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Transient Recovery Voltage at Transformer Limited Fault Clearing

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SUMMARY

Severe Transient Recovery Voltage (TRV) after the current interruption may appear when a fault occurs in the immediate vicinity of a power transformer without any appreciable capacitance between the transformer and the circuit breaker. These faults are called Transformer Limited Fault (TLF), that 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[1][2].

The TRV parameters, that include voltage drop across the transformer, $1^{st}/2^{nd}/3^{rd}$ pole-to-clear-factors, amplitude factor, rate of rise of recovery voltage, fault current levels have been investigated. TRV at the primary side and secondary side of a power transformer for TLF conditions were investigated in the circuit including a power transformer using different system and transformer parameters. Large capacity and high voltage power transformers were developed to reduce the number of legs (iron cores) and coil-groups in order to realize compact and reduced-weight designs. The requirement for a compact design may reduce the equivalent surge capacitance of the transformer resulting in a more severe Transient Recovery Voltage (TRV) in Transformer Limited Fault (TLF) duty. Calculations shows RRRV exceeds the standard values for T10 and T30 for 800/500kV. Therefore, further consideration will be needed for standardization.

Impedance frequency responses from the primary, secondary and tertiary windings of the transformer were also measured by the Frequency Response Analysis (FRA) and then TRVs were reproduced by the simplified transformer model with a series connection of parallel circuit of inductance, capacitance and resistance evaluated by the FRA measurements. A simplified transformer model with a series connection of parallel circuits with capacitance (C), inductance (L) and resistance (R) was estimated based on the FRA measurements corresponding to the number of resonant frequencies. The comparison between the measured TRVs and the reproduced TRVs provide detailed technical information on switching phenomena related to TLF conditions. The results may be used by IEC and IEEE to define frequencies for the specification of TRV wave shapes in case of TLF short-circuit current interruption.

KEYWORDS

Transformer Limited Fault, Circuit Breaker, Transient Recovery Voltage, Rate of Rise of TRV, Amplitude factor, Frequency Response Analysis.

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1. Introduction

Severe Transient Recovery Voltage (TRV) after the current interruption may appear when a fault occurs in the immediate vicinity of a power transformer without any appreciable capacitance between the transformer and the circuit breaker. These faults are called Transformer Limited Fault (TLF), that 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. Upon a request of IEC TC17/SC17A that had to revise its standards to cover UHV switchgears, CIGRÉ decided in 2006 to establish WG A3.22 “Technical Requirements for Substation Equipment exceeding 800 kV” in cooperation with several related Study Committees (SCs)[3][4]. Since IEC TC17/SC 17A also requested background information on TRV parameters when clearing TLF at voltages from 100 kV up to and including 800 kV, CIGRÉ A3.28 “Switching Phenomena for EHV and UHV Equipment” studied TRV for TLF conditions with system and equipment parameters used in different countries[5].

Recently, TLF interruptions were reported, but there are insufficient actual survey results[6][7][8][9][10][11][12][13]. In this paper, the TRV parameters, that include voltage drop across the transformer, $1^{st}/2^{nd}/3^{rd}$ pole-to-clear-factors, amplitude factor, rate of rise of recovery voltage, fault current levels have been investigated.

2. Transformer limited faults

One of the most severe fault current interruption duties of a circuit breaker is the clearing of a transformer limited fault (TLF). In Figure 1 the two topology conditions of a TLF are given: the transformer fed fault (TFF) and the transformer secondary fault (TSF). In both conditions the transformer characteristics are the dominant factors that determine the short-circuit current, its AC- and DC-components, the power frequency recovery voltage (first, second and third pole to clear factor by its neutral treatment; the voltage drop), and the higher frequency TRV.

Due to the dominancy of the transformer impedance, the power frequency voltage drop across the transformer forms the basis to establish the TRV. This voltage drop is a function of the primary short-circuit current fed by the transformer to a secondary fault Ip (TSF) and the short-circuit current from the network in case of a fault at the primary side (without a contribution by the transformer itself) Ip (net). Usually at voltage levels of 100 kV and above the transformer windings are Y-connected and the neutral is solidly earthed or earthed through a reactor or resistor to limit the single phase fault current to that of three-phase faults. In either case the X_0/X_1-ratio will be close to 1.0 or less. Consequently the first-pole-to-clear factor (kpp) for TLF will be about 1.0. The first-pole-to-clear factors as specified in the IEC Standard for circuit-breakers (1.2 for UHV and 1.3 for EHV) are thus certainly larger than those observed in service conditions. In cases where transformer neutrals are isolated from earth or connected by Petersen coils (resonance earthing), kpp has to be specified as 1.5.

3. Voltage drop across the Transformer limited faults

To show the relationship between voltage drop across the transformer and the TLF current, the simple scheme of Figure 2 is introduced. Here Is (net) is the short-circuit current contribution by the network at the secondary side without the transformer’s contribution and Ip (TLF) is the TLF current to be cleared by the circuit breaker at the primary side.

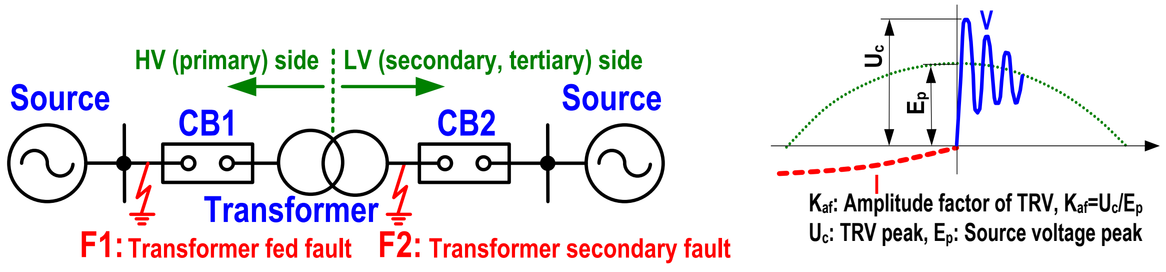


Figure 1: Transient Recovery voltage (TRV) for Transformer limited Faults (TLF)

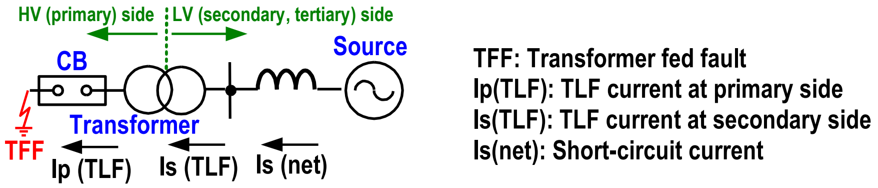


Figure 2: Scheme for voltage drop (ΔV) calculation

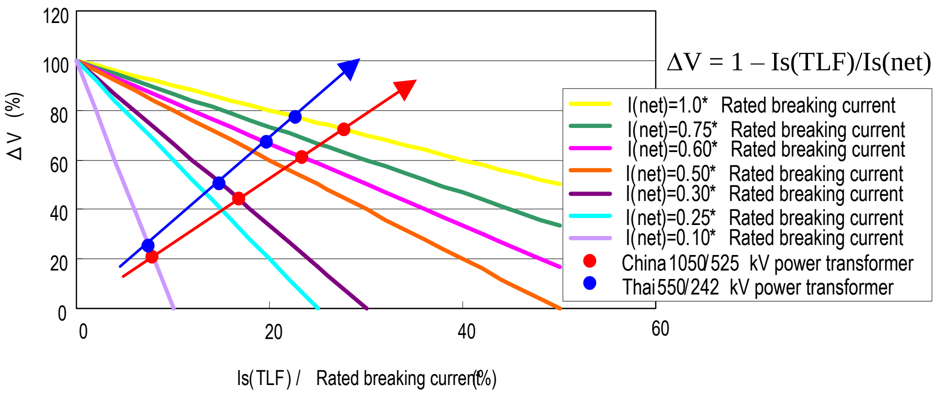


Figure 3: Voltage drop across the transformer(ΔV) for various values

The TFF short-circuit current at the primary side to be cleared by the primary circuit breaker, Ip (TLF), can be determined by Is (TLF) and the transformer ratio. Moreover, by Is (TLF) and Is (net) the voltage-drop across the transformer ΔV can be calculated. When expressed as a percentage of the supply voltage, the voltage drop ΔV is equal to 100% - Is (TLF) as a percentage of Is (net):

$$\Delta V = 1 - Is\,(TLF) \,/\, Is\,(net) \qquad (1)$$

The larger the ratio Is (TLF)/Is (net) the smaller the voltage drop (i.e. the smaller is the influence of the transformer impedance).

The voltage drop across the transformers in the UHV and EHV network in Japan is investigated as shown in Figure 4. These values can be given by the ratio of the system impedance to the impedance of transformer and the rated short-circuit current are specified as 50kA for 1100kVand 275kV, 63kA for 500kV. The voltage drops across the transformers are confirmed almost less than 0.9.

4. First-pole-to-clear factors for TLF conditions

Depending on the neutral treatment of the network and the involved transformer, the X_0/X_1 ratio will vary within wide bands. But, for effectively earthed networks and transformers with an earthed

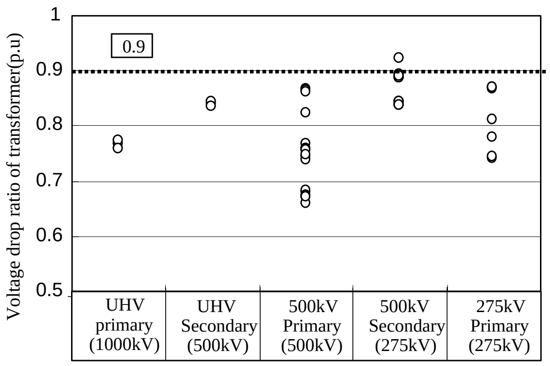
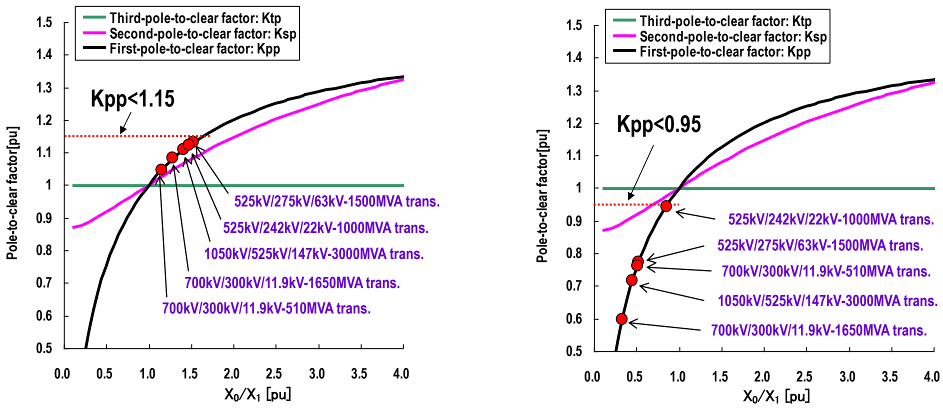


Figure 4: Examples of voltage drop ratio of EHV and UHV power transformers

neutral the X_0/X_1-ratio will be smaller than 1.0, thus leading to a reducing effect on the first pole-to-clear factor (kpp). In other conditions, though, where transformer neutrals are not (always) connected to earth kpp may rise up to 1.5. This, however, is an exception and in general it can be stated that at the transformer side, connected to networks of 100 kV and above, the first pole-to-clear factor for TLF conditions will be close to 1.0 or even lower. Figure 5 shows typical calculated values of kpp for TLF conditions with a delta connection for a tertiary winding of transformers, where kpp for TLF conditions for a primary side range from 1.0 to 1.15 and those for a secondary side lower than 0.95 [13]. 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. They may be used as conservative values for standardization purposes.

A very special case refers to tertiary windings (Δ-windings) in UHV transformers as applied in China and Japan. These windings, with rated voltages of 123 kV or 145 kV in China and 154 kV in Japan may be used for shunt compensation. When circuit breakers are applied in connection to such tertiary windings the duties are very extreme and form therefore no basis for standardization purposes.

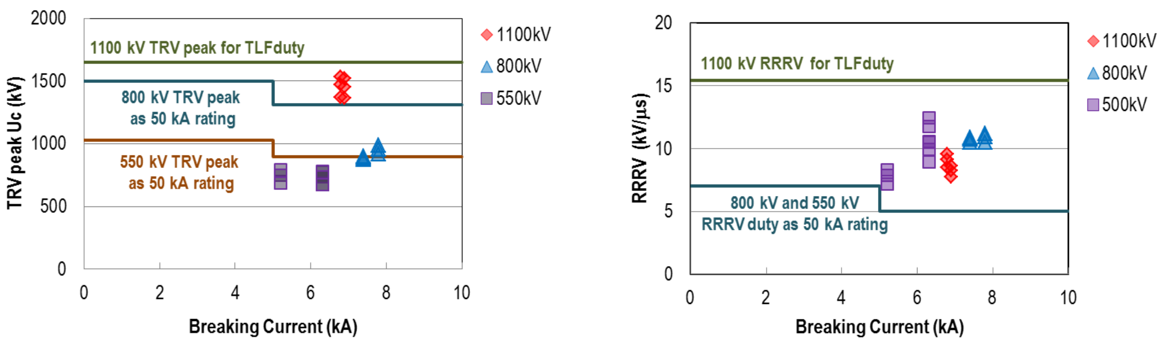


(a)Primary side (b) Secondary side

Figure 5: Typical evaluations of first-pole-clear factor (Kpp) for TLF conditions

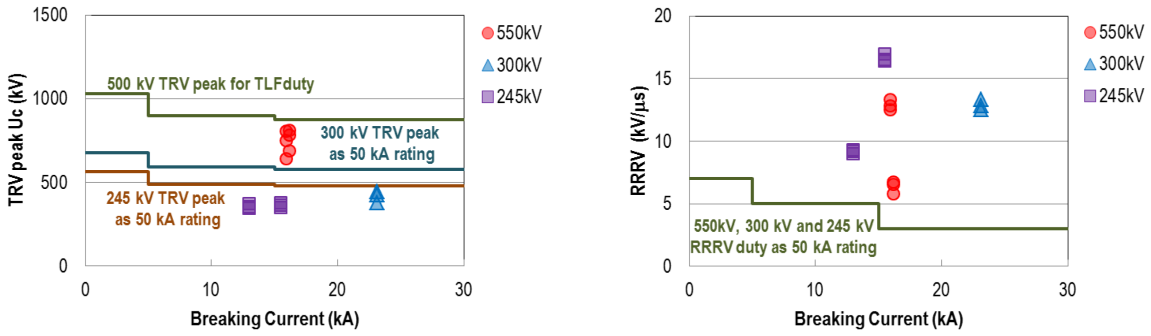
5. TRV TLF conditions at the primary side and secondary side

Figure 6 shows the plots of TRV peak and RRRV calculated with different system and transformer parameters. The RRRV at the primary side 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. Figure 7 shows the plots of TRV peak and RRRV calculated with different system and transformer parameters. The RRRV at the secondary side exceeds the existing specifications in the IEC standard for 525 kV (1100 kV for primary), 300 kV (800 kV for primary) and 242 kV (550 kV for primary) ratings. The maximum RRRV at the secondary side is calculated as 11.0 kV/μs for 550 kV, 13.3 kV/μs for 300 kV and 17.0 kV/μs for 245 kV transformers for secondary side TFF.



(a) TRV peak (b) RRRV

Figure 6: TRV for TLF conditions at primary side of transformer

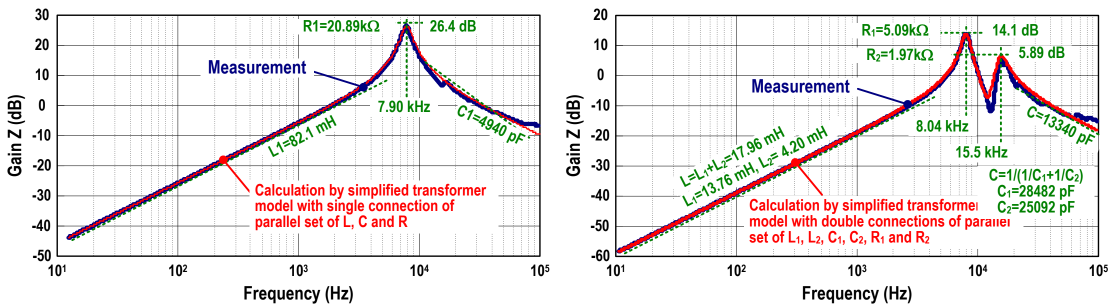


(b) TRV peak (b) RRRV

Figure 7: TRV for TLF conditions at secondary side of transformer

6. Transformer models

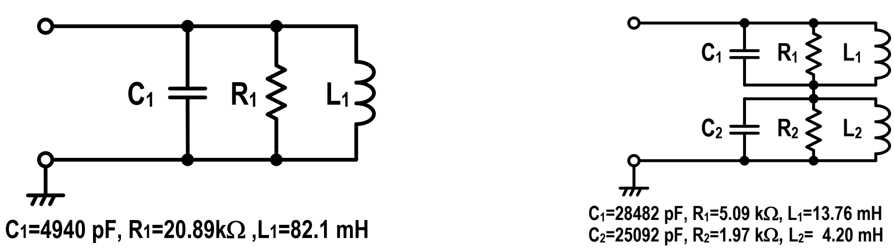
Typical responses obtained by FRA measurements with the first-pole-to-clear at the primary, secondary sides of a 1500 MVA shell-type transformer are also shown in Figure 8. The same circuit as that used for the TRV measurements was used for the FRA measurements.



(a)Primary side (b) Secondary side

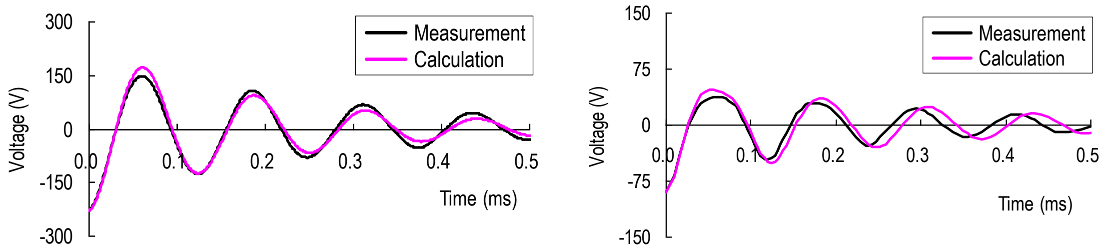
Figure 8: FRA measurement with a 525 kV1500 MVA transformer

TRV waveform can be reproduced by a simplified transformer model with a series connection of multiple parallel circuits of L, C and R based on the FRA measurements and/or a manufacturer model based on the transformer design. The L, C, and R values applicable to the simplified transformer model can be evaluated from the slope of the gain and the gain at these resonant points. The simplified transformer model for the primary and secondary side can be obtained by the response of the FRA measurement as shown in the Figure 8. Frequency responses were also calculated with these simplified transformer models and plotted in the Figure 8. Both calculations showed good agreements with the measured FRA characteristics. Figure 10 shows the TRV waveforms reproduced by the simplified transformer models based on the FRA measurements. The calculated TRV waveforms also showed good agreement with the measured TRVs. Thus it is confirmed that the simplified transformer model with a series connection of multiple parallel circuits sets of L, C, and R based on the FRA measurements can reproduce the TRV waveform for TLF conditions very precisely.



(a)Primary side (b) Secondary side

Figure 9: Simplified transformer models for primary and secondary side



(a)Primary side (b) Secondary side

Figure 10: TRV reproduced by simplified transformer models

7. Detailed manufacture transformer models

Figure 11 shows the cross sectional diagram of transformer coils with two groups used for TRV measurement. The design of the coil is divided into the primary windings (H), secondary windings (M) and tertiary windings (L). Each group has five separate coils consisting of a pair of primary (H) coils, two pair of secondary (M1 and M2) coils and two pair of tertiary (L1 and L2) coils. The circuits between the coils are modeled with a series connected resistance and inductance as well as capacitance as shown Figure 12. The circuits from each terminal to the ground are modeled with the capacitance. 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}.

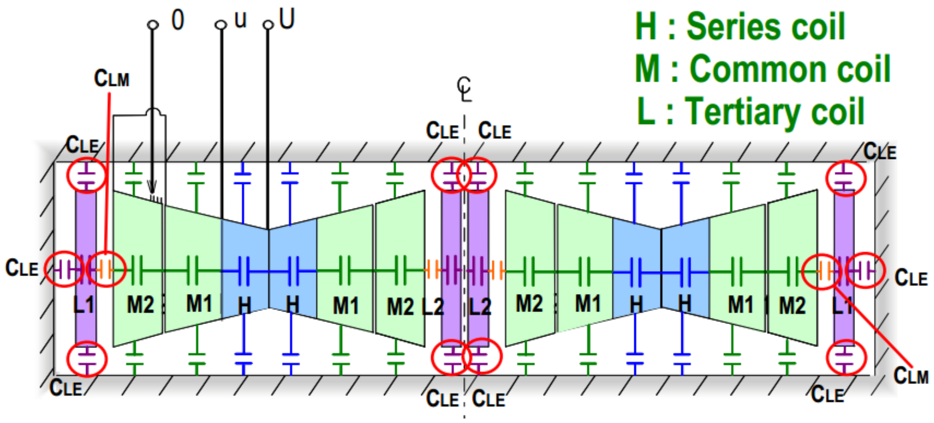


Figure 11: Cross sectional diagram of the transformer coil

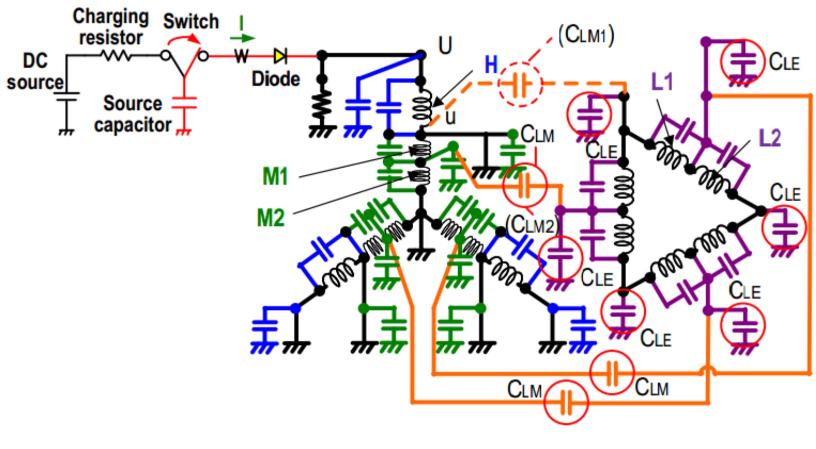
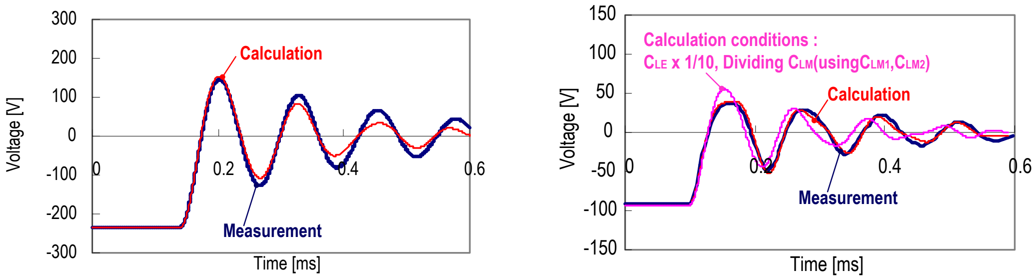


Figure 12: Manufacturer transformer model with five elements model for three-phase autotransformer 525/275/63 kV, 1500 MVA



(a)Primary side (b) Secondary side

Figure 13: TRV reproduced by the manufacturer transformer model

TRV for the primary side was calculated with the manufacturer transformer model based on the transformer design and compared with the measured TRV by the capacitor current injection method shown in the Figure 13. TRV reproduced by the model shows good agreement with the measurements. Relatively large capacitance between the tertiary winding and ground (C_{LE}) could be considered as a main contributor for TRV's deformation. TRV was also calculated with the capacitance (C_{LE}) which is reduced 1/10 in order to confirm the influence of the capacitance on the TRV peak deformation.

8. Conclusion

TRV of TLF conditions were investigated and the following results were obtained.

- The voltage drop across the transformer is shown to be dependent on the ratio of the TLF breaking current/ Rated breaking current, ranging from 0.9 for low TLF breaking currents up to 0.7 for the highest TLF breaking current (typically 30% of rated breaking current).
- First-pole-to-clear factors (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. The reason is that the ratios of the zero-sequence to positive sequence impedance (X_0/X_1) for a primary side is higher than those for a secondary side, because secondary side impedance (X_s) smaller than primary side impedance (X_p).
-TRV at the primary side and secondary side of a power transformer for TLF conditions were investigated in the circuit including a power transformer using different system and transformer parameters. Calculation results shows RRRV exceeds the standard values for T10 and T30 for 800/500kV. Therefore, further consideration will be needed for standardization.
-TRV waveforms were measured with large capacity shell-type transformer by the capacitor current injection method. Deformation from a sinusoidal shape waveform was observed when the TRV possess multiple frequency components higher than a main TRV frequency.
-TRV waveforms were reproduced by the simplified transformer model with a series connection of multiple parallel circuits of L, C, R evaluated by the FRA measurements depending on the number of the resonant frequency.
-TRV reproduced by the transformer model based on the design shows good agreement with the measurements by the capacitor current injection method.

BIBLIOGRAPHY

[1] ANSI C37.06.1, Guide for High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis Designated “Definite Purpose for Fast Transient Recovery Voltage Rise Times”, 2000

[2] IEC 62271-100, Ed.2.1, 2012-09, High-voltage switchgear and controlgear- Part 100: Alternating current circuit breakers

[3] CIGRE WG A3.22, “Technical Requirements for Substation Equipment Exceeding 800 kV AC, Technical Brochure 362, December 2008

[4] CIGRE WG A3.22, “Background of Technical Specifications for Substation Equipment Exceeding 800kV AC”, Technical Brochure 456, April 2011

[5] CIGRE WG A3.28, “CIGRE Technical Brochure 570, Switching Phenomena for UHV and EHV Equipment”, February 2014

[6] A. Janssen, D. Dufournet, The Standardization of TRV at Transformer Limited Fault Clearing, Paper 101, CIGRÉ SC A3 & B3 Nagoya colloquium, September 2015

[7] Draft IEEE C37.06.1 Standard for High-Voltage (>1000 volts) AC Circuit Breakers - Fast Transient (Transformer Limited Fault) Recovery Voltage Rise Times, April 2015

[8] Y. Yamagata, H. Kagawa, M. Kosakada, M. Toyoda, J. Kida, H. Ito, “Considerations on Transformer Limited Fault duty for GCB in UHV and EHV networks with large capacity power transformers”, CIGRE SC A3 Session 2012, Report A3-108

[9] H. Kagawa, T. Maekawa, M. Kosakada, O. Hosokawa, M. Toyoda, K. Kawasaki, “Investigation on transformer limited faults on large capacity power transformers”, Paper 422, CIGRE International Symposium in Auckland, September 2013.

[10] H. Ito, H. Kajino, Y. Yamagata, K. Kamei, T. Idemaru, H. Shinkai, “Study on Transient Recovery Voltages for Transformer-Limited Faults”, IEEE Transactions on Power Delivery, Vol.29, No.5, October 2014

[11] A. Janssen, D. Dufournet, J. Veens, “Determining the Transient Recovery Voltage at Transformer Limited Fault Clearing”, Paper 601, CIGRE SC A2 Shanghai Colloquium September 2015

[12] H. Kajino, H. Ito, K. Kamei, H. Kagawa, “Study on Transient Recovery Voltages for Transformer Limited Faults”, Paper 653, CIGRE SC A2 Shanghai Colloquium September 2015

[13] A. Janssen, D, Dufounet, H.Ito, “Transient Recovery Voltage at Transformer Limited Fault Clearing”, CIGRE Science & Engineering February 2016