Transient phenomena by travelling waves

Cigré WG A3.22	Technical Requirements for Substation Equipment exceeding 800 kV
Cigré WG A3.28	Switching phenomena and testing requirements for UHV & EHV equipment

San Diego, October 4th 2012

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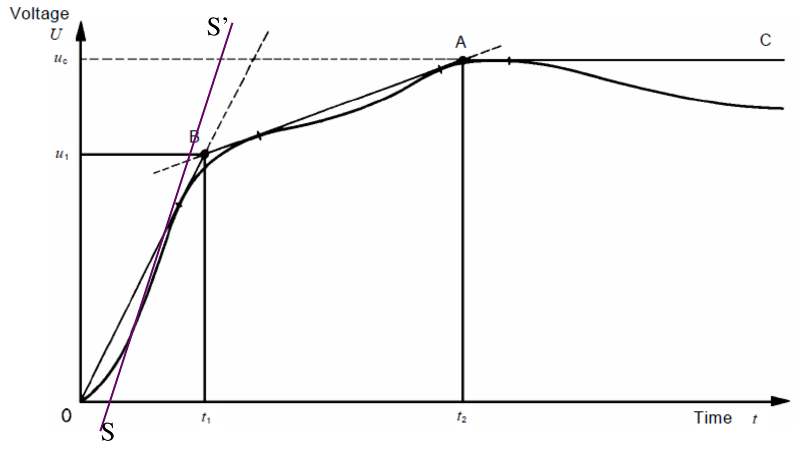
Transient Recovery Voltage envelope

- Current and short-circuit current interruption
- TRV-calculation by current injection at location of CB
- The TRV wave-shape at each side can be seen as the system response to a ramp-function I(t) = S*t, with $S=\omega\sqrt{2}*I_{rms}$ and ω the power frequency
- Generally the system can initially be modelled as R//L//C, with R being the equivalent surge impedance (mainly the OH-lines), L the local inductance (mainly transformers) and C the local capacitance. The system may be overdamped or underdamped, depending on the number of connected OH-lines
- The initial TRV is characterized by a steepness dU/dt, determined by Z_{eq}*dI/dt, and a delay, determined by $Z_{eq}*C_{eq}$
- RRRV (rate of rise of recovery voltage) is the tangent to the TRV waveshape from the origin (0-B)
- Without C_{eq}, the RRRV is equal to the steepness S-S'



Transient phenomena by travelling waves

1. UHV/800 kV and travelling waves
2. Surge impedances
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4. $1^{st}/3^{rd}$ pole clearing 3/1 phase OH-line faults
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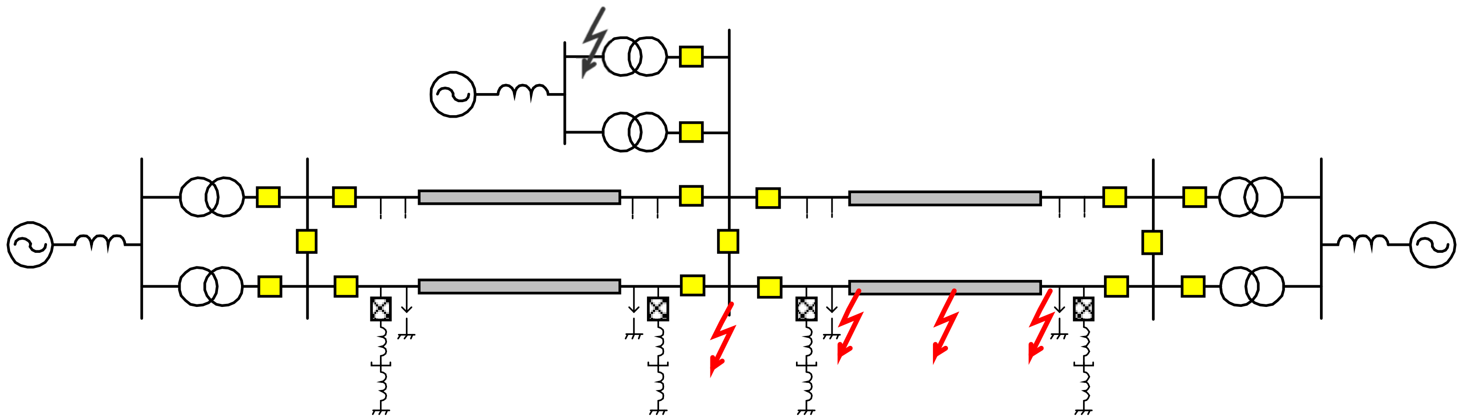
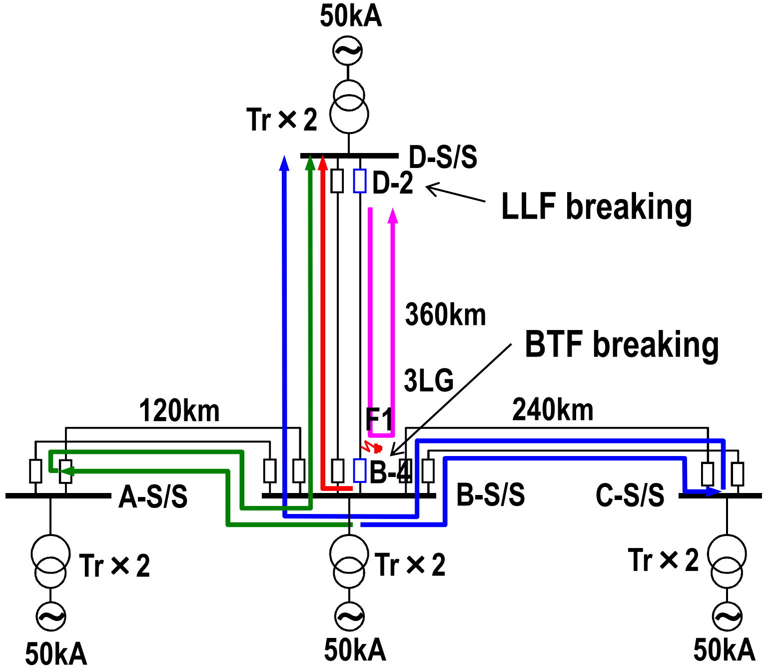
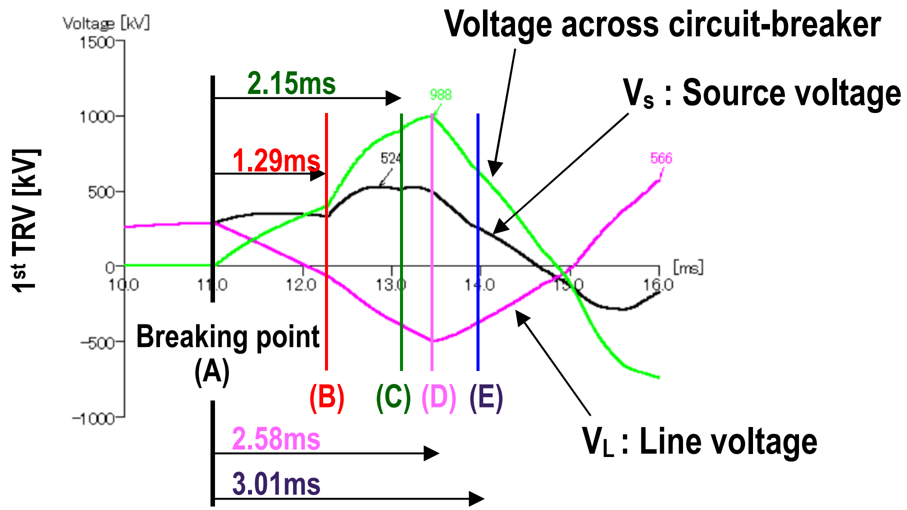
1. UHV/800 kV and travelling waves



- Many faults and fault clearings involve travelling waves
- Simple network configurations give less reflection and refraction
- High voltage, high surge impedance loading, high ampacity, less losses require heavy conductor bundles → low damping of travelling waves
- Back to the basics
- TLF excluded, other phenomena addressed (OoPh, Cap, ITRV)

Inflection points on TRV waveform

Propagation and reflection passes	TRV for LLF of first-pole-to-clear
	

Point A : Breaking point of the first-pole-to-clear

Point B : Arrival of transient propagated from B s/s to D s/s with 360 km travel at 1.29 ms after breaking

Point C : Arrival of transient propagated from B s/s to A s/s and back to B s/s, then form B s/s to D s/s, total travels with 120 km x 2 (0.43 ms x 2) + 360 km (1.29 ms) are 600 km at 2.15 ms after breaking

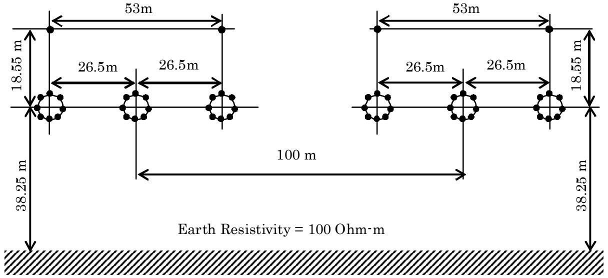
Point D : Arrival of transient propagated from D s/s to B s/s and back to D s/s, total travels with 360 km x 2 (1.29 ms x 2) are 720 km at 2.58 ms after breaking

Point E : Arrival of transient propagated from B s/s to C s/s and back to B s/s, then from B s/s to D s/s, total travels with 240 km x 2 (0.86 ms x 2) + 360 km (1.29 ms) are 840 km at 3.01 ms after breaking, where a propagation velocity = 280 m/μs

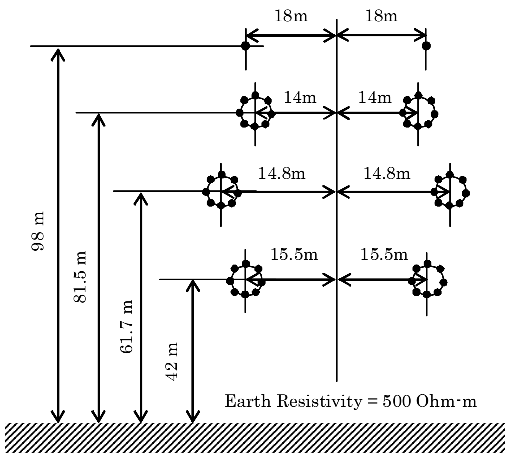
1. UHV/800 kV and travelling waves

← China, single circuit, 1100 kV

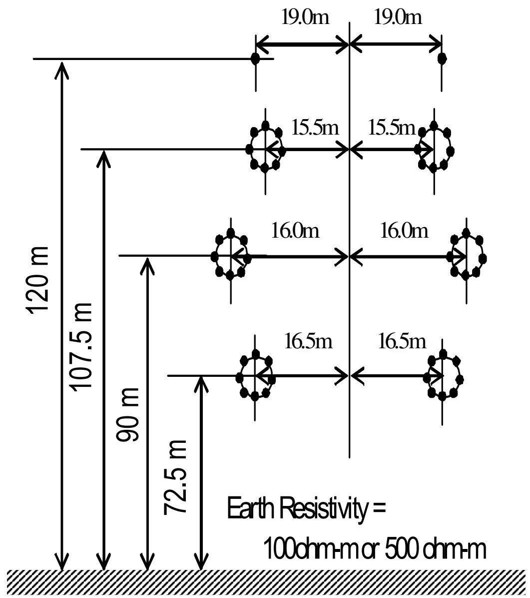
India, single → circuit, 1200 kV



← Japan, double circuit, 1100 kV



China, double circuit, 1100 kV



Japan, double circuit, 1100 kV

1. UHV/800 kV and travelling waves

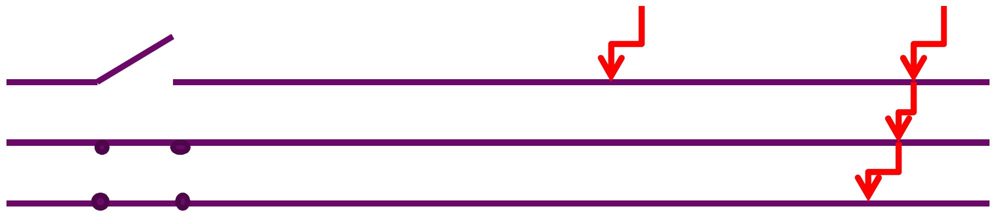
Dimensions in m	Japan	China	India	Canada
Rated voltage, kV	1100	1100	1200	(800)
Nr. circuits	2	2	1	1
Nr. subconductors	8	8	8	4
Diameter subcond.	0.0384	0.055	0.03177	0.03505
Spacing subcond.	0.4	0.4	0.457	0.457
Sag	20	20	-	7.6
Height lower/upper	73/108	42/82	37	27
Nr. shielding wires	2	2	2	2
Diameter shielding	0.0295	0.0175	0.01812	0.0127[1]
Height shielding w.	120	98	55	39
Sag shielding wires	18	18	-	11.7
Earth resistivity, Ωm	100 to 500	500	100	1000

[1]for OPGW: 0.0229

2. Surge impedances

- A surge impedance is not a physical quantity but a ratio
- Ratio between voltage and current component of a travelling wave
- Depends on geometrical configuration of conducting conductors
- Depends not on power frequency currents or faulted phases

For instance for SPAR identical to 1st pole clearing 3-phase fault:



$$Z = \sqrt{(L'/C')}$$

As travelling waves may occur between each pair of conductors and combinations thereof many surge impedances have to be calculated and combined: modal analysis, as used by EMTP or ATP.

2. Surge impedances

some formulae

- Two infinite equidistant (D) conductors with equal radius (r):

$$Z = 60 \ln \{D/r\}$$

as $\sqrt{(\mu_0/\varepsilon_0)}/2\pi = 60$, and Z for each conductor, between conductors: 2Z

- One infinite conductor with constant height (h) above perfect earth:

$$Z = 60 \ln \{2h/r\}$$

earth surface acting as ideal mirror plane:

no penetration of electric and magnetic fields

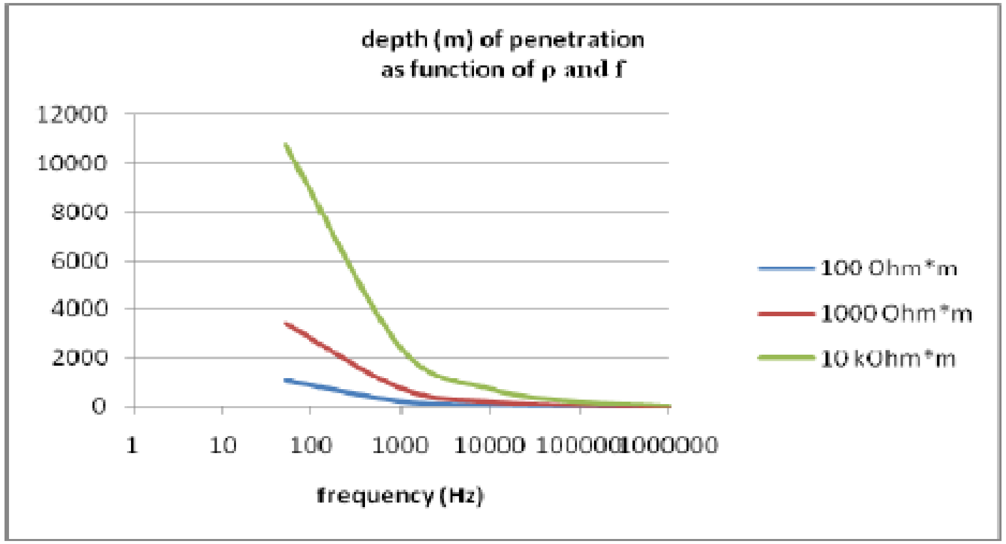
- Imperfect earth:

  especially for magnetic fields

  → depth of conductor' >> h

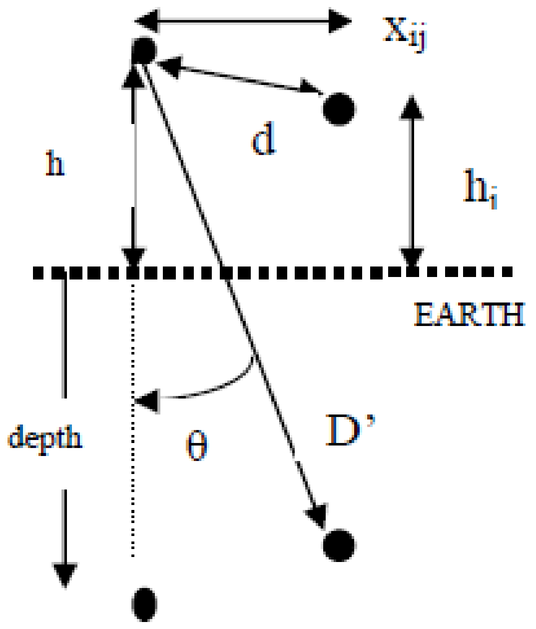
  depth < 25 m :

  - above 100 kHz (100 Ωm)
  - above 1 MHz (1000 Ωm)



2. Surge impedances
some formulae

- Formulae of Carson and Pollaszek for earth return inductance, 1926
- Later, many refinements and practical improvements
- For instance by Taku Noda, IEEE-PD, No.1, Jan. 2005, pp. 472-479
- Simplified for $\theta = 0$:
  $l = 0.2 \ln\{(2h+2\beta p)/r\}$ µH/m
  with $\beta p = 1.07/\sqrt{(\omega\mu_o\sigma)}$ as
  (imaginary) penetration depth
  $Z = 60 \ln\{2h/r\}+30\ln\{1+2\beta p/2h\}$



- For $\theta \neq 0$:
  $l = 0.2 \ln\{D'/d\}$ µH/m
  $Z = 60 \ln\{D/d\}+30 \ln\{D'/D\}$
  with $d=\sqrt{\{(h-h_i)^2+x_{ij}^2\}}$ $D=\sqrt{\{(h+h_i)^2+x_{ij}^2\}}$ $D'=\sqrt{\{(h+h_i+2\beta p)^2+x_{ij}^2\}}$

2. Surge impedances

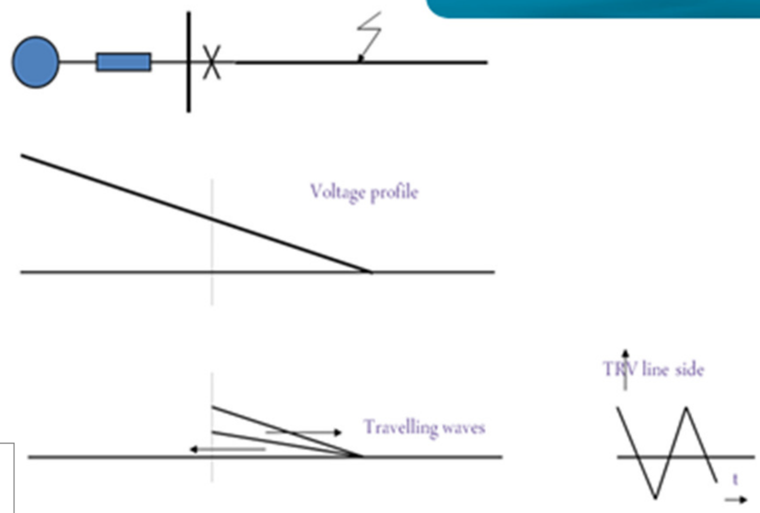
some formulae

- Self surge impedance Z_i with $\theta=0$
  Mutual surge impedance Zij with $\theta\neq0$
  → multi-conductor matrix equations for travelling waves [V]=[Z]*[I]
- By matrix manipulation the mutual terms can be eliminated
  → matrix with self impedances for all travelling wave modes:
  Modal Analysis
- Simple example for a single circuit OH-line:
  $Z_1=\{\Sigma_{i=1to3} Z_{ii} - \Sigma_{i,j=1to3} Z_{ij}\}/3$ $Z_0=\{\Sigma_{i=1to3} Z_{ii} + 2^*\Sigma_{i,j=1to3} Z_{ij}\}/3$

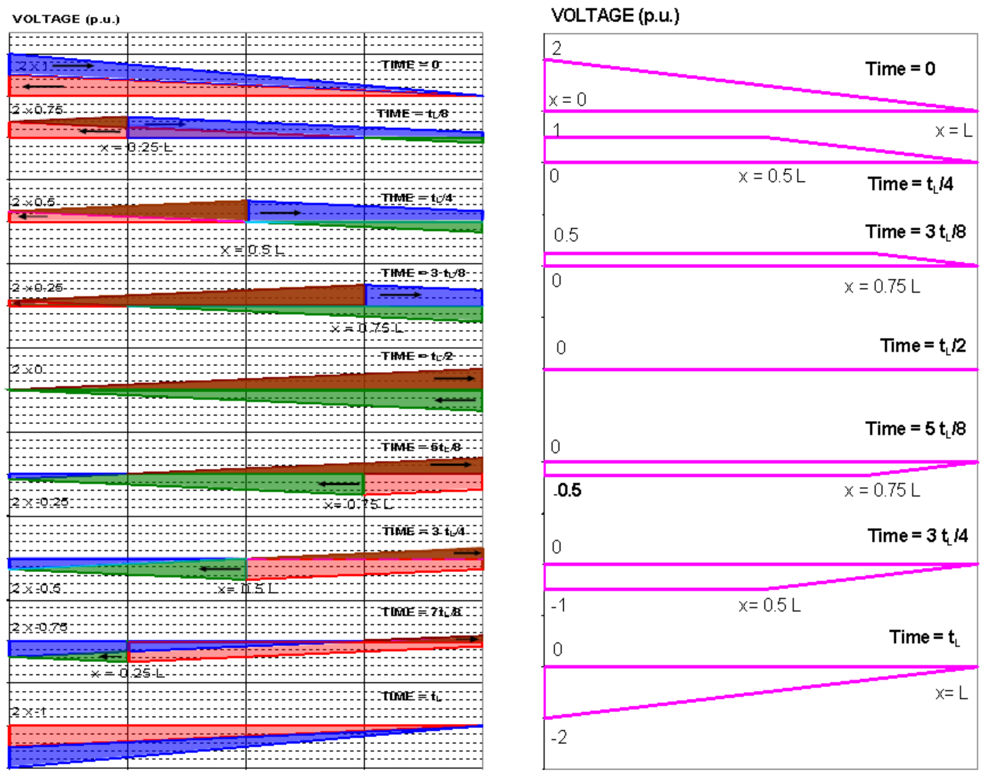
- Height h is height at the tower minus ⅔ of the sag
- Radius r of a symmetrical bundle of N equidistant subconductors is Geometric Mean Radius: $GMR = {}^{N}\sqrt{\{\Pi_{k=1toN} d_k\}}$
  with d_k distance between 1st and kth subconductor , whereas
  d_1=0.78*radius subconductor

3. $1^{st}/3^{rd}$ pole equivalent surge impedance

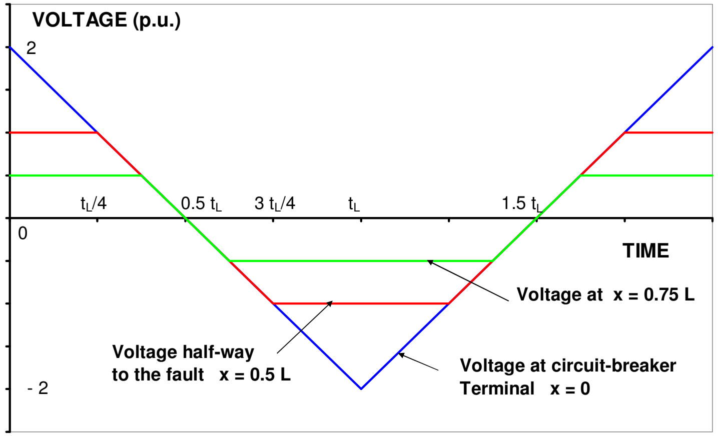
1. travelling waves:



2. voltage pattern along the line:



3. voltage pattern along the time-axis:



3. $1^{st}/3^{rd}$ pole equivalent surge impedance

Example:

- Fault at 1500 m, t_L= 5 µs → 100 kHz
  with 100 Ωm → (imaginary) penetration depth = 25 m
- 8 subconductors, equidistant, d = 0.4 m, r = 0.0192 m →
  GMR = 0.405 m
- Height conductor at tower: 73 m, sag: 20 m → h = 60 m
- Other phase at same height, distance 20 m
- Fault at 150 km: depth 250 m → 1 kHz (not negligible)

sag	h (m)	depth	βp (m)	Zself (Ω)	D' (m)	Zmutual
no	73	no	0	353	147	120
yes	60	no	0	342	121	108
no	73	yes	25	362	197	129
yes	60	yes	25	352	171	118

sag	h (m)	depth	βp (m)	Z1	Z0	Z first	Zlast
yes	60	no	0	234	558	290	342
yes	60	yes	25	234	588	293	352
yes	60	yes	250	244	715	313	401

3. $1^{st}/3^{rd}$ pole equivalent surge impedance

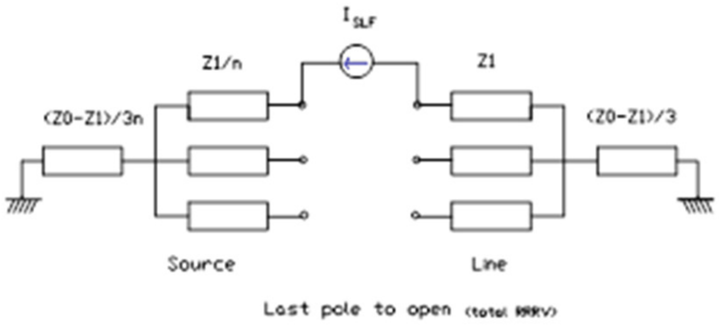
- Take a short-line fault (SLF)
  Current injection with I_{SLF}
- At source side the surge impedance is determined by all n infeeding lines: Z = Z/n
- At each side without capacitance $RRRV=Z_{eq}*\omega\sqrt{2}*I_{SLF}$
- Z_{eq} is independent from neutral treatment and (un)grounded faults
- Z_{eq} expressed in Z_1 and Z_0 through neptune scheme
- For the first and last clearing pole:

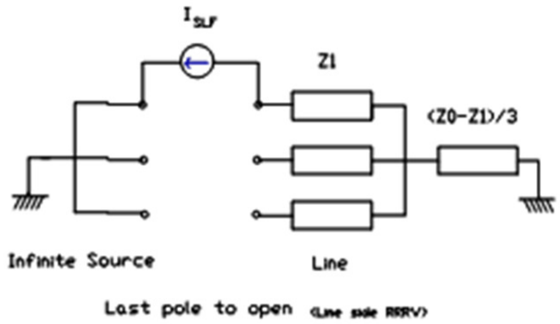
  $Z_{first} = 3Z_0Z_1/(Z_1+2Z_0)$

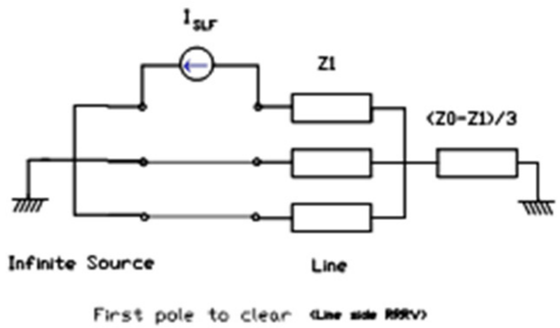
  $Z_{last} = (2Z_1+Z_0)/3$

  $Z_{first} \sim 0.9\ Z_{last}$
- $Z_{neutral} = (Z_0-Z_1)/3 = Z_{mutual}$

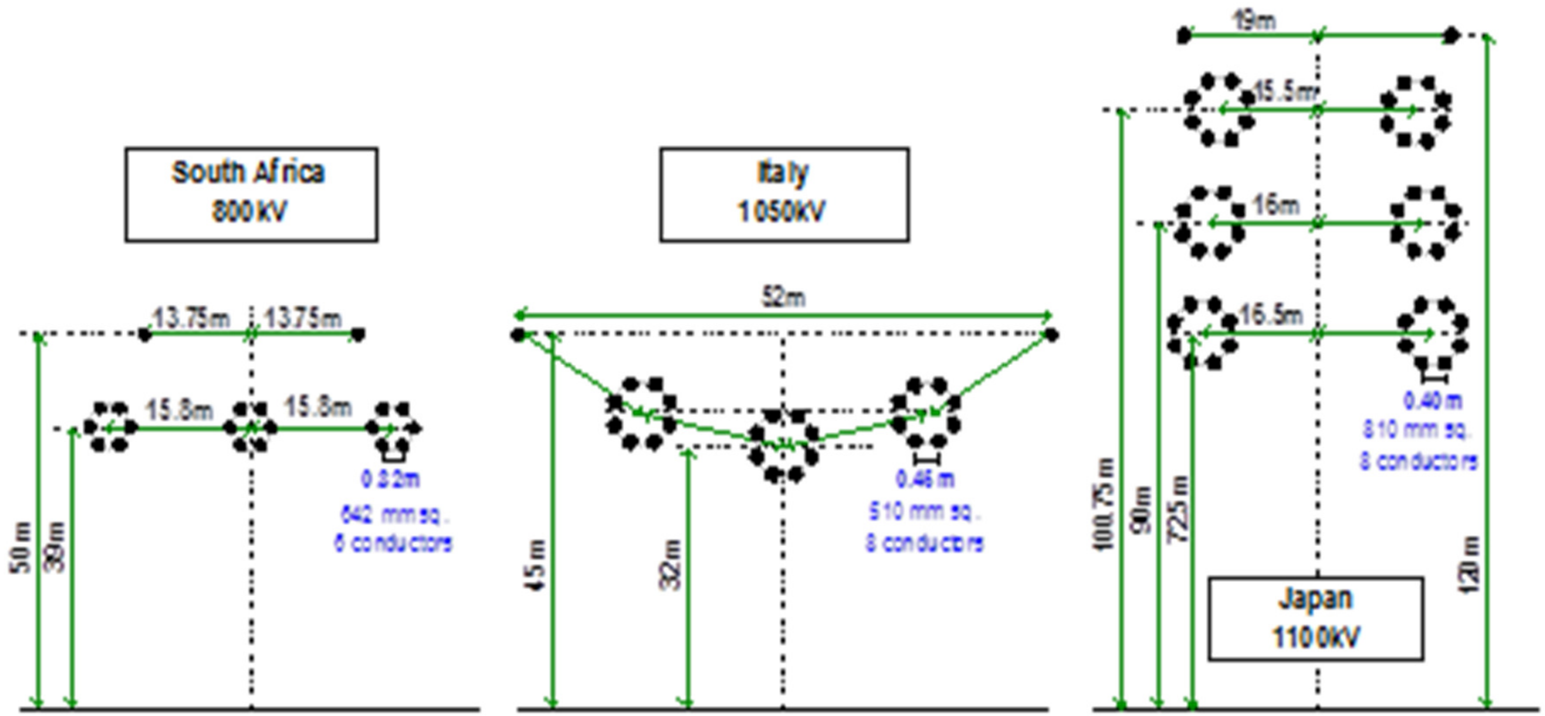
  $Z_{last} = Z_{self} = Z_1+Z_{neutral}$







3. $1^{st}/3^{rd}$ pole equivalent surge impedance



3. 1st/3rd pole equivalent surge impedance

- To IEC 62271-100
  Z_{last} = 450 Ω (≤ 800 kV)
  Z_{last} = 330 Ω (UHV)
- 450 Ω for single conductor or fully contracted bundle
- 360 Ω for not fully contracted bundle
- for ≥ 800 kV 300 to 330 Ω
- For first pole even lower.

Country	Size (mm²)	Number of Conductor	Span (m)	Sub-conductor distance (mm)	Initial tension (kN)	Breaking current (kA)	Time to bundle collision, Cal. (sec)	Time to bundle collision, Exp. (sec)
Italy	520	8	---	450	---	50.0	0.166	---
Japan	410	6	45	400	34	40.8	0.140	0.110
	410	6	45	400	34	53.2	0.106	0.080
Japan	810	4	45	550	49	40.8	0.148	0.124
	810	4	45	550	49	53.2	0.114	0.090
	810	8	50	400	53	50.0	0.202	---
	810	8	45	400	60	50.0	0.149	---

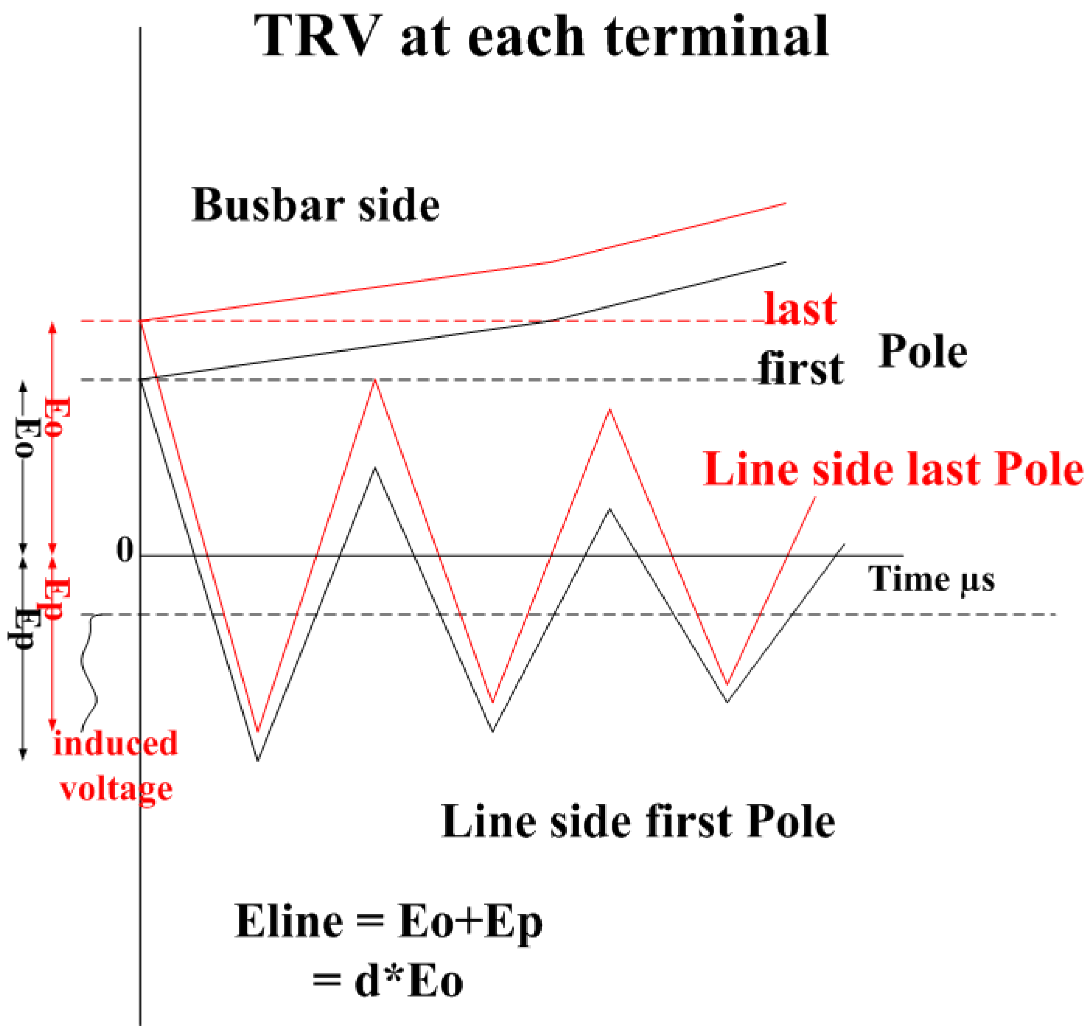
Rated voltage	conductors	frequency	condition	Z_0 Ω	Z_1 Ω	Z_{eq} first	Z_{eq} last
550 (Japan)	8*410 mm²	60 Hz	normal	509	228	279	322
		60 kHz	normal	444	226	270	299
		60 kHz	contract.	580	355	408	430
800 (RSA)	6*428 mm²	50 Hz	normal	561	258	315	359
		27.5 kHz	normal	403	254	290	304
		27.5 kHz	contract.	509	359	398	409
1050 (Italy)	8*520 mm²	50 Hz	normal	485	211	260	302
		26.2 kHz	normal	406	210	250	275
		26.2 kHz	contract.	532	343	389	406
1100 (Japan)	8*810 mm²	50 Hz	normal	504	236	287	325
		25 kHz	normal	476	228	276	311
		25 kHz	contract.	595	339	396	424

3. 1st/3rd pole equivalent surge impedance

Apart from bundle contraction, that has a huge influence, rough indications of the Z_{eq} reduction and addition factors:

Influence	Variation
Other poles conducting	- 10%
Earth wires	- 5% to - 10%
Double circuit on OH-line (conducting)	- 10%
Extra high towers	+ 5%
Very high towers	+ 15%
Very high earth resistivity	+ 5%
High earth resistance in substation	+ 15%
Higher frequency (shorter distance to fault)	- 5%

4. 1st/3rd pole clearing 3/1 phase OH-line faults



3-phase fault, first versus last pole:

- Fixed fault location on line
- Same fault current for last as for first pole assumed (depends on X_0/X_1-ratio at busbar-side and at line side)
- First pole compared to last pole: somewhat lower Z → lower RRRV
- Excursion or d-factor: ratio line-side (hf) peak value to initial (lf) voltage: $Eline/E_0 = \{|Ep|+|E_0|\}/E_0$
- Roughly last pole d ≈ 1.6

  theoretically first pole d ≈ 2.4

  practically first pole d ≈ 2.0 (losses, different propagation speeds, etc.)
- d-factor for first pole larger due to induced low frequency voltage

but physically it is damped travelling wave phenomenon

4. 1st/3rd pole clearing 3/1 phase OH-line faults

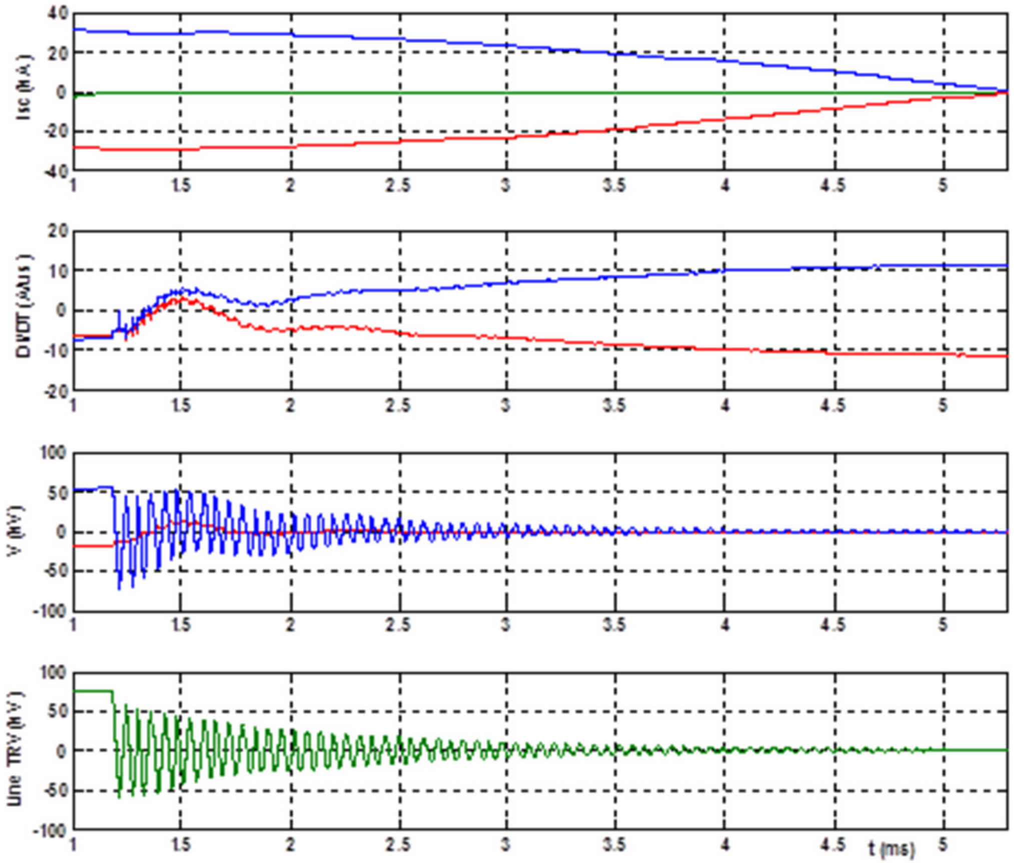
Fault currents: green is first interrupted phase current

dI/dt of blue and red phase fault currents

Line-side TRV of first pole (blue) and (lf) induced voltage (red)

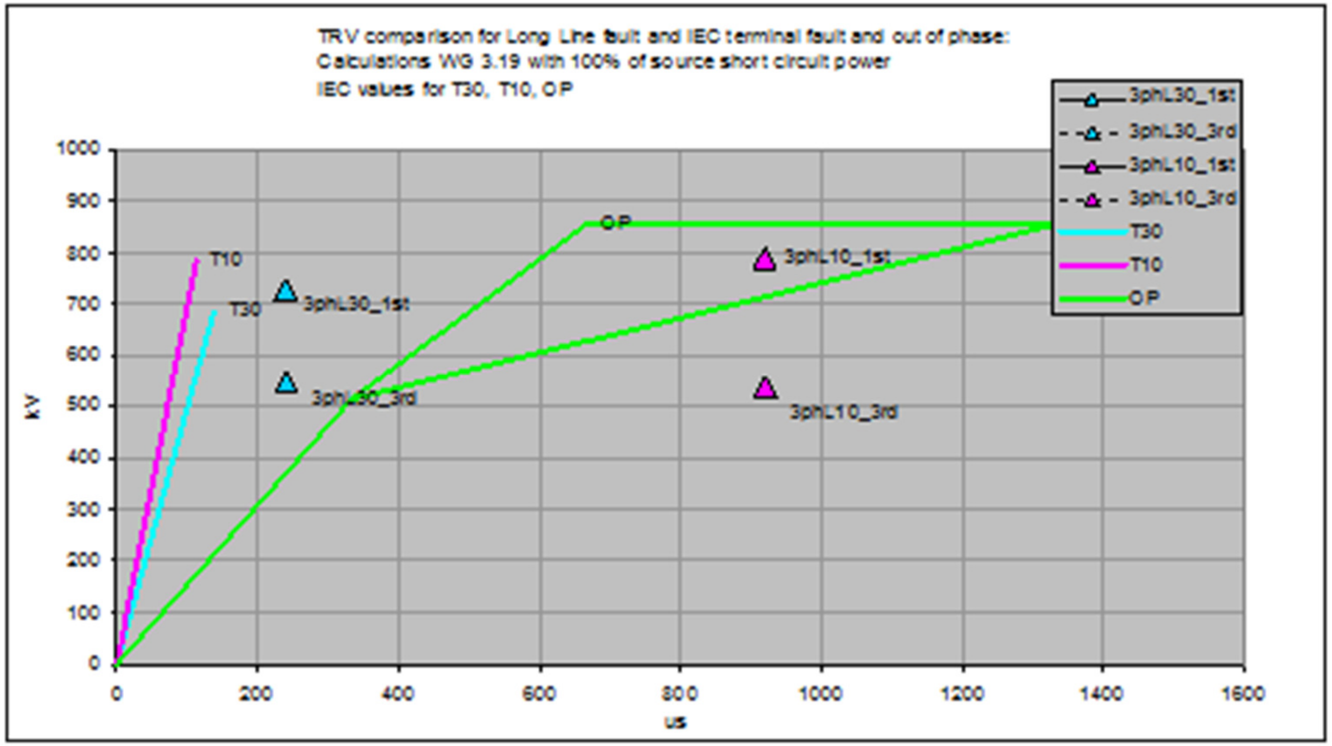
Line-side TRV without (lf) induced voltage (green)

Note blue and green reference Ep/E_0



4. 1st/3rd pole clearing 3/1 phase OH-line faults

- Long line faults, covered by T10, T30 and OP
- Low fault current, relatively low RRRV
- Large time to peak, steadily increasing line-side TRV
- Relatively low frequency, large depth, relatively high Z, larger d-factors
- Last pole TRV-peak lower than first pole TRV-peak, due to lower current!



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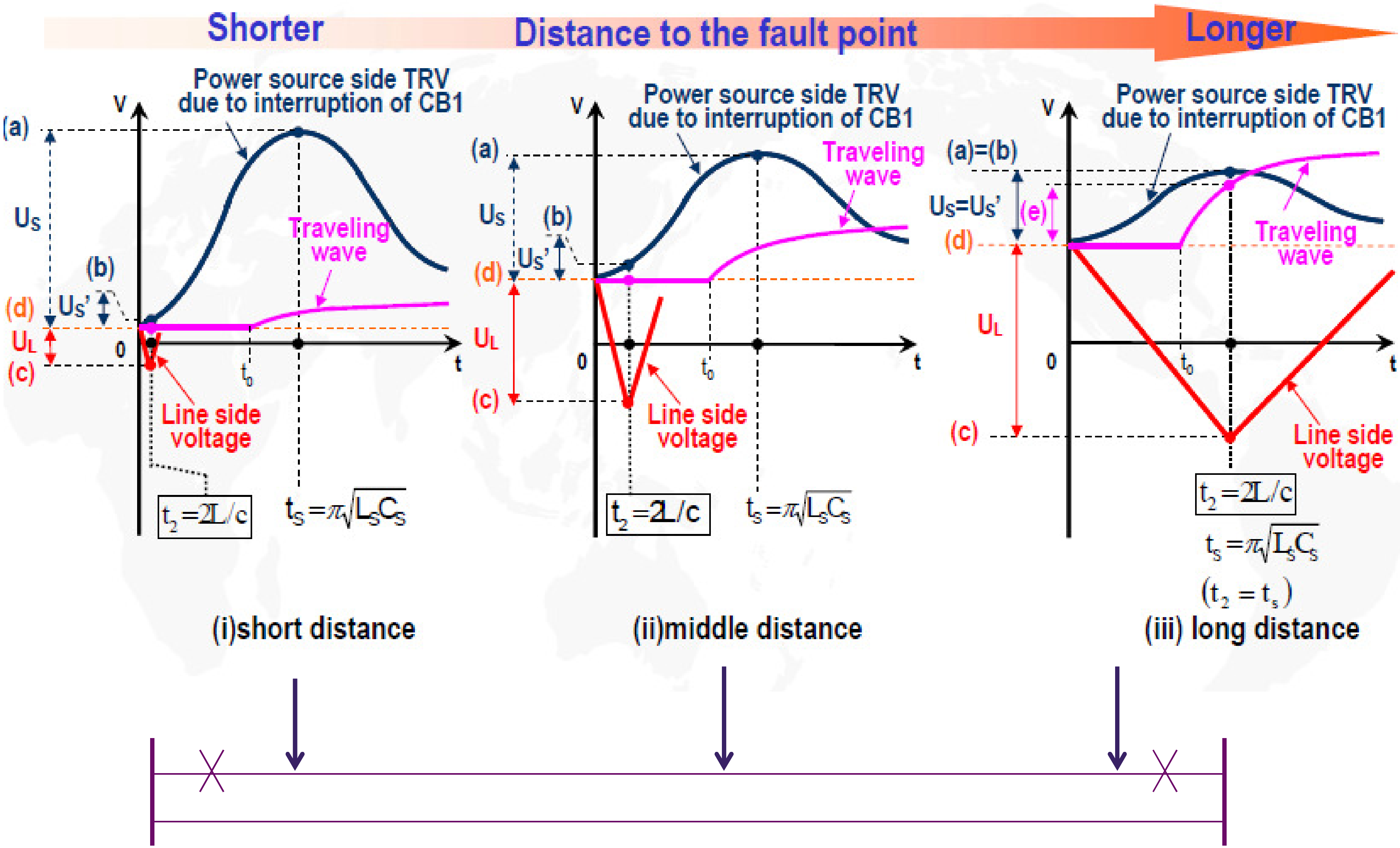
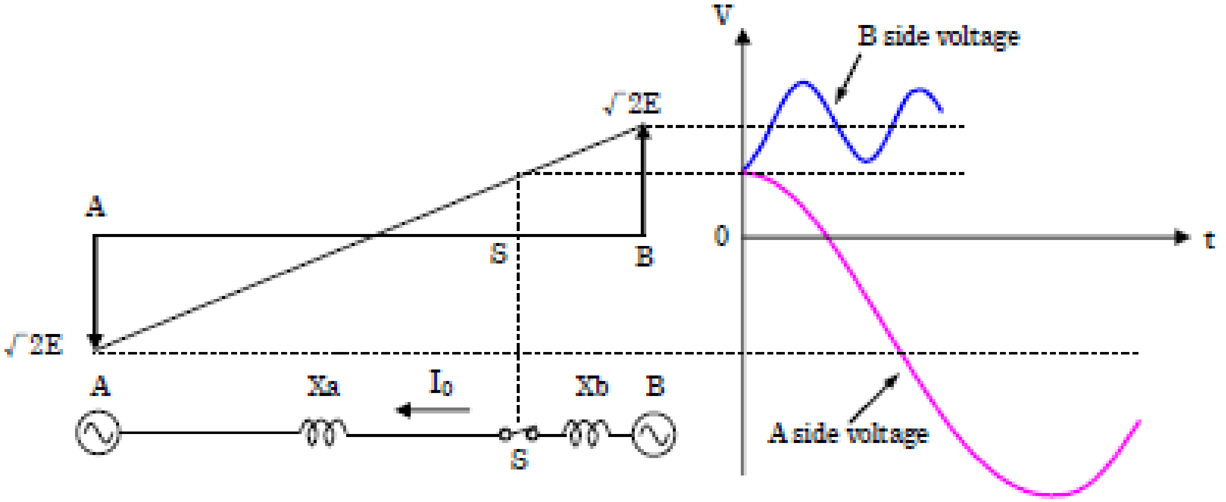


5. Other line-side phenomena (OofPh, Cap.)



$$I_0 = 2E * \sin(½\theta) / (X_a + X_b)$$

$$= 2E / (X_a + X_b) \quad (\text{When } \theta = 180 \text{ degree})$$

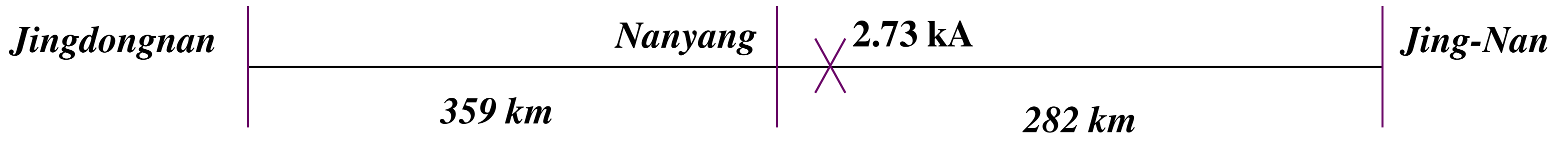
Equilibrium point on OH-line is not a fault location, so no reflection point.

At clearing OP: travelling waves along the whole line length, and possibly also along the source-side lines.

RRRV depends on out-of-phase current I_0 (out-of-phase angle θ) and on the equivalent surge impedance Zeq. For first clearing pole it will be less than 300 Ω (UHV, one circuit).

5. Other line-side phenomena (OofPh, Cap.)

Two UHV examples from China: (1) single circuit 1100 kV pilot



Positive reflections
after 1.88 ms
(after 2.39 ms)
until 1.88 ms:
RRRV=0.65 kV/µs
540 Ω, twice 270 Ω

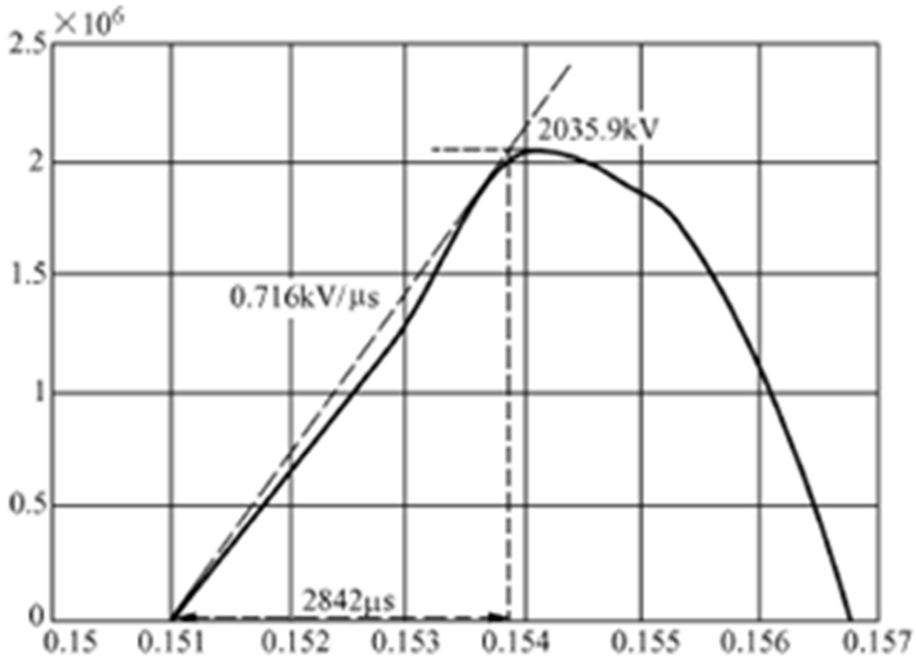
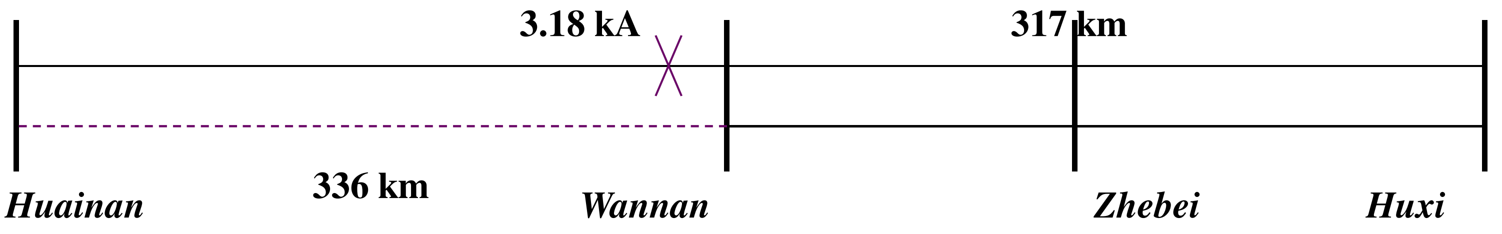


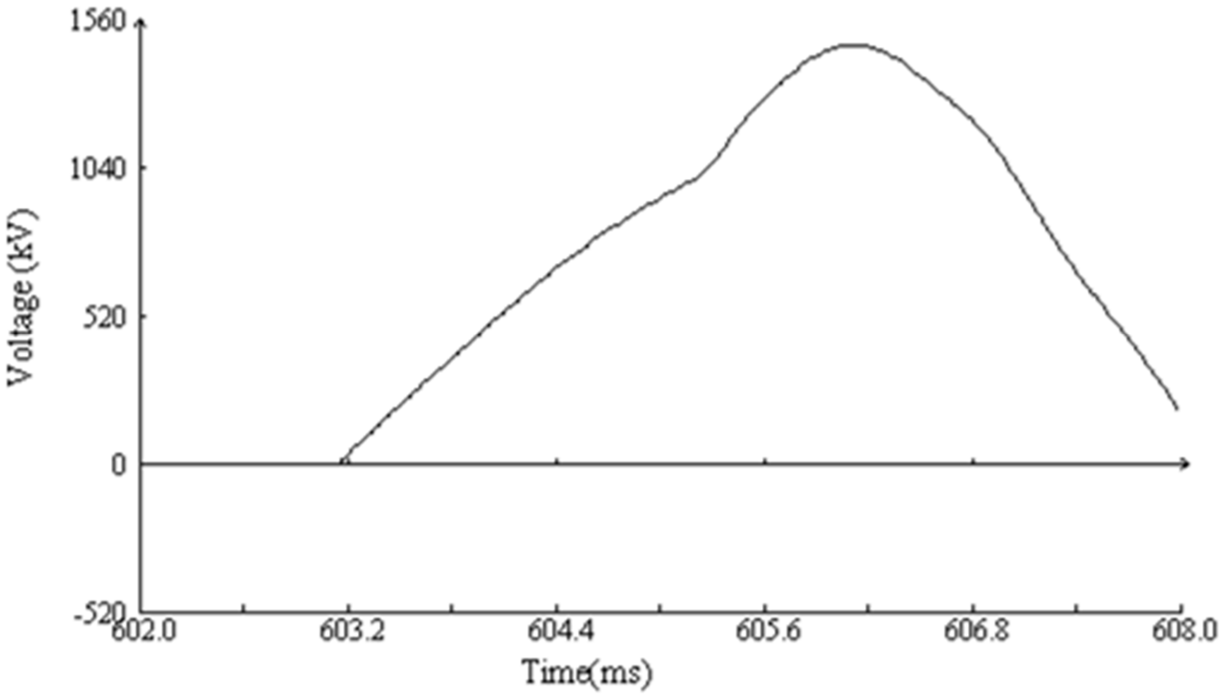
Fig. 5 TRV waveform of Nanyang CB during out-of-phase while the oscillation center is in Jing-Nan line

5. Other line-side phenomena (OofPh, Cap.)

Two UHV examples from China (2): double circuit 1100 kV-line



Positive reflection
after 2.1 and 2.2 ms
RRRV = 0.542 kV/µs
Zeq = 383 Ω = 1½ Z
Z = 256 Ω
Natural freq. 170 Hz
by line capacitance
short-circuit react.



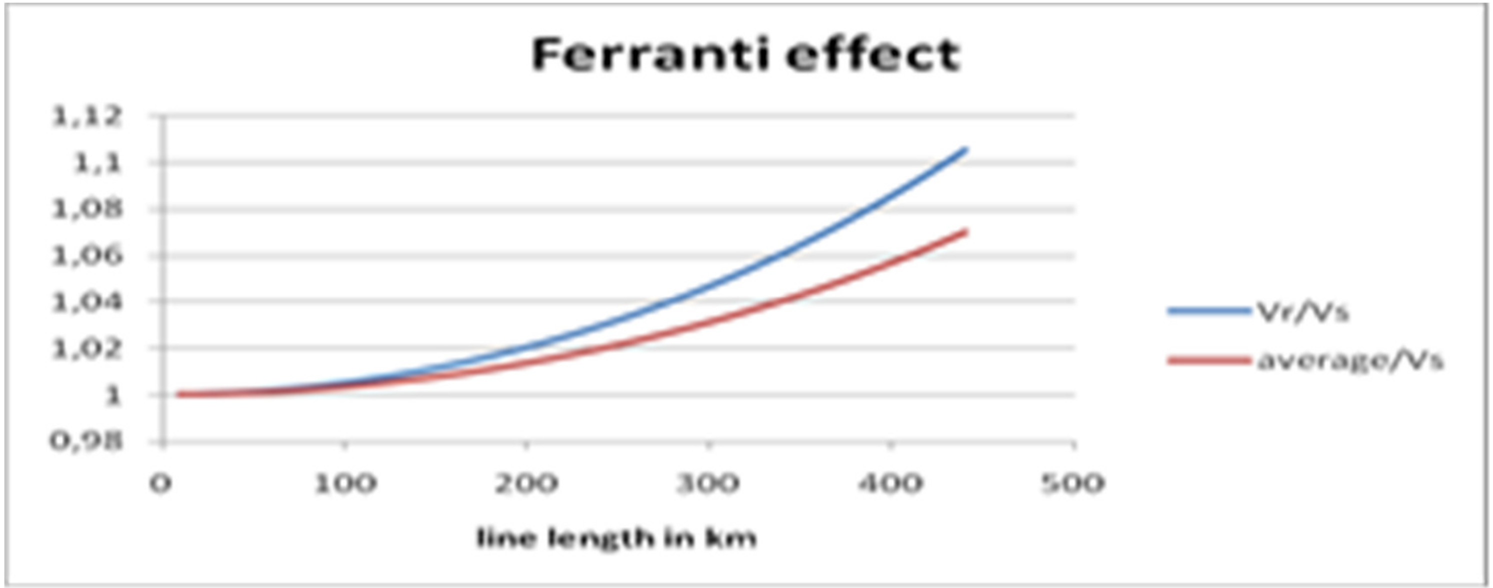
5. Other line-side phenomena (OofPh, Cap.)

Switching off an unloaded OH-line (line-charging current switching)

Voltage along OH-line (Ferranti-effect):

$$V(x) = V_r \cos\{\beta(L-x)\}$$

with V_r voltage at open end, line length L, x the distance from CB at beginning of line, $\beta=\omega/c=0.001$ rad/km (for 50 Hz), $V_s=V(0)$ voltage at CB.



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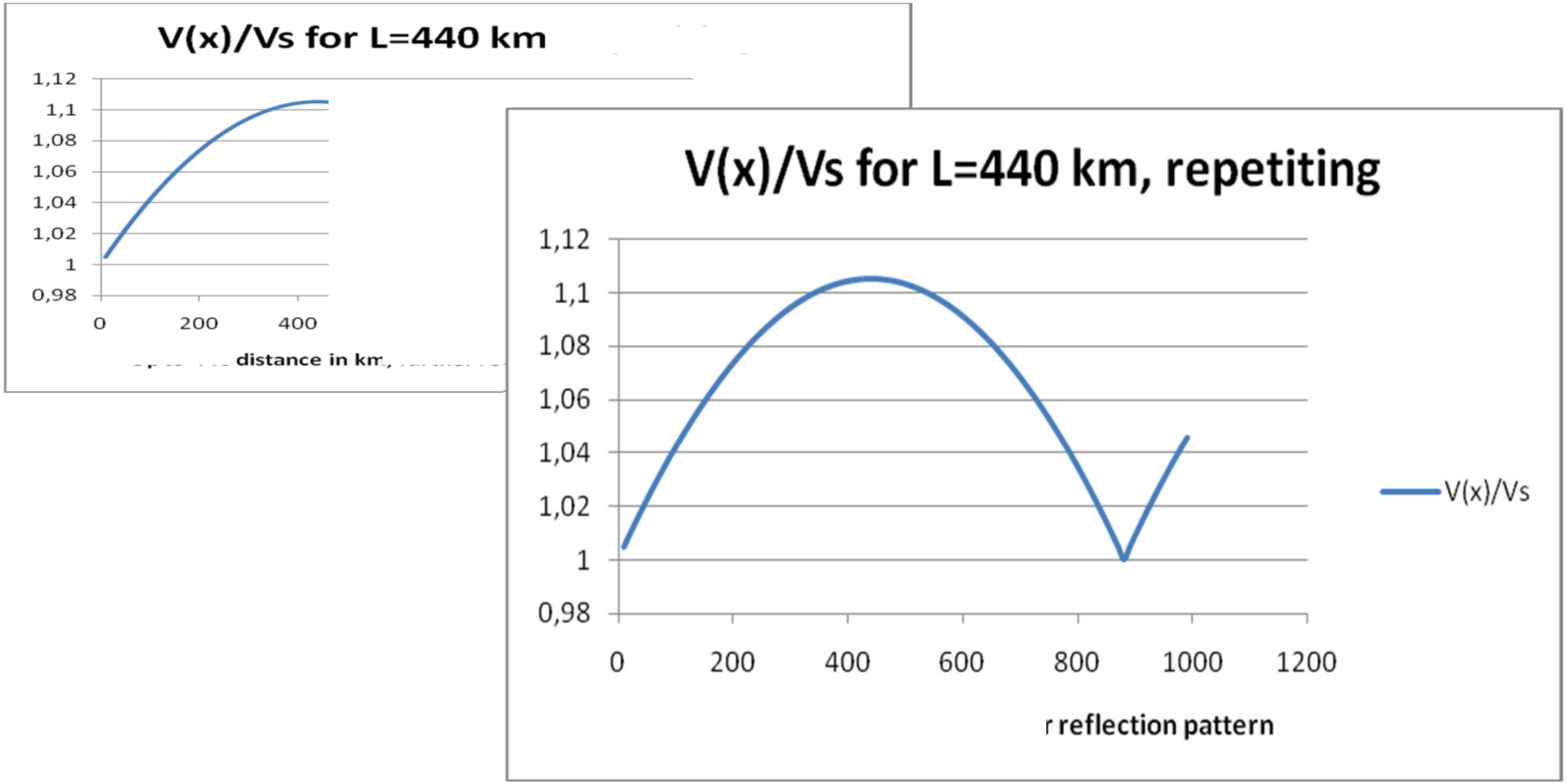

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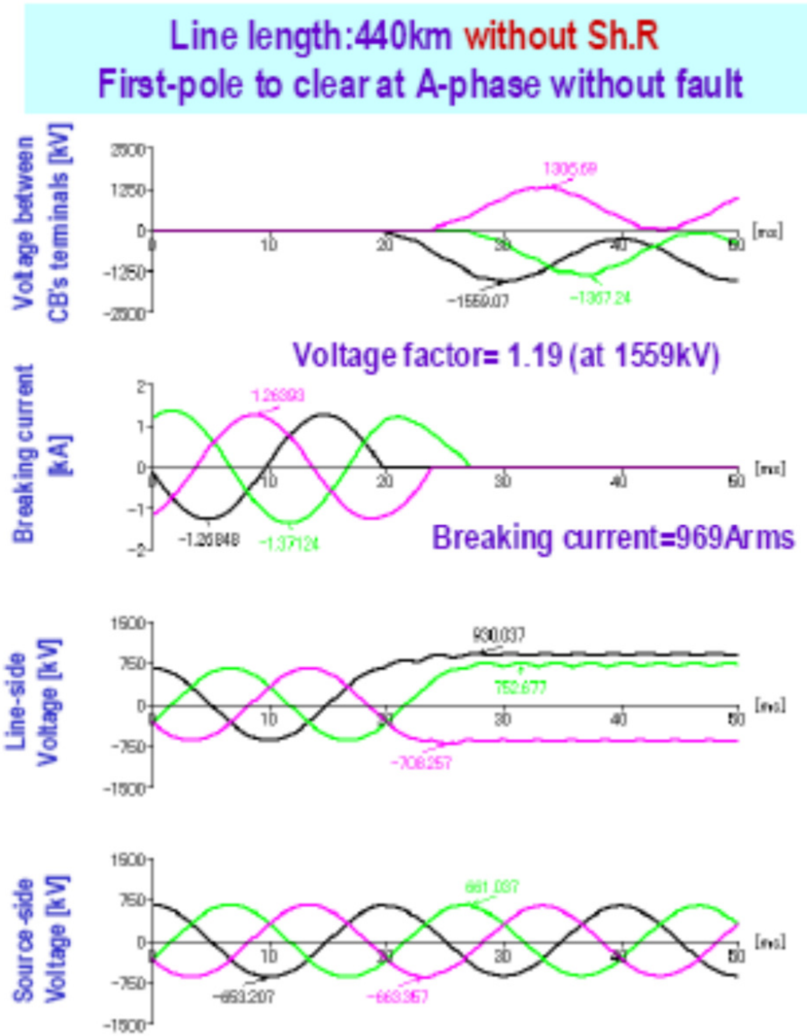
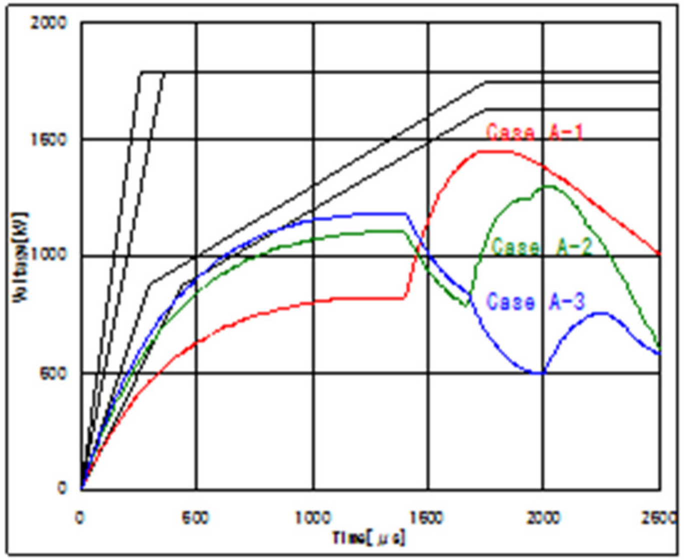
Switching off an unloaded OH-line (line-charging current switching)

800 kV-simulation:



6. Source-side phenomena (BTF, MOSA)

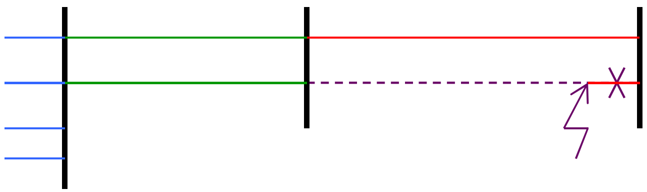
- Reflections in source side connected OH-lines
- Travelling wave in parallel circuit , example Tepco, 210 km double circuit OH-line to substation with BTF



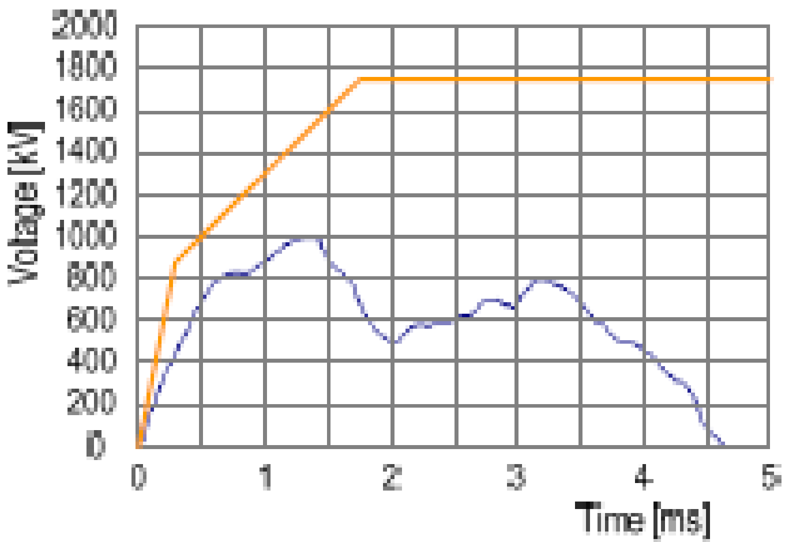
← parallel circuit switched off (1.4 ms)

A-1: no OH-lines at other end

A-2 and A-3: a double circuit OH-line at other end

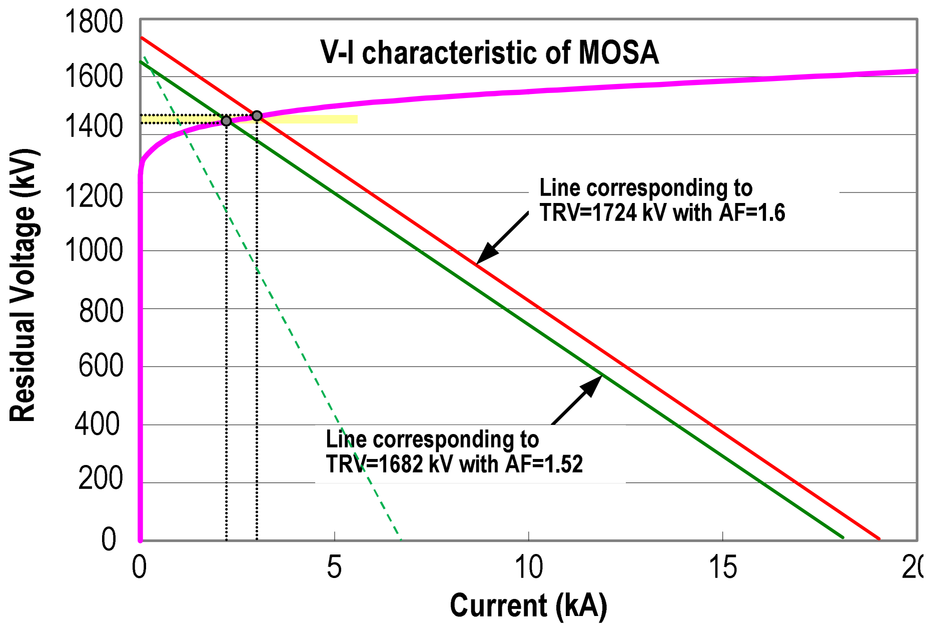


case A-3 with parallel circuit ↓ (0.8 ms): - - - - -

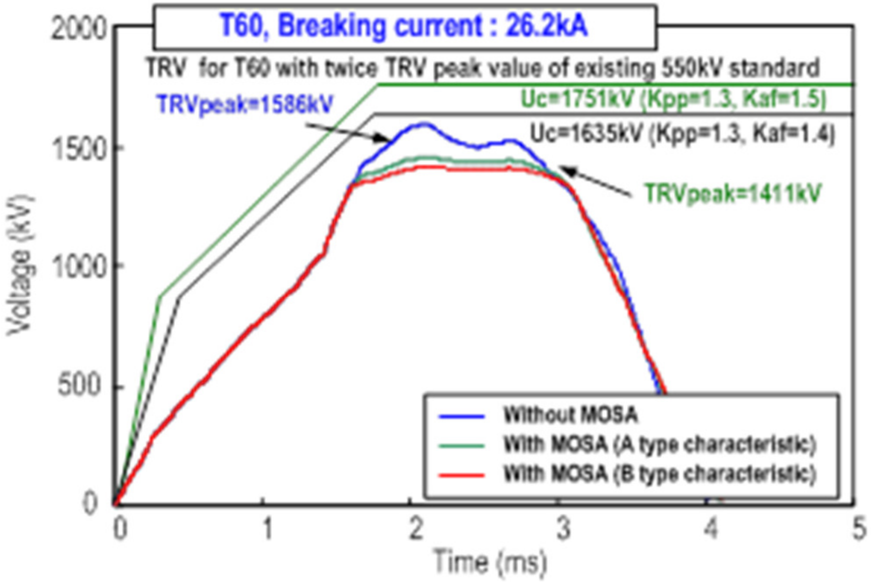


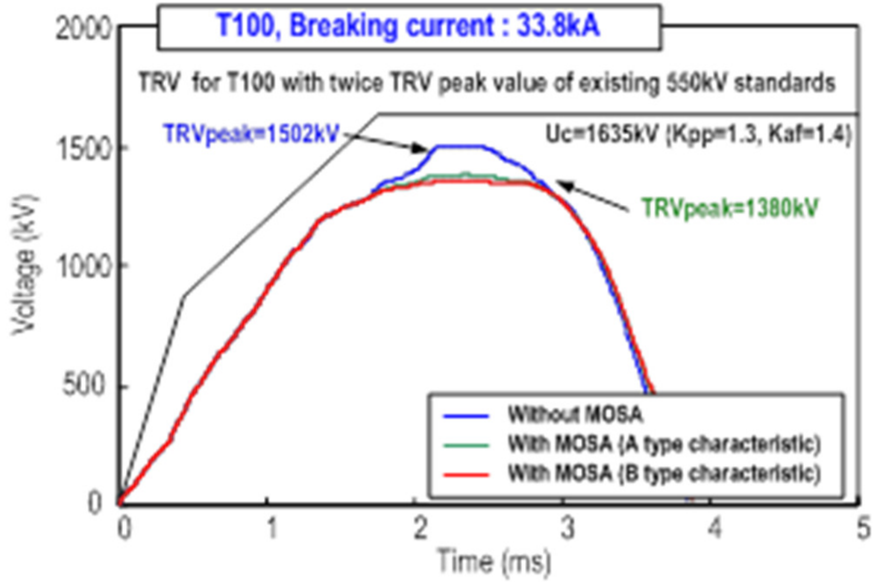
6. Source-side phenomena (BTF, MOSA)

- Because of linearity and superposition:
  TRV-calculations by current injection
  RRRV = Zeq * dI/dt
  initial part of TRV = Zeq * I(t)
- Effect of MOSA, when diverting a current I_A is similar:
  a negative current injection - $I_A(t)$
  $\Delta TRV(t) = -Zeq * I_A(t)$
- Seen from the MOSA: Zeq = Z/n with Z the surge impedance of a OH-line circuit and n the number of circuits
- For $I_A(t) = 0$ the voltage at the MOSA will be actual TRV value without MOSA interference, for instance Uc
  For $I_A(t) \neq 0$ the voltage at the MOSA will be $Uc - Zeq * I_A(t)$
- With m MOSA parallel $I_A(t)$ becomes $I_A(t)/m$
- So, by n>> and by m>> line becomes steeper: - - - -



6. Source-side phenomena (BTF, MOSA)





7. ITRV

Travelling waves inside a substation

- Initial TRV: small triangular waveforms during first µs, due to travelling waves inside AIS substation.
- Busbar surge impedance depending on height, diameter and additional capacitance. Example from Indian design for 1200 kV AIS:

  height connections and busbars are at several heights, e.g. 18 m, 38 m, 50 m

  diameter 1.17 m for octogonal bundle conductors (or 0.321 m for twin Al tubes)

  additional 1 pF/m for post insulators, 1.4 pF/m for CTs, etc. → 20% reduction of Z

  → Zself ≈ 260 Ω

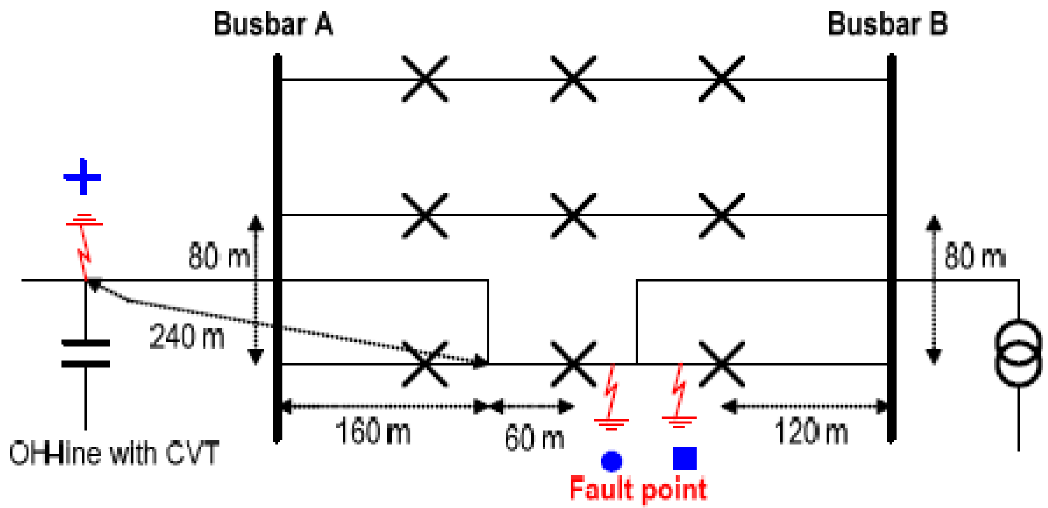
- UHV GIS show a surge impedance of 90 Ω and equipment/bushings a large time delay, low enough to neglect ITRV
- HIS or MTS the effects of GIS-busbars beyond 15 m and equipment/bushing capacitances is so large that they can be treated as GIS
- Deadtank-breakers are to be treated as life tank
- UHV AIS gives severe ITRV stresses due to the large dimensions

7. ITRV

- Fault ■ gives a travelling wave that reflects after 120 m with -⅓ at busbar B and again after 80 m at next diameter (→ peak value)
- Fault ● gives a reflection after 60 m, unless left connection doesn't exist → reflection after 220 m (1.5 µs) or more
- Fault + gives travelling waves at both sides of CB, to be compared with L90:

  SLF with 90% @ 450 Ω (standard for EHV) → RRRV ~ 405

  Double side ITRV with, say, 75% @ 260 Ω → RRRV ~ 390



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THANK YOU