real time.
- **Feeder automation**: line reclosure, load break switches, sectioning, capacitor banks
- **Consumer side automation**: Advanced Metering Infrastructure (AMI) and Automatic Meter Reading (AMR), Demand Side Response (DSR)

Electric faults on Overhead Lines (OHL)

- **Fault nature**:
  - TRANSIENT FAULTS 90% (system over-voltages, lightening, growing trees and plants, etc.)
  - PERMANENT FAULTS 10% (wire failure due to ice, snow, wind, birds, fallen trees, etc. or tower failure due to snowstorm, excessive wind, landslide, etc.)
- **Fault type:**

Fault type	Occurrence
Phase-to-Ground	85 %
Phase-to-Phase	8 %
Double Phase-to-Ground	5 %
Three Phase short circuit	~ 2 %


Source: Relectic.com


Source: Cleantechagency.com

Fault location and nature identification

- **Why is fault nature identification important**?
  - Transient: arcing fault (try auto-reclose)
  - Permanent: arcless fault (metal, bolted faults, block auto-reclose)
- **Why is precise fault distance important**?
  - In case of a permanent fault, the powerline restoration team should be sent to the very place of the fault, especially in severe weather conditions, so to minimise the time needed for line restoration

Research on Fault Location Algorithms (FLA)

Various algorithm approaches:

- Time domain
- Frequency (spectral) domain
- Voltage and current measurements
- Current measurements only
- Voltage measurements only
- Parameter settings-free
- One-port approach
- Two-port approach

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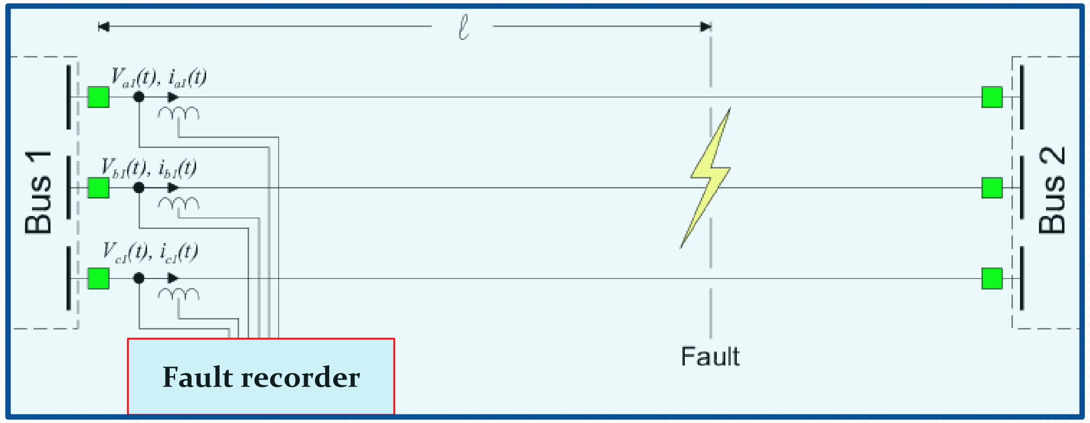
Padmanabhan, …

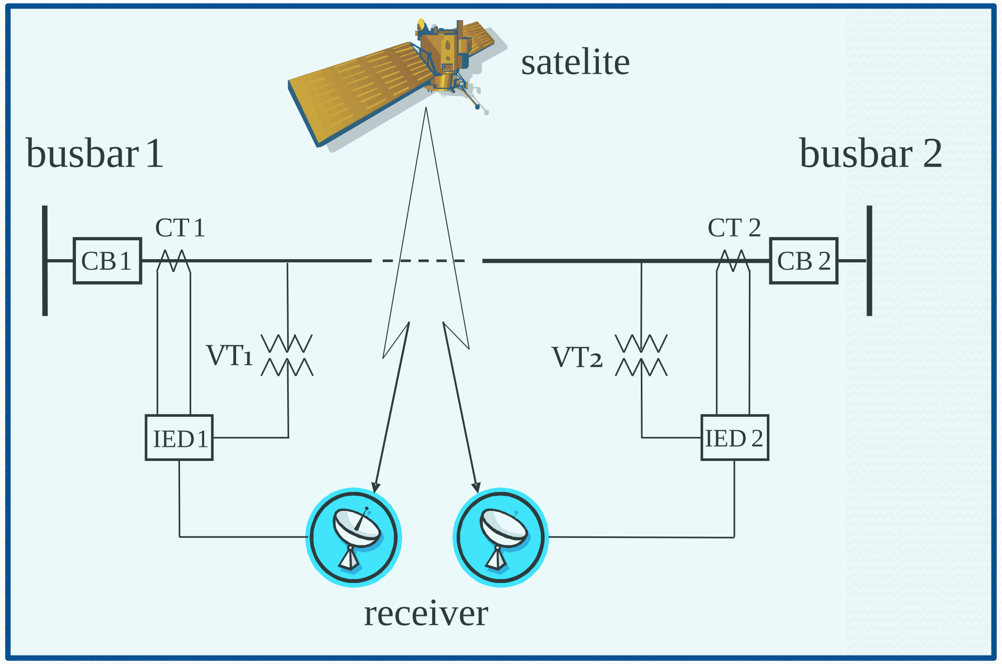
One-port vs. Two-port Fault Location Approach

- One-port fault location approach



Measurements are taken only at one side of the OHL

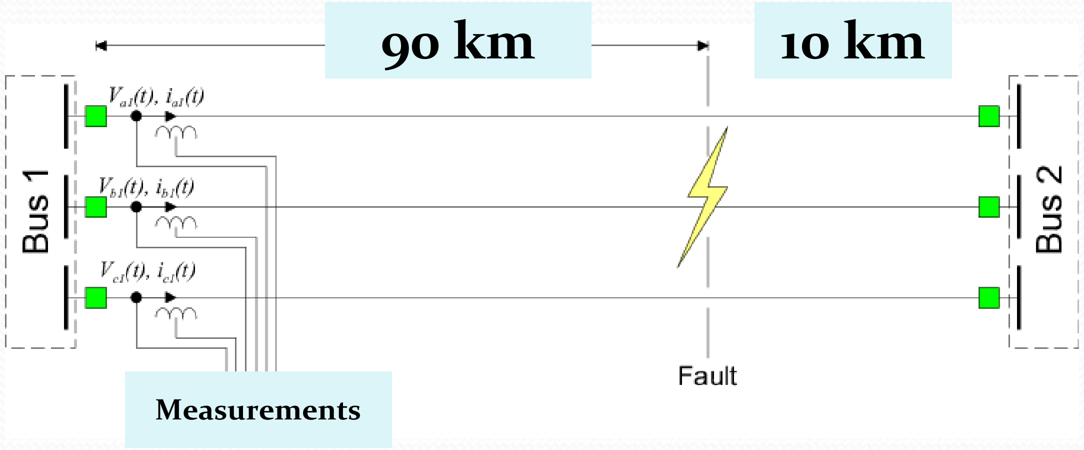
- Two-port fault location approach

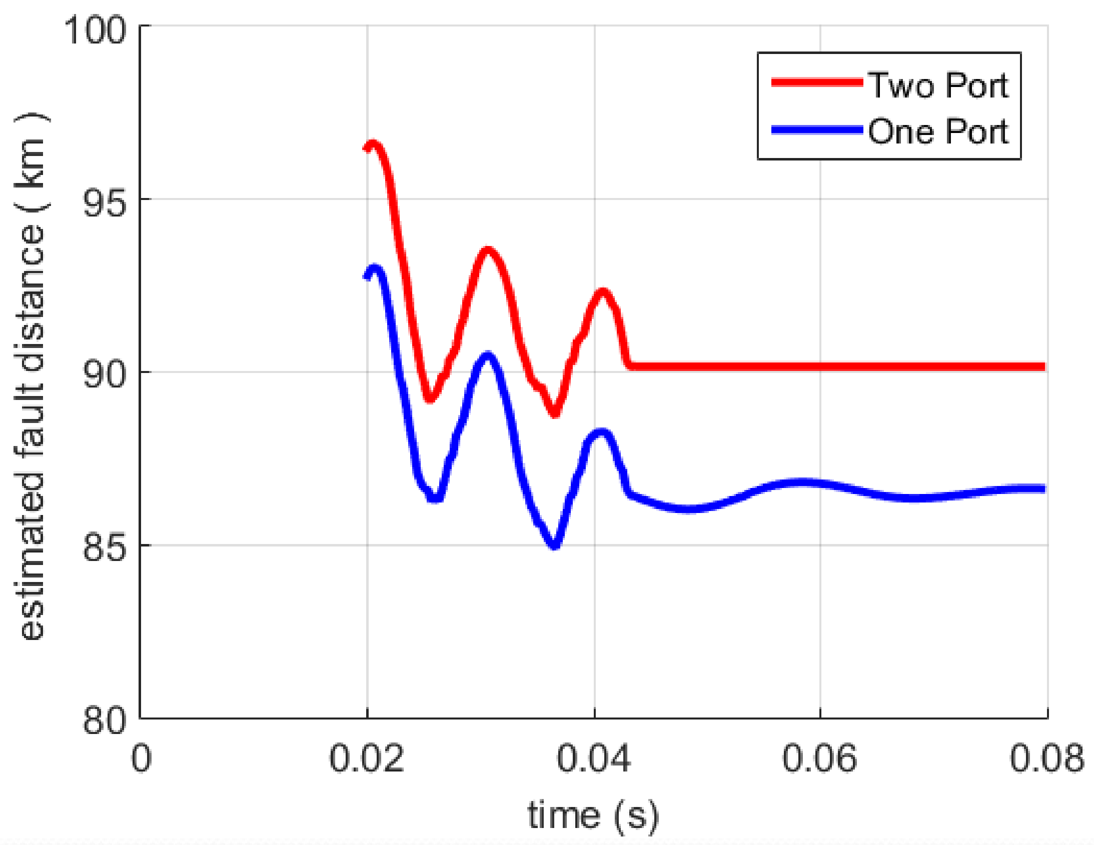


Measurements are taken at both sides of the OHL

One-port vs. Two-port FLA: accuracy does matter

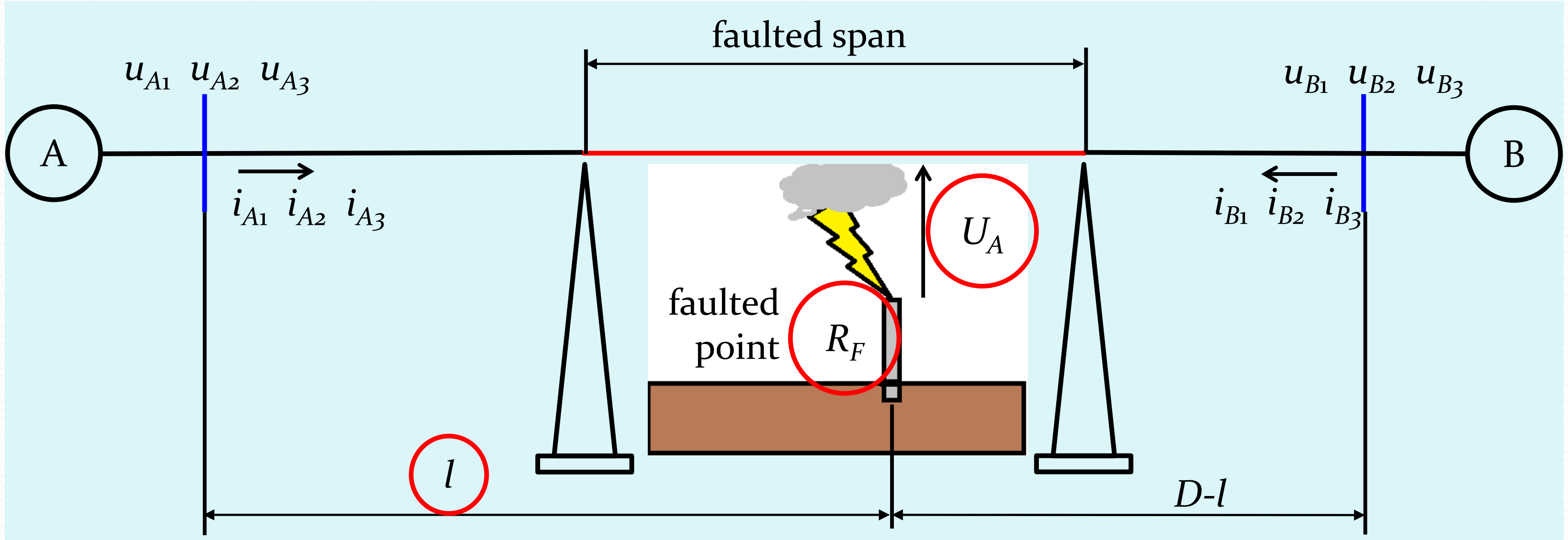
- OHL 400 kV, 100 km long
- Single-phase to ground arcing fault simulated at 90 km from the left-hand side
- Measurements taken at the left-hand side for one-port FLA





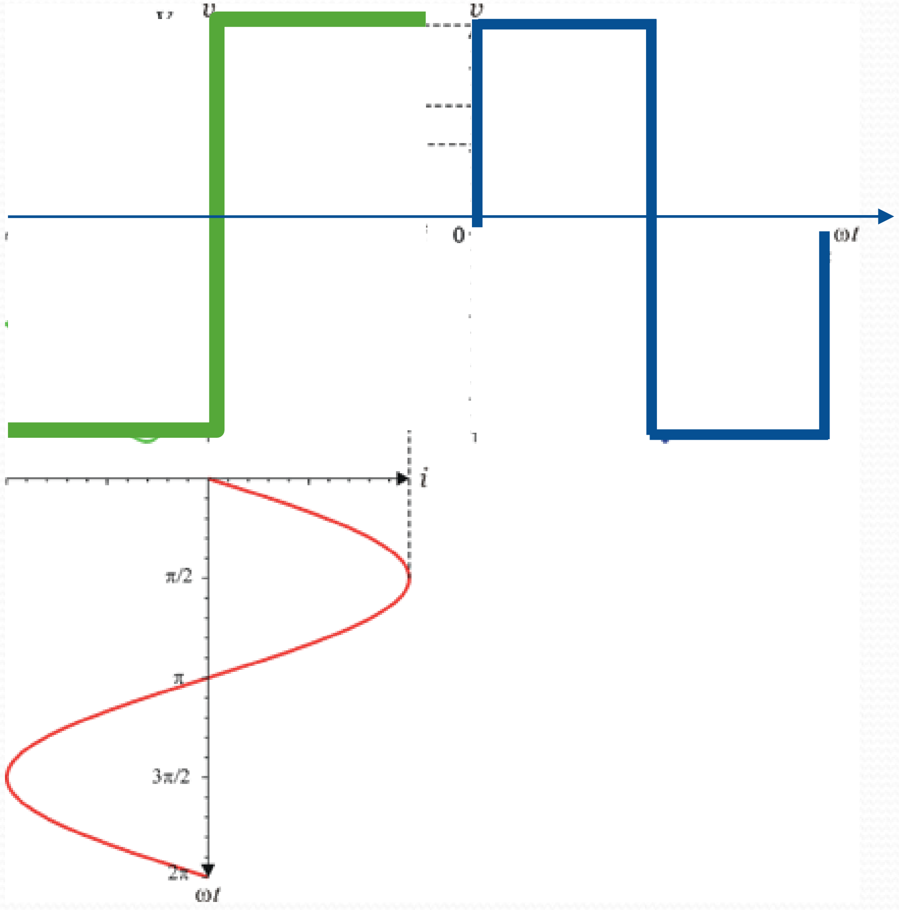
Two-port Fault Location Algorithm

- Measured values: currents and voltages at both line terminals (using WAMS data)
- Single Phase-Ground fault
- Estimated unknown parameters:
  - distance to fault location (l)
  - arc voltage magnitude (u_a)
  - fault resistance or tower footing resistance (R_F)

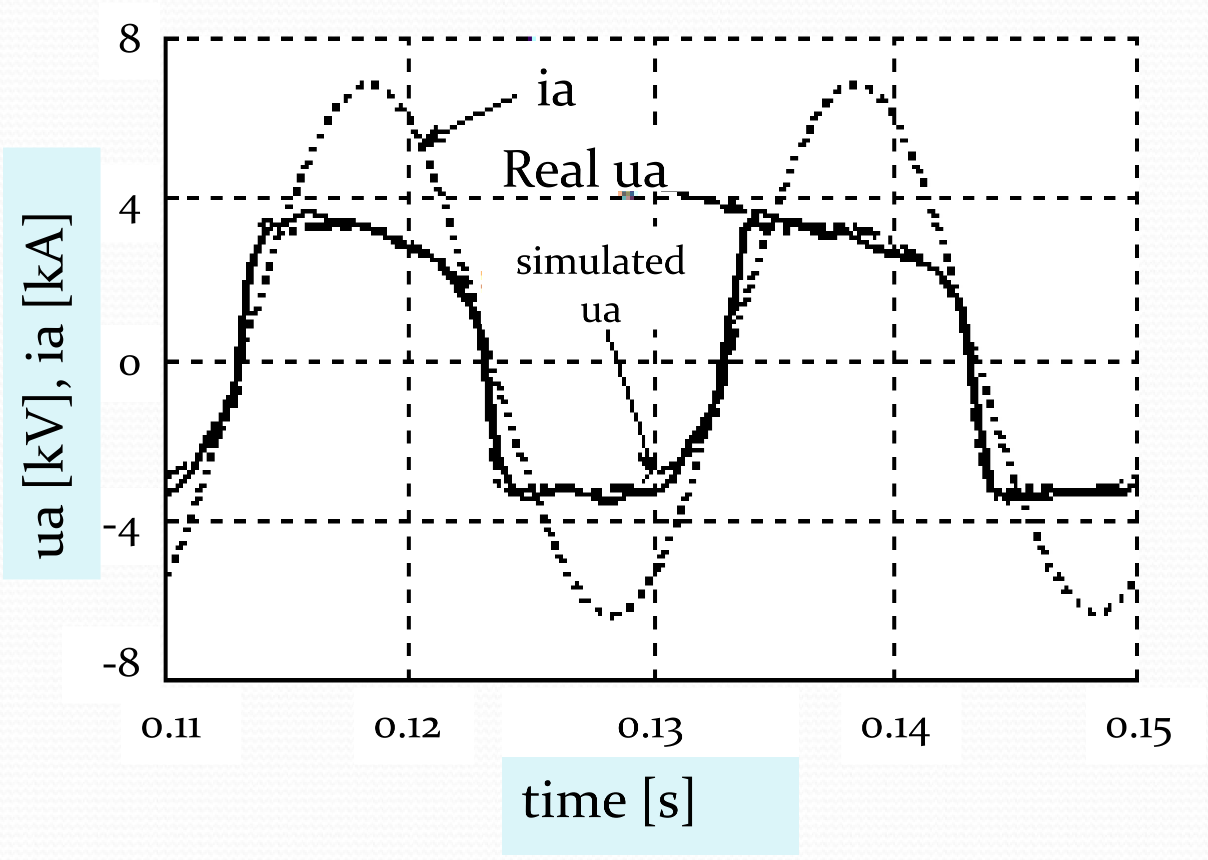


Model of the Electric Arc in Still Air

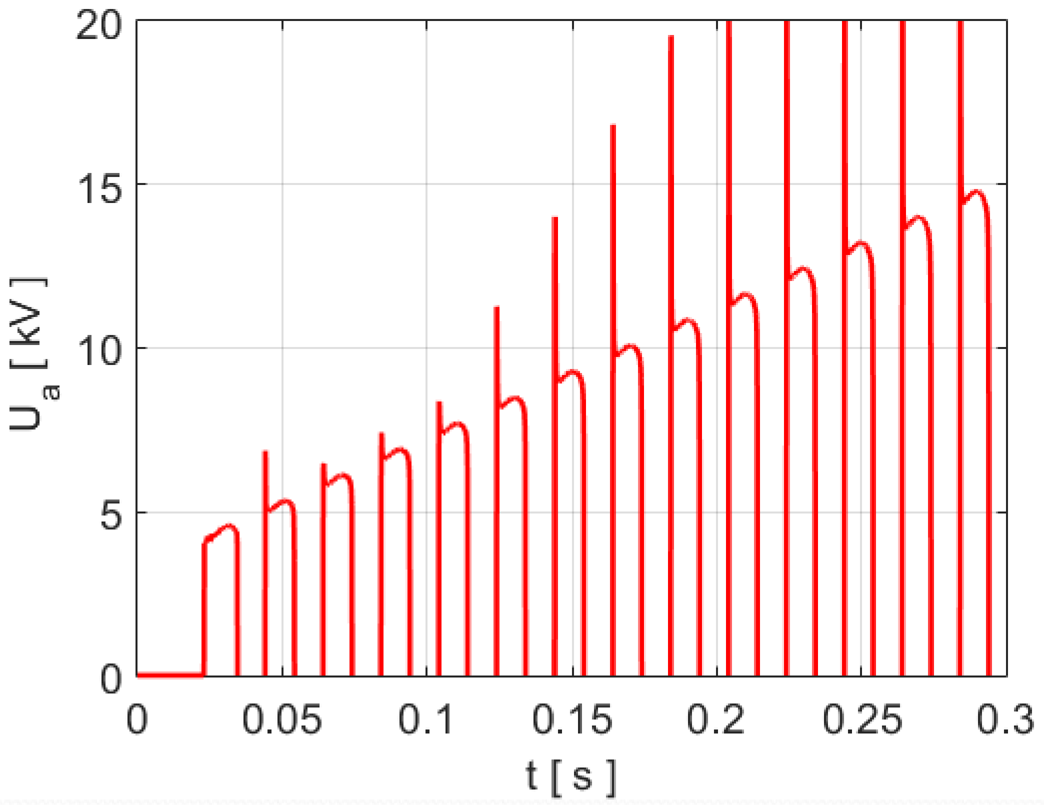
- Simple Arc model (simplest: rectangular wave)



- Advanced Arc model



Model of the Long Arc in Still Air – elongation effect

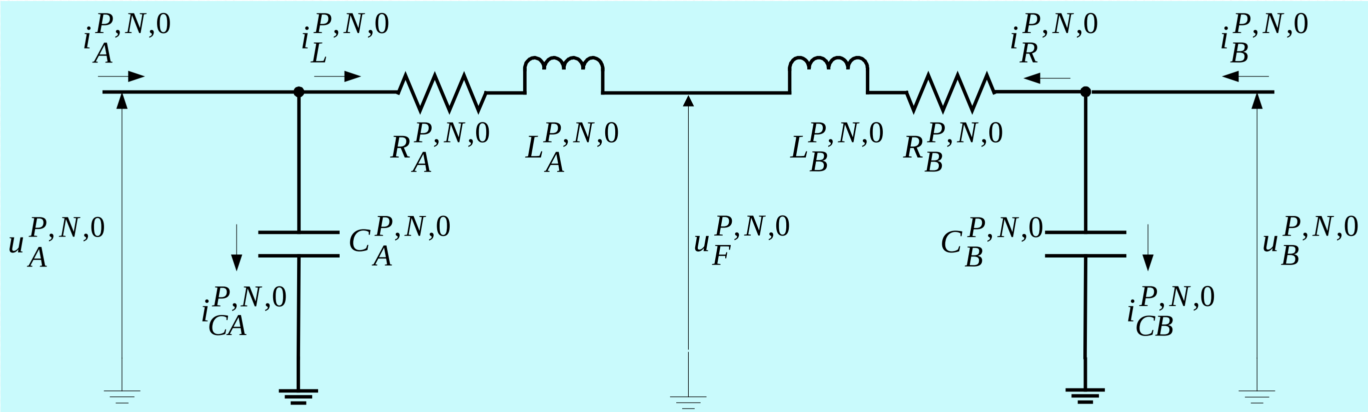


Simulated Arc voltage with increasing length

Two-port Fault Location Algorithm

- Mathematical description of the phenomenon is relatively complex

$$u_A = R_A^P\left[i_A - i_{CA} + K_R\left(i_A^0 - i_{CA}^0\right)\right] + L_A^P\left[\frac{d}{dt}\left(i_A - i_{CA}\right) + K_L\frac{d}{dt}\left(i_A^0 - i_{CA}^0\right)\right] +$$
$$+ \; U_a \operatorname{sgn}(i_A - i_{CA} + i_B - i_{CB}) + R_F\,(i_A - i_{CA} + i_B - i_{CB})$$



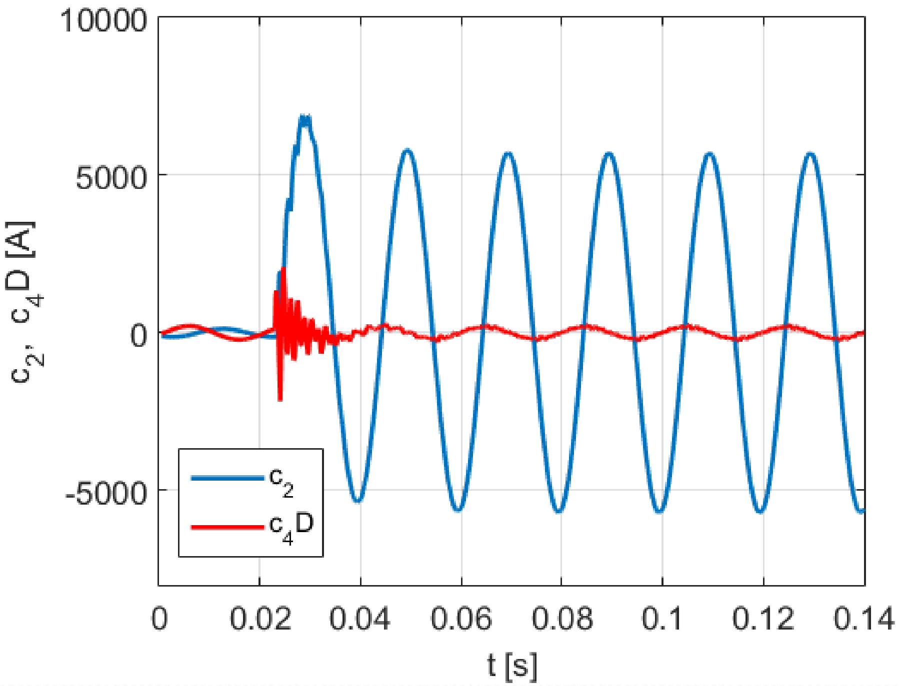
$$u_A = r^P\left[i_A + K_R i_A^0\right]\cdot l - \frac{r^P}{2}\left[c^P\frac{du_A}{dt} + \left(c^P K_C + c^0 K_R\right)\frac{du_A^0}{dt}\right]\cdot l^2$$
$$+ l^P\left(\frac{di_A}{dt} + K_L\frac{di_A^0}{dt}\right)l - \frac{l^P}{2}\left[c^P\frac{d^2u_A}{dt^2} + \left(c^P K_C + c^0 K_L\right)\frac{d^2u_A^0}{dt^2}\right]\cdot l^2$$
$$+ U_a \operatorname{sgn}\left\{i_A + i_B - \frac{c^P}{2}D\left(\frac{du_B}{dt} + K_C\frac{du_B^0}{dt}\right) - \frac{c^P}{2}\left[\frac{du_A}{dt} - \frac{du_B}{dt} + K_C\left(\frac{du_A^0}{dt} - \frac{du_B^0}{dt}\right)\right]\cdot l\right\}$$
$$+ \left[i_A + i_B - \frac{c^P}{2}D\cdot\left(\frac{du_B}{dt} + K_C\frac{du_B^0}{dt}\right)\right]\cdot R_F - \frac{c^P}{2}\left[\frac{du_A}{dt} - \frac{du_B}{dt} + K_C\left(\frac{du_A^0}{dt} - \frac{du_B^0}{dt}\right)\right]\cdot R_F\, l$$

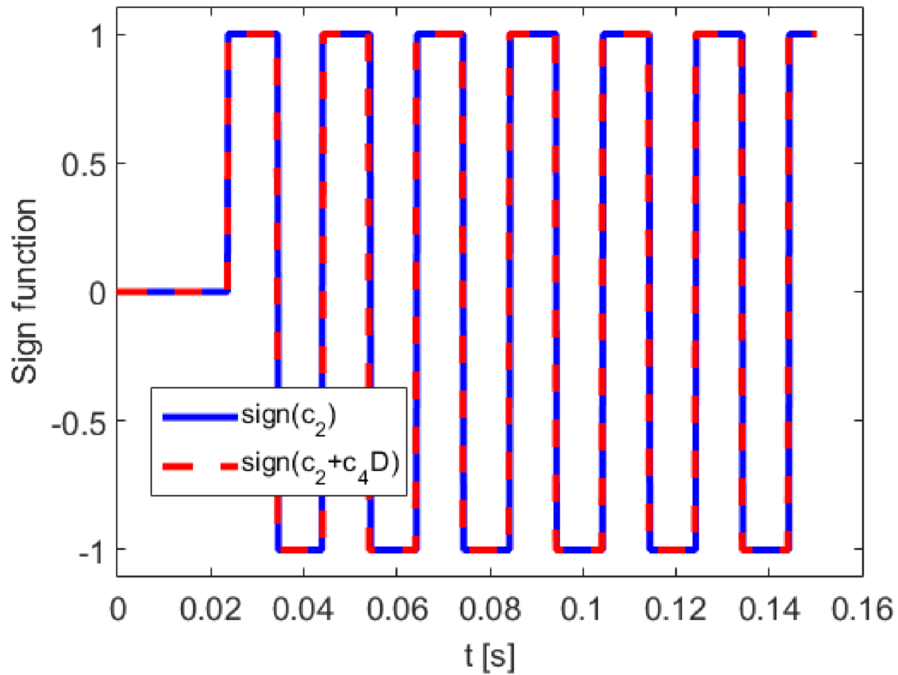
Two-port Fault Location Algorithm: Non-linearity

- Challenge: Non-linearity of the equations:

$$u_A = c_1 \cdot l + c_2 \cdot R_F + c_3 \cdot l^2 + c_4 \cdot R_F \cdot l + U_a \,\mathrm{sign}(c_2 + c_4 \cdot l)$$

- Non-linearity caused by capacitance of the OHL
- Engineer's approach: $c_2 \gg c_4 \cdot l$ $\Rightarrow$ $u_A = c_1 \cdot l + c_2 \cdot R_F + c_3 \cdot l^2 + U_a \,\mathrm{sign}(c_2)$





Two-port Fault Location Algorithm: Derivatives

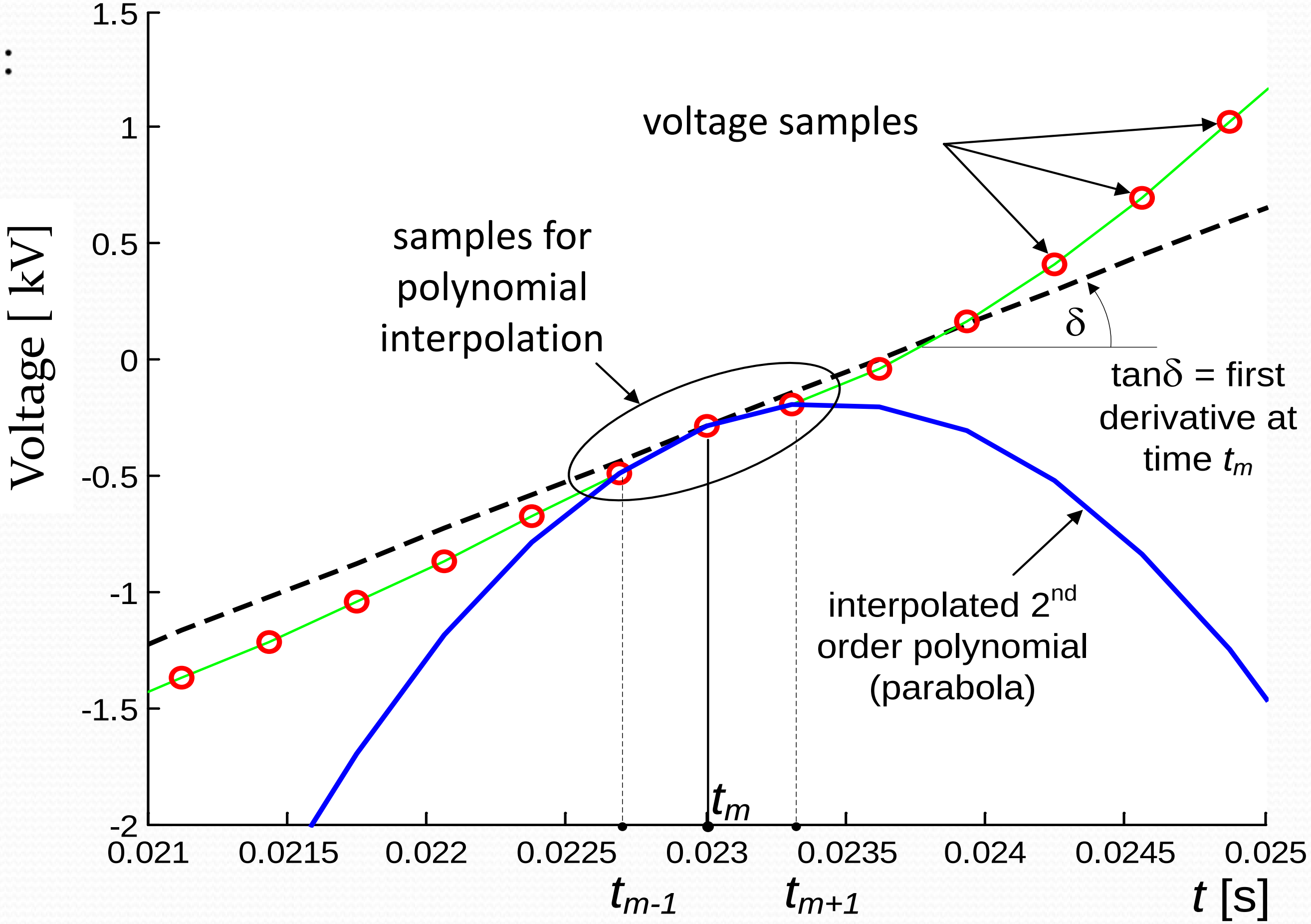
Challenge: Second-order derivative of measured voltage with respect to time:

- Parabola (second-order polynomial):

$$u_A(t) = a \cdot t^2 + b \cdot t + c$$

$$\frac{du_A(t)}{dt} = 2a \cdot t + b$$

$$\frac{d^2u_A(t)}{dt^2} = 2a$$

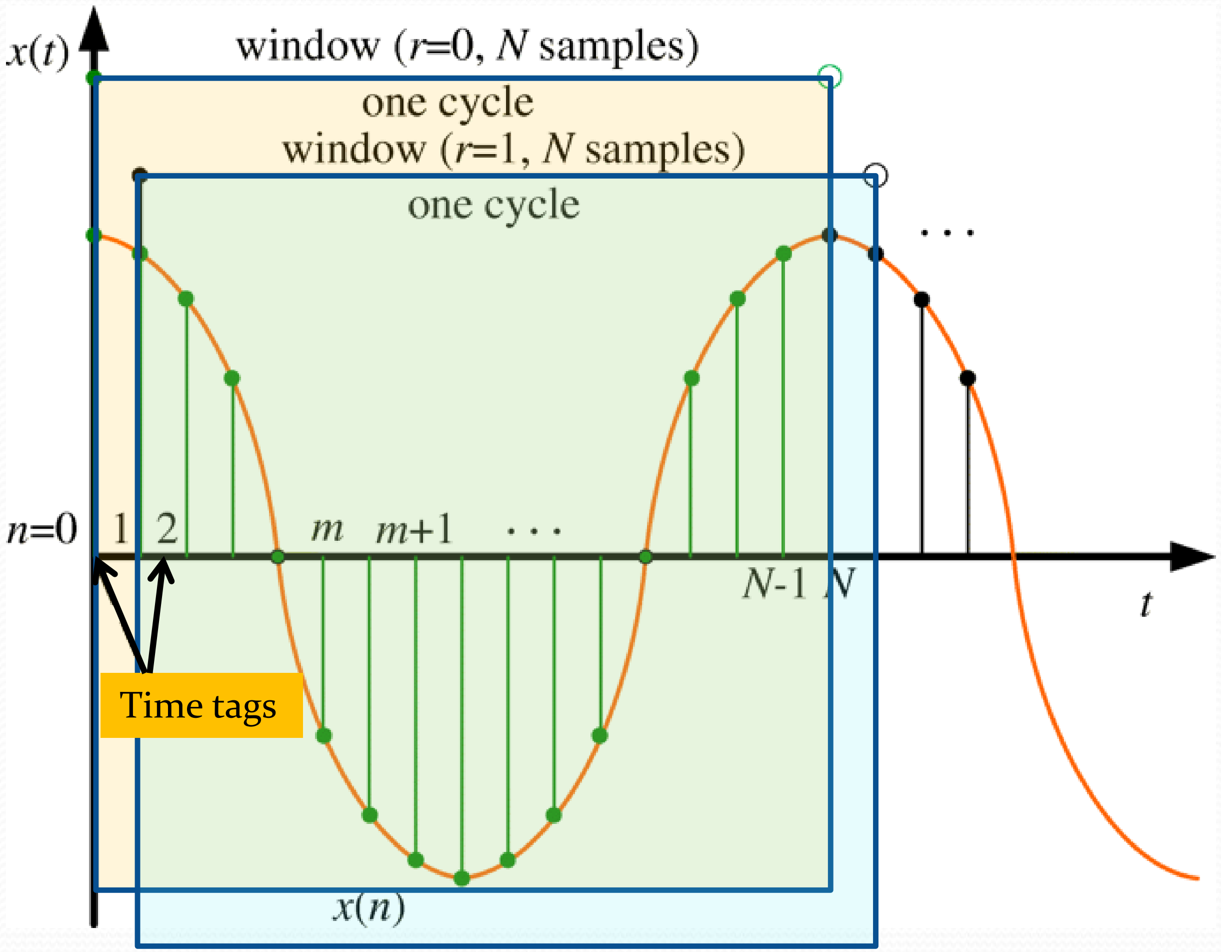


Two-port Fault Location Algorithm: Data Window

- Sampling frequency f_s
- Moving Data window technique:

$$\mathbf{u_A} = \begin{bmatrix} u_A(t_1) \\ \vdots \\ u_A(t_N) \end{bmatrix} = \begin{bmatrix} u_{A1} \\ \vdots \\ u_{AN} \end{bmatrix} \qquad \mathbf{u_B} = \begin{bmatrix} u_B(t_1) \\ \vdots \\ u_B(t_N) \end{bmatrix} = \begin{bmatrix} u_{B1} \\ \vdots \\ u_{BN} \end{bmatrix}$$

$$\mathbf{i_A} = \begin{bmatrix} i_A(t_1) \\ \vdots \\ i_A(t_N) \end{bmatrix} = \begin{bmatrix} i_{A1} \\ \vdots \\ i_{AN} \end{bmatrix} \qquad \mathbf{i_B} = \begin{bmatrix} i_B(t_1) \\ \vdots \\ i_B(t_N) \end{bmatrix} = \begin{bmatrix} i_{B1} \\ \vdots \\ i_{BN} \end{bmatrix}$$



Newton-Raphson iterative method

Linearisation:

$$u_A(t_1) = f(\mathbf{x}_0, t_1) + \frac{\partial f_{t_1}}{\partial \mathbf{x}}\bigg|_{(\mathbf{x}=\mathbf{x}_0)} \cdot \Delta\mathbf{x} + \mu(t_1)$$

$$\vdots$$

$$u_A(t_N) = f(\mathbf{x}_0, t_N) + \frac{\partial f_{t_N}}{\partial \mathbf{x}}\bigg|_{(\mathbf{x}=\mathbf{x}_0)} \cdot \Delta\mathbf{x} + \mu(t_N)$$

Vector of unknown parameters:

$$\mathbf{x} = \begin{bmatrix} l \\ U_a \\ R_F \end{bmatrix}$$

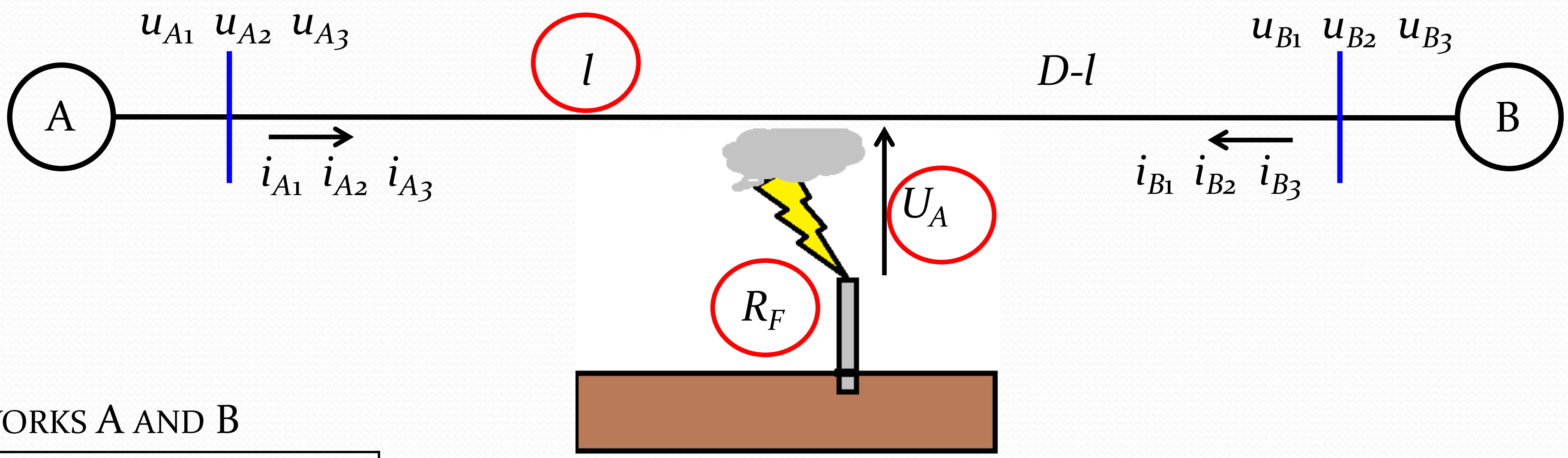
Key equations of the Newton-Raphson method:

$$\mathbf{u_A} = \mathbf{f(x_o)} + \mathbf{J\Delta x} + \boldsymbol{\mu}$$

$$\Delta\mathbf{x}_{i+1} = \left(\mathbf{J}_i^{\mathrm{T}}\mathbf{J}_i\right)^{-1} \cdot \mathbf{J}_i^{\mathrm{T}}\left(\mathbf{u_A} - \mathbf{f}(\mathbf{x}_i)\right)$$

$$\mathbf{x}_{\boldsymbol{i+1}} = \mathbf{x}_{\boldsymbol{i}} + \boldsymbol{\Delta}\mathbf{x}_{\boldsymbol{i+1}}$$

Two-port FLA: Simulation



PARAMETERS OF NETWORKS A AND B

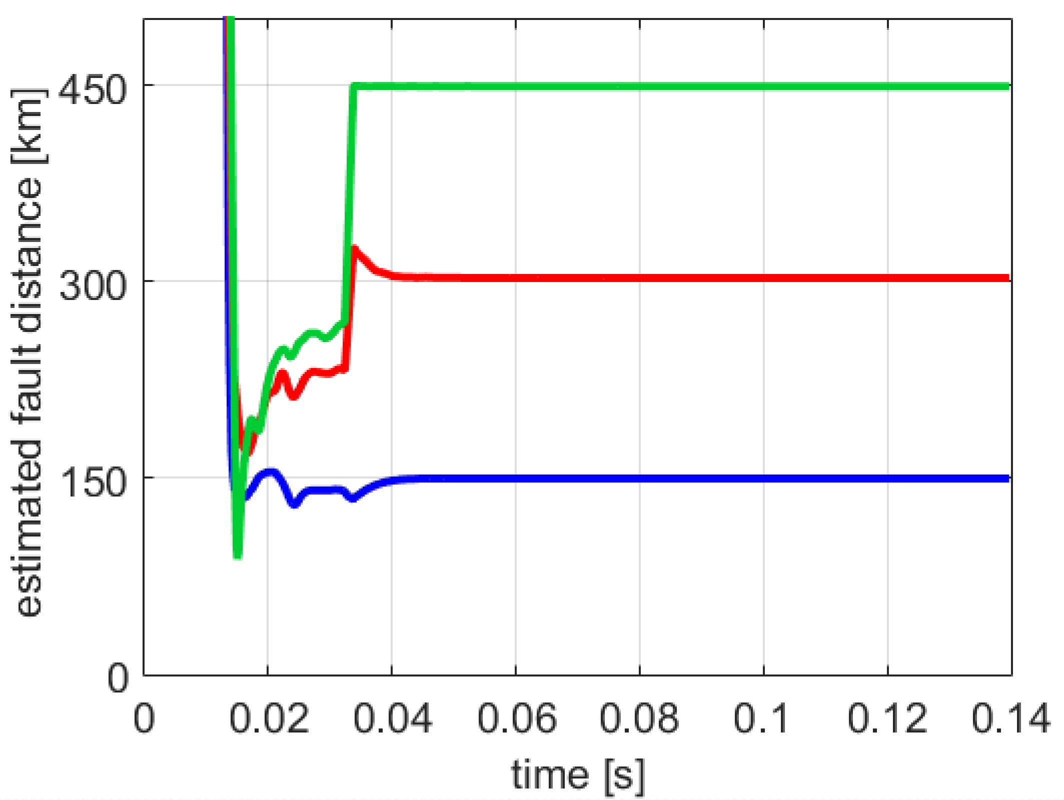
Parameters	Networks	
	A	B
$U_{LL,RMS}$ [kV]	416	400
φ_1 [°]	0	-20
R [Ω]	1.0185892	0.6366183
L [H]	0.0509295	0.0318309
R_0 [Ω]	2.0371785	1.2732366
L_0 [H]	0.1018589	0.0636618

TRANSPOSED LINE PARAMETERS, 400 KV, 500 KM

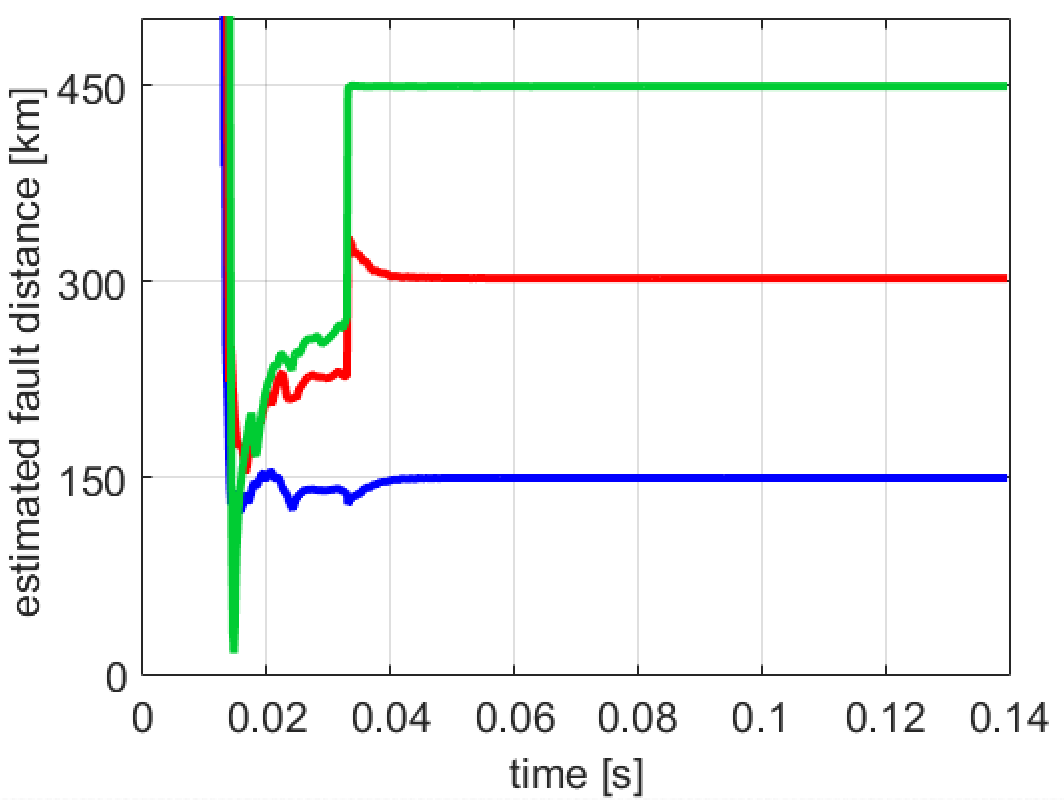
Parameter	p- and n-sequence	0-sequence
Resistance [Ω/km]	0.02021	0.1024
Inductance [mH/km]	1.07	3.82737
Capacitance [nF/km]	10.938	7.815

Estimated fault distance

- Estimated fault distance for arcing faults (u_A=5 kV R_F = 15 Ohm)



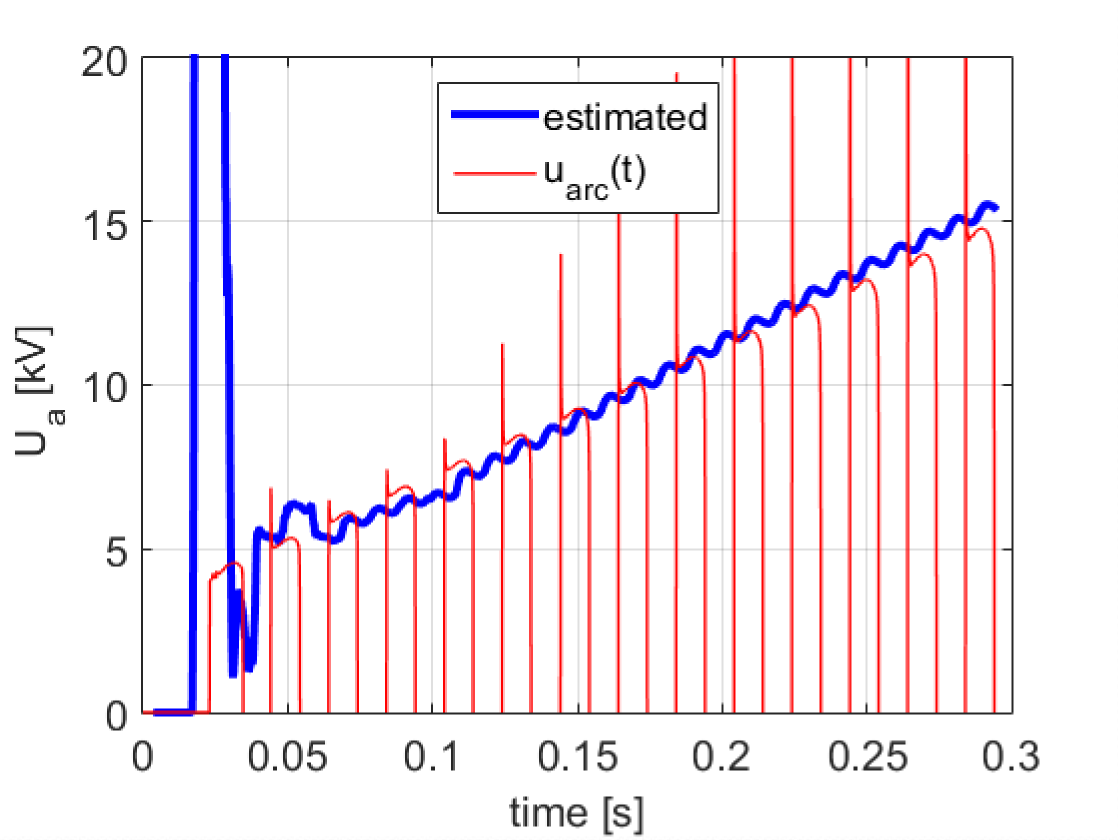
- Estimated fault distance for arcless faults (u_A=0 kV R_F = 15 Ohm)



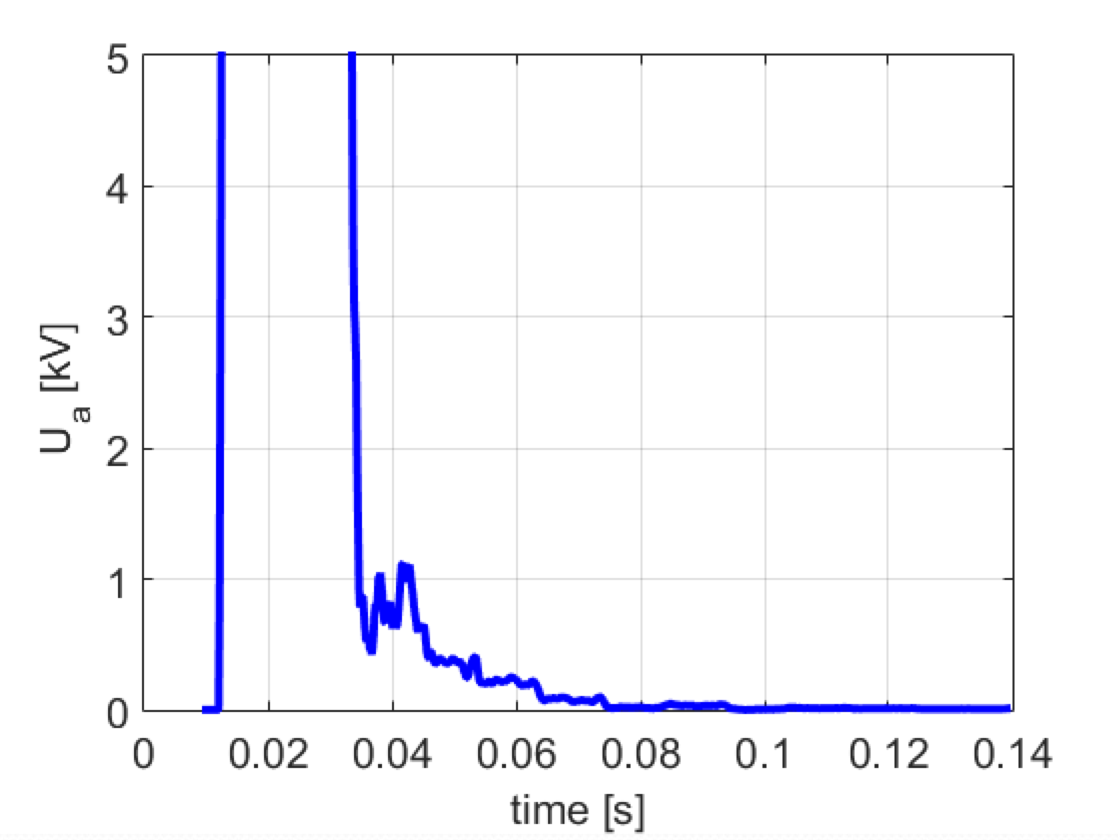
Estimated arc voltage

Estimated arc voltage magnitude with elongating arc:

- starting arc voltage 5 kV,
- elongation rate 40 m/s
- (L=150 km, R_F=15 Ω)

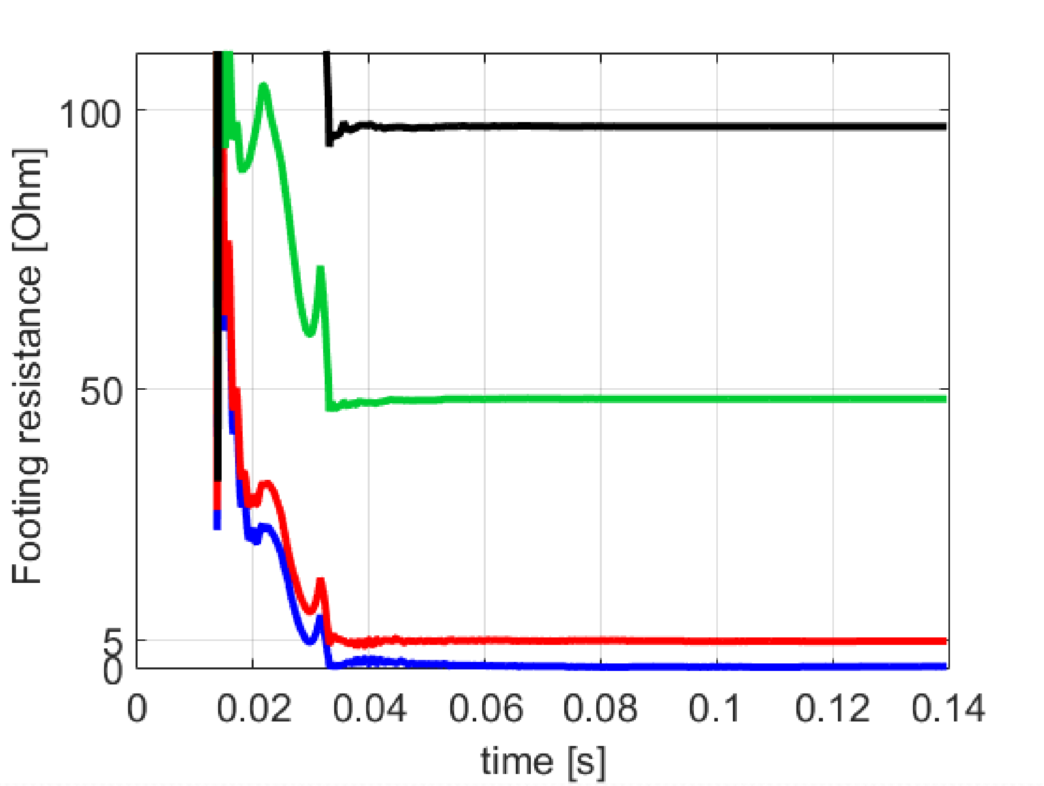


Estimated arc voltage for arcless fault:
(L=150 km, R_F=15 Ω, u_A=0 kV)

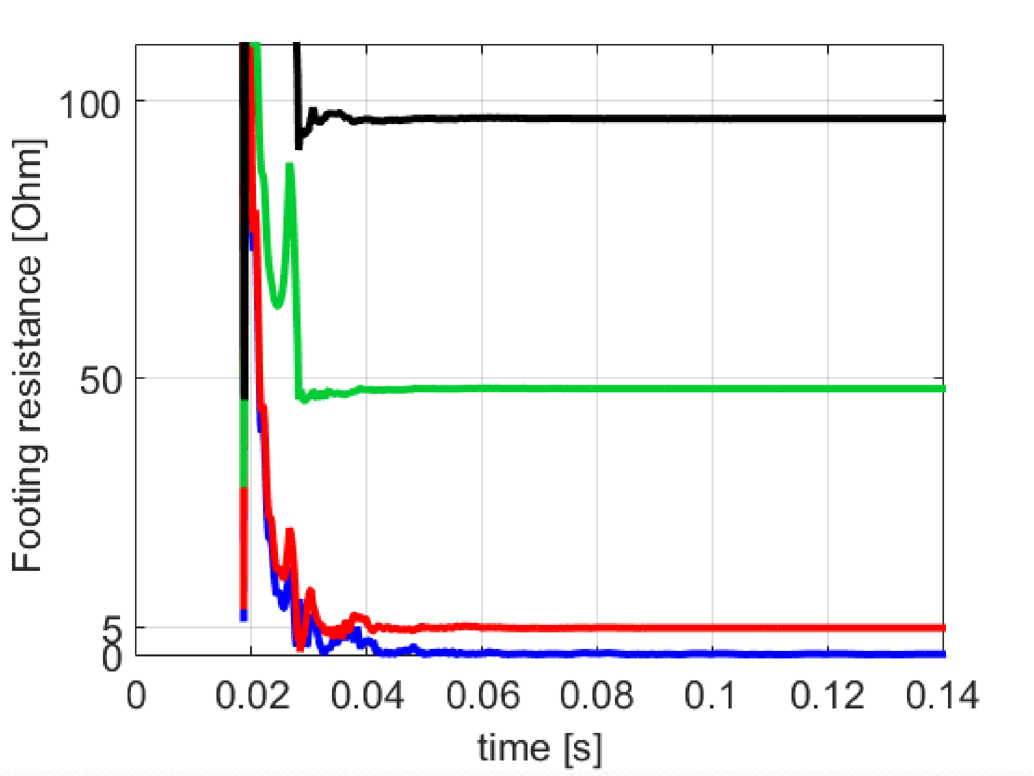


Estimated tower footing resistance

- Estimated tower footing resistance for arcing faults (L=150 km, u_A= 5 kV)

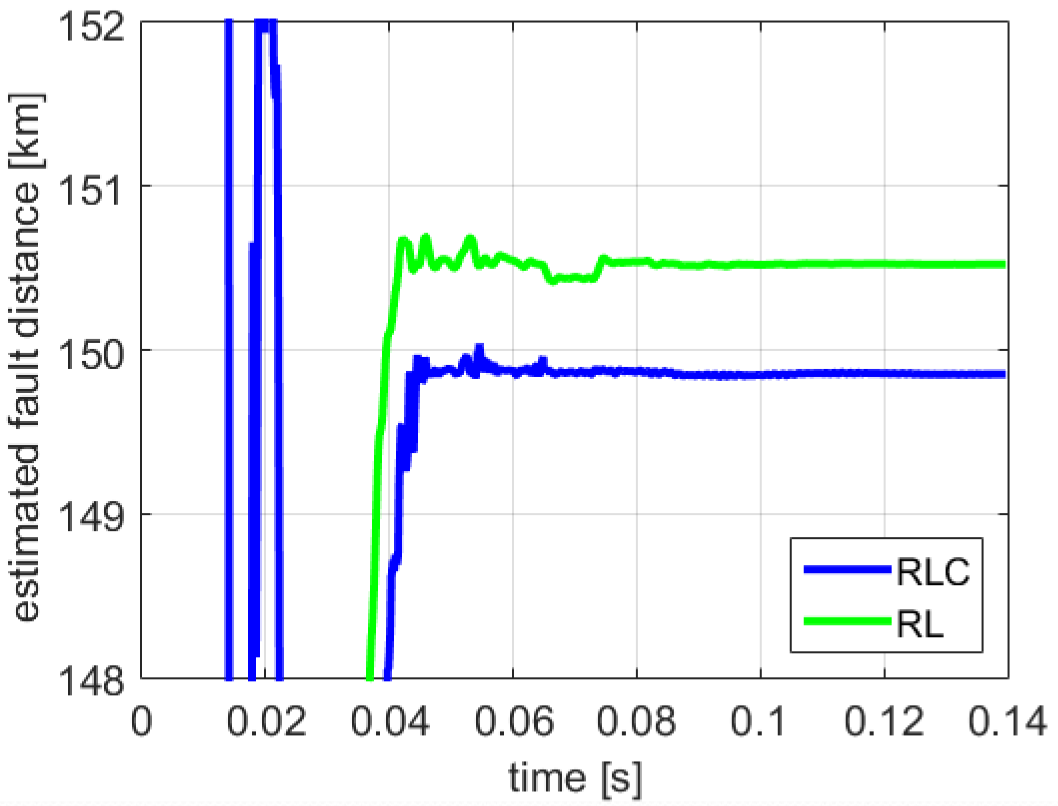


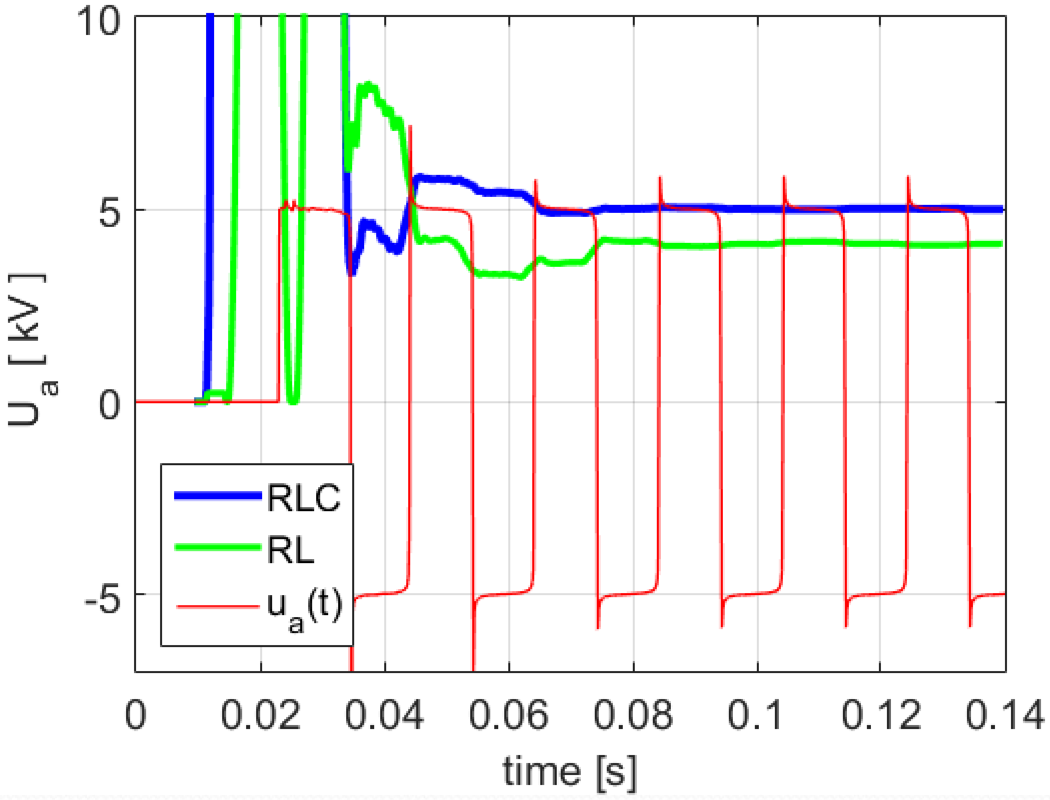
- Estimated tower footing resistance for arcless faults (L=150 km, u_A= 0 kV)



Estimated arc voltage (RLC vs. RL)

- Arc voltage waveform and estimated arc voltage magnitude by RLC and RL algorithms for the arcing fault at 150 km from the LHS terminal.





Conclusions

- Time-domain, adaptive parameter estimation, numerical algorithm for the analysis of L-G faults on long OHL.
- The algorithm utilizes synchronized measurement technology.
- Realistic electric Arc model used in simulations
- Fault distance, arc voltage and footing resistance successfully estimated for in broad range
- Excellent dynamic-tracking algorithm capabilities in fast-changing conditions
- The algorithm has proved to be robust and accurate enough with a high speed convergence

THANK YOU !

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EMC

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