# Transient Recovery Voltage at Transformer Limited Fault Clearing

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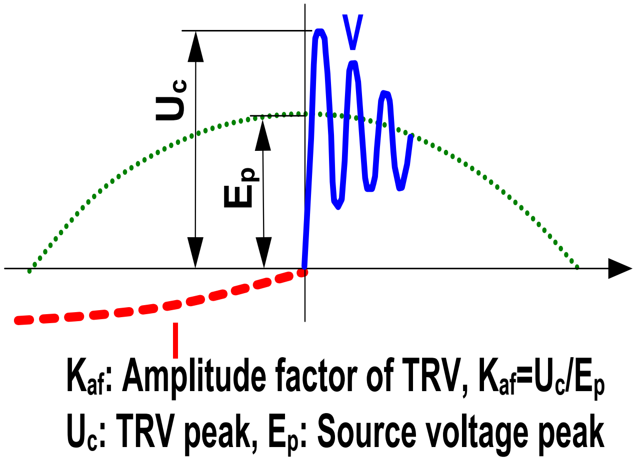
# Background and Introduction

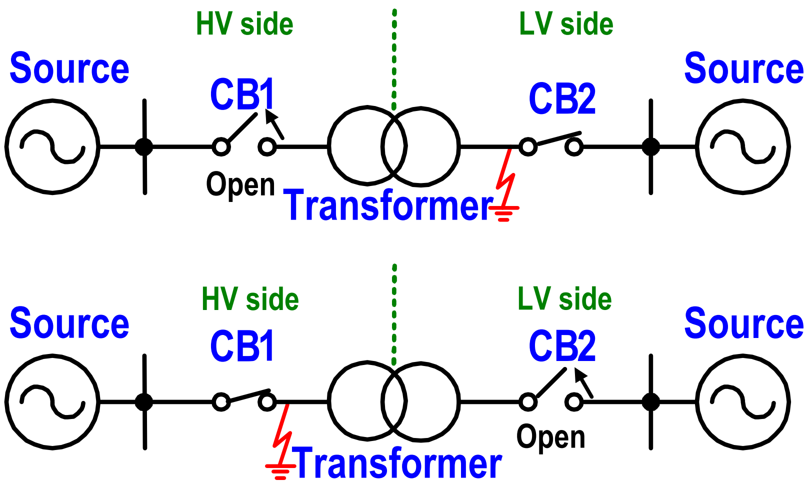
- Severe Transient Recovery Voltage (TRV) after the current interruption may appear when a fault occurs in the immediate vicinity of a power transformer.
- These faults are called Transformer Limited Fault (TLF).



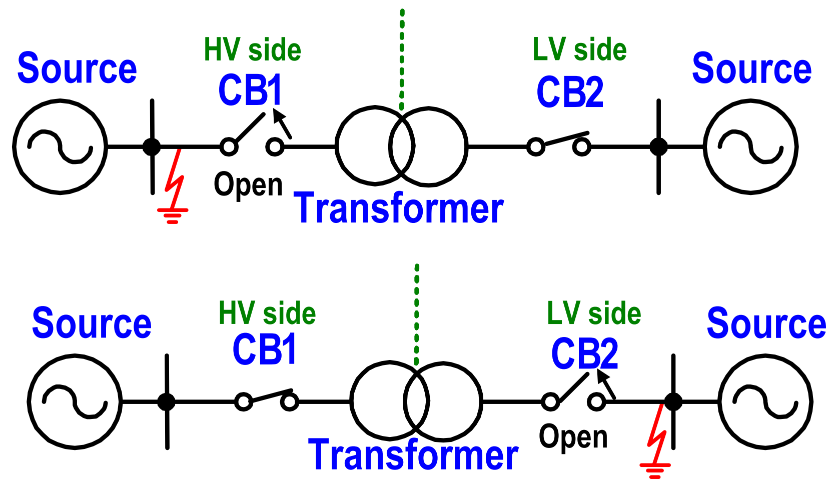

TRV for TLF conditions

- TLF may cause higher Rate-of-Rise of TRV (RRRV) than the standard values specified for terminal fault test duties T10 and T30 of IEC 62271-100 and IEEE standard C37.06.
- TRV parameters, that include the voltage drop across the transformer, the 1st/2nd/3rd pole-to-clear-factors, the amplitude factor, the rate of rise of recovery voltage have been investigated.

# TRV for TLF




Transformer secondary faults(TSF)

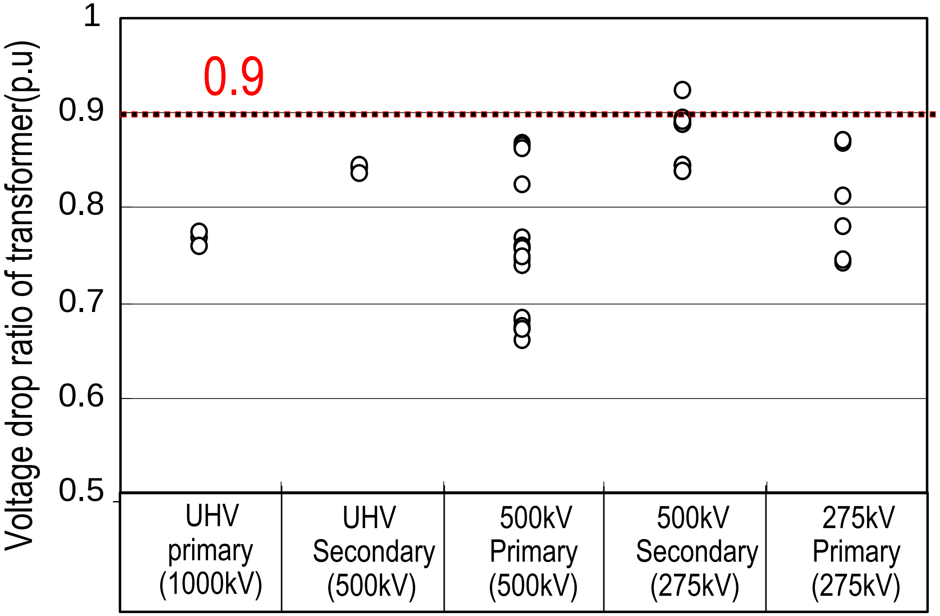



Transformer fed faults(TFF)

## Transformer Limited faults(TLF)

- The TRV frequency is generally determined by the inductance and the equivalent surge capacitance of the transformer.
- In such cases, the Rate-of-Rise of TRV (RRRV) may exceed the values specified in the standards for terminal fault test duties T10 and T30.

# Voltage drop across the transformer

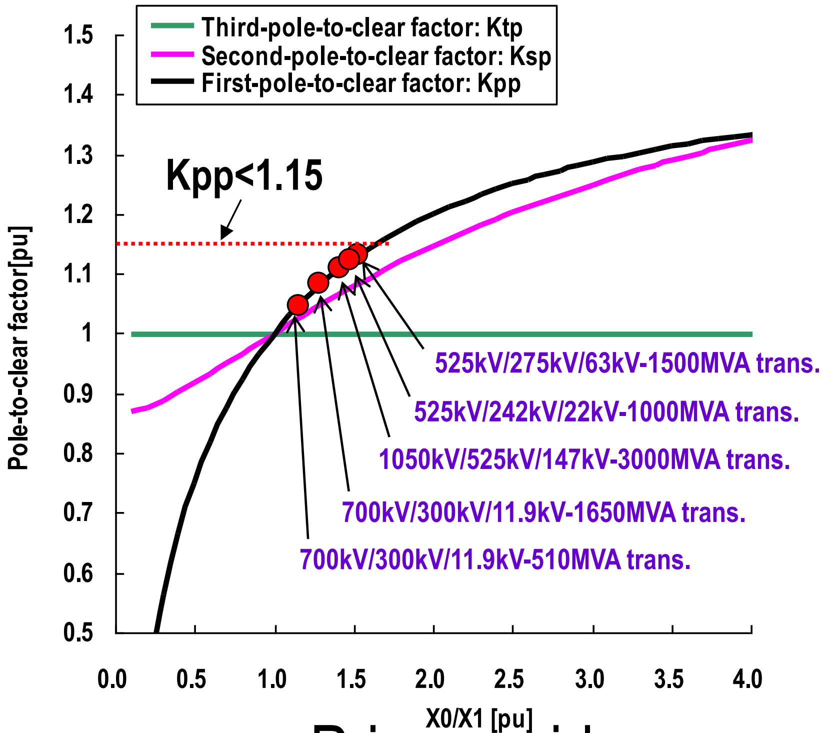



Voltage drop ratio of transformer in Japan

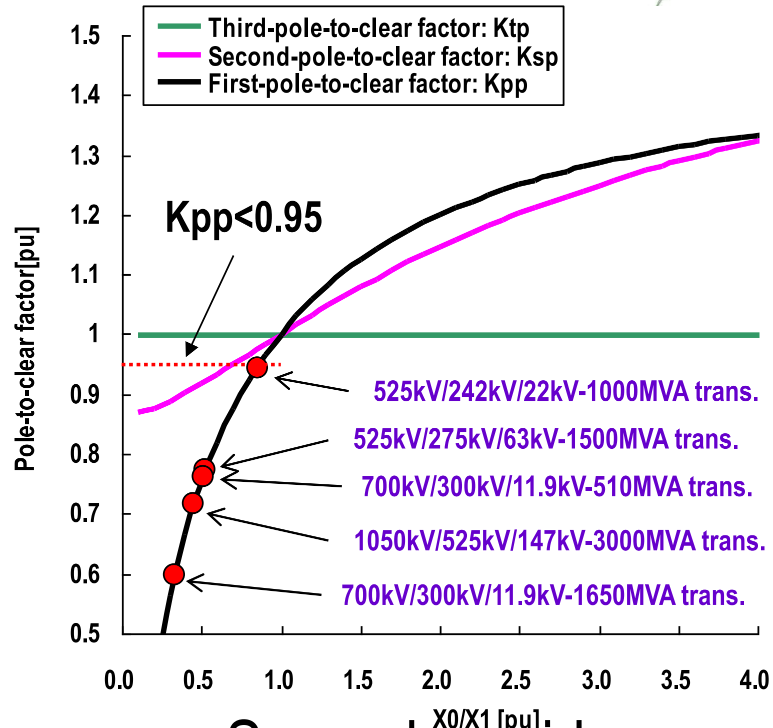
- TLF short-circuit current is determined by the back impedance and the impedance of transformer.
- In the IEC Standard, the voltage drop ratio is 0.9 in the voltage range from 100 to 800 kV.

- These values can be given by the ratio of the system impedance to the impedance of transformer.
- The voltage drops across the transformers are confirmed almost less than 0.9.

# First-pole-to-clear factors(Kpp) for TLF conditions (1)



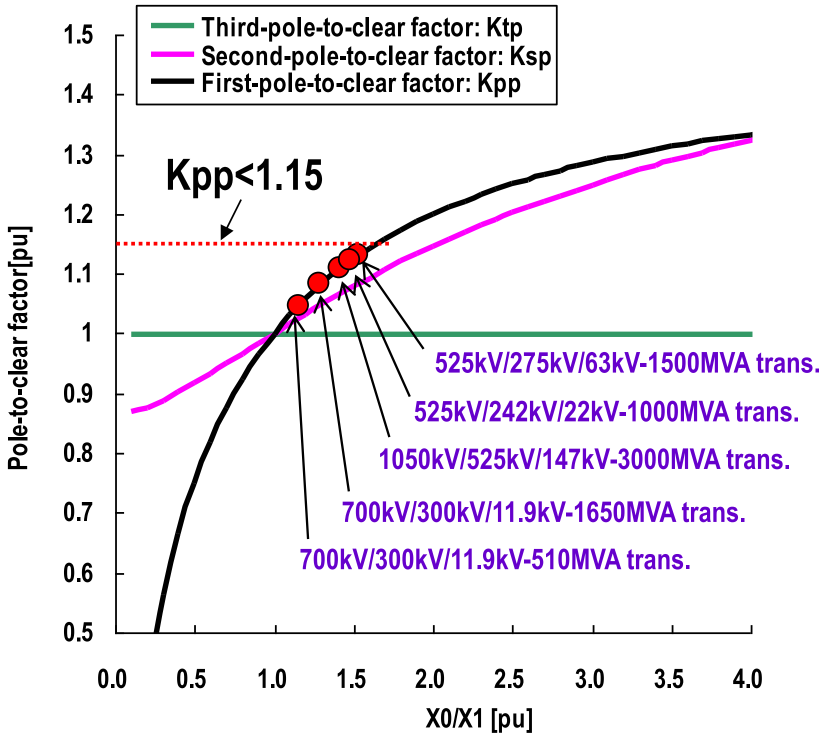

Primary side



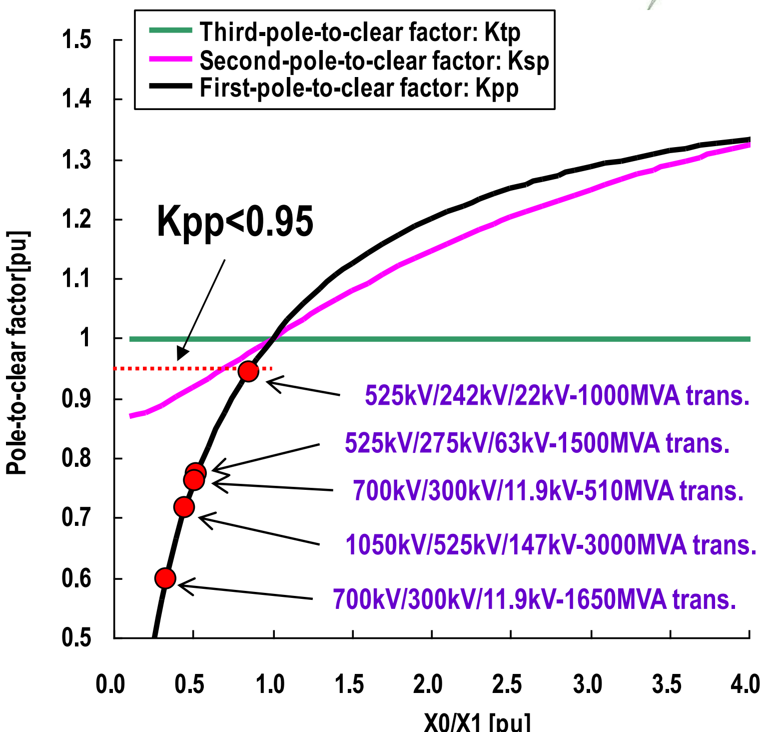

Secondary side

- Typical calculated values of **kpp** by symmetrical coordinate methods using positive and zero-sequence impedance values for various power transformer used in **different projects of the rated voltages from 550kV to 1100 kV**.
- Those transformers have a delta connection for a tertiary winding.

# First-pole-to-clear factors(Kpp) for TLF conditions (2)



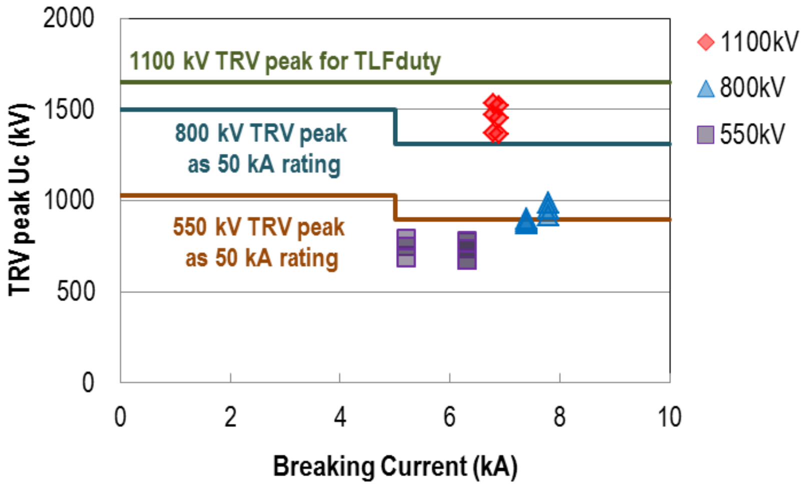

Primary side



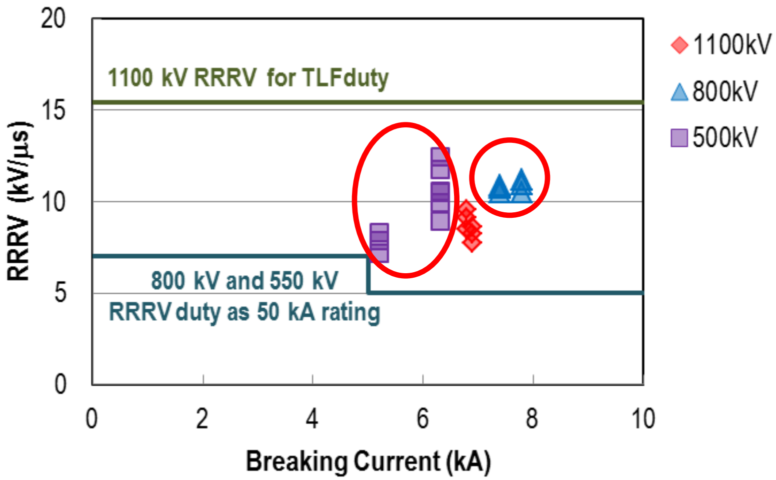

Secondary side

- The kpp for TLF conditions for a primary side range **from 1.0 to 1.15** and those for a secondary side is **lower than 0.95**.
- The kpp specified in IEC for terminal fault T10 and T30 (i.e. **1.2 for UHV and 1.3 up to 800 kV**) are certainly higher than those commonly observed in real cases for TLF conditions.

# TRV for TLF conditions at primary side



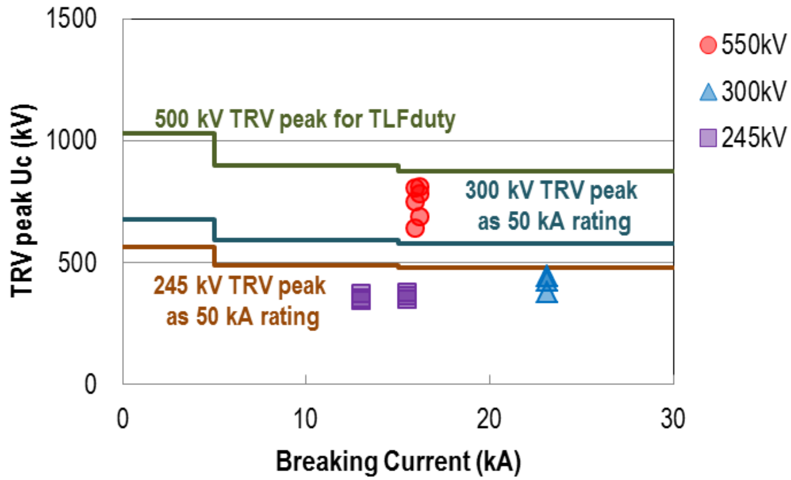

TRV peak

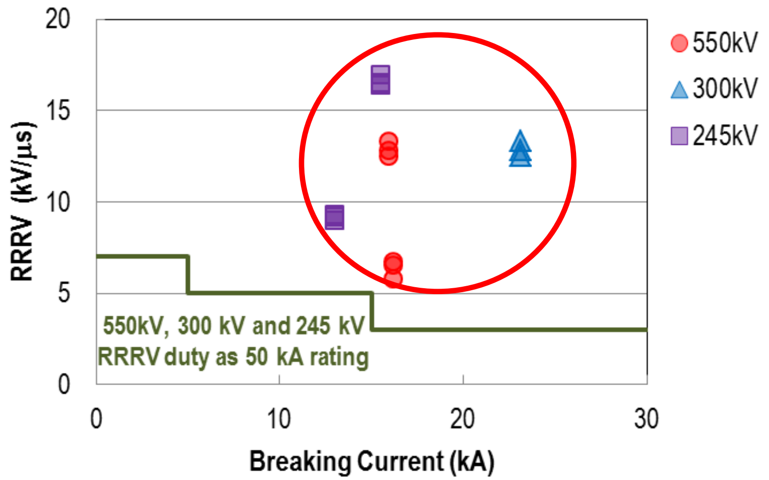



RRRV

- TRV peak and RRRV calculated with different systems and transformer parameters.
- The TRV peak can be covered by the specifications in the IEC standard for all cases.
- The RRRV can be covered by the new recommendation for UHV ratings, but exceed the existing specifications in the IEC standard for 800 kV and 550 kV ratings.

# TRV TLF conditions at secondary side




<u>TRV peak</u>

<u>RRRV</u>

- The RRRV at the secondary side exceeds the existing specifications in the IEC standard for 525 kV, 300 kV and 242 kV ratings.
- The maximum RRRV at the secondary side is calculated as 17.0 kV/µs for 245 kV transformers for secondary side TFF.

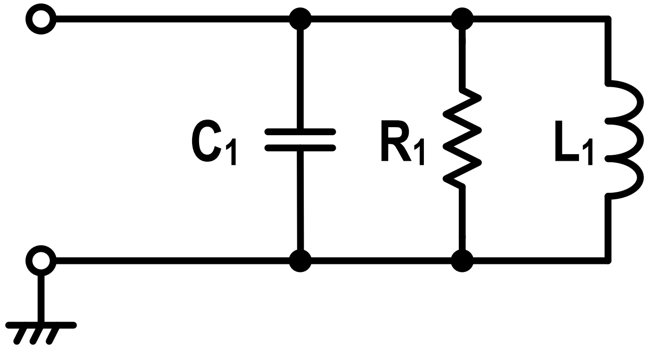
# Transformer models

| | | |
|---|---|---|
| Rated voltage | Primary | 525 kV /√3 |
| | Secondary | 275 kV /√3 |
| | Tertiary | 63 kV |
| Rated capacity | Primary / Secondary | 1500 MVA |
| | Tertiary | 450 MVA |
| Short-circuit Impedance (measured values, based on 1500 MVA) | Primary - Secondary | 13.8 % |
| | Primary - Tertiary | 70.3 % |
| | Secondary - Tertiary | 44.8 % |

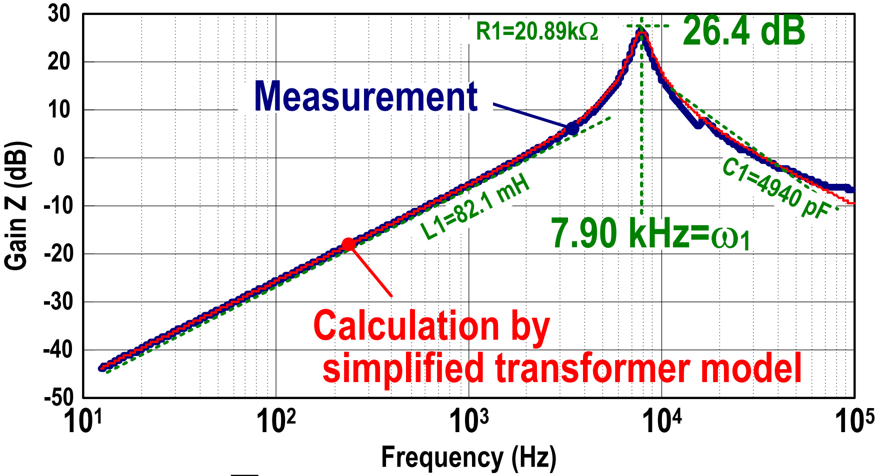
525kV-1500 MVA shell-type three-phase transformer

- Frequency responses were obtained by FRA measurements with 525 kV-1500 MVA shell - type power transformer.
- The same circuit that was used for the TRV measurements was used for the FRA measurements.

# Transformer models(Primary side)




$C_1$=4940 pF, $R_1$=20.89kΩ ,$L_1$=82.1 mH



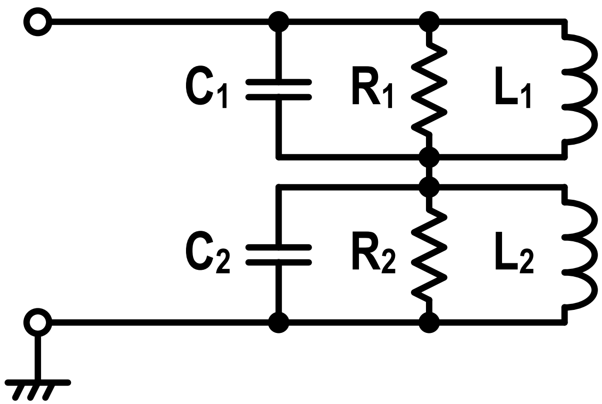

Simplified transformer model

Frequency response

Primary side

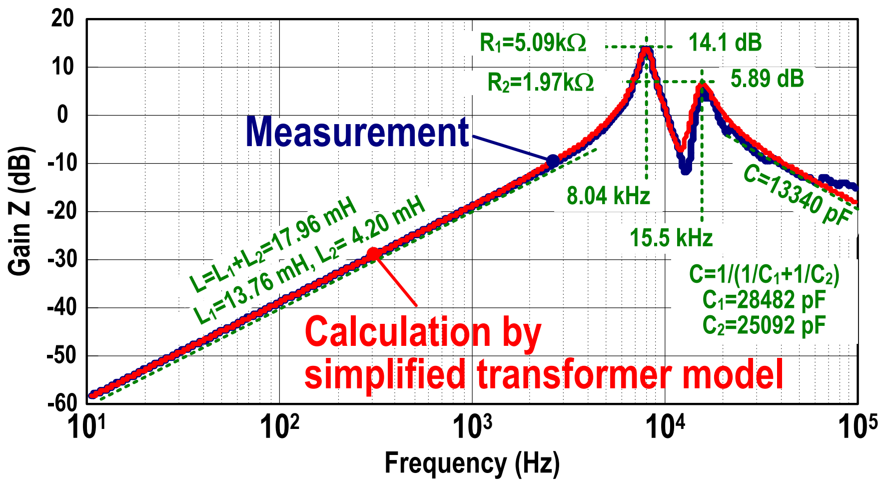
- The simplified transformer model can be obtained by the response of the FRA measurement.
- The $L_1$, $C_1$, and $R_1$ values applicable to the simplified transformer model can be evaluated from the slope of the gain and the gain at the resonant points.
- The impedance response evaluated with the simplified transformer model agreed with the FRA measurement as well.

# Transformer models(Secondary side)




$C_1$=28482 pF, $R_1$=5.09 kΩ, $L_1$=13.76 mH
$C_2$=25092 pF, $R_2$=1.97 kΩ, $L_2$= 4.20 mH

Simplified transformer model

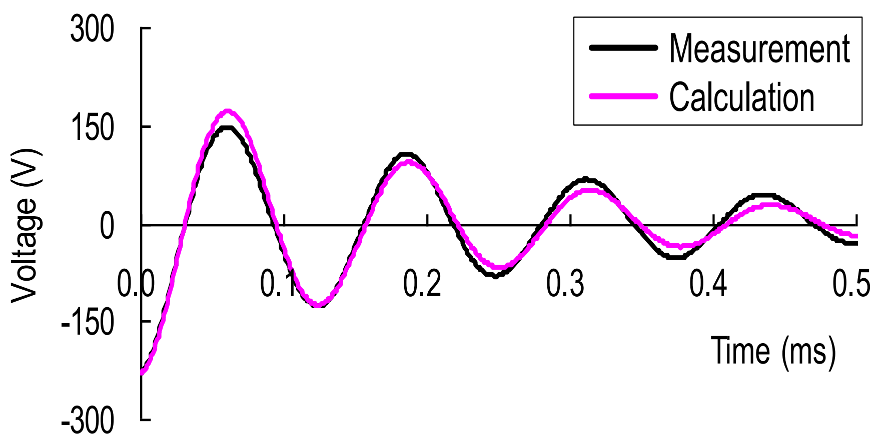



Frequency response

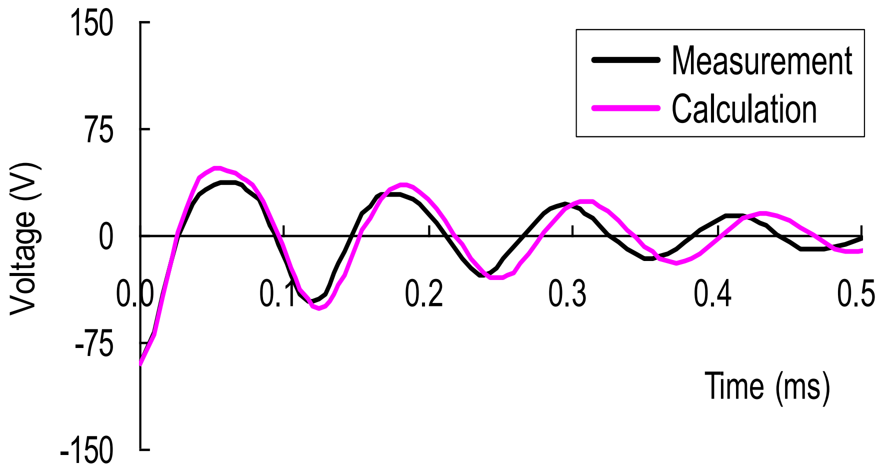
Secondary side

- The result of FRA measurement has two resonant frequencies at 8.04 kHz and 15.5 kHz.
- It means that the simplified transformer model has a double stack of R-L-C parallel circuit.
- The impedance response evaluated with the simplified transformer model agreed with the FRA measurement as well.

# TRV reproduced by the simplified model



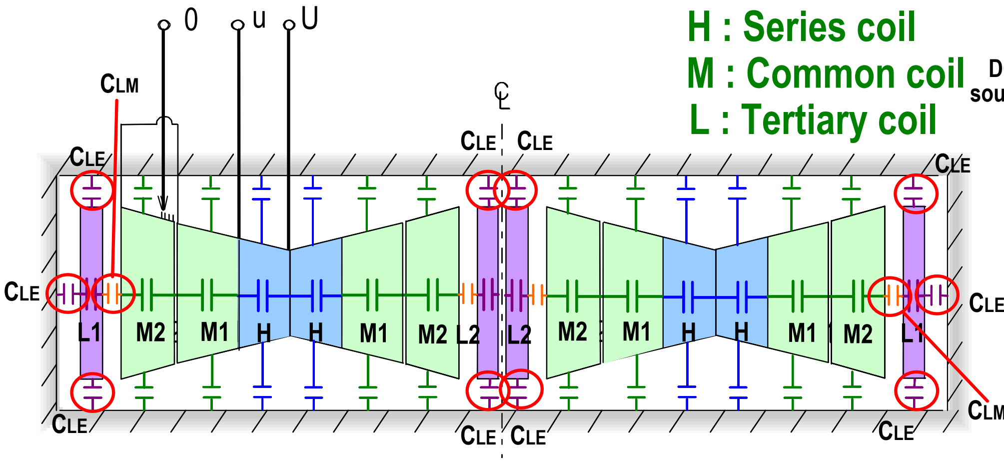

Primary side



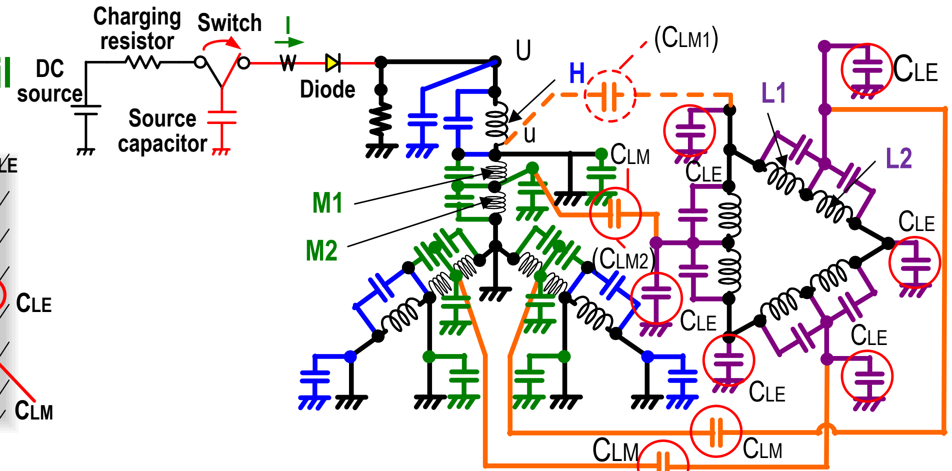

Secondary side

- The TRV calculated with the simplified transformer model compared with the measurement of the TRV by the capacitor current injection method.
- The calculated TRV waveforms showed good agreement with the measured TRVs.
- The simplified transformer model obtained the FRA measurements can reproduce the TRV waveform for TLF conditions very precisely.

# TRV reproduced with Manufacturer model



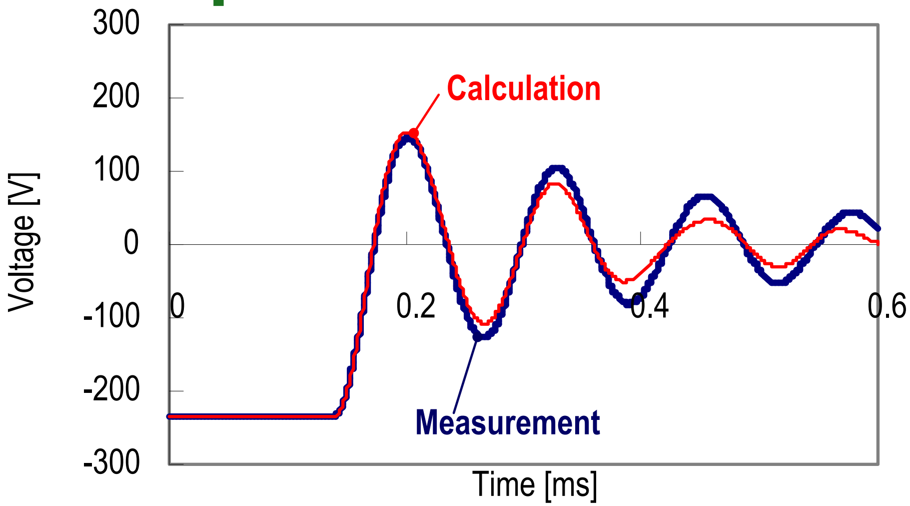

Cross section of the coil



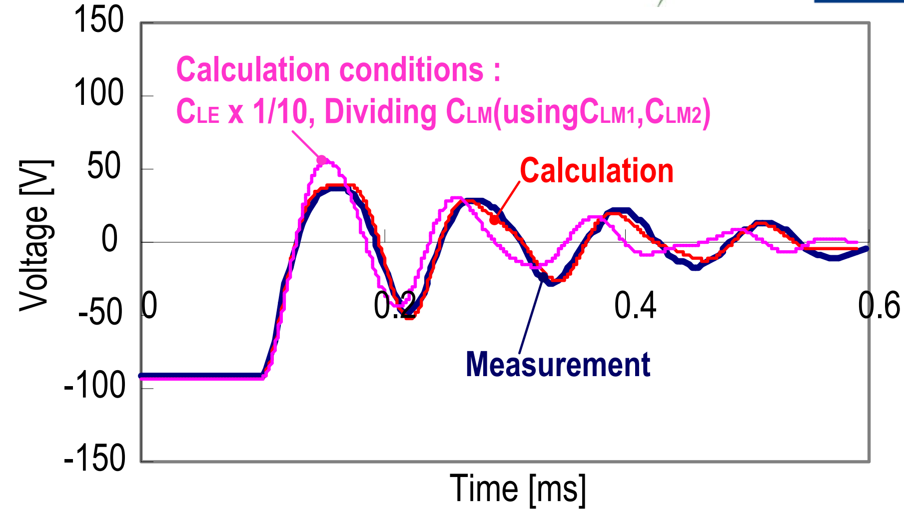

Manufacture transformer model

- Each group has five separate coils consisting of a pair of primary (H) coils, two pair of secondary ($M_1$ and $M_2$) coils and two pair of tertiary ($L_1$ and $L_2$) coils.
- The capacitance from the tertiary coil to the ground is expressed as $C_{LE}$, and that between the tertiary coil and secondary coil is expressed as $C_{LM}$.

# TRV reproduced with Manufacturer model




Primary side




Secondary side

- TRV reproduced by the manufacturer model based on the transformer design shows good agreement with the measurements.
- TRV was also calculated with the capacitance ($C_{LE}$) which is reduced 1/10.
- Deformation of the TRV is caused by the capacitance between the tertiary winding and the ground.

# Conclusion

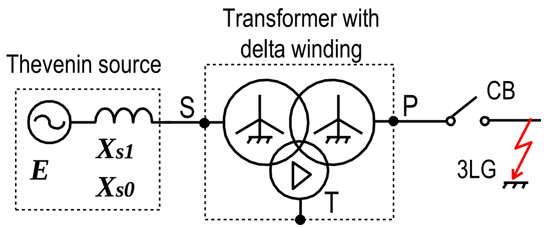
- The voltage drop across the transformers in the UHV and EHV network in Japan are confirmed almost less than 0.9.
- Kpp for TLF conditions for a primary side ranges from 1.0 to 1.15 and those for a secondary side ranges from 0.95 to 1.0.
- TRV for TLF conditions were investigated using different system and transformer parameters. Calculation results shows RRRV exceeds the standard values for T10 and T30 for 800/500kV.
- TRV waveforms were reproduced by the simplified transformer model and the transformer model based on the design. Calculations results  shows good agreement with the measurements.

# Thank you for your kind Attention.

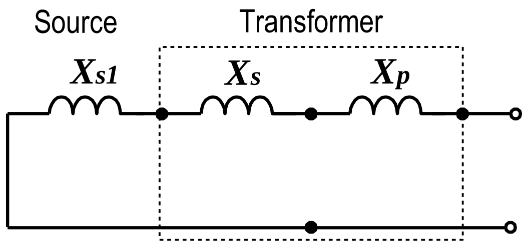
# First-pole-to-clear factors for TLF conditions

## Kpp : By symmetrical coordinate method

### Simplified circuit for primary fault

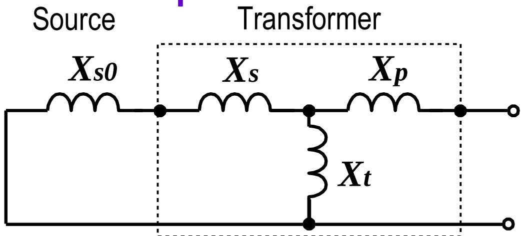



**> Positive-sequence reactance**




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

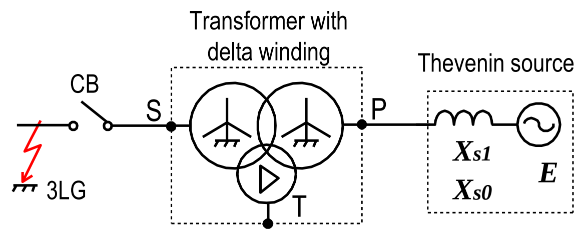
**> Zero-sequence reactance**



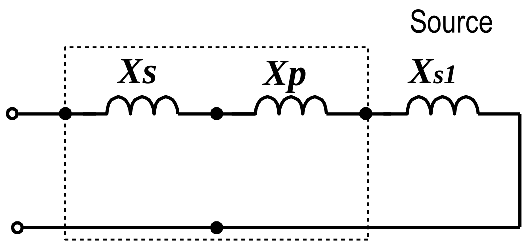

$$X_0 = X_p + \frac{X_t(X_s + X_{s0})}{X_t + (X_s + X_{s0})}$$

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

### Simplified circuit for secondary fault

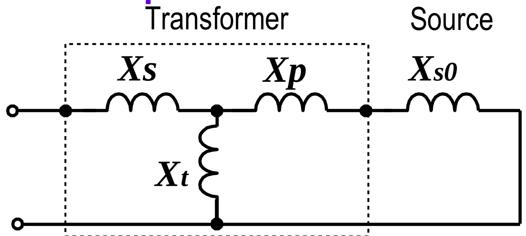



**> Positive-sequence reactance**




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

**> Zero-sequence reactance**




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

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