Comparative Study of Synthetic Test Circuits for Testing of MV and HV AC Circuit Breakers According to IEC Std. 62271

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***Abstract*— Ratings of circuit breakers are currently as high as 1100 kV of rated voltage and at the same time 63 kArms of short circuit rated current to enable developments of power transmission grids up to Ultra High Voltage levels of 1100 kV and more. These voltage and current ratings correspond to a rated short circuit power of 120 GVA. Testing of such highly rated circuit breakers is not feasible with direct circuits where the short circuit power is to be supplied from power grid directly or by means of large synchronous generators. Synthetic test circuits are widely used to reproduce the switching conditions of circuit breaking by separating high current and high voltage phases of the switching process and thus allowing to significantly increase the testing capabilities of short-circuit laboratories. The aim of this paper is to present simulations of three principle synthetic test circuit topologies and to discuss their applicability for development of synthetic test circuit at a short circuit laboratory. The simulations are conducted with the use of EMTP-ATP package for Parallel Current Injection Synthetic Test Circuit (STC), Series Current Injection STC, and Voltage Injection STC. The aim of the simulations presented in this paper is to evaluate testing conditions in the circuits analyzed to ensure the equivalence between synthetic and direct testing with required accuracy and acceptable development and operational efforts.**

Keywords—synthetic testing, circuit breaker, switching capability, indirect switching tests

I. Introduction

Circuit breakers has been for years recognized as critical technology enablers for development of high-power transmission grids. Nowadays, AC power grids ranges from medium voltage up to a sub-transmission voltage levels of approximately 72.5 kV and more, and then to a transmission grids up to Ultra High Voltage (UHV) levels of 1100 kV and more [1]. As an example, China has announced [2] ten more UHV lines to be built just until 2020 except for those that are currently already in service at this ultra-high voltage level. For these systems to be feasible, a development of the circuit breaker components with the required voltage and current ratings, and yet with cost effective design and development process, is a vital part of a project [3].

For the breaker development, physical testing of its breaking capability is a critical part, involving highly expensive testing at short circuit laboratory. Breaking of high short-circuit power has been always a demanding task due to its multi-physical nature involving high pressure and high temperature switching arc plasma channel and variety of thermal and voltage breakdown phenomena. Except for the voltage and current ratings by themselves, the principle designs of the breakers are in constant development process also. As an example, a huge effort is currently being invested among technology community [4] into a search for new gases that can substitute for SF6 gas being recognized as highly inadvisable in HV and UHV circuit breakers due to its adverse environmental impact.

Critical part of the circuit breakers development process sets for the highly costly testing of the breaker switching capabilities at short circuit laboratory. New testing methods and test set-ups are thus being developed [5,6,7] to provide accurate and yet cost-effective testing of circuit breakers [8].

For the world's largest short-circuit testing laboratories, the maximum short-circuit power available for direct testing is of the order of 15 GVA [5], while the 800 kV circuit breaker rated at 63 kVrms short circuit fault current reaches the short-circuit power of 87.3 GVA (which is as much as 6 times higher). Therefore, demonstration of performance of the breaker switching capabilities, and thus development of HV and UHV circuit breakers, requires testing capabilities that exceeds power levels available at laboratories or utility systems.

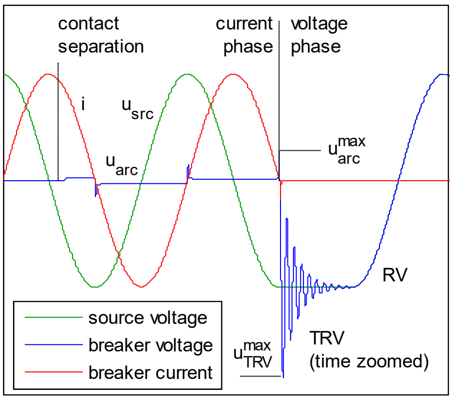

Fig. 1. Switching process of AC current with indicated high current phase for a breaker in closed position before current interruption, high voltage phase for a breaker in open position after interruption, and interaction phase in between the high current and high voltage phases [9]

Variety of testing methods have been thus developed to extend short-circuit power switching capabilities of direct testing circuits [9]. One phase testing involves only third fraction of the rated short-circuit power of a breaker (however this method cannot be used e.g. for 110 kV Gas-Insulated Switchgear circuit breaker, GIS CB, as designed with three phases enclosed in a single pressure tight chamber and thus requiring to be tested in three-phase circuit due to interaction of the switching arc in the three phases during testing). Also,

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part testing is a possible option when one chamber from the series connected chambers chain can be tested independently from the whole breaker pole arrangement.

The principle technique to extend testing capabilities of direct circuits is to use test circuits with multiple sources [9], which is commonly identified as synthetic testing. This method has been widely proven as technically and economically feasible for testing of MV AC and HV AC circuit-breakers. It has been acknowledged that proper design of the synthetic testing circuit provides testing conditions that are equivalent to direct testing [10,11].

II. SYNTHETIC TESTING

A. Principle of synthetic testing

Fig. 1 [12] shows the switching process with three stages indicated: high current phase for a circuit breaker in closed position before current interruption, high voltage phase for a breaker in open position after current interruption, and the so-called interaction phase in between the two latter phases [9]. The concept behind synthetic testing is to separate current and voltage stresses imposed on a breaker during switching transition from its high current state to the high voltage state. For the closed position, the breaker conducts current with negligible voltage across the contacts. Then in the open position the breaker is expected to withstand the voltage stress across the contacts: Transient Recovery Voltage (TRV) as appearing during the transient state, and then the Recovery Voltage (RV) appearing during the steady state for fully opened contact position. As the current and the voltage stresses are separated in time, the synthetic circuit supplies current during an arcing period first, which is before current breaking, to provide thermal stress to the breaker chamber before interruption. Then the TRV and RV are supplied to provide dielectric stress during voltage withstand period after interruption [5]. Between these two dominating phases there is a short interaction period where the switching arc voltage increases significantly before current interruption and then the post arc current cases to flow between the opened contacts after interruption.

The high-current phase ranges from the contact separation to the significant change in the arc voltage preceding current interruption. During this period the energy supplied from the circuit allows to establish arc plasma channel with high ionization, temperature and pressure. The interaction phase spans from the time of the arc voltage increase prior to current zero and ranges until the post-arc current ceases to flow after successful interruption. This phase is critical for thermal failure mode of the current breaking process. The arc voltage rises to charge the parallel capacitance between the breaker's contact system which has two effects: distorts the current waveshape passing through the arc just before current zero and stands for the voltage initial condition that increases TRV after current zero. The post arc after current zero can mitigate TRV having an effect to limit the energy supplied to the still-ionized contact gap. Then the high current stress transforms into the high voltage stress when the contact gap is stressed with the TRV and then RV. The exact shapes of the TRV and RV voltage stresses in the test circuit need to be adequately reproduced to correspond the waveshapes associated with the prospective current of the relevant test duty.

The equivalent short-circuit power of the synthetic circuit is the product of the current at the high-current phase and the voltage at the high-voltage phase.

B. Synthetic test circuit operation and components

Synthetic test circuits consist of two major parts [13,14,15]: the high current part supplying the breaking current during the high current phase, and the high voltage part supplying the TRV during the high voltage phase. For applying the TRV to the tested breaker, two types of methods are being used: current injection methods (parallel and series) and voltage injection method. In each method an accurate synchronization of the TRV is required, in a reference to the time instance of the current zero from high current part.

The current injection methods are realized with the Weil-Dobke circuits [16]. In the circuits of this type, shortly before the current zero of the high current part i_{HC} (see Fig. 2), the high voltage part is being triggered to supply the arc current i_{HV} to the test circuit breaker. Then the sum of the two currents (i_{HC} + i_{HV}) are conducted through the test breaker, after interruption of which the TRV is supplied by the high voltage part. Fig. 2 [12] shows the outlined schema for the Parallel Current Injection Synthetic Test Circuit. This circuit is the one most frequently used at short testing laboratories as it best reproduces the corresponding direct tests and operational switching conditions, and requires less-critical timing of synchronization between high current and high voltage circuits.

For the voltage injection methods, the high voltage circuit is being used to supply the TRV only. These methods require more critical synchronization between high current and high voltage circuits.

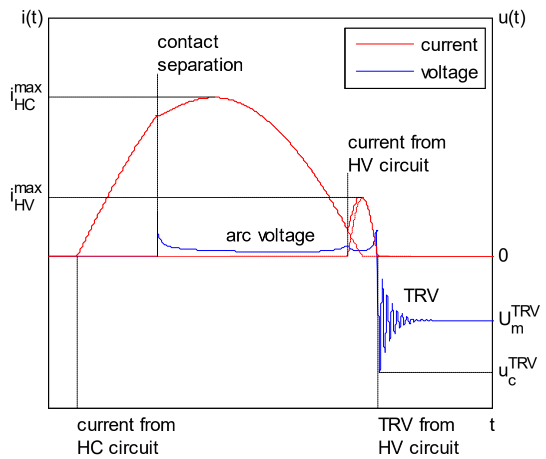

Fig. 2. Current and voltage waveshapes in Parallel Current Injection Synthetic Test Circuit [9]

The high current circuit can be constituted by direct connection to power grid, a transformer, a generator, a capacitive-inductive LC circuit, or a combination of these components. The purpose of the high current circuit is to supply the required current through the test breaker with the minimum voltage at the same time. The voltage of the high current circuit is to be high enough to drive the current that is necessary to establish the arc conditions at the tested breaker, which is substantially lower than that of the corresponding direct circuit.

The high voltage circuit is typically constituted by a pre-charged capacitor bank that is discharged via inductive component. A high voltage source can also be used for this purpose, with voltage characteristics varying from direct current (DC) to high frequency voltage. The purpose of the high voltage circuit is to supply the required TRV across the test circuit breaker during the high voltage phase. The current of the high voltage source may be substantially lower than that of the corresponding direct circuit. The impedance of the high-voltage circuit is low enough to allow the potential voltage breakdown to be clearly measurable.

C. *Switching test conditions for synthetic testing*

Requirements for testing conditions of MV AC and HV AC circuit breakers are governed by the IEC Std. 62271-100 [17] for both making and breaking tests. For current breaking tests this document defines TRV waveshapes for different prospective current test duties (100, 90, 60, and 30 percentage of the rated short-circuit breaking current, named as T100, T90, T60, T30 test duty respectively). The TRV for each test duty is defined with either two-parameter envelope (for circuit breakers rated lower than 100 kV) and four-parameter envelope (for the circuit breakers rated higher and equal to 100 kV). Fig. 3 shows the example of two-parameter envelope with the standardized parameters marked. The TRV parameters are defined to represent testing conditions at major switching scenarios, i.e. for clearing of terminal faults, clearing of short-line faults, and for out-of-phase switching (the scenarios choice is dependent on the rated voltage level).

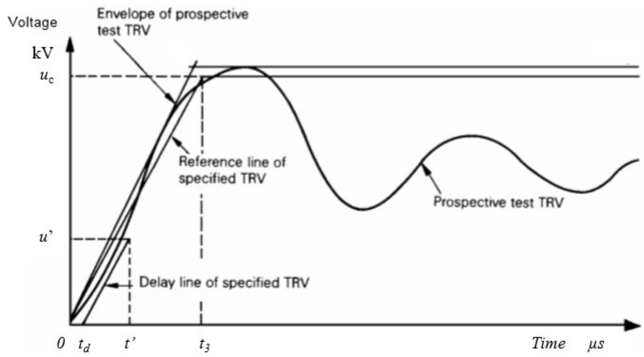

Fig. 3. Example of transient recovery voltage along with its envelope with the standardized parameters marked to meet the type test requirements [17]

The IEC Std. 62271-101 standardize synthetic test circuits and testing procedures. Key aspects of switching conditions related to synthetic testing are outlined below. As the current circuit supplies current at low voltage level, it is prone to be distorted by the arc voltage of the tested breaker and the auxiliary breaker (after connecting the high current circuit with the auxiliary breaker, these two breakers are being consecutively opened). This can reduce the duration and the peak value of the high current waveform (see Fig. 2). When designing the test circuit, it should be ensured that the duration and the peak value of the actual current is not less than 90% of the values specified in the IEC 62271-100 standard based on rated current for symmetrical and asymmetrical tests. Also, these values are to be not more than 110% of the required values based on rated current for asymmetrical tests.

For the voltage conditions, the voltage source (being either in a form of a capacitor bank or of other variable voltage type) should be capable and flexible enough to maintain the recovery voltage with the parameters according to IEC Std. 62271-100. As shown in Fig. 4, the instantaneous value of the recovery voltage during a time period of 1/8 of the rated frequency cycle (see P_1 in Fig. 4a) shall be not less than specified in the IEC Std. 62271-100.

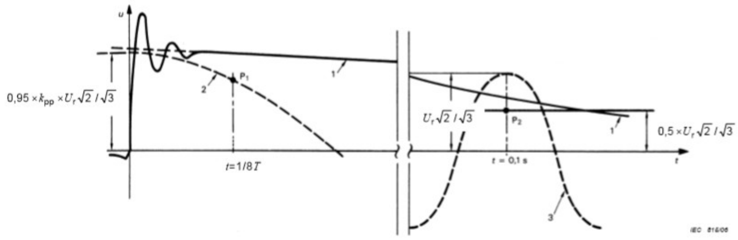

Fig. 4. Prospective transient recovery voltage [14]: 1 – recovery voltage across circuit-breaker during a synthetic test, 2 – power frequency recovery voltage of first extinguishing pole in the equivalent direct test, 3 – power frequency recovery voltage after interruption of all currents

Moreover, for a test with symmetrical current, the TRV peak value shall be not less than $0.95 \cdot k_{pp} \cdot U_r \cdot \sqrt{2/3}$ (see Fig. 4a), where: k_{pp} is the first pole to clear factor, U_r is the rated voltage of the circuit breaker. If a resonant LC source serves as the high voltage source in the voltage circuit, the recovery voltage may decay due to the energy capability of the capacitor bank. In such a case, the instantaneous value of the recovery voltage and its peak value should be kept as close as possible to $U_r\sqrt{2/3}$ (see Fig. 4b), and specifically, in less than 100 ms it must not fall below the value of $0.5 \cdot U_r \cdot \sqrt{2/3}$ (see P2 in Fig. 4b).

III. SYNTHETIC TESTING WITH CURRENT AND VOLTAGE INJECTION

Three major types of methods are introduced in IEC Std. 62271-101 for synthetic testing: current injection methods (of two subtypes: parallel and series), voltage injection method, and the so-called duplicate circuit method (based on transformer circuit, also known as Skeats circuit [21], [22]). Other methods are also indicated (see e.g. [14], Annex O) as applicable for special testing conditions (for circuit-breakers with specific characteristics or to cover specific performance of a breaker). In the present paper the current and the voltage injection methods are analyzed.

A. *Current injection methods (parallel and series)*

In the current injection methods, the power-frequency current through the test circuit breaker is first supplied from the current circuit by closing an auxiliary switch. Then, the high frequency current from the voltage circuit is superimposed on the power-frequency current at the test circuit breaker shortly before the zero crossing of the power-frequency current. The power-frequency current from the current circuit is then interrupted by an auxiliary circuit breaker, which makes only the voltage circuit current continue to flow through the test circuit breaker. The high frequency current from the voltage circuit is then interrupted by the test circuit breaker at the zero crossing, after which the breaker is immediately exposed to the voltage from the voltage circuit. The voltage circuit has an impedance that is representative to the reference system conditions which makes the voltage stress being a specified (and standardized) transient recovery voltage. As the test circuit breaker is naturally exposed on the voltage circuit immediately after current interruption, there is no delay between current stress and the application of the voltage stress at the test breaker.

It is of importance that prior to zero crossing at the test breaker (i.e. just before the interaction phase), the current wave at the test circuit breaker corresponds to that on the specified breaking current prior to the current zero (same rate of rise), and that the voltage after zero crossing corresponds to the specified TRV (same TRV envelope parameters).

Among several current injection methods, the principle ones are of two kinds: parallel, and series current injected methods, as shown in Fig. 5. The difference in these two types of current injected methods are in the current course. In both cases, the rate of decrease of injected current (*di/dt*) at the current zero are adjusted to correspond to that of the prospective power-frequency current. Fig. 6 shows injection timing for parallel (see Fig. 6a) and series (see Fig. 6b) current injection methods.

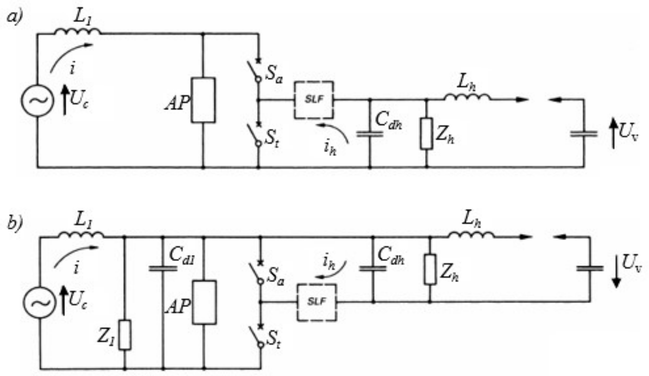

Fig. 5. Typical current injection circuits with voltage circuit parallel to test (a) and auxiliary (b) circuit-breaker [14]: U_c, U_v – voltages of current and voltage circuits, L_1, L_h- inductances of current and voltage circuits, *AP* – arc prolonging circuit, S_a, S_t – auxiliary and test circuit-breakers, C_{dh}, C_{dl}, Z_1, Z_h – impedance forming transient recovery voltage

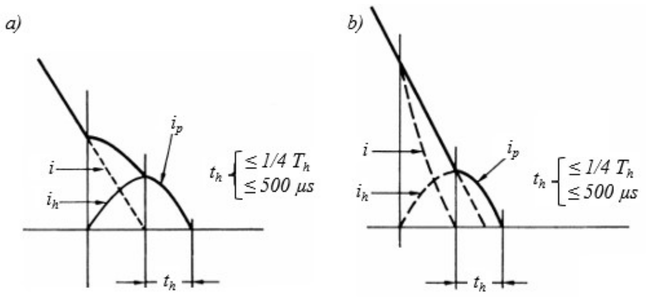

Fig. 6. Injection timing for parallel (a) and series (b) current injection [14]: i – current from current circuit, i_h – injected current from voltage circuit, i_p – current in tested circuit-breaker, t_h – time during which the arc is fed only by the injected current

The parallel injected method is the one that is most commonly used by the test laboratories. It is characterized with good equivalence between test and service conditions and has less-critical timing of synchronization between voltage and current circuits as compare to voltage injected method (i.e. current stress in current injected methods is naturally followed by the voltage stress at the test breaker) [5].

B. Voltage injection method

In the voltage injection method, power frequency current through the test circuit breaker is firstly applied from the current circuit as it is for the current injected methods. Then the power-frequency current is interrupted by the test circuit breaker and the initial voltage stress starts to build up at the test circuit breaker from the current circuit. Then the voltage stress is applied from the voltage circuit at the test circuit-breaker. The voltage circuit is typically connected to the test circuit breaker close to the peak value of the transient recovery voltage from the current circuit. The TRV at the test circuit-breaker is thus constituted by a superimposition of the voltage stress from both current (first) and voltage (then) circuits.

In the voltage injection method, the test circuit-breaker is exposed to the current circuit only before and at the interaction phase and to the voltage circuit only after the interaction phase. Therefore, this method can be used to check dielectric behavior after current interruption but cannot be used to investigate thermal behavior of the circuit-breaker. To investigate thermal behavior of the breaker, the current interaction methods can be used.

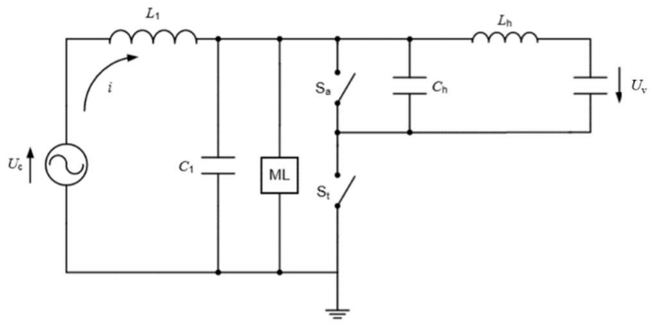

Fig. 7. Typical voltage injection circuit with voltage circuit parallel to auxiliary circuit-breaker [14]: U_c, U_v – voltages of current and voltage circuits, L_1, L_h – inductances of current and voltage circuit, *ML* – multi-loop re-ignition circuit, S_a, S_t – auxiliary and test circuit-breaker, C_1, C_h – Capacitances forming transient recovery voltages

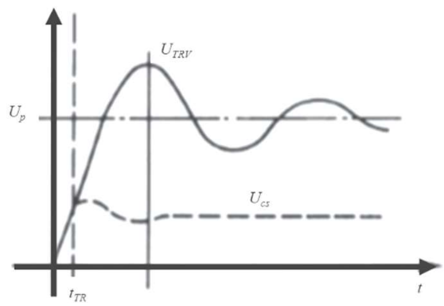

Fig. 8. Transient recovery voltages in voltage injection circuit: U_{cs} – transient recovery voltage from current circuit, U_p – power-frequency recovery voltage, U_{TRV} – transient recovery voltage on test circuit breaker, t_{TR} – time instance of switching of the voltage circuit

In both types of methods (with current and voltage injection), the auxiliary breaker is needed to connect the power-frequency current from the current circuit first and then to insulate the current circuit from the voltage circuit at the time of the TRV dielectric voltage stress. In the current injected method this insulation takes place before interaction phase at the test circuit breaker, while in the voltage injected method it is after the interaction phase. In the current injection method, the auxiliary switch (or any device with breaking capability) cannot be used to interrupt current through the test circuit breaker, which would change thermal conditions of the test circuit breaker.

IV. SIMULATIONS OF SYNTHETIC TEST CIRCUITS

In this section simulations are presented for synthetic testing of a circuit breaker of 7.2 kV rated voltage and 20 kA rated short circuit breaking current [18]. For these ratings, the parameters of the Transient Recovery Voltage are shown in Table I as specified in IEC Std. 62271-100 [17]. The parameters are given for a class S1 circuit breaker (i.e. intended to be used in a cable system) with rated voltage higher than 1 kV and lower than 100 kV. As the breaker is rated at voltage lower than 100 kV, the TRV is represented with two-parameter envelope.

TABLE I. STANDARD PARAMETERS OF PROSPECTIVE TRANSIENT RECOVERY VOLTAGE FOR 7.2 KV CIRCUIT BREAKER AS SPECIFIED IN IEC STD. 62271-100 [17]

Test Duty	T100	T60	T30	T10
First pole to clear factor k_{pp} [p.u.]	1.5	1.5	1.5	1.5
Amplitude factor k_{af} [p.u.]	1.4	1.5	1.6	1.7
TRV peak value u_c [kV]	12.3	13.2	14.1	15
Time t_3 [us]	51	22	11	11
Time delay t_d [us]	8	3	2	2
Voltage u' [kV]	4.1	4.4	4.7	5.0
Time t' [us]	25	11	5	5
RRRV u_c/t_3 [kV/us]	0.24	0.60	1.28	1.36

Simulation models were developed with the use of EMTP-ATP simulation software [19], [20] according to the synthetic test circuits shown in Fig. 5 (for the current injected parallel and series methods) and in Fig. 7 (for the voltage injected method). The parameters of the models were selected based on two criteria: 1) to ensure equivalence between synthetic and direct testing, 2) the breaking current and the TRV wave and its envelope parameters to meet the requirements specified in IEC Std. 62271-100 [17]. For the power frequency current in current circuit, a value of 50 Hz was selected. For the high frequency injected current from the voltage circuit a value of 500 Hz was employed. It was assumed that the switching tests would be simulated for 60% of the rated short circuit breaking current. For the assumed 60% current the crest value of TRV according to Table 1 (13.2 kV) is slightly higher than for the 100% current (12.3), which makes the voltage waveforms around zero current crossing more illustrative. For the assumed 7.2 kV / 20 kA breaker, the T60 current stands for 12 kA (rms), for which the amplitude value of $I_{\max} = 12\text{ kA} \cdot \sqrt{2} = 16.97$ kA was implemented in the current circuit.

Parameters of the voltage circuit are selected to ensure the recovery voltage, RV, of 8.82 kV, according to the formula [17]:

$$U_{\max} = k_{pp}\sqrt{2/3}\,U_r$$

where $k_{pp} = 1.5$ is the first pole to clear factor according to Table I, and $U_r = 7.2$ kV is the rated voltage of test circuit breaker.

The amplitude of the high frequency current injected from the voltage circuit was selected as approximately 10 times lower than the amplitude of the current in the current circuit (1.697 kA versus 16.87 kA). The time duration of the voltage circuit connection to the current circuit for the current injected methods (both parallel and series) was set to approximately 1/4 of the injected current period before zero crossing of the power frequency current from the current circuit. These settings (amplitude of the injected current and the time duration of connection of the voltage circuit to the current circuit) allows to ensure the required rate of rise of the injected current at current zero, which is required to be similar to the one obtained from a direct circuit. This implies that the current waveforms in the current circuit and the current through the test circuit breaker (composed of the current from the current circuit and the superimposed injected current) have the same slopes in proximity of their zero crossings.

Table II shows time instances of the breakers' operation in synthetic test circuits: opening of auxiliary switch in current circuit after connecting of the current circuit, connecting of voltage circuit, opening of test circuit breaker.

TABLE II. TIME INSTANCES OF SWITCHES IN SYNTHETIC TESTING [18]

Closing and opening time of a breaker switch	Current circuits		Voltage circuit
	Parallel	Series	
Auxiliary switch in current circuit opening time [ms]	7.00	7.00	7.00
Voltage circuit switch closing time [ms]	9.65	9.65	10.01
Test circuit breaker opening time [ms]	10.00	10.00	10.00

A. Simulation results

Fig. 9 and Fig. 10 show current and Transient Recovery Voltage waveforms, respectively, simulated for synthetic circuit with parallel current injection. In this test circuit, same current flows through the auxiliary switch and the test circuit breaker. The current from the current circuit is set to T60 test duty, i.e. 12 kA for 20 kA rated breaking current, standing tor 17 kA maximum value of the half-wave power frequency current. The current through the test circuit breaker is the superimposition of the power frequency current from the current circuit and the high frequency current from the voltage circuit. The overall current is interrupted in the test circuit breaker at the time instance of its zero crossing. As a result of the current interruption, after the switching arc extinction, the TRV starts to build up across the contact system of the test circuit breaker. The TRV is supplied from the voltage circuit, in which the supply voltage is set to 8.82 kV as commented previously. Additional components are used to shape up the transient part of the recovery voltage. In the simulations shown in Fig. 10, the TRV was applied with the crest value of $u_c = 13.37$ kV and the time parameter $t_3 = 18$ µs (see fig. 10).

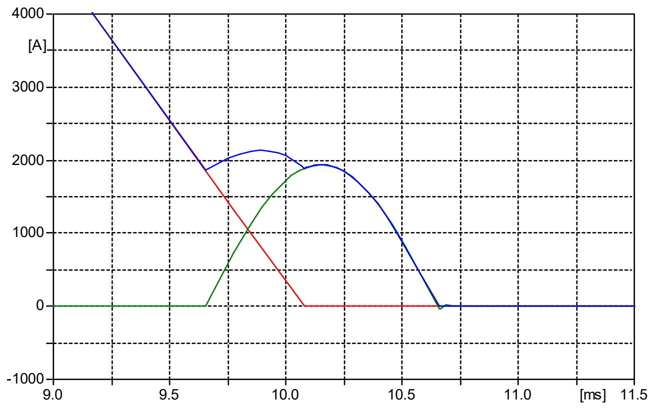

Fig. 9. Current waveforms simulated for synthetic testing **with parallel current injection**; red color – current at the current circuit (through the auxiliary switch), green color – current at the voltage circuit, blue color – current at the test circuit breaker

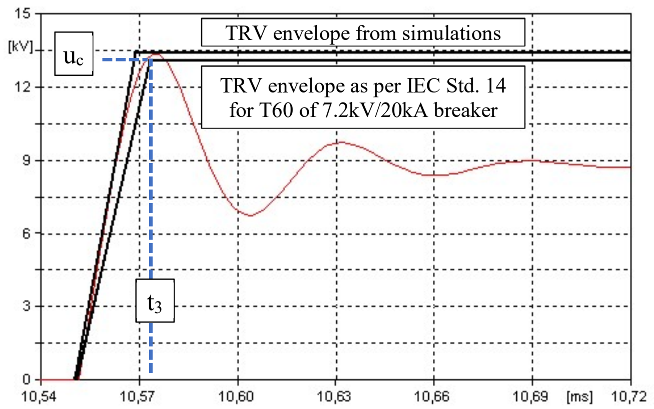

Fig. 10. Transient Recovery Voltage simulated for synthetic testing **with parallel current injection**; with two two-parameter envelopes: for the TRV simulated, for the TRV according to IEC Std. 62271-100 (i.e. with $u_c = 13.2$ kV, and $t_3 = 22$ µs as per Table I for T60)

Fig. 11 and Fig. 12 show current and Transient Recovery Voltage waveforms, respectively, simulated for synthetic circuit with series current injection. In this test circuit, the current through the test circuit breaker is composed of the two currents: the current from the voltage circuit subtracted from the current from the current circuit (see Fig. 11). The current through the test circuit breaker is interrupted at the time instance of its zero crossing. As the result of the current interruption, the TRV builds up at the test circuit breaker. In the simulated model, the TRV was reproduced with the parameters of its envelope: the crest value of u_c = 13.28 kV and the time parameter of t_3 = 18 µs (see Fig. 12).

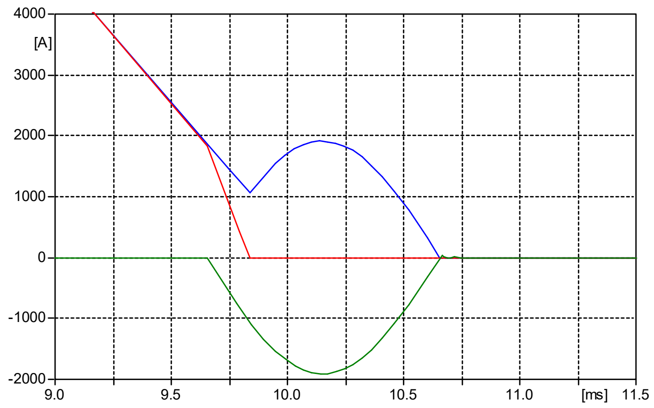

Fig. 11. Current waveforms simulated for synthetic testing **with series current injection**; red color – current at the current circuit (through the auxiliary switch), green color – current at the voltage circuit, blue color – current at the test circuit breaker

Fig. 13 and Fig. 14 show current and Transient Recovery Voltage waveforms, respectively, simulated for synthetic circuit with voltage injection. In this test circuit, after interruption of current from the current circuit at the test circuit breaker, there are two phases of voltage supply to the opened contacts of the test circuit breaker. In the first phase, the TRV is supplied from the current circuit only. Connection of the voltage circuit is then performed at the time instance of the crest value of the TRV formed from the current circuit (see Fig. 13 for the simulated waveforms and Fig. 8 for illustrative waveforms according to IEC Std. 62271-100 [17]). The maximum values of the voltage waveforms simulated in the models are: 3 kV for the current circuit, 12.5 kV for the voltage circuit, and 13.2 kV for the TRV at the test circuit breaker (see Fig. 13 and Fig. 14). The time parameter t_3 of 20 us was obtained (see Fig. 14).

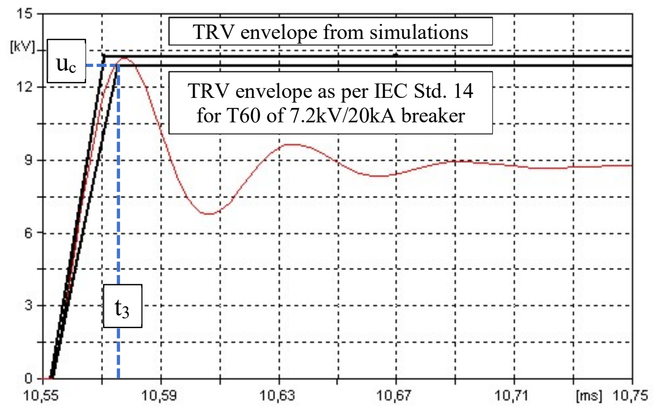

Fig. 12. Transient Recovery Voltage simulated for synthetic testing **with series current injection**; with two two-parameter envelopes: for the TRV simulated, for the TRV according to IEC Std. 62271-100 (i.e. with $u_c = 13.2$ kV, and $t_3 = 22$ µs as per Table I for T60)

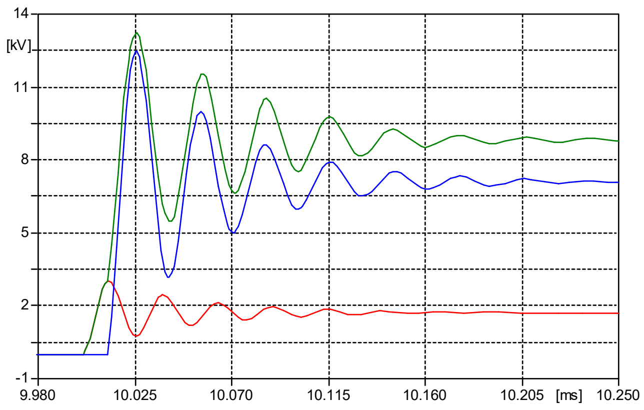

Fig. 13. Voltage waveforms simulated for synthetic testing **with voltage injection**; red color – voltage waveform from the current circuit, green color – voltage waveform from the voltage circuit, blue color – TRV at the test circuit breaker (a sum of the two latter voltage waveforms)

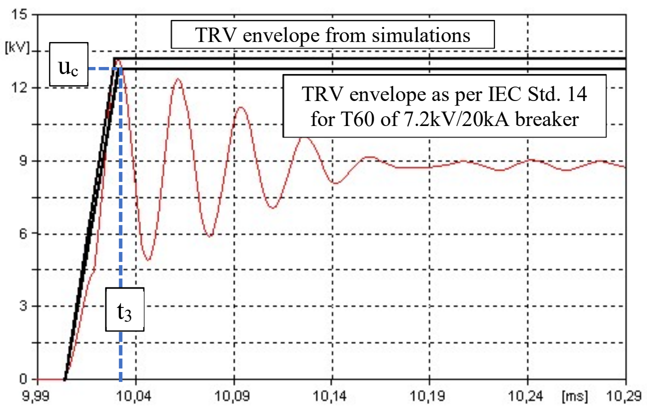

Fig. 14. Transient Recovery Voltage simulated for synthetic testing **with voltage injection**; with two two-parameter envelopes: for the TRV simulated, for the TRV according to IEC Std. 62271-100 (i.e. with u_c = *13.2* kV, and t_3 = *22* µs as per Table I for T60)

B. Discussion

For the test circuits with current injection, the notable difference between the series and parallel circuits is in the waveshapes of the current through the auxiliary breaker. In the series circuit the current through the auxiliary breaker is a substitute of the voltage circuit current from the current circuit current, while in the parallel circuit the current through the auxiliary breaker is the sum of the current components from the current and the voltage circuits. A subtle difference between the series and parallel circuits with current injection is for the slight difference in the recovery voltage (after extinction of the TRV, transient components) at the test circuit breaker. The voltage level in series circuit is of approximately 60 V lower than that of the parallel circuit. The waveshape of the TRV is similar.

Assessing the circuit with voltage injection, the highest difference as compare to the circuits with current injection, is for the TRV waveshape. It is caused by the fact that for the circuit with voltage injection, after the current interruption at the test circuit breaker, the voltage is firstly supplied by the current circuit, and then from the voltage circuit. This is in oppose to the circuit with current injection, where the TRV is applied from the voltage circuit immediately after the current interruption at the test circuit breaker. For this reason, in order to obtain the TRV parameters as required by the IEC Std. 62271-100 [17], significant adjustment of parameters is needed for the simulated synthetic circuit with voltage injection as compare to the test circuits with current injection.

V. Summary

Synthetic test circuits were compared in this paper according to IEC Std. 62271-100 [17]. The simulation models were developed with the use of EMTP-ATP [19] simulation software. The parameters of the synthetic circuits were selected by means of simulations to reproduce current and voltage waveshapes according to the standard. The simulations were performed for an example of test circuit breaker of 7.2 kV rated voltage and 20 kA rated short circuit breaking current.

The simulations reflect the known fact that the synthetic circuit with voltage injection method requires more precise synchronization of the voltage circuit. The voltage circuit in this method needs to be connected precisely at the time instance of the maximum value of the voltage waveform as originating from the current circuit. Moreover, obtaining of the required rate of rise of recovery voltage (RRRV) is a challenging task (time consuming and costly), requiring several iterations to identify (by means of simulations) the parameters of the synthetic test circuit to provide the required RRRV parameters. The reason for this is that any discrepancy of the parameters can cause unsuccessful test (i.e. testing with parameters of TRV not complying with IEC Std.).

Investment cost of the synthetic test circuit with the voltage injection may be similar to that of the current injection method. However, the operation cost of the circuit with the voltage injection method may be considerably higher than that of the alternative test circuits with current injection, which is due to lengthy iterative process of parameters selection.

The simulations presented in this paper confirm that the synthetic test circuit with current injection is equivalent to the direct test circuit, when the parameters of the synthetic test circuit are properly selected. The important feature of the synthetic test circuit with the current injection is that the current and the voltage circuits are not connected simultaneously at the current zero crossing through the test circuit breaker. Full separation between the voltage and the current circuits, jointly with the good representation of the current waveshape at the current zero, are thus reproduced. Moreover, as the current injection from the voltage circuit takes place at approximately 0.50-0.25 us before zero crossing of the power frequency current at the auxiliary and test breakers, there is enough time for the auxiliary breaker to build up its dielectric withstand after interrupting the power frequency current, so the auxiliary breaker can withstand the high TRV appearing at the test breaker after interruption of the high frequency current at its zero crossing.

The initial investment cost of the synthetic test circuit with current injection may be significantly higher than that for the circuit with voltage injection, which is due to the need to use a bank of high voltage capacitors. However, the circuit with current injection is highly predictable in operation, requiring little synchronization as compare to the voltage injected circuit. This implies savings on the testing time, which directly turns into significant operational and thus product development savings.

The advantage of the synthetic test circuit with voltage injection is lower distortion of the current waveshape in proximity of zero current crossing at the test breaker, as compare to the circuit with current injection (this effect was not shown in this paper). Moreover, the TRV at the test breaker, is a sum of the voltage from the current and the voltage circuits. The disadvantages of the synthetic test circuit with the voltage injection include the need for a precise synchronization, selection of test circuit parameters in iterative process to reproduce the required TRV parameters, the need for banks of capacitors or voltage sources that must be insulated from earth. Moreover, due to the series connection of the voltage and the current circuits, there might not be feasible to select components to fulfill the requirements for the high current waveform before zero crossing at the test breaker and at the same time for the high voltage TRV after zero current crossing at the test breaker.

For all of the synthetic test set-ups analyzed in the present paper, the TRV was obtained as required by the IEC Std. 62271-100 [17]. This was achieved by means of adjusting the two-parameter envelope of the TRV according to parameters outlined in Table I. Together with the equivalence of the previously discussed current waveforms (i.e. in terms of the amplitude and the rate or rise at the current zero), it can be concluded that performing the tests in a physical test set-up with the parameters obtained in this paper, can be considered as equivalent to the testing in direct circuits.

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