Realization of Transient Recovery Voltages for Ultra High Voltage Circuit Breakers in Testing

R.P.P. Smeets, S. Kuivenhoven, A.B. Hofstee

***Abstract*—The most critical transient a circuit breaker has to endure during its operation is the transient recovery voltage (TRV), initiated by the electric power system as a natural reaction on current interruption. For circuit breakers intended to operate in ultra-high voltage systems (with rated voltage above 800 kV), the realization of realistic transient recovery voltages in testing of these circuit breakers becomes a real challenge.**
In this contribution a new method is described of creating adequate TRVs by a double stage synthetic test circuit. Due to the extremely high voltages, to be applied immediately after interruption of very high fault current, a two-stage approach is necessary. This is the only way to perform full-pole testing, the realistic laboratory simulation of service conditions during fault current interruption.

***Keywords*: Ultra high voltage, testing, circuit breaker, short-circuit.**

I. INTRODUCTION

Long distance transmission of electrical energy calls for the need of ever higher voltage transmission systems. The most recent example is the commissioning of a 1100 kV AC transmission system in China early 2009. The key switching component in such systems is the circuit breaker, consisting of 2 – 4 interrupters in series. Its main function is to interrupt fault current, in case a fault occurs in the system, most likely on an overhead line. After the fault current has been interrupted at power frequency current zero, the natural reaction of the power system is the generation of a transient recovery voltage (TRV) that arises across the circuit breaker. It consists of a contribution from the upstream- and from downstream side of the breaker, since after current interruption and separation of the two circuit parts, up- and downstream side circuits generate transients completely independently. The challenge for the breaker is (1) initially the very fast rate of rise of TRV during the breaker's recovery from the thermal arcing stresses before current zero and (2) later the dielectric stresses due to the high peak value of TRV, overshooting the power frequency voltage.
The process of fault current interruption and its associated transient recovery voltage is shown in the simplified sketch of fig. 1. In the case of fig. 1, a single frequency TRV is drawn. However, in practice a very complicated TRV wave-shape is generated depending on the network (earthing), type and location of fault etc. After decay of the transient, the breaker stress reduces to the power frequency Recovery Voltage (RV).

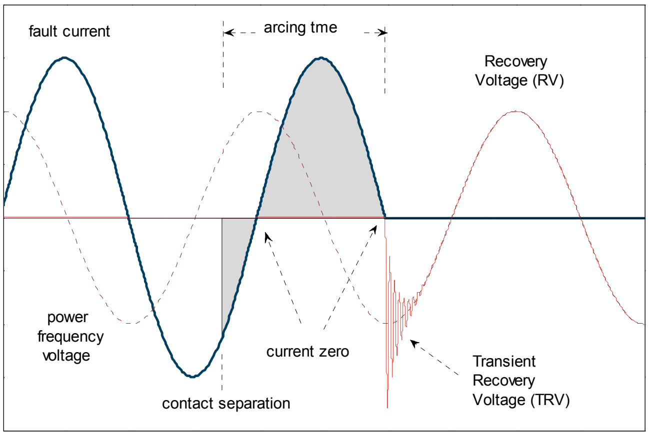

Fig. 1. Principle of current interruption in a single phase case

For the purpose of type testing, a standardized system of TRV description is developed by the International Electro-technical Commission (IEC). In the relevant IEC standard [1], TRV envelopes are described for a variety of fault switching duties. These TRV envelopes are simply two or three connected lines, each characterized by two parameters. Thus, a two- or a four-parameter TRV can be constructed easily [1].
Test authorities need to produce TRV in high-power test that are in conformity with the IEC four-parameter envelopes.

II. SYNTHETIC TESTING OF CIRCUIT BREAKERS

Testing (ultra-)high voltage circuit breakers is a challenge in itself, since no test facility has sufficient power available to provide current and voltage as during a fault in the high-voltage networks. Given a (three-phase) fault current of 63 kA in an 800 kV system, the short-circuit power is 87.3 GVA, this is approx. 10 times higher than the direct power that world's largest test laboratory can provide. To overcome this, test-laboratories employ the synthetic test technology. The philosophy behind synthetic testing is the availability of sufficient current during the current period (including the arcing time) - in order to provide sufficient thermal stress to the breaker before interruption – and adequate TRV after interruption – in order to provide realistic dielectrical stresses during the TRV and RV period. Generally, the fault/arc current is provided by short-circuit generators (the current

The authors are with KEMA Testing, Inspections and Certification, Utrechtseweg 310, 6812 AR Arnhem, the Netherlands (e-mail of corresponding author: rene.smeets@kema.com).

Paper submitted to the International Conference on Power Systems Transients (IPST2011) in Delft, the Netherlands June 14-17, 2011

circuit), whereas TRV is supplied by a high-voltage circuit (the voltage circuit), energized by a pre-charged capacitor bank.

For proper synchronization of TRV to be applied exactly at current zero, two methods are in use:

1) Current injection schemes or Weil-Dobke circuits [2], in which shortly before interruption the voltage circuit takes over the supply of arc current and supplies the complete TRV after interruption. This circuit is mostly used in synthetic testing because of its equivalence and non-critical timing.

2) Voltage injection schemes, in which the voltage circuit only supplies the TRV.

In both cases, at least one auxiliary breaker is required to insulate the current circuit from the voltage circuit at the moment TRV is applied.

A. Principle limitations of current injection

The application of parallel current injection is limited in its applicability for principal reasons [3]. First, there is a maximum allowable deviation of inductance ratio L_s/L_d, L_s being the principal series inductance of the current injection circuit, and L_d its equivalent of the associated direct circuit. This ratio may not exceed 1.5 [4]. Furthermore, the injection frequency must be between 250 Hz and 1000 Hz [4]. Both requirements originate from the required arc energy equivalence in the region closely before interruption.

In fig. 2 the relationship of L_s/L_d and current injection frequency is given for a number of voltage ratings for circuit breakers in effectively earthed neutral systems. This relationship is not depending on rated short-circuit current nor on number of units nor on power frequency.

As can be seen, 550 kV is the maximum circuit breaker rating that can be tested, full pole, with current injection circuits in compliance with the IEC equivalence requirements regarding injection frequency and inductance ratio.

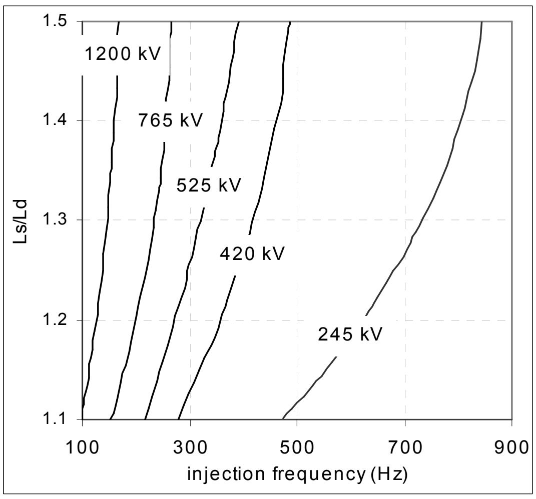

Fig. 2: Limitations of parallel current injection method by injection frequency and ratio Ls/Ld for 4-parameter TRV [5].

B. Current distortion by the arc voltage

All UHV circuit breakers are equipped with more than one interrupter (arcing chamber) in series to cope with the very high system voltage and transients. Full pole synthetic tests on UHV circuit-breakers lead to test circuits with at least 4 interrupters (2 -4 belonging to the test object and 2 - 4 to the auxiliary breakers) in series during the high-current interval. Since the current source supplies the arc current with a much lower voltage (typically several tens of kV) than in service (several hundreds of kV) the summed arc voltages in synthetic circuits take up a relatively large fraction of the supply voltage. This results in a reduction of short-circuit current and thus of arc energy during synthetic tests, compared to the situation in service or during direct tests. The associated reduction of arc energy can ease the testing of puffer type CBs, but can reduce the extinction capability of arc assisted CBs (self-blast, self-compression etc.) [6].

In fig. 3, a (calculated) example is given of the effect of supply voltage with 60 kV and 24 kV in a UHV tests with 8 interrupters in series. In order to prevent too much current distortion, the supply voltage of the current source, and therefore the power of the current source, has to be large enough. Supply voltage in the range of 48 to 60 kV for UHV test circuits should be recommended.

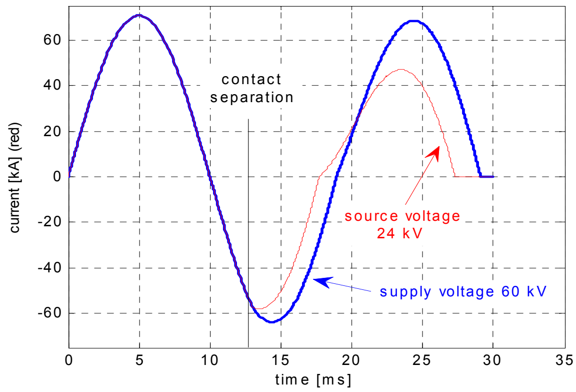

Fig. 3: Comparison of test-current with 24 kV of supply voltage (red) and 60 kV supply voltage (blue) in UHV synthetic test-circuit with 8 breaker chambers

III. UNIT TESTING OF METAL ENCLOSED CIRCUIT BREAKERS

Circuit breakers for rated voltage > 550 kV always consist of multiple interruption chambers in series, because single chambers are not able to withstand the (recovery) voltage at that level. Also at voltages in the range 245 - 550 kV, breakers often consist of multiple interruption chambers. Grading capacitors across each interruption chamber usually guarantee an "approximately equal" share of the voltage by each interruption chamber.

For the E(xtra) and U(ltra) High Voltage levels (245-800 kV and > 800 kV respectively), instead of testing the complete pole of a circuit breaker, separate interrupter units are often tested with the appropriate portion of the rated voltage ('unit-testing', or 'half-pole' testing if one pole consists of two interrupter units).

A. Transient dielectric stresses at current interruption.

Half-pole tests on metal-enclosed circuit breakers do not represent the correct (full) dielectric stresses between live parts and enclosure, at least for the short-circuit current tests (see fig. 4a), since only half the service voltage is between live internal parts and the enclosure. The hot exhaust gases, produced by the circuit breakers during fault current interruption may also deteriorate the dielectric withstand capability of the space surrounding the arcing chambers (between poles, across the chamber, to the enclosure), see fig. 4. With GIS and dead-tank circuit breakers gas dynamic phenomena and the influence of (hot, ionized, contaminated) exhaust gas have to be taken into account with respect to the decision to perform unit- or full-pole tests and with respect to the decision to which side of the circuit breaker the largest dielectric stress has to be applied.

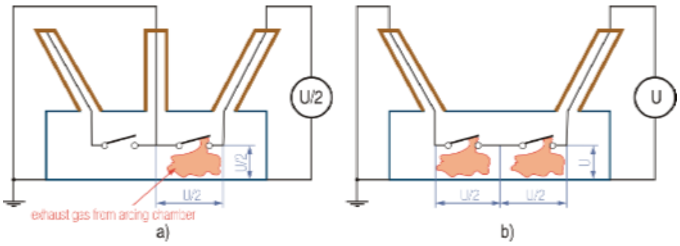

Fig. 4: Voltage stresses during transient recovery voltage at current interruption of metal enclosed circuit breakers. a) Half-pole test, b) full-pole test [8]

B. *Grading capacitors*

In testing of circuit breakers with grading capacitors (including live-tank type), unit tests may not represent the transient stresses that occur due to unequal dielectrical stress of the arcing chambers. In unit tests, stresses on grading capacitors (such as occur in pre-strikes) and on the breaker chambers are not represented. This not trivial, since recent work from CIGRE identified grading capacitors as a major contributor to circuit breaker failures [7].

A safety margin of some percent is usually applied in unit testing. This is to include an unequal voltage distribution because of an unequal distribution of (stray-) capacitance of the breaker units. Because grading capacitors are normally much larger than these stray capacitances, the unequal voltage distribution is covered by a safety margin of a few percent of voltage above 50% (for a two-chamber breaker). In case of designs without grading, this small safety margin is no longer adequate.

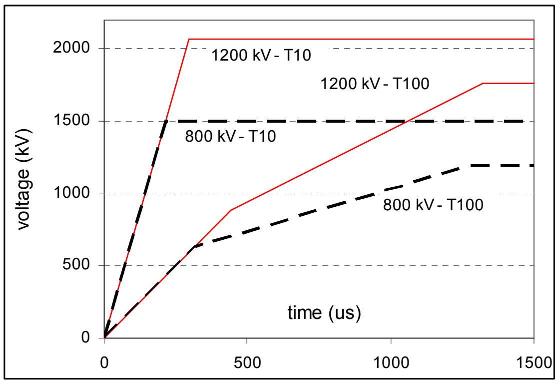

Fig. 5: (Proposal of) standardized envelopes for TRV in testing with 100% (T100) and 10% (T10) short-circuit current for circuit breakers with rated voltage of 800 and 1200 kV.

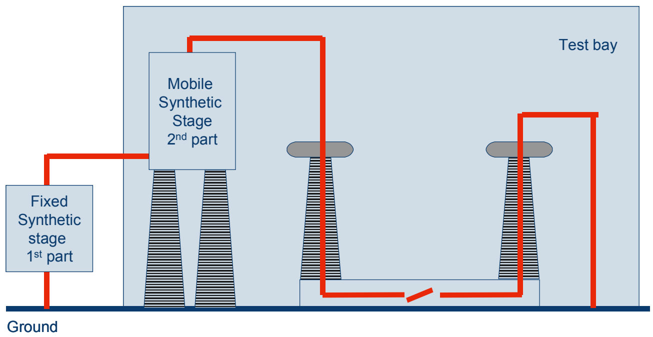

Fig.6: Principal lay-out of two-stage TRV application in UHV testing

Half-pole tests, without taking into account the fore-mentioned stresses, give inadequate evidence for the correct performance of the test object in service. Full-pole test are closer to the actual network situation, (see fig. 4b) as recognized in the IEC Standard.

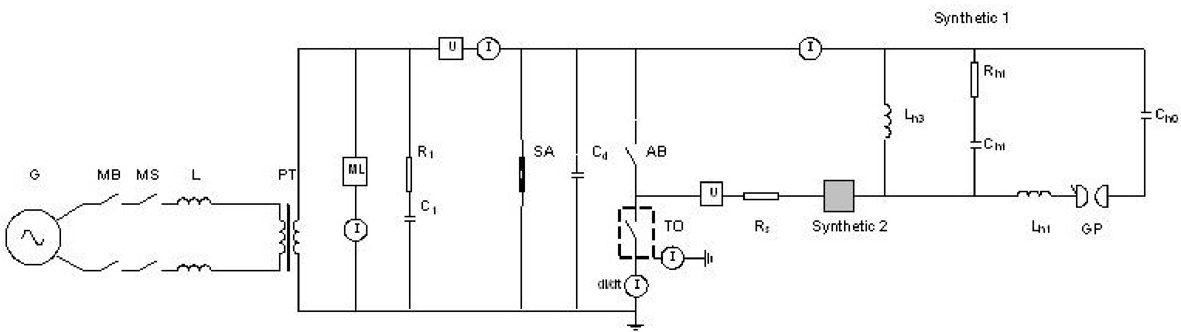

Fig. 7: Principal electrical lay-out of two-stage synthetic voltage injection circuit for UHV testing. G: 4 generators, MB: master breakers, MS: making switch, L: current limiting reactors; PT: short-circuit transformers; ML: Multi-loop device (for re-ignition); U,I: voltage and current measurement; GP: triggered spark gap; TO: test-object; AB: Auxiliary breaker; SA: surge arrester; L_x,R_x,C_x: lumped element reactors, resistors, capacitors; Synthetic 1, 2: TRV wave-shaping circuitry.

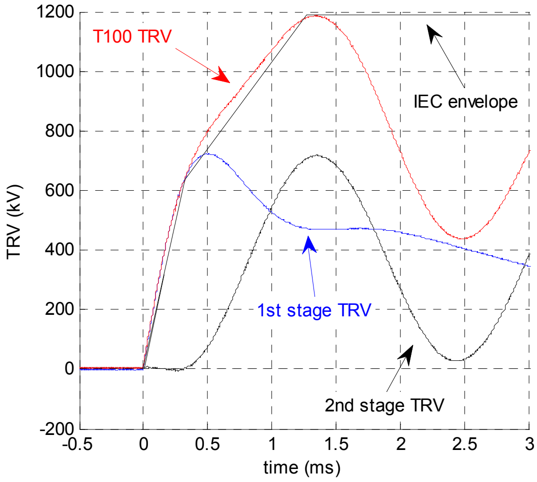

Fig. 8: Oscillogram of double stage synthetic 4 parameter TRV for 800 kV circuit breakers and IEC envelope.

IV. Two-Stage Synthetic Test Circuit

In order to avoid discussions regarding half-pole testing a new test-circuit is designed for full-pole short-circuit current interruption testing of circuit breakers up to 1200 kV. In fig. 5, the TRV envelopes are shown for the test with maximum (test-duty T100 as defined in [1]) and minimum short-circuit current (T10) for rated system voltages of 800 and 1200 kV (the 1200 kV envelopes are under consideration at the time of writing, and are not standardized yet).

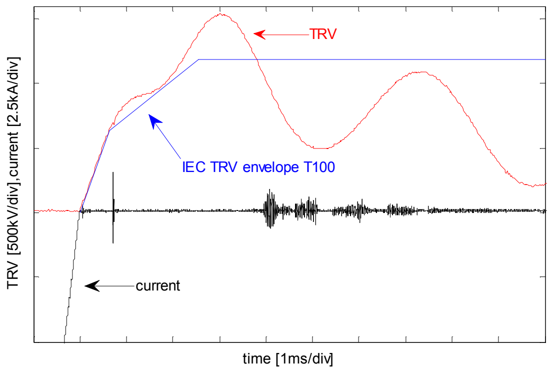

Fig. 9: Oscillogram of synthetic testing of an 800 kV circuit breaker (T100a test duty) and IEC TRV envelope.

In principle, a test-method can be used in which 50% of the voltage is applied at both terminals of the breaker, so that the full TRV is applied across the gap. This implies that the breaker must be installed on an insulated platform. Especially for the very large breakers this is highly unwanted, so that from the beginning on, a solution has been sought in which the breaker under test can remain on ground (potential).

In order to realize this, a two-stage synthetic solution was adopted - see fig. 6 for the functional lay-out - in which a new mobile synthetic installation (2nd part in fig. 6) in the test-bay provides the second stage of the (4 parameter) TRV super-imposed on the voltage wave shape from the permanent synthetic installation (1st part in fig. 6).

The electrical circuit is shown in fig. 7. When applying voltage injection for TRV representation, the very first (few tens of micro-seconds) TRV rise must be produced by the supply circuit (R_1, C_1, C_d). Then, after firing of the spark-gap (SG), the components R_{h1}, L_{h1}, C_{h0} and C_{h1} (synthetic 1 circuitry) provide the first stage of TRV, whereas a similar circuitry (synthetic 2) adds the UHV part to the TRV in the second stage, triggered by a second spark gap. Reactor L_{h3} is tuned with C_{h0} to provide (part of) the power frequency recovery voltage.

Circuitry ML provides forced re-ignition (by discharge of a pre-charged capacitor bank) at first (and sometimes) second arc current zero, in order to achieve arcing times that are realistic for circuit breakers operating in HV systems. Absence of such a circuitry would cause interruption already after a short arcing time, since the low supply side TRV cannot re-ignite the arc.

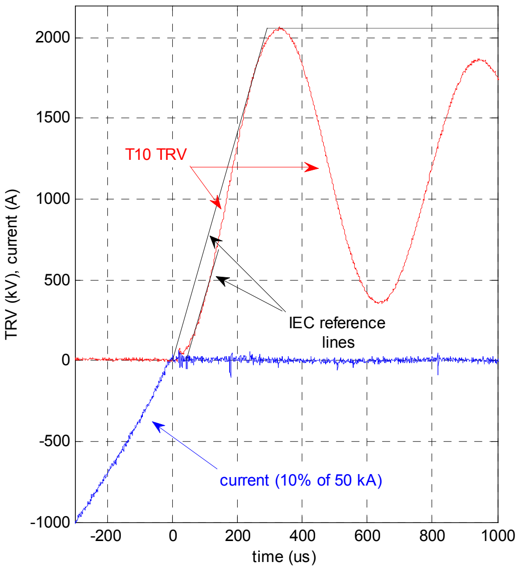

Fig. 10: Realized TRV of T10 test duty for circuit breaker and IEC envelopes (proposed) for 1200 kV

This method makes 800 and 1100 kV and even 1200 kV testing possible without overstressing the test building's bushings and components, originally not designed for UHV testing.

As can be seen, the main feature of the circuit is its capability to perform full-pole synthetic tests with the test breaker (TB) remaining on ground potential. Another major advantage with respect to UHV synthetic test schemes proposed earlier [3] is the need for only one auxiliary circuit breaker (AB in fig. 7).

In fig. 8, the principle of two-stage synthetic TRV application is shown in a laboratory test. Fig. 9 shows an example of a (asymmetrical current) synthetic test at 100% of the rated short-circuit breaking current. In this case, a higher TRV peak value than required in the standard was realized.

Using the same principle, full-pole tests up to 1200 kV rated voltage were demonstrated. In fig. 10, an oscillogram is shown of test-duty T10. As can be seen, by proper timing of the two circuits relative to each other, also a two parameter (single frequency) TRV as required for the T10 duty can be constructed. In order to maintain an undistorted fault current during the arcing phase (8 arcs in series), a supply voltage of 60 kV is chosen.

Calculations were performed to predict the overvoltages after re-ignition of the test-breaker. This is necessary, because in voltage injection, re-ignition current is low, resulting in early interruption by the test breaker. This, in turn, leaves the capacitor banks only partially discharged, with the risk of unrealistic voltages after re-ignition. Suitable protection measures against these escalating voltage effects are taken.
Several components, like reactors, and capacitor banks, have to be raised above ground potential to withstand a significant voltage (> 2000 kV switching impulse type level) to earth, some were modified and a new set of triggered spark gaps was developed.

V. Conclusions

A new synthetic test-circuit for testing ultra-high voltage circuit breakers regarding their fault interruption capability is presented. It basically consists of two cascaded voltage injection circuits. By proper dimensioning of its electrical parameters and by adequate coupling and timing, all standardized TRV can be realized in combination with all practical levels of short-circuit current. Test-objects can remain at ground (potential). Full-pole testing with high value of supply voltage must guarantee a high degree of equivalence with the situation in service.

VI. References

[1] International Standard IEC 62271-100: *High-Voltage Switchgear and Controlgear – Part 100: High-Voltage Alternating-Current Circuit-Breakers*, Edition 2.0, 2008-04

[2] J. Biermans, *The Weil circuit for testing of high-voltage circuit-breakers with very high rupting capacities*, CIGRE Report 102, 1954

[3] B. Sheng, *A New Synthetic Test Circuit for Ultra-High-Voltage Circuit Breakers*", Ph.D. thesis, Delft University of Technology, 1995

[4] IEC Standard 62271-101, *High-Voltage Switchgear and Controlgear – Part 101: Synthetic Testing (2006)*

[5] L. van der Sluis, G.C. Damstra, H.W. Kempen, W.A. van der Linden, "*Synthetic Test Methods: Experience and Future Developments*", CIGRE Conference, p. 13-203, 1992

[6] L. van der Sluis, B.L. Sheng, "The Influence of the Arc Voltage in Synthetic Test Circuits", IEEE Trans. on Pow. Del., Vol. 10, No. 1, 1995, pp.274-279

[7] CIGRE Technical Brochure 368: "Operating Environment of voltage grading Capacitors Applied to High Voltage Circuit Breakers", CIGRE WG A3.18, 2009

[8] M. Kapetanovic, "High voltage circuit breakers", Sarajevo 2010, ISBN 978-9958-629-39-6