Transformer Limited Fault TRV

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Tutorial made at the IEEE Switchgear Committee Meeting in San Diego (USA), on October 4th, 2012.

Content

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1 - Introduction

TLF / Introduction

- Severe TRV conditions may occur when there is a fault with a short-circuit current fed by a transformer without any appreciable capacitance between the transformer and the circuit breaker*.

  These faults are called Transformer Limited Faults (TLF).

  In such case, the rate-of-rise of recovery voltage (RRRV) exceeds the values specified in the standards for terminal faults.

  For example in case of a 362 kV 63 kA circuit breaker, the RRRV (Rate of Rise of Recovery Voltage) in ANSI Guide C37.06.1 is

  - 2.2 to 4.4 times the value for a terminal fault with a short-circuit current respectively equal to 7% and 30% of rated value, i.e.
  - 15.4 kV/µs and 22.2 kV/µs respectively for breaking currents of 4.4 kA and 18.9 kA.

* In usual cases TLF is covered by terminal fault test duties T10 and T30.

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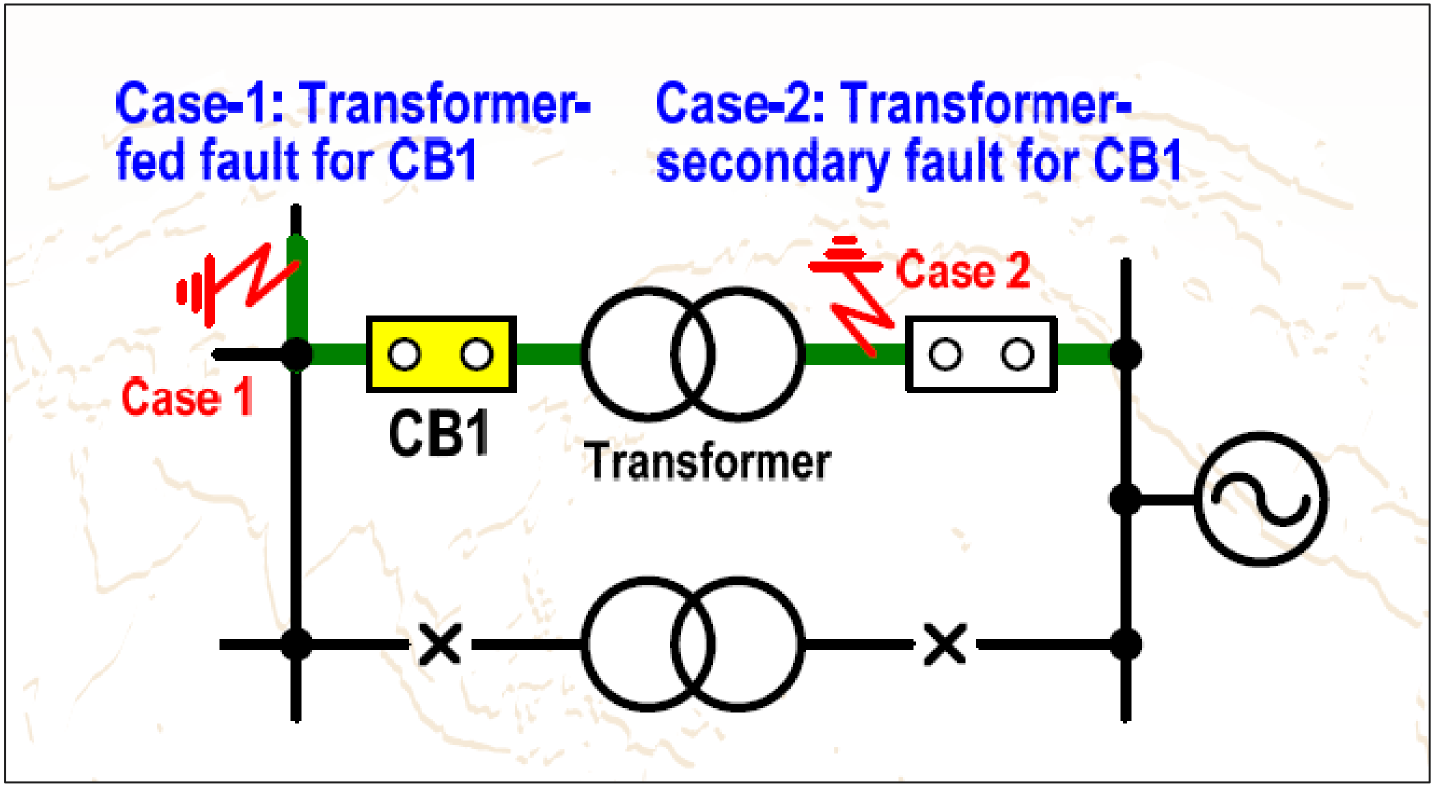
TLF / Introduction

- In Standards or Guides, the TLF duty covers two cases



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2 - Options for the Specification of TLF in IEEE C37.011-2011

TLF / Options for Specification

- As explained in IEEE C37.011-2011 (Guide for the Application of TRV for AC High-Voltage Circuit Breakers), the user has several basic possibilities
  1. Specify a fast TRV for TLF with values taken from standards or guides (e.g. ANSI C37.06.1),
  2. Specify a TRV calculated for the actual application taking into account
     - the natural frequency of the transformer,
     - and/or (depending on the knowledge of system parameters) additional capacitances present in the substation, sum of stray capacitance, busbar, CVT etc
  3. Add a capacitor to reduce the RRRV

TLF / Options for Specification

- **Option 1**: Specify a fast TRV for TLF with values taken from Guides (e.g. ANSI C37.06.1)
  - ANSI Guide C37.06.1 is assumed to cover the large majority of all cases for this switching duty.
  - TLF TRVs are given for two fault currents: 7% and 30% of rated short-circuit current.
  - They are based on the assumption of a negligible capacitance between the circuit breaker and the transformer.

TLF / Options for Specification

- **Option 1 (Cont'd)**: TRV values in ANSI C37.06.1

Table 3B–Transient recovery voltage ratings fast time-to-peak (T_2) values for definite purpose circuit breakers 123 kV and above

				Rated Transient Recovery Voltage (1)		Definite Purpose TRV Parameters at 30% of Rated Short-Circuit Current			Definite Purpose TRV Parameters at 7% of Rated Short-Circuit Current		
Line	Rated Maximum Voltage kV, rms (1)	Rated Voltage Range Factor (1)	Rated Short-Circuit and Short-Time Current kA, rms (1)	Peak Voltage E_2 kV, peak	Time to Peak T_2 µsec	Current kA, rms	Peak Voltage kV, peak	Time to Peak µsec	Current kA, rms	Peak Voltage kV, peak	Time to Peak µsec
No.	Col 1	Col 2	Col 3	Col 4	Col 5	Col 6	Col 7	Col 8	Col 9	Col 10	Col 11
1	123	1.0	20	216	275	6	245	28.3	1.4	253	48.7
2	123	1.0	40	216	260	12	245	23.5	2.8	253	36.5
3	123	1.0	63	216	260	19	245	21.4	4.4	253	31.0
4	145	1.0	20	255	330	6	288	30.9	1.4	299	53.4
5	145	1.0	40	255	310	12	288	25.8	2.8	299	40.0
6	145	1.0	63	255	310	19	288	23.5	4.4	299	34.0
7	145	1.0	80	255	310	24	288	22.6	5.6	299	31.2
8	170	1.0	16	299	395	8	338	35.2	1.1	350	63.4
9	170	1.0	31.5	299	360	9.5	338	29.1	2.2	350	47.0
10	170	1.0	40	299	360	12	338	27.8	2.8	350	43.2
11	170	1.0	50	299	360	15	338	26.4	3.5	350	35.7
12	170	1.0	63	299	360	19	338	25.4	4.4	350	36.7
13	245	1.0	31.5	431	520	9.5	487	34.8	2.2	505	56.2
14	245	1.0	40	431	520	12	487	33.3	2.8	505	51.6
15	245	1.0	50	431	520	15	487	31.6	3.5	505	47.4
16	245	1.0	63	431	520	19	487	30.3	4.4	505	43.8
17	362	1.0	40	637	775	12	720	40.7	2.8	745	63.2
18	362	1.0	63	637	775	19	720	37.1	4.4	745	55.7
19	550	1.0	40	968	1325	12	1094	49.0	2.8	1133	76.1
20	550	1.0	63	968	1325	19	1094	44.7	4.4	1133	63.9
21	800	1.0	40	1408	1530	12	1591	60.7	2.8	1647	94.1
22	800	1.0	63	1408	1530	19	1591	55.3	4.4	1647	79.9

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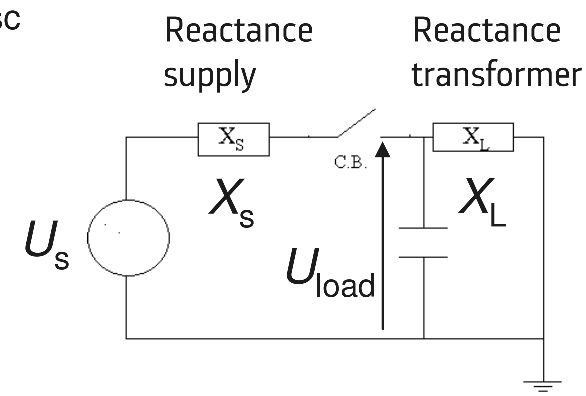
TLF / Options for Specification

- Explanation on TRV value in ANSI C37.06.1

Case: U_r = 362 kV , I_{sc}= 63 kA, I_{TLF} = 7% I_{sc}



– Load voltage at the time of interruption

$$U_S = (X_S + X_L) \times 0.07\, I_{SC} \;\; = X_S \times I_{SC}$$

$$0.07\, X_L = 0.93\, X_S \qquad X_L = \frac{0.93}{0.07} X_S$$

$$U_{load} = X_L \times 0.07\, I_{SC} \;\; = 0.93\, X_S\, I_{SC} = 0.93\, U_S$$

– TRV peak (neglecting the contribution on the supply side)

$$U_c = k_{af} \times \sqrt{2} \times U_{load} = k_{af} \times \sqrt{2} \times 0.93 \times k_{pp} \times \frac{U_r}{\sqrt{3}}$$

with k_{pp} = 1.5 (assumed in ANSI C37.06.1) and k_{af} = 1.8

$$U_c = 1.8 \times \sqrt{2} \times 0.93 \times 1.5 \frac{362}{\sqrt{3}} = 742\, kV$$

TLF / Options for Specification

- **Option 1 (Cont'd):** TRV values in ANSI C37.06.1

Calculation TLF TRV peak - Case 7% rated short-circuit current

Ur	Ur sqrt(2/3)	kp	kaf	kvd	Calculated Uc	ANSI C37.06.1
rated voltage	system peak phase-ground voltage	pole-to-clear factor	amplitude factor	voltage drop across transformer	TRV peak	TRV peak
kV	kV	pu	pu	pu	kV	kV
123	100,4	1,5	1,8	0,93	252,2	253
145	118,4	1,5	1,8	0,93	297,3	299
170	138,8	1,5	1,8	0,93	348,5	350

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- Questions at this point
  - What are the relevant factors (k_p, k_{af} and k_{vd}) for higher currents (e.g. 30% Isc) ?
  - What are the relevant factors for higher rated voltages (e.g. 362 kV and above) ?
- Answers from CIGRE WG A3-28 will be given in section 6.

Note:

k_p is the pole to clear factor (for any pole)

k_{pp} is the first pole to clear factor

TLF / Options for Specification

- **Option 1 (Cont'd)**
  - As indicated in ANSI/IEEE Std C37.016-2006, time t_3 is given by the following equation:

$$t_3 = 0.106\sqrt{\frac{U_r \times C}{I_{TLF}}}$$

where U_r is the rated voltage in kV, C is equal to the lumped equivalent terminal capacitance to ground of the transformer in pF, and I_{TLF} is equal to the transformer-limited fault current in kA.

C = 1480 + 89 I_{TLF} (pF) for rated voltages less than 123 kV

C = 1650 + 180 I_{TLF} (pF) for rated voltages 123 kV and above

  - For $U_r \geq 123$ kV, time t_3 can be also expressed as follows:

$$t_3 = \frac{3.18 \times \sqrt{U_r}}{I_{TLF}^{0.21}}$$

t_3 decreases (and RRRV increases) when the fault current increases.

TLF / Options for Specification

- **Option 2a** Check the actual TRV time to peak from the natural frequency of the transformer(s)

$$T_2 = \frac{1}{2 \times f_{nat}}$$

where T_2 is the time to TRV peak (= 1.15 t_3)

f_{nat} is the natural frequency of the transformer

  - If T_2 is longer than the value in ANSI C37.06.1 it may be cross-checked with available test results.
  - Determination of the transformer natural frequency can be done in several ways as explained in part 3.

TLF / Options for Specification

- **Option 2b** TRV calculation for a given application
  - Calculate the TRV for the given application, taking into account additional available capacitances or additional added capacitances i.e. line to ground capacitors, CVT's, grading capacitors etc.
  - The additional capacitance increases the time to TRV peak (T_{2mod}) and reduces the stress for the circuit breaker according to the following equations

$$T_{2\,\mathrm{mod}} = \pi \sqrt{L \times (C_{\mathrm{nat}} + C_{\mathrm{add}})}$$

where

$$L = \frac{\frac{k_{\mathrm{pp}}}{\sqrt{3}} \times U_{\mathrm{r}}}{2\pi \times f_r \times I_{\mathrm{sc}}} \times \left(\frac{I_{\mathrm{sc}}}{I} - 1 \right)$$

$$C_{\mathrm{nat}} = (2 \times T_2)^2 / (4\pi^2 \times L)$$

TLF / Options for Specification

- **Option 2b (Cont'd)**

  where

  k_{pp} is the first pole to clear factor

  U_r is the rated maximum voltage

  I_{sc} is the rated short circuit current

  I is the transformer limited fault current

  f_r is the power frequency

  L is the equivalent inductance of the transformer

  C_{nat} is the equivalent capacitance of the transformer (2/3 of the surge capacitance in case of 3-phase ungrounded fault)

  C_{add} is the equivalent additional capacitance (2/3 of the capacitance added phase to ground in case of 3-phase ungrounded fault)

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TLF / Options for Specification

- **Option 2b (Cont'd) : Example**
  - Rated maximum voltage : 362 kV
  - Rated short circuit current : 63 kA
  - Based on 30% of rated short circuit current, the required test current is 18.9 kA.
  - TRV parameters as defined in ANSI C37.06.1
    - $T_2 = 37.1\ \mu s$ $u_c = 720\ kV$
  - The equivalent inductance and capacitance of the transformer are derived using previous equations
    - $L = 30.7\ mH$ $C_{nat} = 4.54\ nF$
  - Taking into account additional (equivalent) capacitances present in the substation (sum of stray capacitance, busbar, CVT etc.) of 3.5nF, the modified time to peak T_{2mod} is equal to 49 µs. This T_{2mod} would be the shortest time to peak TRV that the breaker has to withstand in service and during testing.

TLF / Options for Specification

- **Option 3** Additional capacitor
  - Test reports may be available for the circuit breaker showing a certain T_2 value which is higher than the T_2 value given in ANSI C37.06.1.
  - Such a breaker could be used for this application by adding a capacitor to ground which changes the actual T_2 to a value where a proof for the circuit breaker capability exists.

$$C_{\text{add}} = \frac{T_{2\ \text{test}}^{2}}{L \times \pi^{2}} - C_{\text{nat}}$$

  where $T_{2\ \text{test}}$ value is the time to peak of tested TRV.

  - If for example, a circuit breaker has been tested with a time $T_{2\ \text{test}}$ of 70 µs, a current equal to 30 % of its rated short circuit current of 63kA and a rated maximum voltage of 362 kV, this would require an additional capacitance of 11.6 nF in order to make the breaker feasible for this application.

3 - Transformer Frequency & Model

TLF / Transformer Frequency & Model

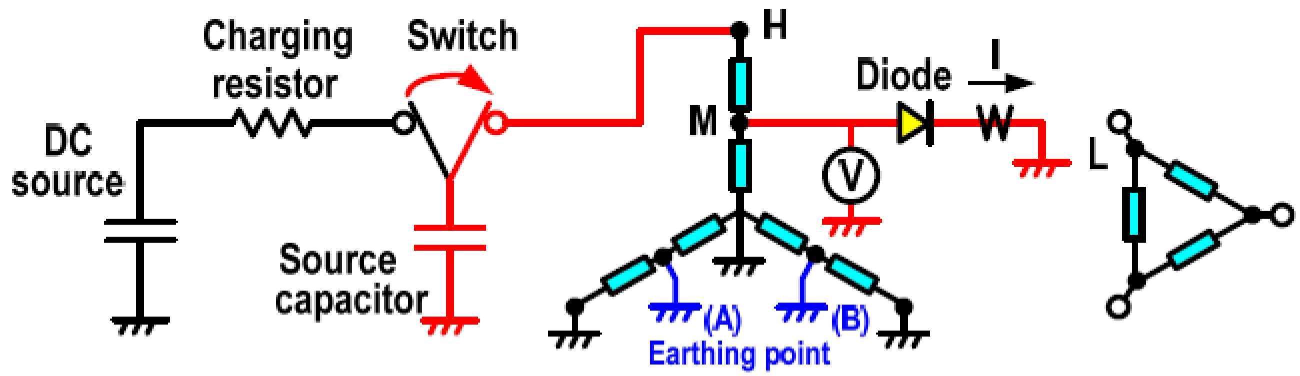
- The transformer frequency can be derived from measurements by
  - Current injection,
  - Resonant frequency measurement,
  - Daini-kyodai method.
- The transient response on the transformer side is quite complicated in most cases, so that two approaches are possible:
  1. A simplified model with an equivalent RLC circuit that gives the main TRV frequency and associated amplitude factor.
  2. Detailed models that are able to reproduce the multi-frequency phenomena,

  Examples are given in the following, taken from papers A3-107 [3] & A3-108 [4] presented at CIGRE session 2012.

TLF / Transformer Frequency & Model

Determination of transformer natural frequency

- Current injection method
  - The method is described in Annex F of IEC 62271-100
  - It provides the TRV for the first-pole-to-clear



  - TRVs for the second and third-pole-to-clear can also measured with the core type by removing the earthing points at A or at A and B, respectively.

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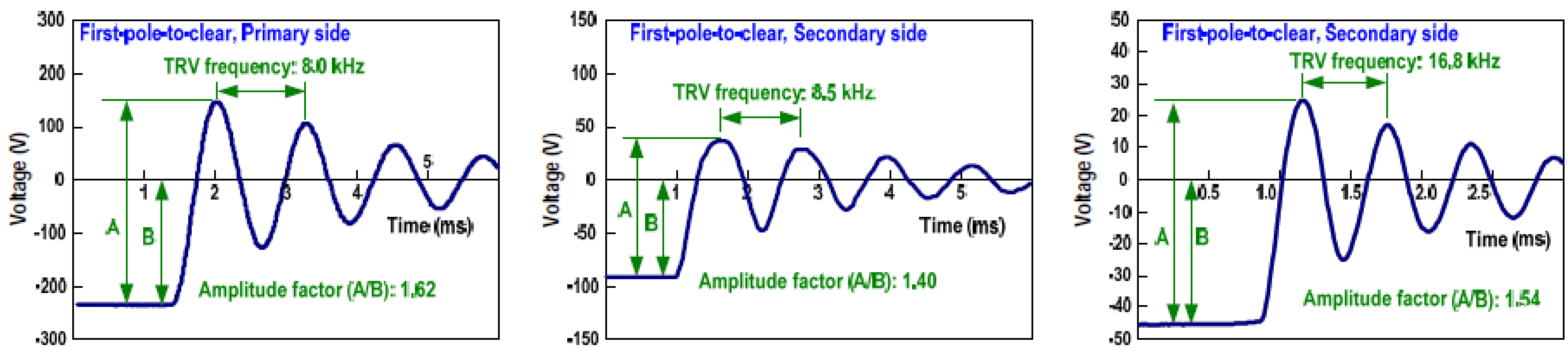
Determination of transformer natural frequency

- Current injection method (Cont'd)
  - Example of TRV measurement (CIGRE paper A3-108_2012)



(a) Primary side, shell type (b) Secondary side, shell type (c) Secondary side, core type

TRVs for TLF conditions with 525 kV-1500 MVA shell and core type transformers

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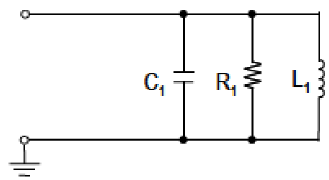
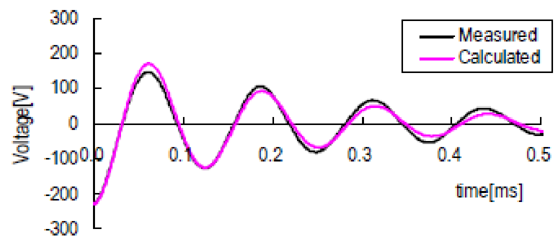
TLF / Transformer Frequency & Model

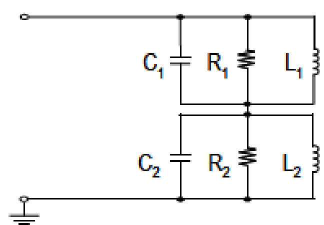
Reproduction of TRV waveforms by simplified transformer models

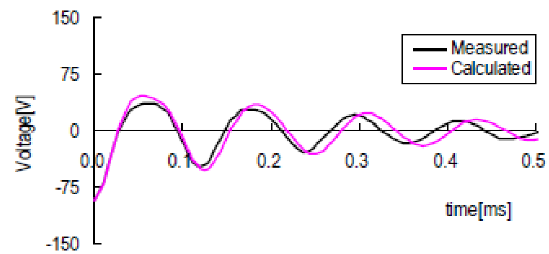
Primary (500kV) side model with single set of parallel L-C-R circuit (single resonant frequency)



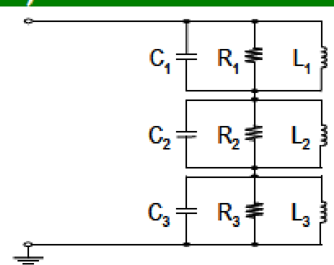


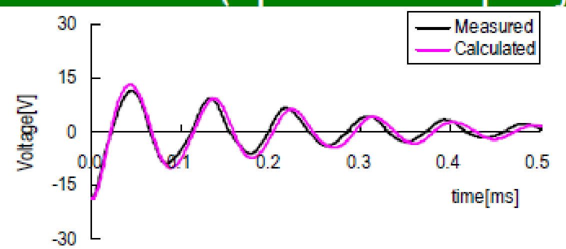
Secondary (275kV) side model with two set of parallel L-C-R circuits (double resonant frequency)





Tertiary (63kV) side model with three set of parallel L-C-R circuits (triple resonant frequency)





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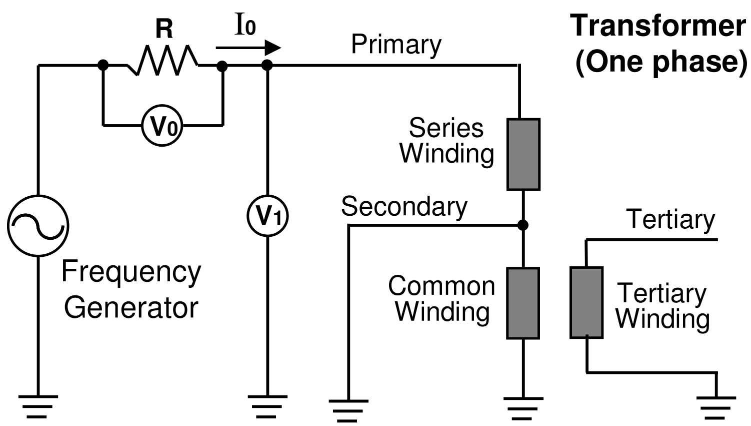
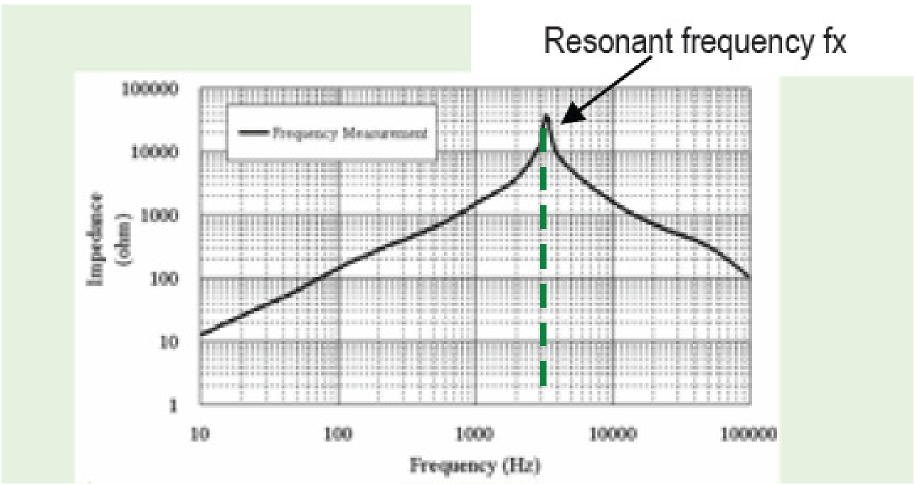
TLF / Transformer Frequency & Model

Determination of transformer natural frequency

- Resonant frequency measurement (FRA)
  - Test circuit and example of measurement





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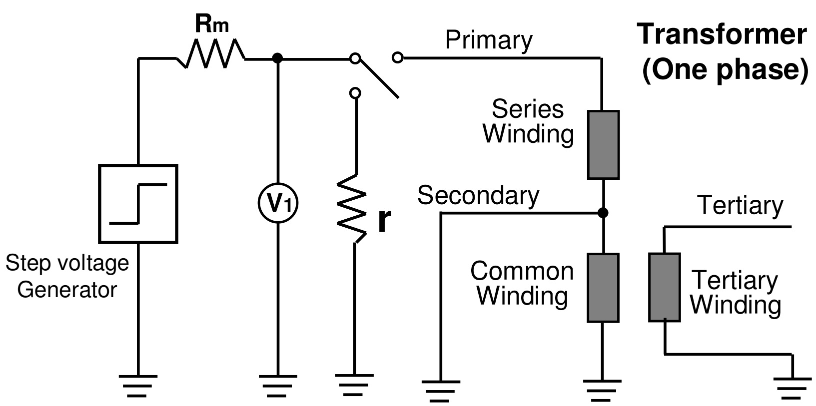
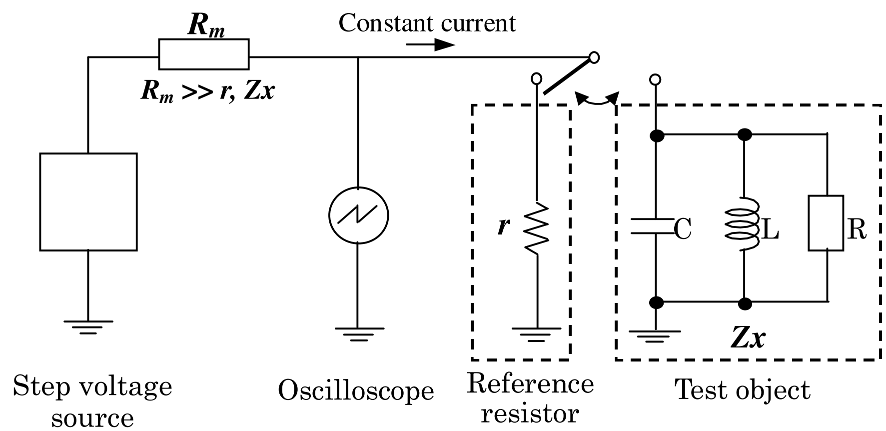
TLF / Transformer Frequency & Model

Determination of transformer natural frequency

- Daini-kyodai method
  - Test circuit

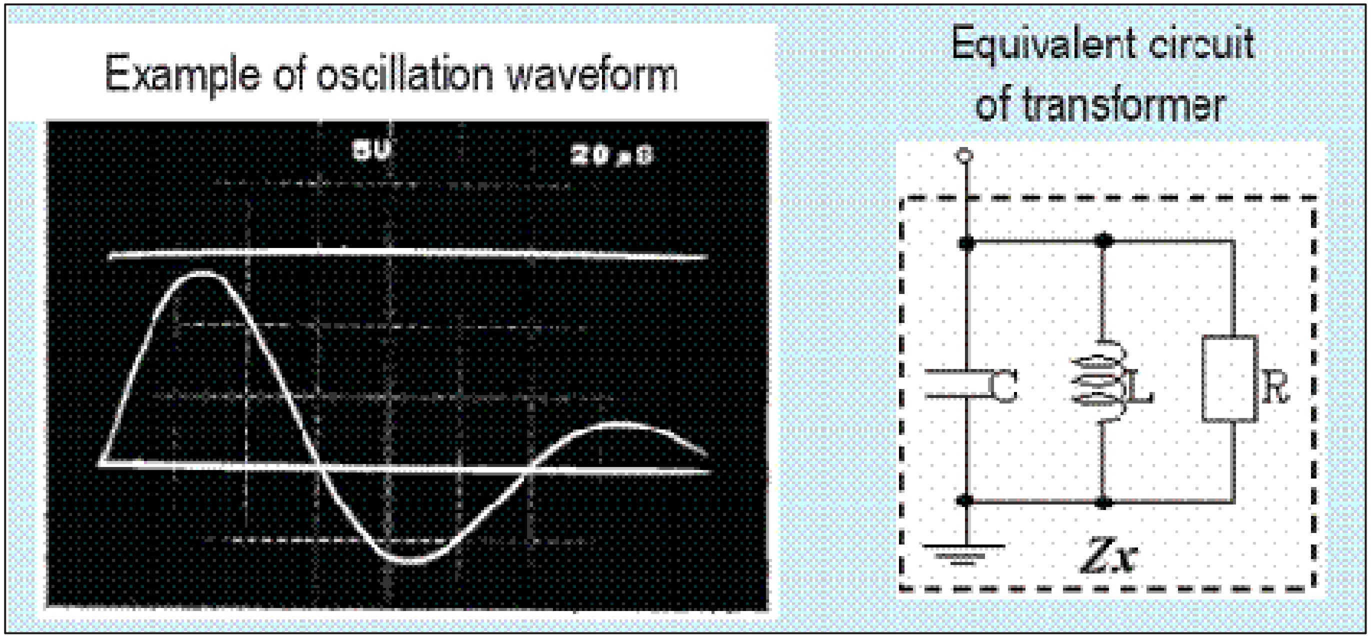




TLF / Transformer Frequency & Model

Determination of transformer natural frequency

- Daini-kyodai method
  - Example of measurement

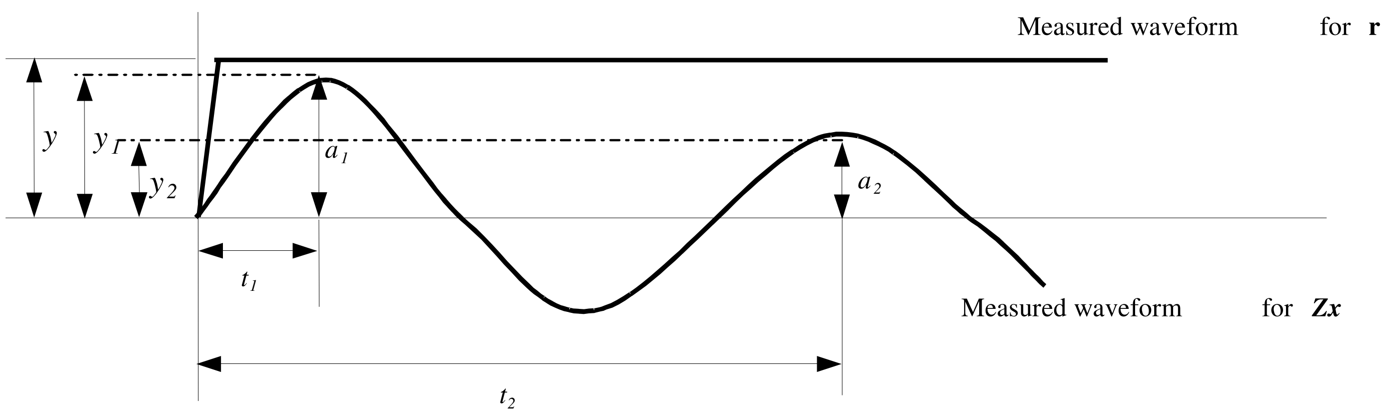


Determination of transformer natural frequency

- Daini-kyodai method

The oscillation waveform of *Zx* directly shows the transient impedance of the test object.

The components *C*, *R* and *L* of *Zx* can be calculated from the waveform of *Zx* by a comparison with the waveform obtained with *r* (see Annex B).

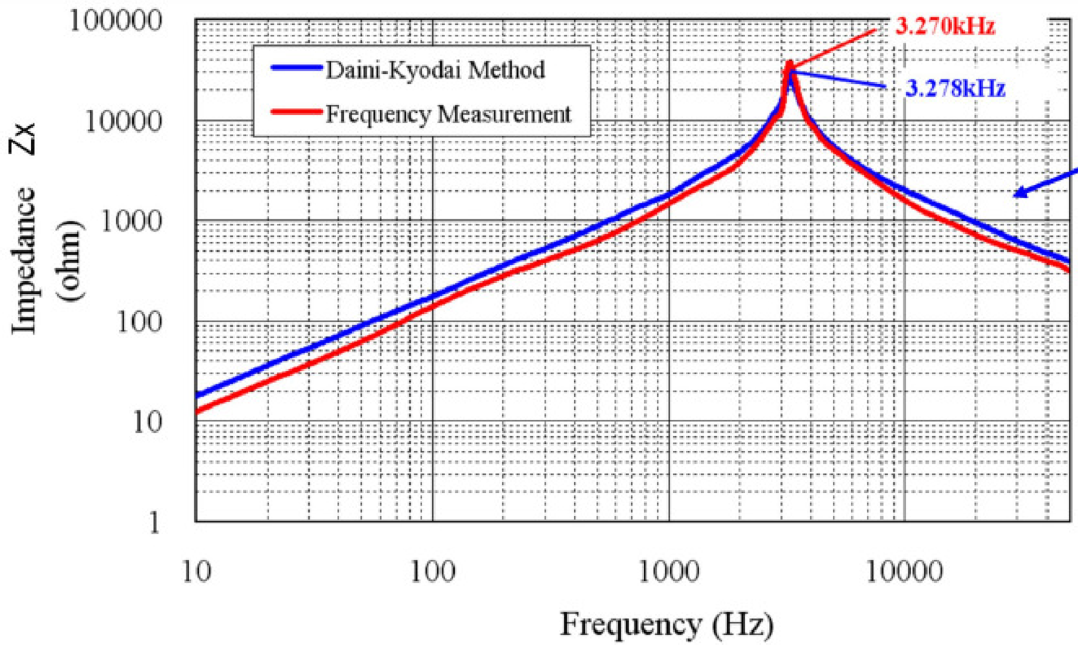


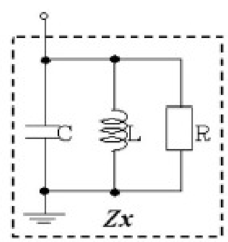
$a_1 = r \times y_1 / y$ (Ω) $a_2 = r \times y_2 / y$ (Ω)

TLF / Transformer Frequency & Model

Determination of transformer natural frequency

- Comparison of frequency measurement and Daini-kyodai method





Comparison of measurement results with UHV transformer

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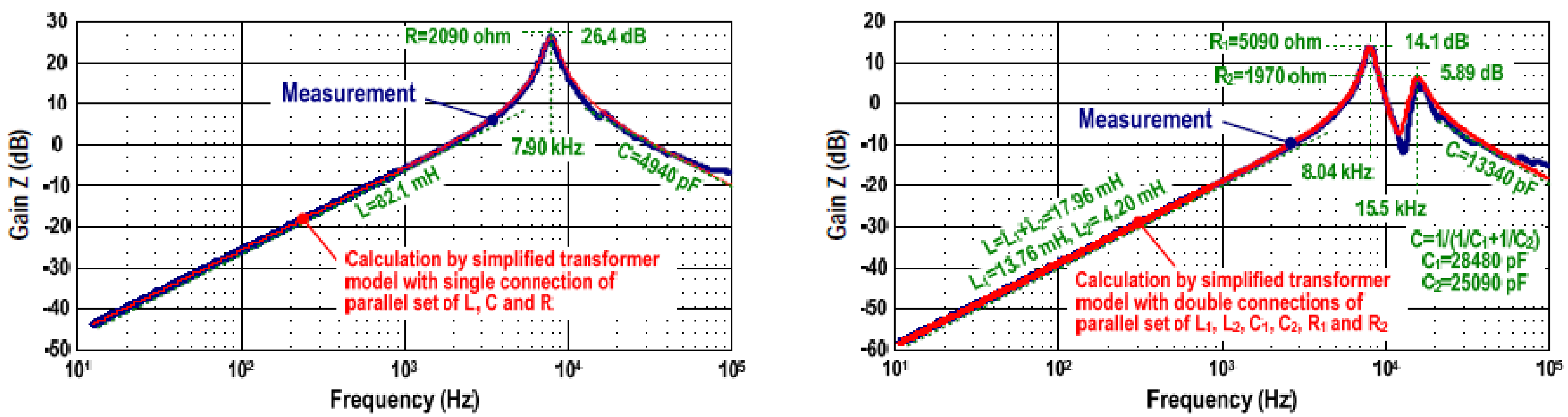
TLF / Transformer Frequency & Model

Transformer Model: Simplified RLC Model from FRA

- In this example *L*, *C*, and *R* values are evaluated from the slope of the gain and the gain at the resonant frequency obtained by FRA (Frequency Response Analysis) measurements for the first-pole-to-clear at the primary and the secondary sides of a shell-type transformer.



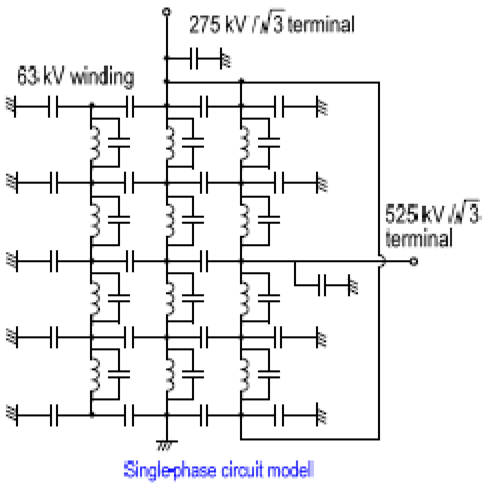
(a) First-pole-to-clear at primary side (525 kV) (b) First-pole-to-clear at secondary side (275 kV)

Fig.5 Frequency response with FRA measurement for the 1500 MVA shell type transformer

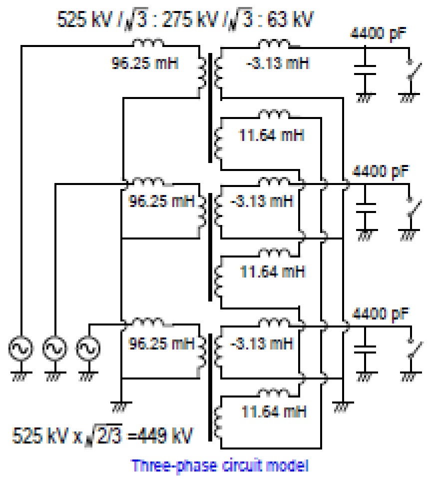
TLF / Transformer Frequency & Model

Transformer Model: Detailed Model

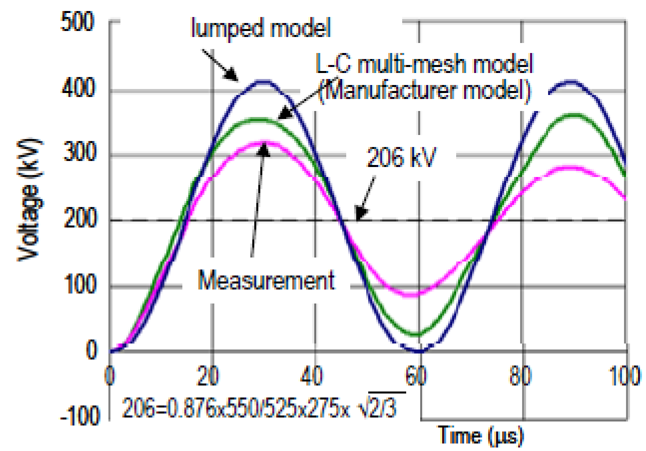
- First example from CIGRE paper A3_108_2012 [4]
  - Multi-mesh and lumped models



(a) L-C Multi-mesh model



(b) Lumped model

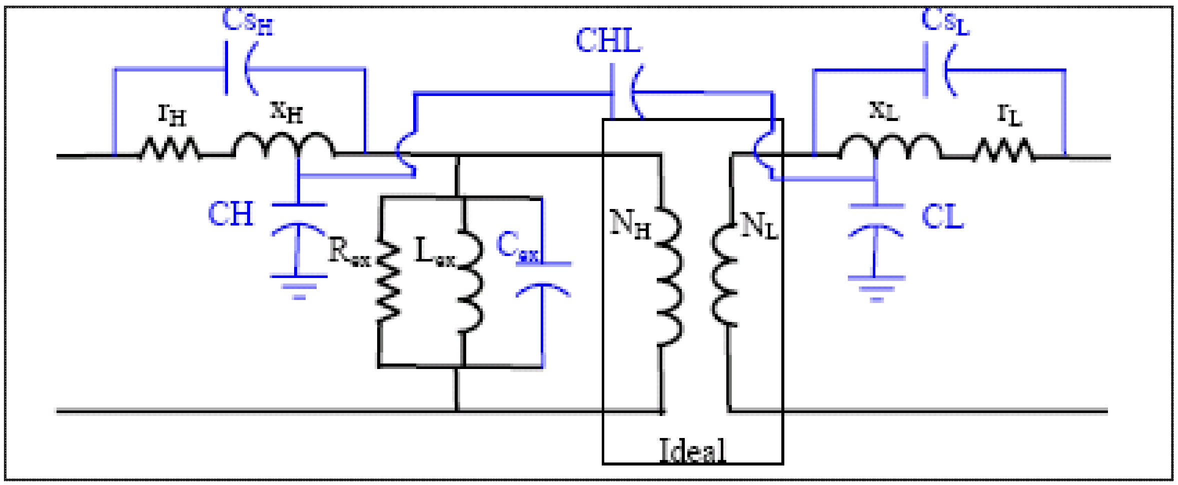


(c) Comparison of TRV with different models

TLF / Transformer Frequency & Model

Transformer Model: Detailed Model

- 2nd example from CIGRE paper A3_107_2012 [3]
  - Conventional model with capacitances to earth & between windings (manufacturer model)



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TLF / Transformer Frequency & Model

Transformer Model: Detailed Model

- 2nd example from CIGRE paper A3_107_2012 (Cont'd)
  - Black-box model having an admittance matrix with self and mutual components that are frequency dependent. Fitting technique leads to

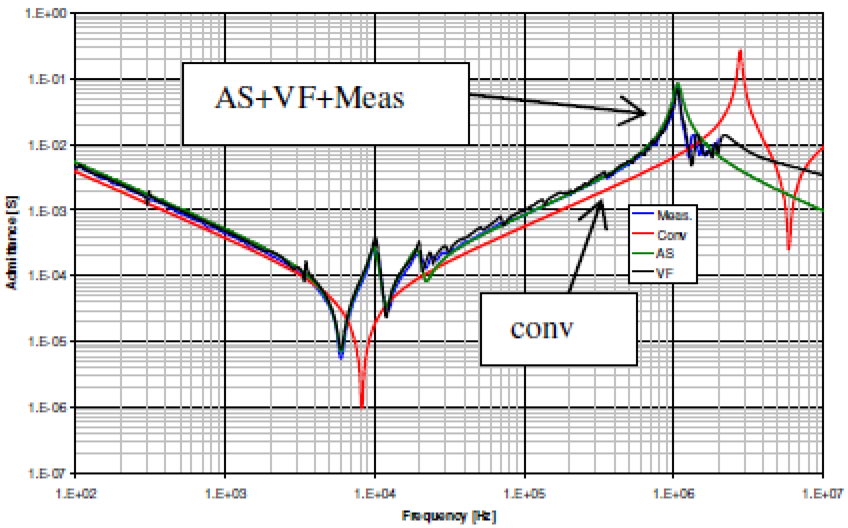
$$Y(j\omega) = \sum_{m=1}^{N} \frac{R}{j\omega - a_m} + D + j\omega E$$

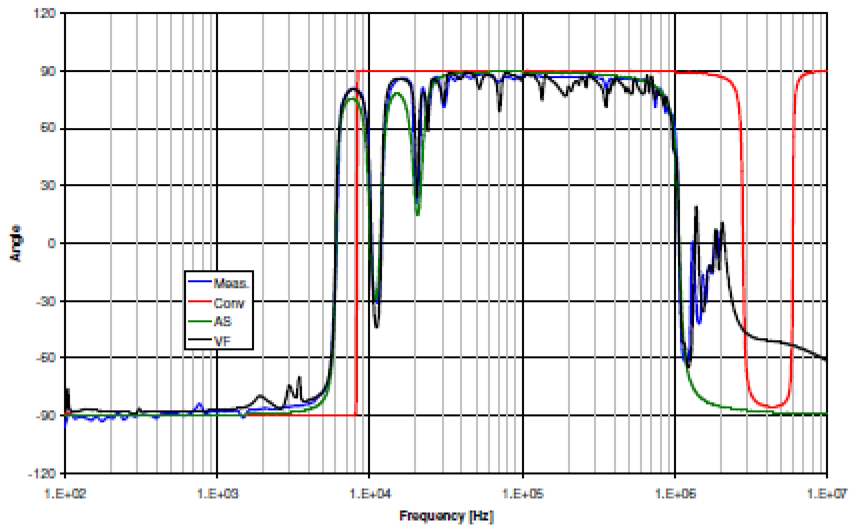
    where R is a residue matrix, D and E are real matrices.
  - This model can be implemented in MATLAB using MatrixFitting.
  - Comparison of transformer modeling and field measurements done by A. Rocha et al. is given in the next slide.

TLF / Transformer Frequency & Model

Transformer Model: Detailed Model

- 2nd example from CIGRE paper A3_107_2012 (Cont'd)
  - Comparison of 25 MVA single-phase transformer self-admittance and angle by black box model with rational fitting (black curve) and by field measurement (blue curve).





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TLF / Transformer Frequency & Model

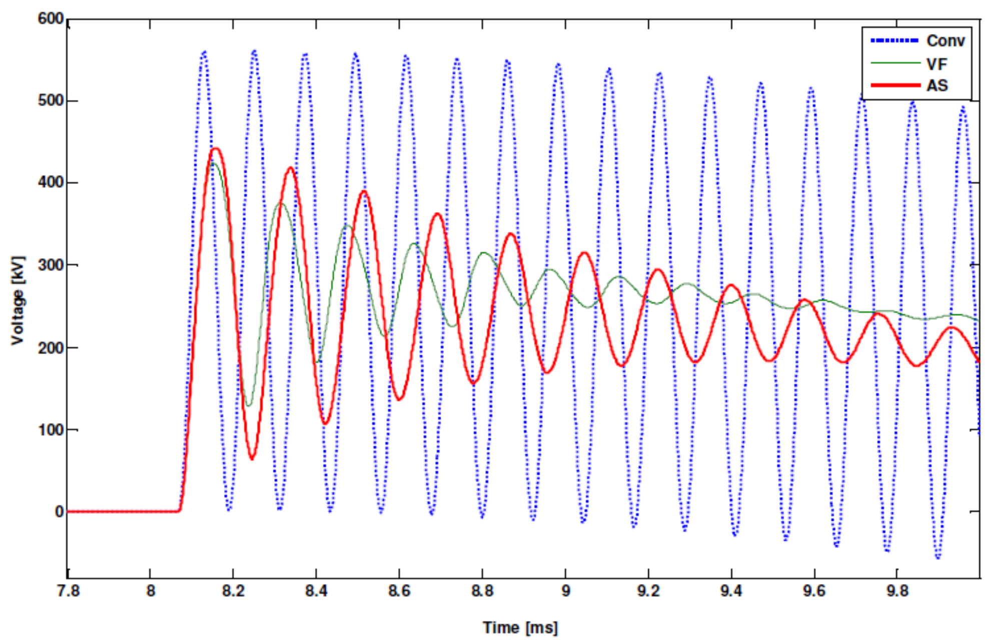
Transformer Model: Detailed Model

- 2nd example from CIGRE paper A3_107_2012 (Cont'd)
  - Comparison of 3-phase ungrounded transformer secondary fault TRV with conventional model (in blue) and black-box or rational fitting model (in green). Fault current is 2 kA.

Comparison of RRRV

9.1 kV/µs : conventional model

5.07 kV/µs : rational fitting model



Note: AS (curve in red) is another method called asymptotic synthesis described in the next slide, it gives an RRRV of 5.09 kV/µs

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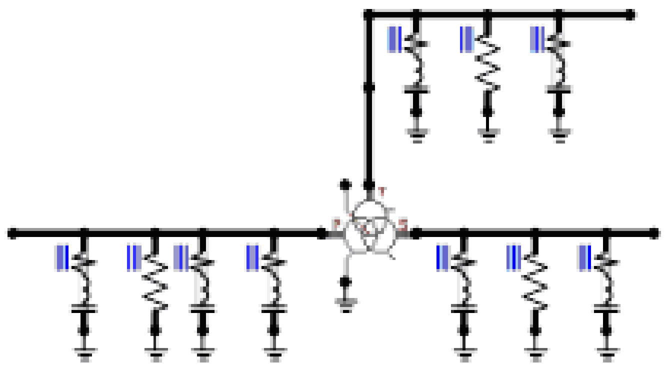
TLF / Transformer Frequency & Model

Transformer Model: Detailed Model

- 2nd example from CIGRE paper A3_107_2012 (Cont'd)
  - Asymptotic synthesis model

    Conventional 50/60Hz transformer model with terminals connected to RLC circuits calculated in order to fit the self-admittance of each of the windings (primary and two secondary in this case).

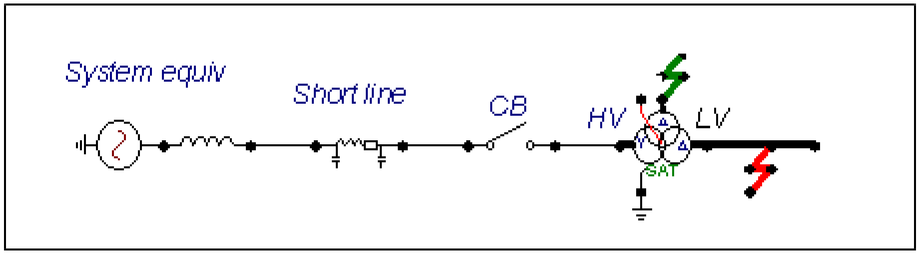
For three winding transformer secondary fault, the terminal admittance considered to model the transformer is dependent on the winding where the short circuit-circuit occurred.

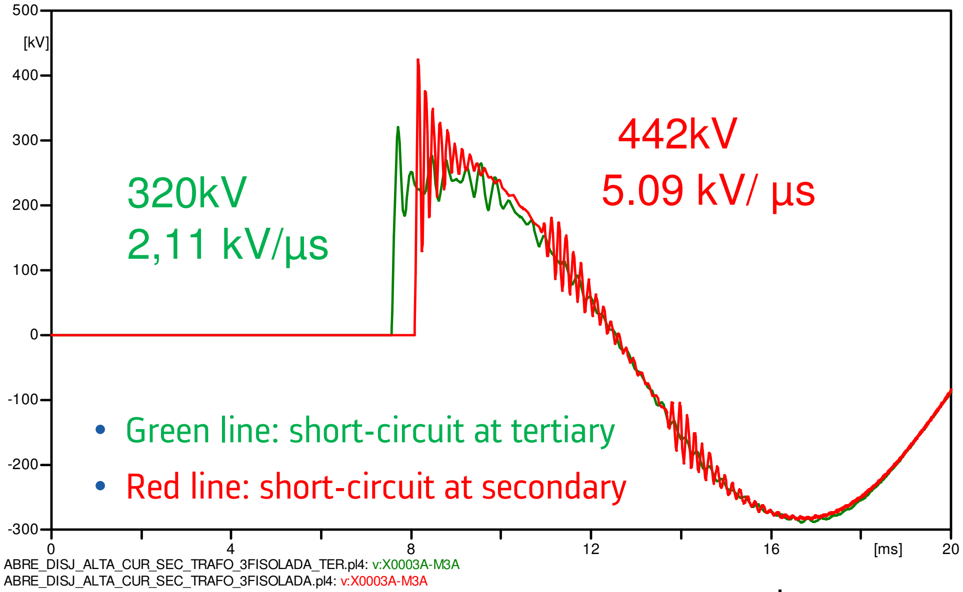


TLF / Transformer Frequency & Model

- Example of dependence of TRV on short-circuit point (on secondary or tertiary)*

More than one model is necessary to represent all the short-circuit conditions





* CIGRE 2012 SCA3 PS1
Angélica C. O. ROCHA
(Brazil) CEMIG GT

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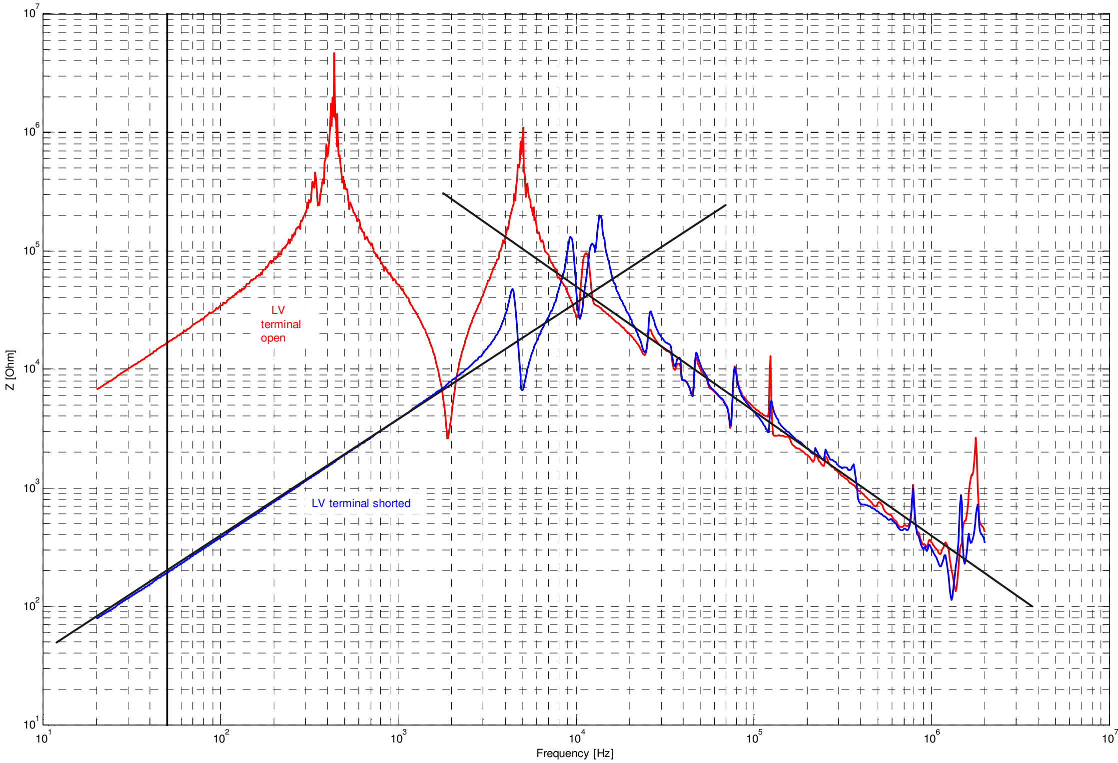
4 –Surge Capacitance of a Transformer and TRV from FRA Measurements

TLF / Surge Capacitance of a Transformer

- From the initial part of the FRA-measurement an equivalent inductance (short-circuit inductance) can be determined, whereas in the higher frequency region (some hundreds of kHz) the surge capacitance can be approached.



- Example

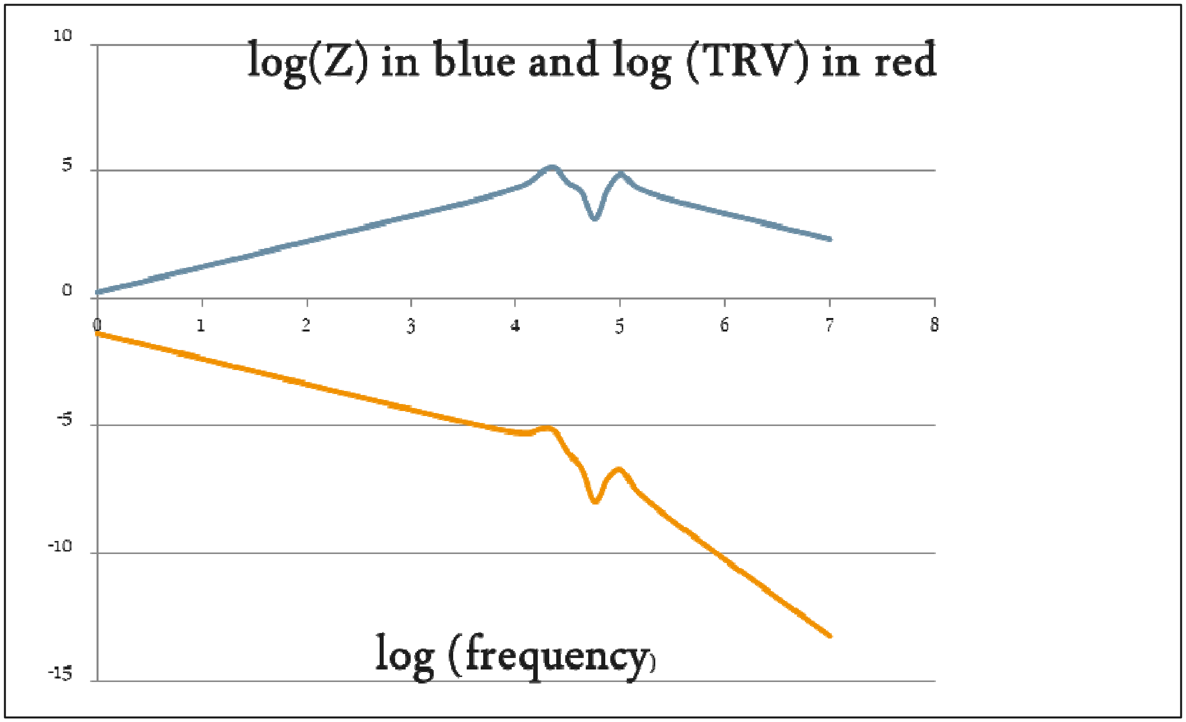
  80 MVA, 400 kV

  L=640 mH, C=400 pF

Reverse Fourier Transform

FRA = $Z(\omega)$ and $I(t) = S*t$ with $S = 2\pi f\sqrt{2} * Irms$

$TRV(\omega) = I(\omega)*Z(\omega) = S*Z(\omega)/\omega^2 \rightarrow TRV(t)$



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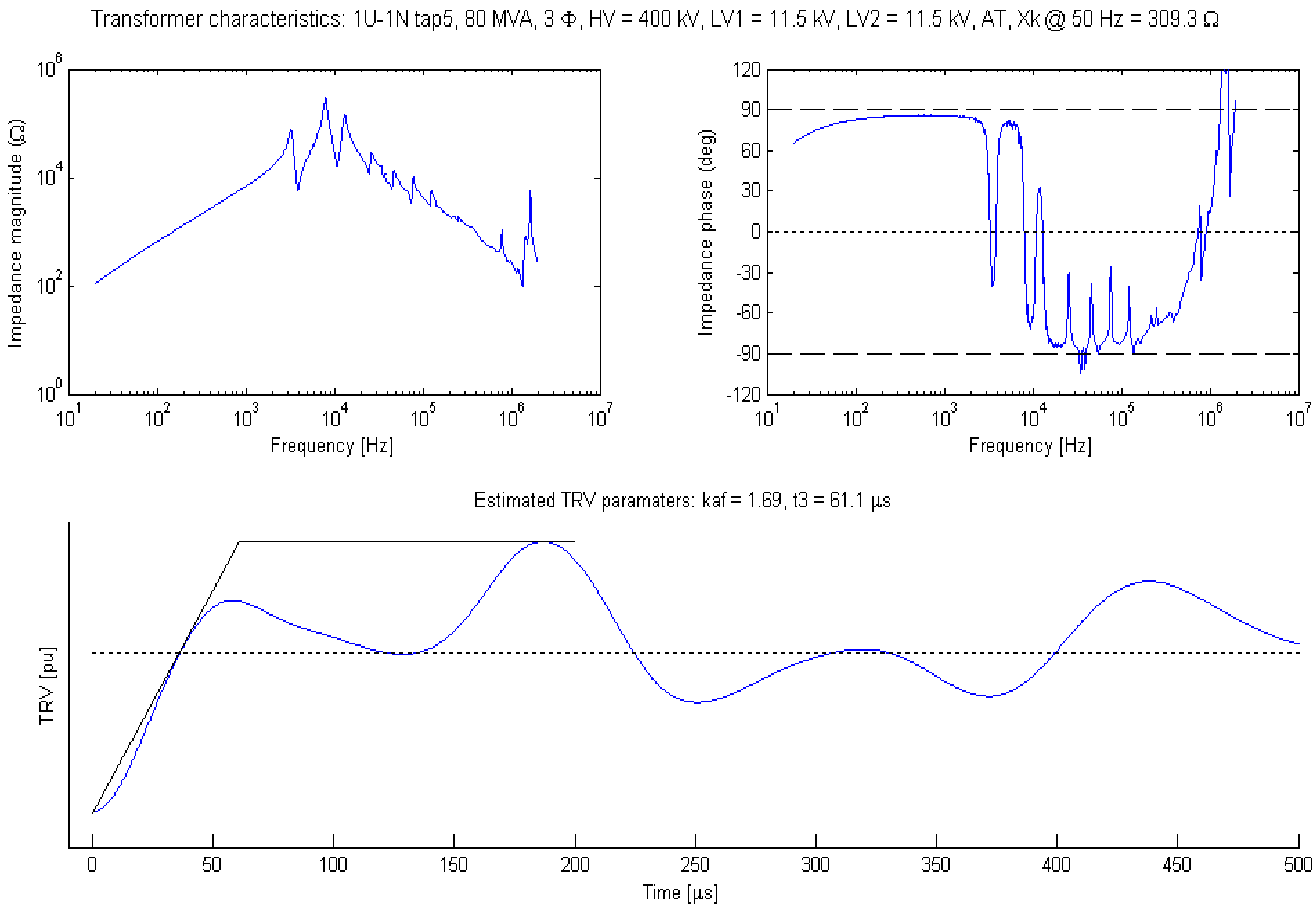
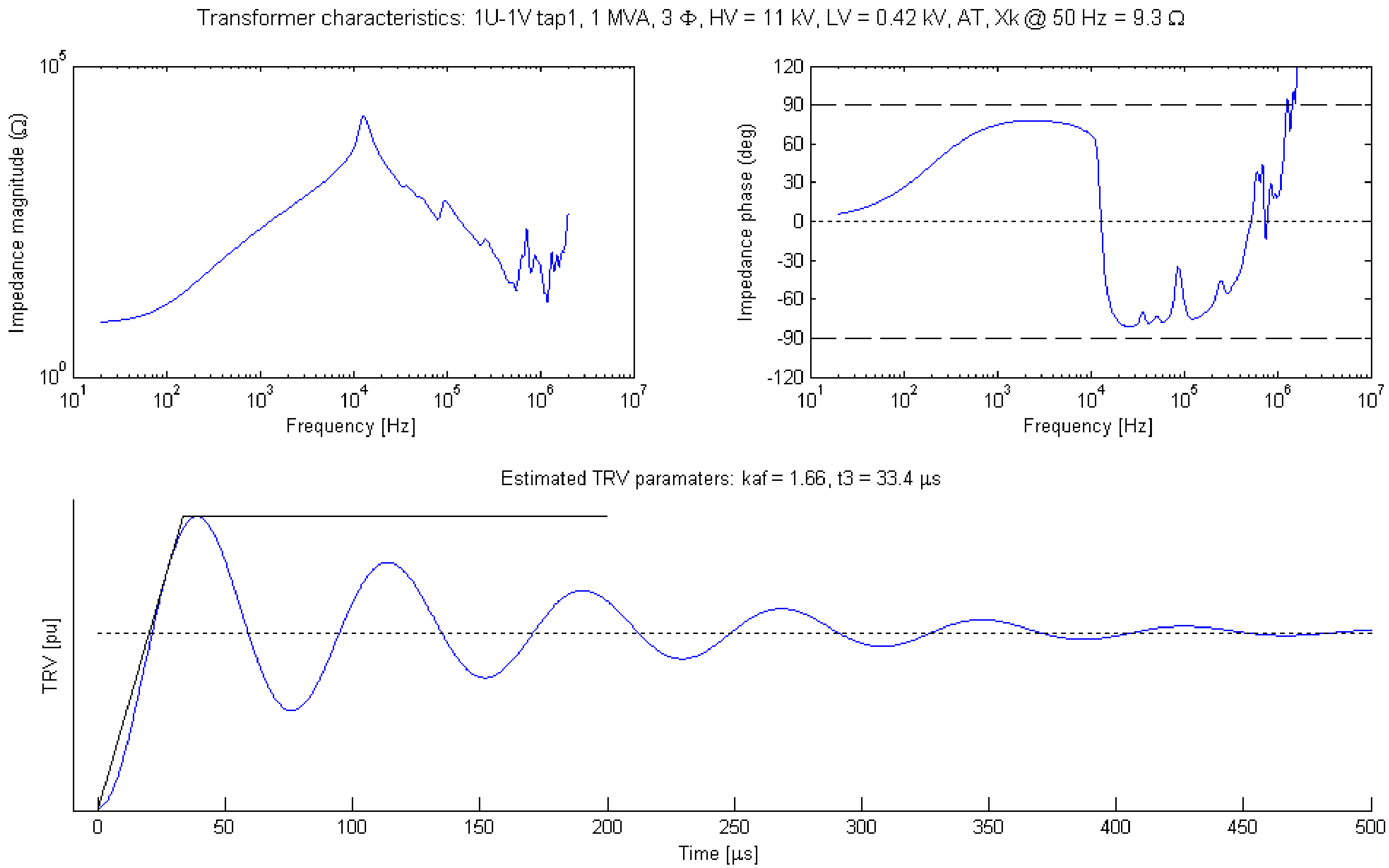
Examples TRV from FRA-measurements (KEMA HPL)



Examples TRV from FRA-measurements (KEMA HPL)



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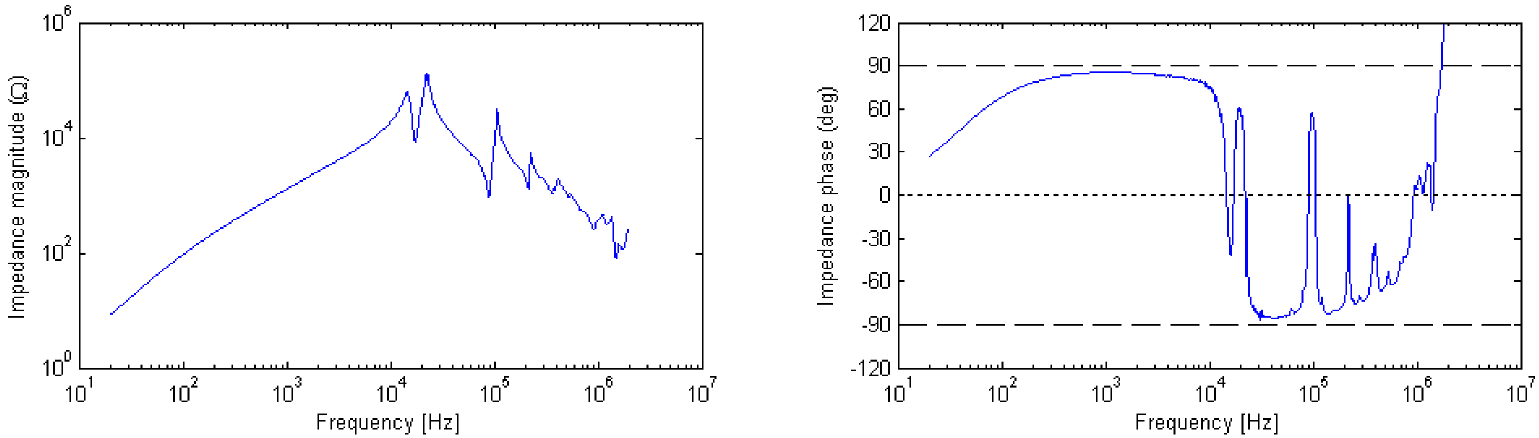
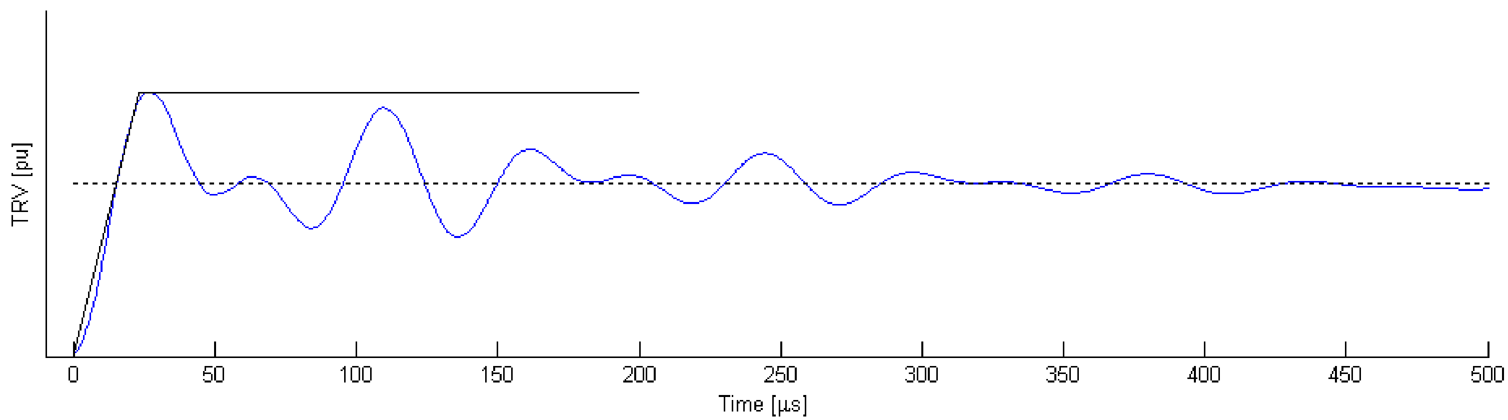
Examples TRV from FRA-measurements (KEMA HPL)

Transformer characteristics: 1.1-1.2 tap5, 102 MVA, 1 Φ, HV = 230.9 kV, LV = 16 kV, AT, Xk @ 50 Hz = 34 Ω



Estimated TRV paramaters: kaf = 1.54, t3 = 23.1 μs



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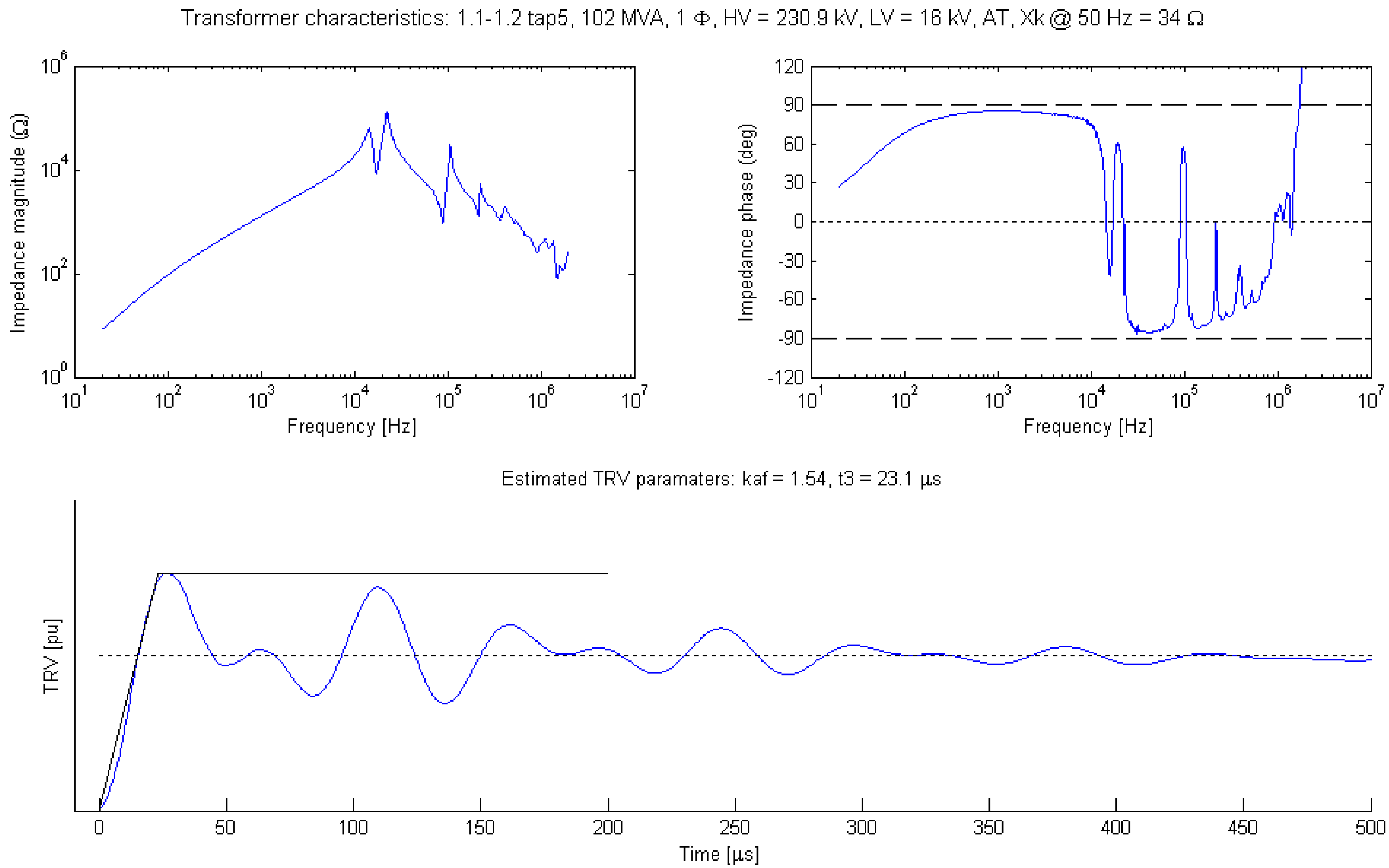
Examples TRV from FRA-measurements (KEMA HPL)



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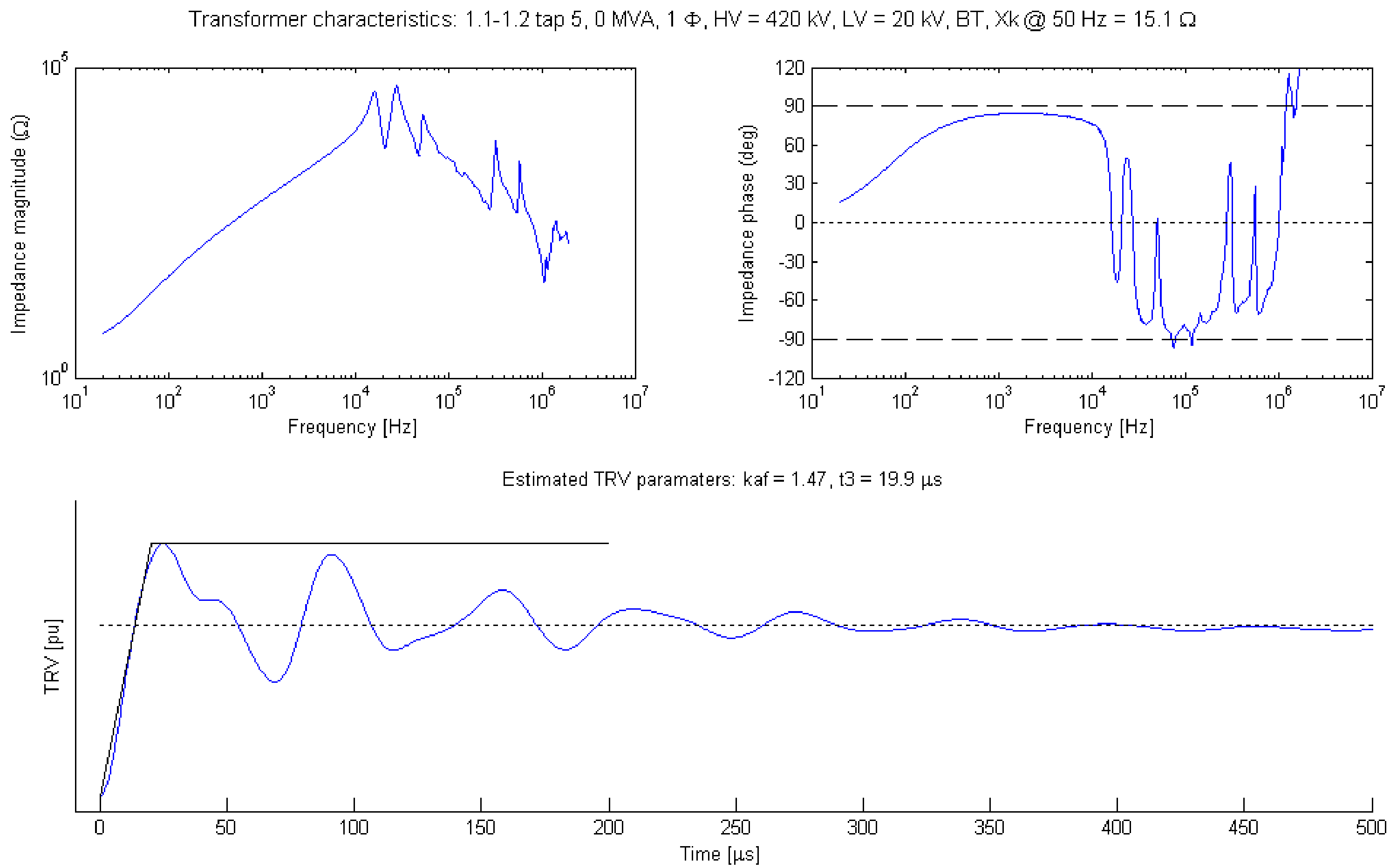
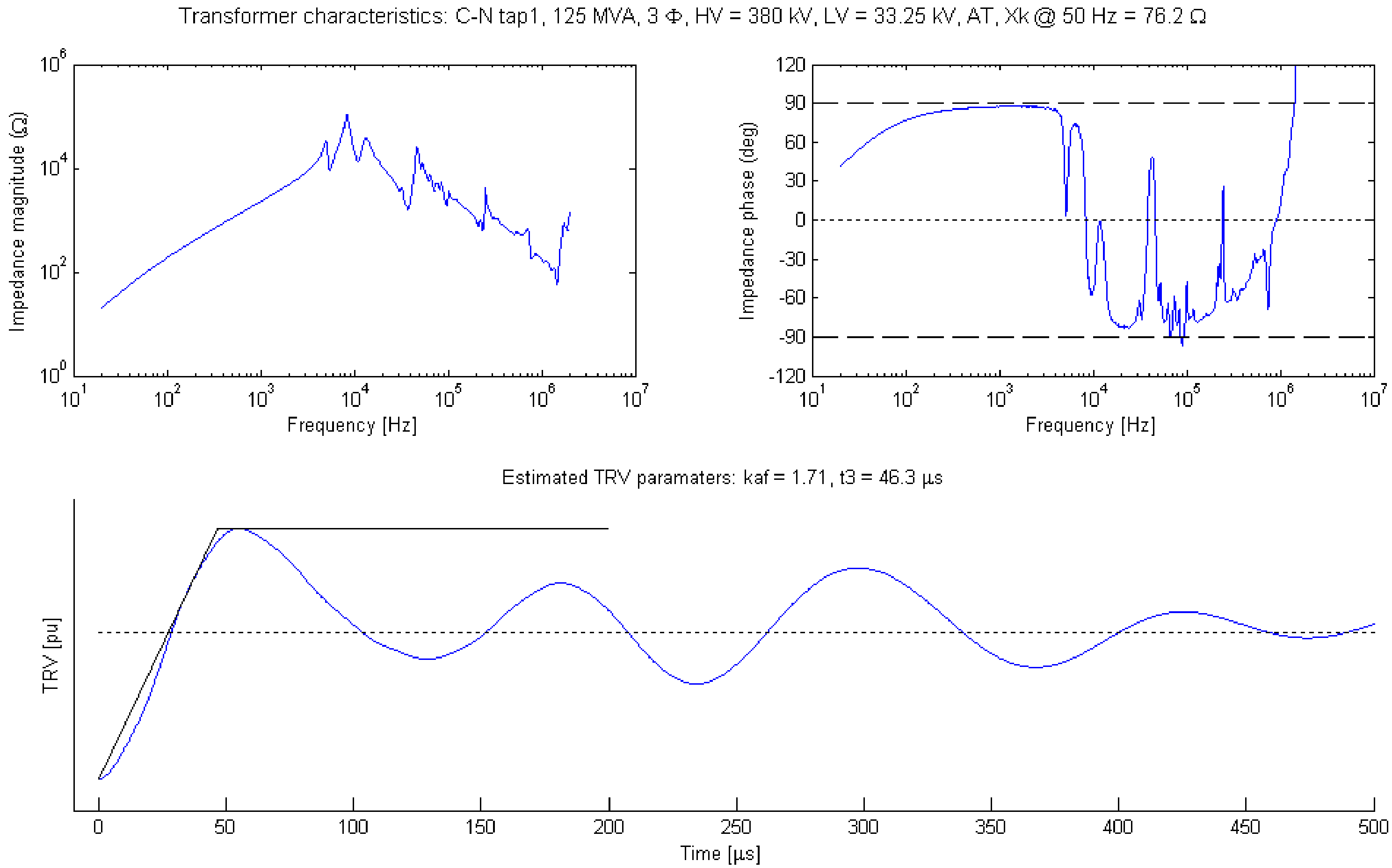
Examples TRV from FRA-measurements (KEMA HPL)



Examples TRV from FRA-measurements (KEMA HPL)



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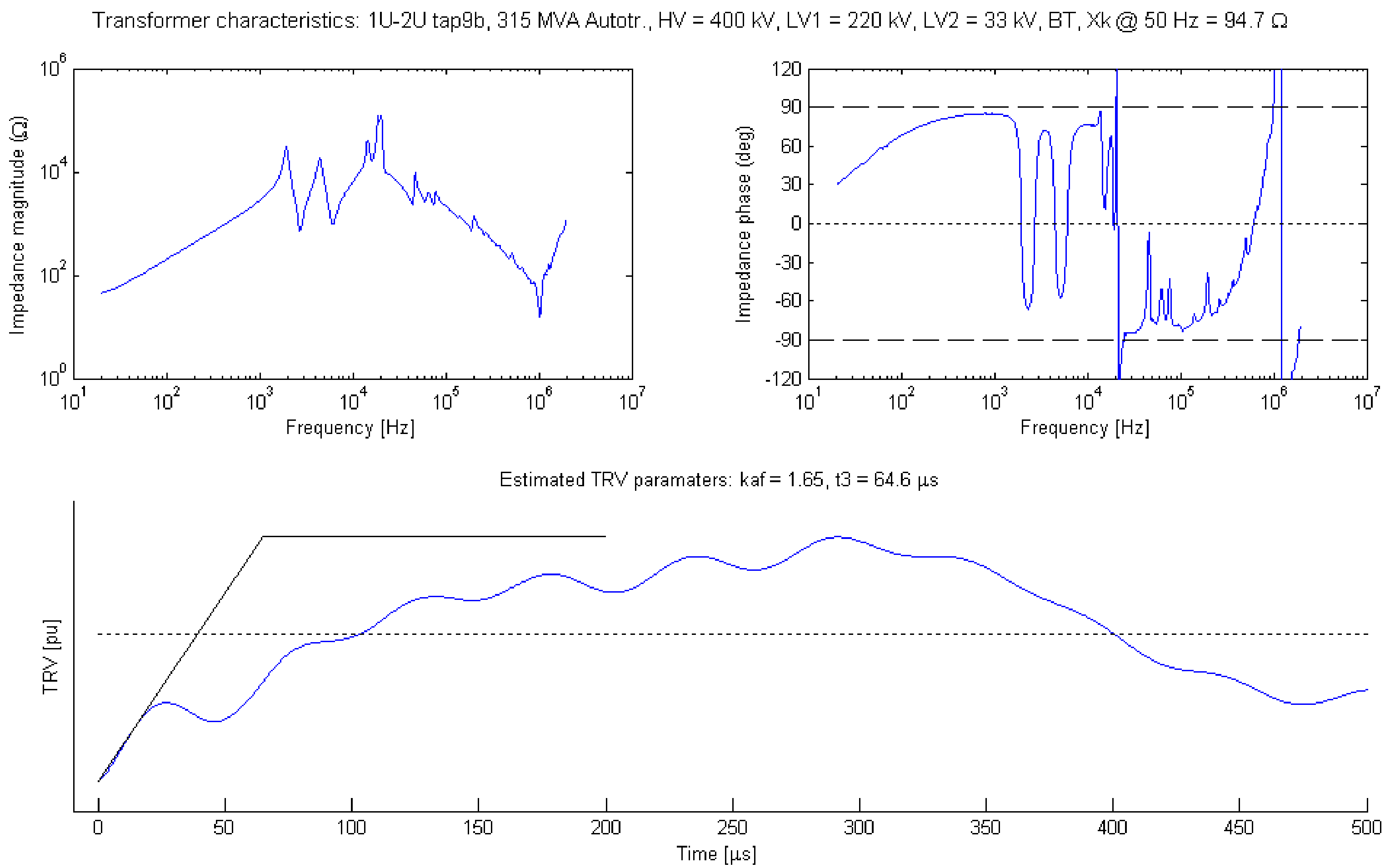
Examples TRV from FRA-measurements (KEMA HPL)



Comparison with single frequency model

Based on short-circuit inductance and surge capacitance

2-parameter TRV values

	Case 4	Case 8	Case 9	Case 10	Case 11	Case 12
KEMA* t3 (µs)	39.2	61.1	33.4	64.6	50.5	46.3
Simple t3 (µs)	43.5	53.0	35.0	49.0	56.5	33.5
KEMA* AF	1.75	1.69	1.66	1.65	1.54	1.71
Simple AF	1.80	1.84	1.74	1.80	1.78	1.78
KEMA* kV/µs	44.6	27.7	49.7	25.5	30.5	36.9
Simple kV/µs	41.4	34.7	49.7	36.7	31.6	53.1

KEMA*: from reverse Fourier transform
Simple: from LCR parallel circuit

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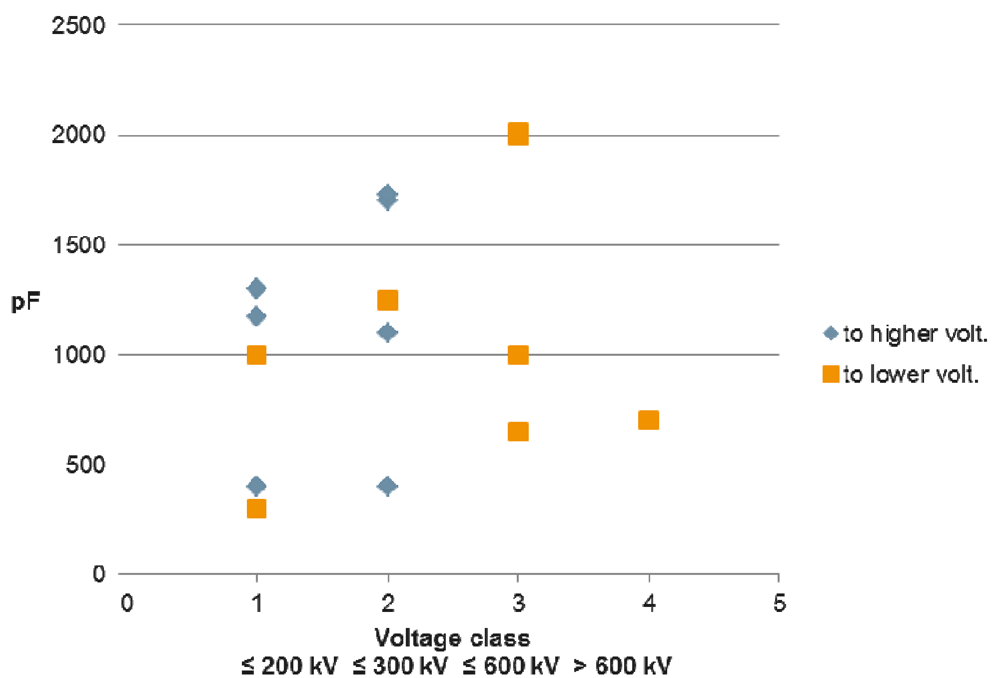
5 – Influence of External Capacitances Between Circuit Breaker & Transformer

Influence of external capacitance

- Shift of surge capacitance to the left, lower frequencies by $\sqrt{\frac{Csurge}{(Csurge+Cext)}}$
- FRA-patron with peaks shifts also to left
- Peak-values do not change (in resonance points determined by R)
- Larger C, lower Z=√L/C, higher R/Z-ratio, somewhat higher AF
- Minimum values:



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TLF / Additional Capacitances

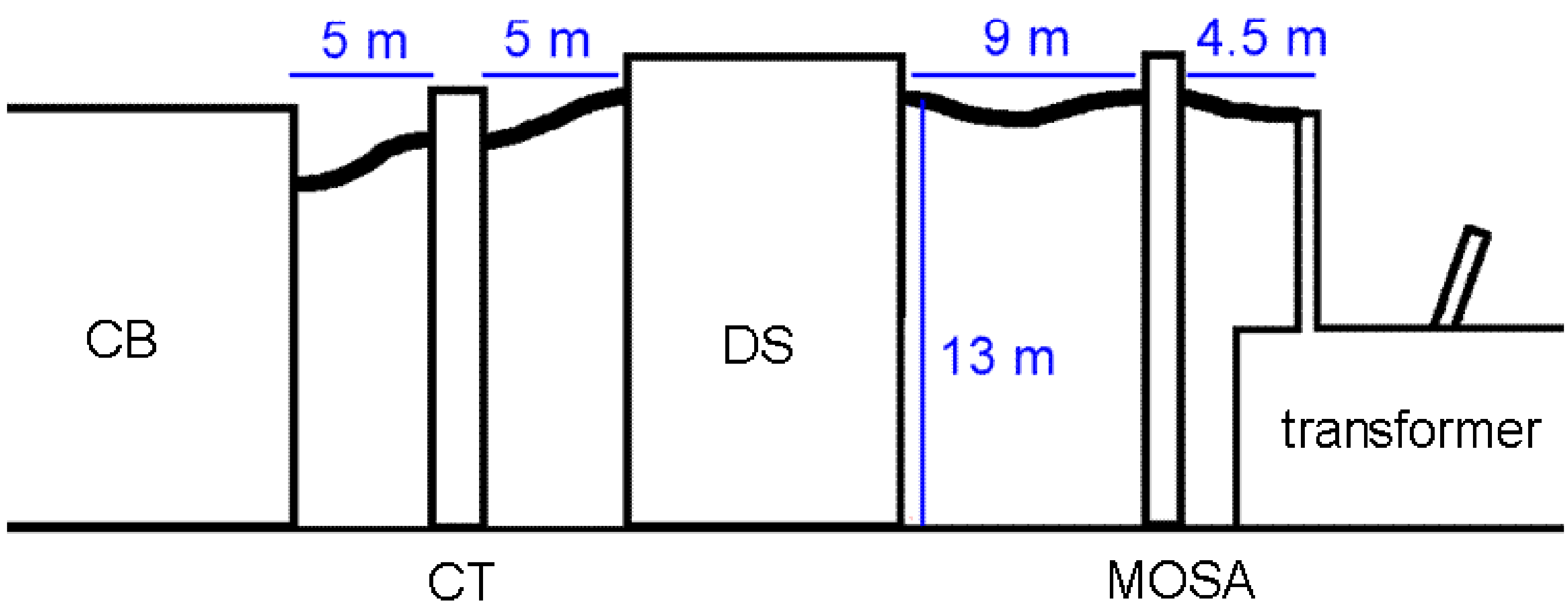
Capacitance according to IEEE C37.011-2011

- Busbar for air-insulated bus: 8.2-18.0 pF/m.
- Surge arrester 80-120 pF
- CT / VT
  - the capacitance of an outdoor current transformer is: 150–450 pF
  - the capacitance of an outdoor potential transformer is: 150–450 pF
- CVT

Voltage class (kV)	Capacitance (pF)
145	4 000–22 000
170	4 000-16 500
245	3 000–12 500
362	2 150–9 500
550	1 500–6 300
800	2 000–6 200

TLF / Additional Capacitances

- Example of connection between circuit breaker and transformer: Hydro Quebec 735kV side of transformer



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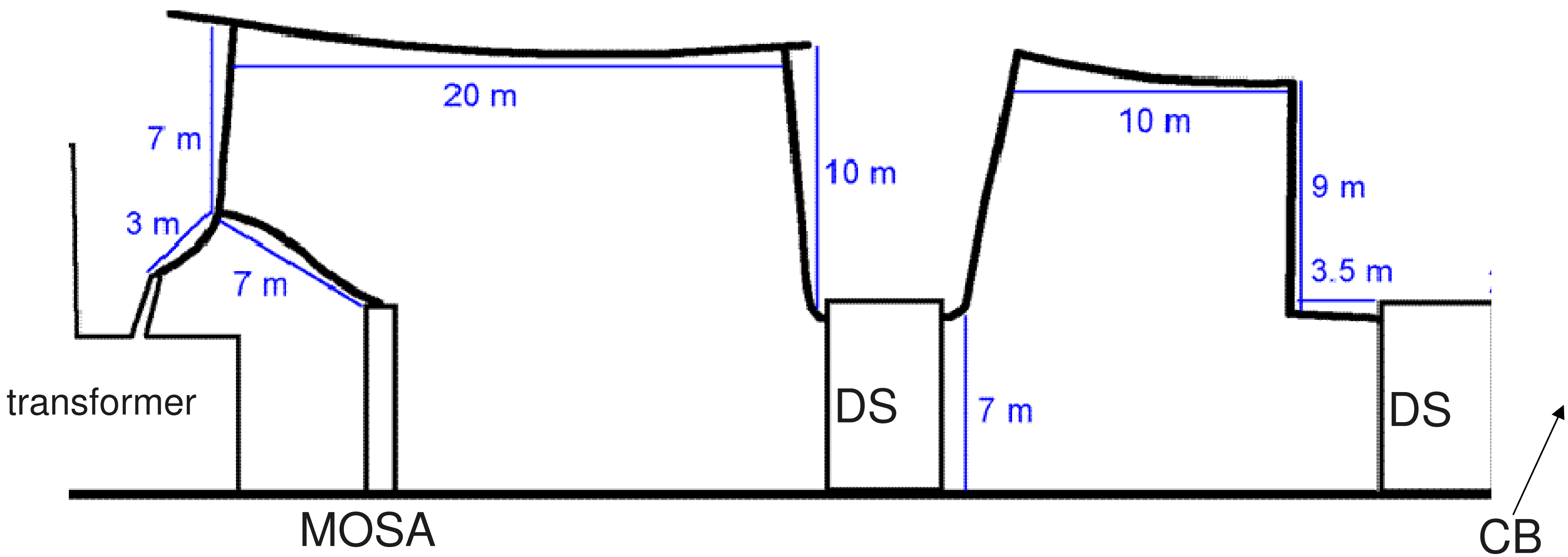
TLF / Additional Capacitances

- Example of connection between circuit breaker and transformer: Hydro Quebec 230kV side of transformer



6 – TLF TRV Peak Factors

Pole-to-clear factor, Amplitude Factor & Voltage Drop Ratio

TLF TRV Peak / Pole-to-clear factor

- The TRV peak is function of 3 factors as shown in the following equation

$$U_c = k_p \times k_{af} \times k_{vd} \times \frac{U_r \sqrt{2}}{\sqrt{3}}$$

k_p = pole-to-clear factor, k_{af} = amplitude factor, k_{vd}= voltage drop across the transformer

- Pole-to-clear factor
  - On the EHV or UHV side, the transformer neutral is effectively grounded,

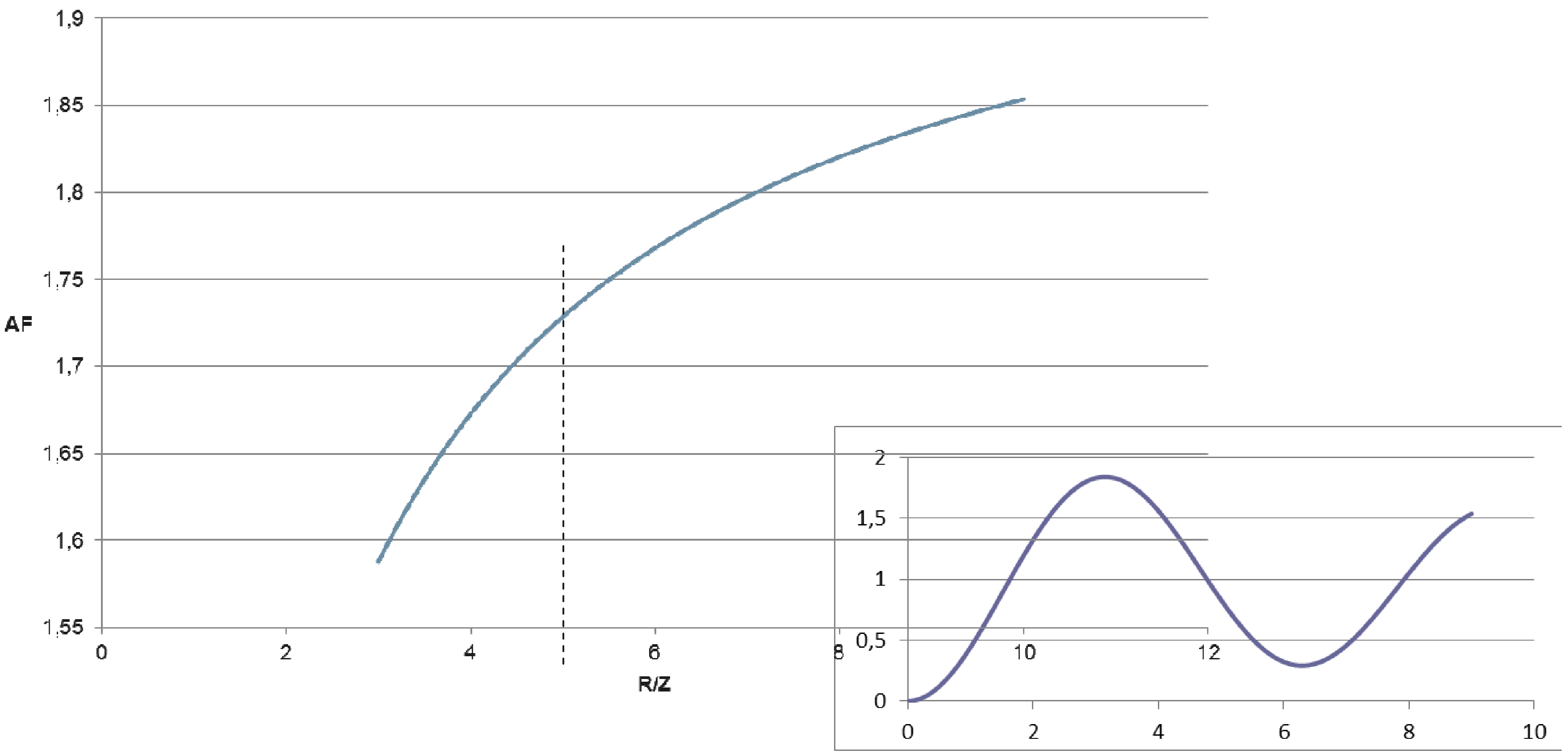
    as a consequence, pole-to-clear factors are between 1.0 and 1.15 (see calculation in Annex).
  - A conservative value could be taken as equal to 1.3.

TLF / TRV Amplitude Factor

- From the initial part of the FRA-measurement an equivalent inductance can be determined. In the higher frequency region (some hundreds of kHz) the equivalent capacitance can be approached.
- From these two values (*L* and *C*) both a single frequency can be determined and an equivalent value Z.
- The ratio between the highest peak of the FRA-impedance measurement and this value Z determines the amplitude factor.
- A ratio R/Z of 5, as found in a case studied by WG A3-28, gives an amplitude factor of 1.73.
- In CIGRE paper A3-108-2012, values of amplitudes factors are equal or lower than 1.62.

Damping or Amplitude factor
Single frequency model

Alan Greenwood's: *Electrical Transients in Power Systems*, 2nd



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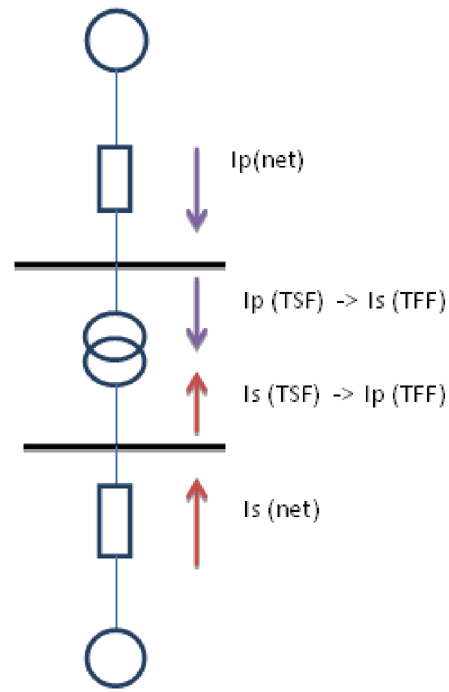
TLF / Voltage Drop Ratio

- In IEC & IEEE standards, the voltage drop ratio is assumed to be 0.9 for terminal fault test duty T10.
- The voltage drop ratio is function of the ratio of TLF current ($I_{p\text{-}TLF}$) and the bus short-circuit current minus the contribution from the faulted transformer ($I_{p\text{-}net}$)

Considering the circuit breaker at the primary side, the voltage drop in case of transformer secondary fault (TSF) is

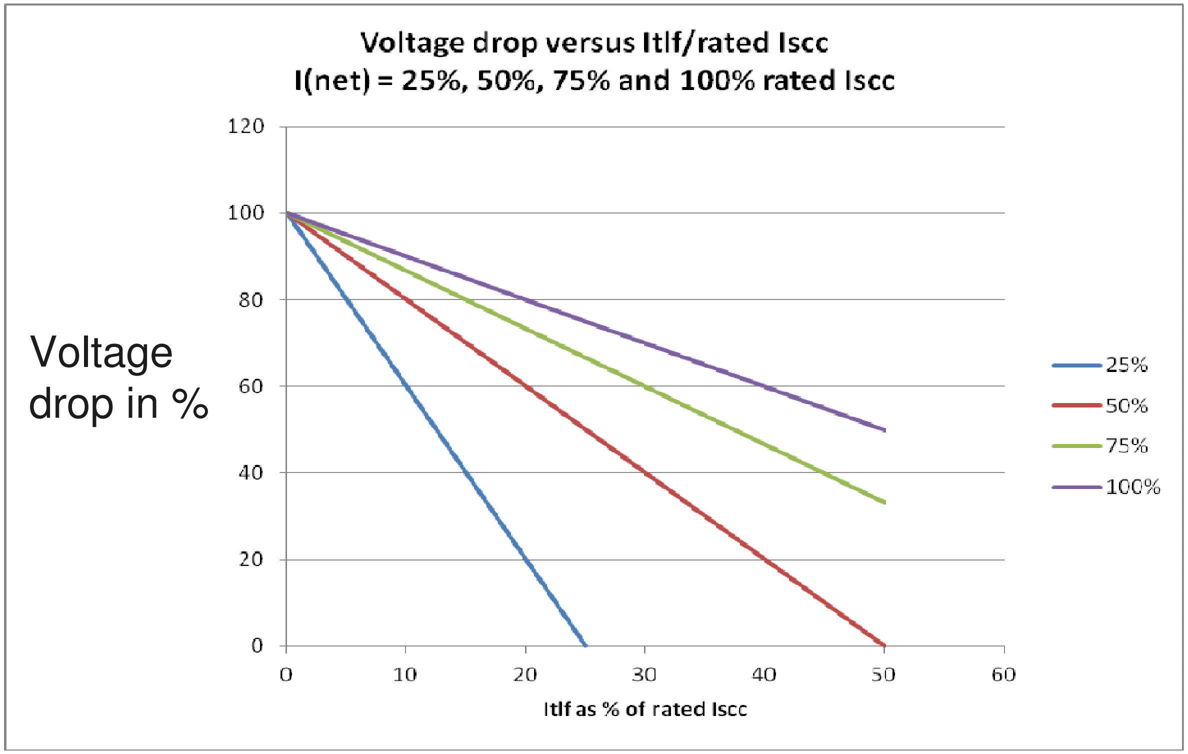
$$\Delta V = 1 - \frac{I_{p-TLF}}{I_{p-net}}$$



TLF / Voltage Drop Ratio

- Based on the previous equation, the voltage drop can be expressed as function of the ratio TLF fault current divided by rated short-circuit current (in percentage) assuming different possible values of the bus short-circuit current

Voltage drop in %



I_{TLF} in % of rated short-circuit current I_{sc}

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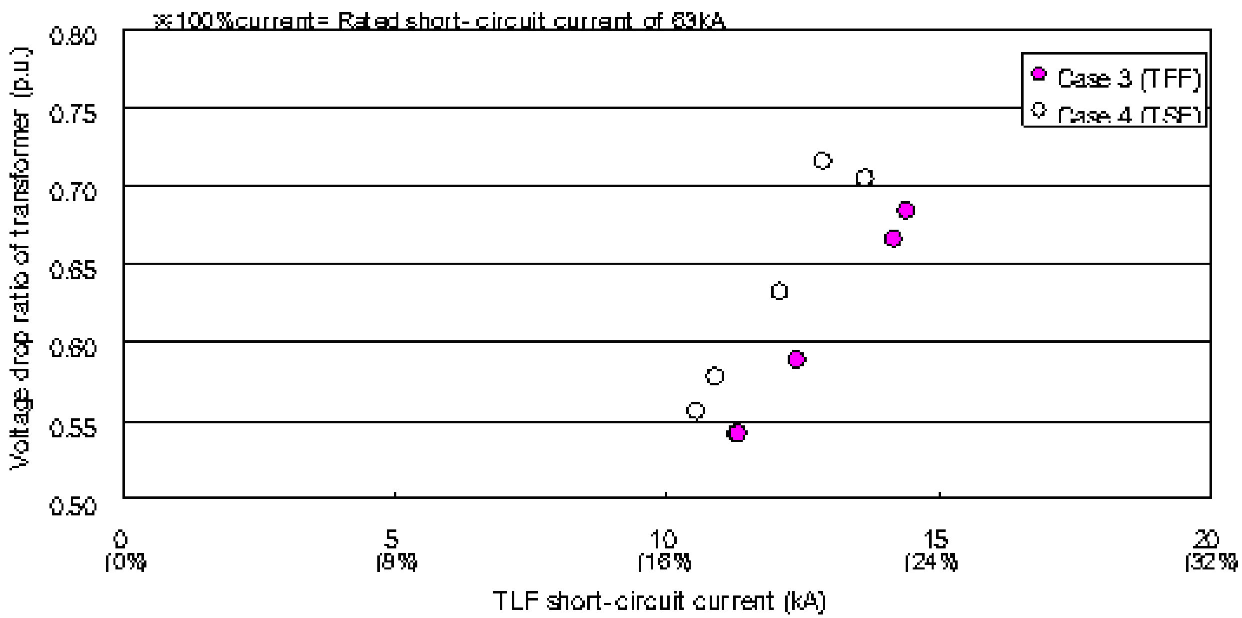
TLF / Voltage Drop Ratio

- CIGRE WG A3.28 has started a survey of voltage drop values for EHV and UHV. Preliminary results for 550kV in Japan (TEPCO) are given below. The maximum value is 72%.
- First results for EHV show that for TLF currents in the range 25-30% Isc the voltage drop is close to 70% (or voltage factor = 0.7).

Voltage drop in %



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7 – Standardization of TLF for UHV in IEC 62271-100

Standardization of TLF for UHV in IEC 62271-100

- Transformer limited fault (TLF) is covered in Annex M.
- M.4 is for rated voltages higher than 800kV
  - The system TRV can be modified by a capacitance and then be within the standard TRV capability envelope. As an alternative, the user can choose to specify a rated transformer limited fault (TLF) current breaking capability.
  - The rated TLF breaking current is selected from the R10 series in order to limit the number of testing values possible. Preferred values are 10 kA and 12,5 kA.
  - TRV parameters are calculated from the TLF current, the rated voltage and a capacitance of the transformer and liaison of 9 nF.
  - The first-pole-to clear- factor corresponding to this type of fault is 1,2. Pending further studies, conservative values are taken for the amplitude factor and the voltage drop across the transformer. They are respectively equal to 1,7 and 0,9.

Standardization of TLF for UHV in IEC 62271-100

Calculation of TLF TRV by IEC MT36 TF UHV (Pierre Riffon)

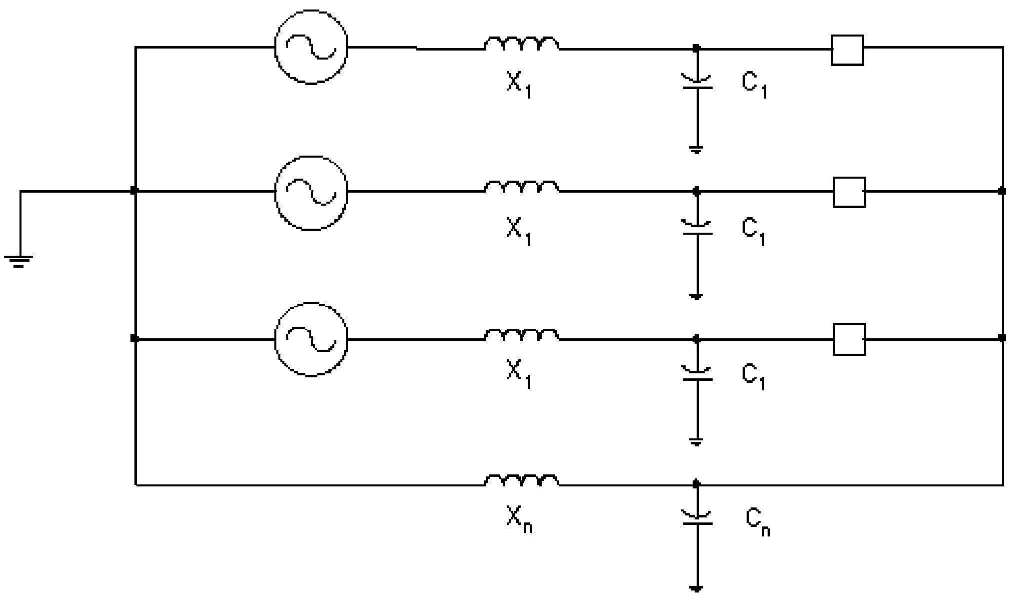
- Calculation assumptions
  - First-pole-to-clear factor: 1,2
  - Fault currents: 10 and 12,5 kA (50Hz and 60Hz)
  - Amplitude factor: 1,7 x 0,9 (90% voltage drop in the transformer)
- Basic circuit

$$X_1 = \frac{U_r}{\sqrt{3} \times I_{fault}}$$

$$X_n = 0{,}33 \times X_1$$

$$C_1 = 9\ nF$$

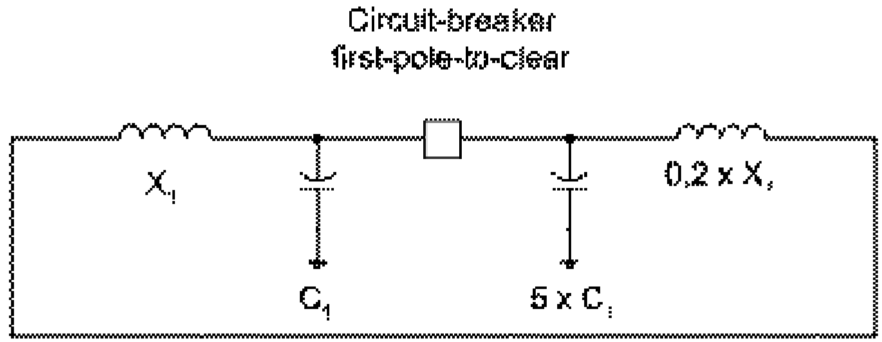
$$C_n = 3\ C_1$$



Back

Standardization of TLF for UHV in IEC 62271-100

- Equivalent circuit for first-pole-to-clear



- The worst case regarding RRRV is for 60 Hz, values in IEC are based on 60Hz and cover the need for 50 Hz.

- Equation for TRV peak value $$U_c = \frac{U_r \times \sqrt{2} \times 1{,}2 \times 1{,}7 \times 0{,}9}{\sqrt{3}}$$

- Time delay $$t_d = 0{,}15 \times t_3$$

- Reference voltage coordinate $$u' = U_c / 3$$

Back

Standardization of TLF for UHV in IEC 62271-100

- Reference time coordinate $$t' = {u'}/{RRRV} + t_d$$

- TRV Table

Table M.2 – Standard values of prospective transient recovery voltage for circuit-breakers with rated voltages higher than 800 kV intended to be connected to a transformer with a connection of low capacitance

Rated voltage U_r kV	TLF fault current kA r.m.s. sym.	First-pole-to-clear factor k_{pp} p.u.	Amplitude factor k_{af} p.u.	TRV peak value u_c kV	Time t_3 µs	Time delay t_d µs	Voltage u' kV	Time t' µs	RRRV[a] u_c/t_3 kV/µs
1100	10	1.2	1,7 x 0,9	1649	107	16	550	51	15,4
1100	12,5	1,2	1,7 x 0,9	1649	96	14	550	46	17,2
1200	10	1,2	1,7 x 0,9	1799	112	17	600	54	16,1
1200	12,5	1,2	1,7 x 0,9	1799	100	15	600	48	18,0

[a] RRRV = rate of rise of recovery voltage.

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8 - Conclusion

Conclusion

- Transformer-limited-faults produce fast TRVs with a high RRRV if there is a low capacitance between the transformer and the circuit-breaker.
- For this duty, it is important to properly evaluate the capacitance (frequency) of the transformer and the capacitance of the liaison between the circuit breaker and the transformer.
- Several methods were presented for the evaluation of a transformer surge capacitance/ TRV frequency: by current injection or from FRA measurements.
- RRRV is also function of the TRV peak, as it is the ratio of the TRV peak by the time to peak (related to the TRV frequency).
- TRV peak is function of several factors (pole-to-clear, amplitude factor, voltage drop across transformer) that must be properly chosen in standards.

9 - Annexes

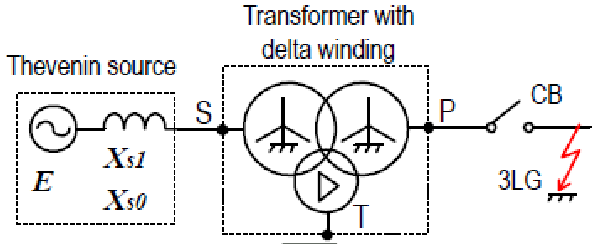
Annex A - Calculation of k_{pp} for TLF

Annex B - Calculation *C*, *R* and *L* by Daini-kyodai method

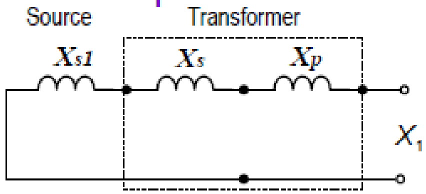
Annex A / Calculation of k_{pp} for TLF

Case: Three-phase to ground fault

Simplified circuit for primary fault

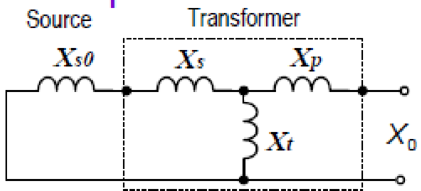


> Positive-sequence reactance



$$X_1 = X_p + X_s + X_{s1}$$

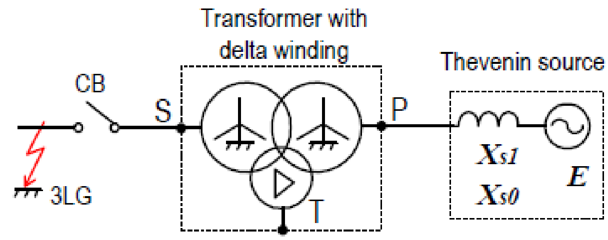
> Zero-sequence reactance



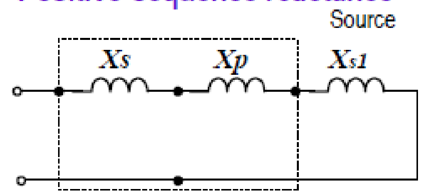
$$K_{pp} = \frac{3X_0}{2X_0 + X_1}$$

$$X_0 = X_p + \frac{X_t(X_s + X_{s0})}{X_t + (X_s + X_{s0})}$$

Simplified circuit for secondary fault

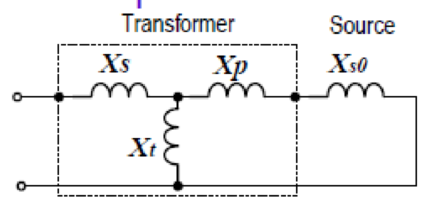


> Positive-sequence reactance



$$X_1 = X_s + X_p + X_{s1}$$

> Zero-sequence reactance



$$K_{pp} = \frac{3X_0}{2X_0 + X_1}$$

$$X_0 = X_s + \frac{X_t(X_p + X_{s0})}{X_t + (X_p + X_{s0})}$$

Annex A / Calculation of k_{pp} for TLF

- First-pole-to-clear factor for 3-phase to ground faults
  - First-pole-to-clear factor for TLF was evaluated in case of a power transformer with delta connection for tertiary winding providing lower voltage networks with short-circuit power of 50kA (system with effectively-grounded neutral).
  - The study shows that
    - k_{pp} for a primary fault is lower than 1.15
    - k_{pp} for a secondary fault is lower than 0.95.

Annex B / Calculation *C*,*R* and *L* by Daini-kyodai method

The procedure to calculate the constants of C, R and L from the waveforms shown in figure 4 is described bellow. The oscillation waveform *Zx (t)* can be expressed by equation 1,

$$Zx(t) = A \cdot e^{-\alpha t} \cdot \sin \omega t \quad \cdots\cdots (1)$$

where parameters a1 and a2 are defined by equation 1 and 2.

$$a_1 = A \cdot e^{-\alpha t_1} \quad \cdots\cdots (2)$$

$$a_2 = A \cdot e^{-\alpha t_2} \quad \cdots\cdots (3)$$

The values of parameters a1 and a2 can be obtained from the waveform as follows.

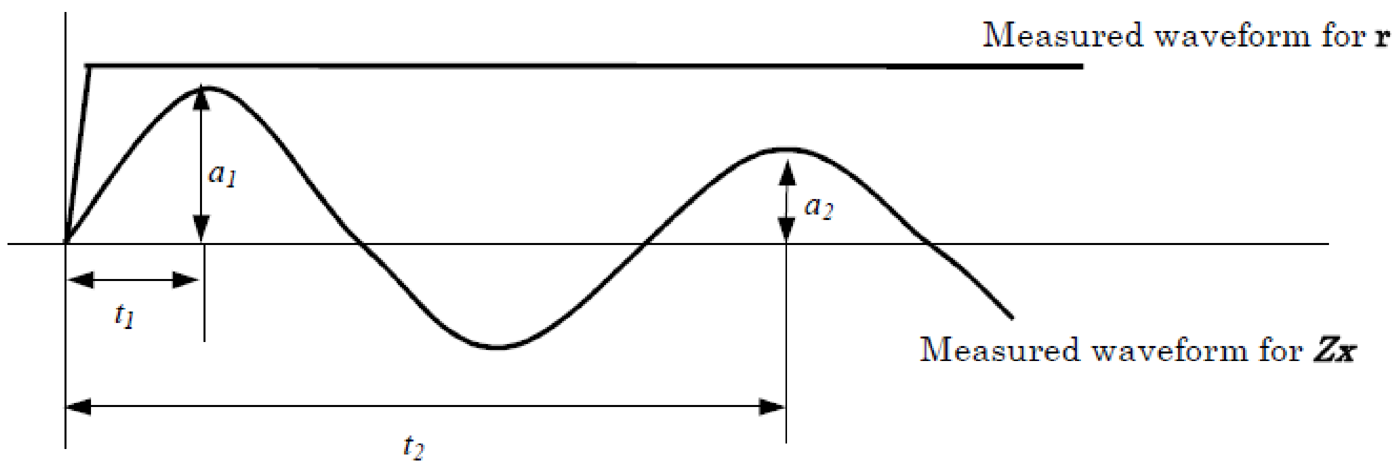


Figure 3 Schematic illustration of a transient waveform

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Annex B / Calculation *C*,*R* and *L* by Daini-kyodai method

$$a_1 = \frac{y_1}{y} r\,(\square), \quad a_2 = \frac{y_2}{y} r\,(\square)$$

(see Figure 4)

And the times t_1 and t_2 can also be obtained from the waveform.

Then equation 4 is given as follows.

$$\alpha = \frac{1n\dfrac{a_1}{a_2}}{t_2 - t_1} \quad \cdots\cdots (4)$$

Equation 5 is given by equation 2 and equation 4.

$$A = a_1 \cdot e^{\frac{1n\frac{a_1}{a_2}}{t_2 - t_1} \cdot t_1} \quad \cdots\cdots (5)$$

Then the operational function Zx (p) is given as follows;

$$Zx(p) = \frac{1}{\dfrac{1}{A\omega} p + \dfrac{2\alpha}{A\omega} + \dfrac{\alpha^2 + \omega^2}{A\omega} \dfrac{1}{p}} \quad \cdots\cdots (6)$$

where $\omega = 2\pi \dfrac{1}{t_2 - t_1}$.

Annex B / Calculation *C*,*R* and *L* by Daini-kyodai method

And the operational function Zx (p) of test object in figure 1 can also be expressed by equation 8.

$$Zx(p) = \frac{1}{Cp + \dfrac{1}{R} + \dfrac{1}{Lp}} \quad \cdots\cdots (7)$$

Then, surge impedance of power transformer can be given as follows.

$$C = \frac{1}{A\omega}, \quad R = \frac{A\omega}{2\alpha}, \quad L = \frac{A\omega}{\alpha^2 + \omega^2}$$

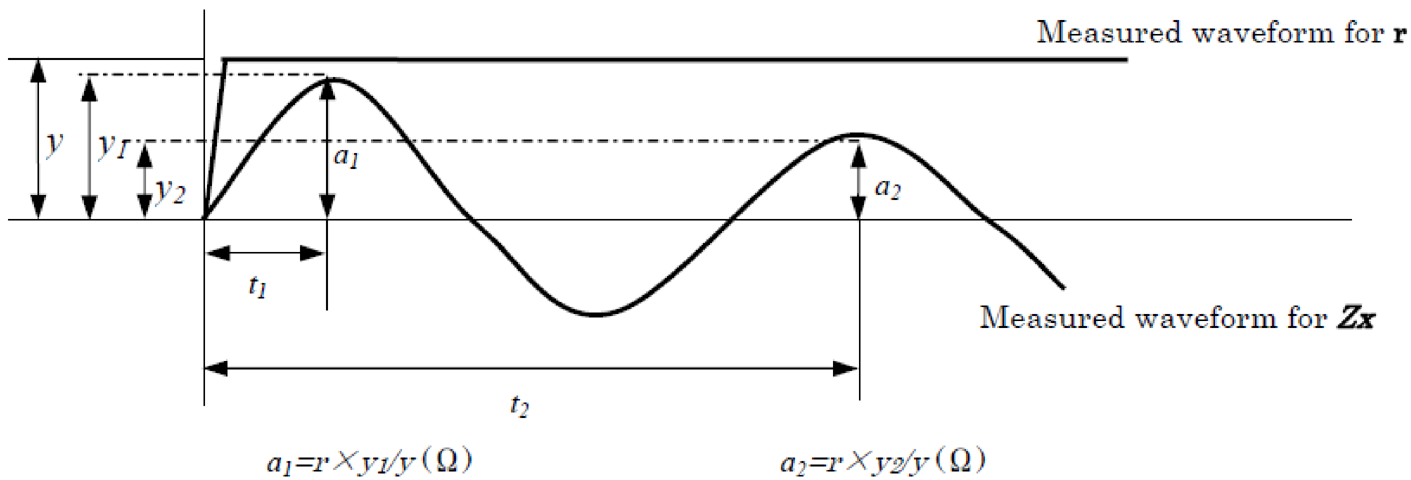

Figure 4 Calculation of waveform parameters

10 - Bibliography

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Thank you for your attention

Questions ?

Thanks to Members of CIGRE WG A3-28 for their input and to
Dr Hiroki Ito (Chairman of CIGRE SC A3).

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Skyline of Downtown San Diego by Wikipedia / J.Dewes