Revision of TRV Requirements for the Application of Generator Circuit-Breakers

M. Palazzo, M. Popov, A. Marmolejo and M. Delfanti

***Abstract*-- The requirements imposed on generator circuit-breakers greatly differ from the requirements imposed on other transmission and distribution circuit-breakers. Due to the location of installation between the generator and the associated step-up transformer, a generator circuit-breaker must meet high technical requirements with respect to rated normal currents, short-circuit currents, fault currents due to out-of-phase conditions and transient recovery voltages. The question whether the transient recovery voltage requirements laid down in IEEE Std C37.013-1997 (R2008) and in its amendment IEEE Std C37.013a-2007 are still adequate for the application of generator circuit-breakers in modern power stations is considered in the present work.**

In order to quantify the transient recovery voltage requirements for the application of generator circuit-breakers a comprehensive survey of different fault conditions occurring in several power stations has been performed. The fault transients' simulations have been performed by means of the Electromagnetic Transients Program (EMTP).

***Keywords*: Fault current, generator circuit-breaker, transient recovery voltage.**

I. Introduction

THE requirements imposed on generator circuit-breakers (GenCBs) greatly differ from the requirements imposed on general purpose transmission and distribution circuit-breakers. Due to the location of installation, high technical requirements are imposed on GenCBs with respect to rated normal currents, short-circuit currents and fault currents due to out-of-phase conditions. Furthermore, the currents of very high magnitude which GenCBs have to deal with are associated with very steep transient recovery voltages (TRVs).

According to the international standards, the stresses imposed on GenCBs in case of faults differ from the stresses imposed on general purpose circuit-breakers mainly in the following aspects:

- the relatively long d.c. time constant of the system-source short-circuit current results in a high degree of asymmetry at contact separation;
- the generator-source short-circuit current may exhibit a degree of asymmetry higher than 100% thus leading to delayed current zero crossing;
- the rate-of-rise of the TRV (RRRV) appearing after the interruption of a system-source short-circuit current may be as high as 6.0 kV/μs and the corresponding time delay (t_d) as short as 1 μs;
- the RRRV appearing after the interruption of a generator-source short-circuit current may be as high as 2.2 kV/μs and the corresponding t_d as short as 0.5 μs;
- a GenCB shall be capable of interrupting fault currents due to out-of phase conditions with extremely severe TRVs.

The out-of-phase conditions are abnormal circuit conditions due to loss or lack of synchronism between generator and power system at the instant of operation of the GenCB. The phase angle difference between rotating phasors representing the generated voltages on each side of the GenCB may exceed the normal value and may be as much as 180° el. [1].

The test quantities given for general purpose transmission and distribution circuit-breakers for short-circuit and out-of-phase current switching tests do not adequately cover the above requirements. The only standard which covers the requirements for GenCBs is IEEE Std C37.013-1997 (R2008) with its amendment IEEE Std C37.013a-2007 [1], [2]. This standard in particular covers the requirements imposed on GenCBs regarding the degree of asymmetry of the fault currents and specifically addresses the phenomenon of delayed current zeros.

The installation of a GenCB between the generator and the associated step-up transformer, where its performance directly influences the output of the unit, places high demands on its reliability. The required equipment quality and reliability can only be achieved by exhaustive testing of all the relevant aspects. The question whether the requirements laid down in [1], [2] are still adequate for the application of GenCBs in modern power stations is considered in the present work.

In order to quantify the requirements for the application of GenCBs a comprehensive survey of different fault conditions occurring in 185 power stations has been performed. Technical parameters of power station equipment have been collected from combined cycle, gas turbine, conventional thermal, nuclear, conventional hydro and pumped storage power stations.

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Paper submitted to the International Conference on Power Systems Transients (IPST2015) in Cavtat, Croatia June 15-18, 2015

The fault transients' simulations have been performed by means of the Electromagnetic Transients Program (EMTP) [3]. The parameters peak value (E_2), RRRV and t_d of the resulting TRVs have been analysed.

II. Power Station Equipment Models Adopted for the Simulations

A typical power station layout used for this investigation is depicted in Fig. 1.

The system-source short-circuit current is the short-circuit current to be interrupted by the GenCB in case of a three-phase fault occurring between the generator and the GenCB. This fault location is identified by "Fsys".

The generator-source short-circuit current is the short-circuit current to be interrupted by the GenCB in case of a three-phase fault occurring between the step-up transformer and the GenCB. The source of this current is the generator through no power transformer. This fault location is identified by "Fgen".

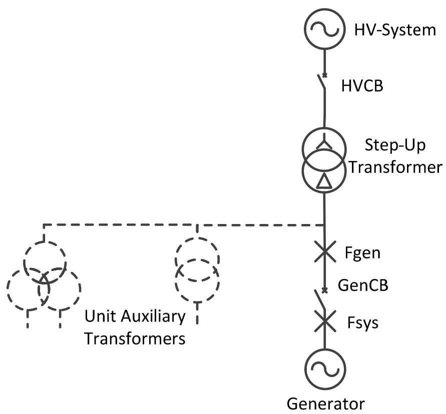

Fig. 1. Power station layout with one generator connected to a two-winding step-up transformer

As recommended in published literature, for the range of frequencies involved in this type of duty, generator, power transformers and busduct have been modelled with distributed parameters [4]-[7]. Both, the generator and the power transformers have been modelled with distributed parameters according to the model presented in [8]. They have shown to fit very well with the results of measurements. The power station components considered are:

- generator;
- step-up transformer;
- connection between generator and GenCB;
- connection between GenCB and step-up transformer;
- connection between unit auxiliary transformers and GenCB;
- GenCB;
- unit auxiliary transformers;
- voltage and current transformers;
- HV-system.

The generator model consists of 10 inductance modules per phase paralleled by resistance elements and 11 capacitance-to-ground elements (see Fig. 2).

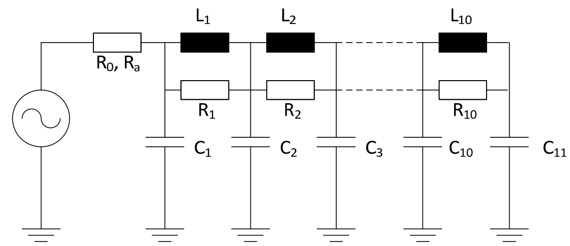

Fig. 2. Model of generator

The corresponding model of the power transformer again consists of 10 modules per phase (see Fig. 3). Each module is made of a single-phase transformer with short-circuit inductance, capacitances to ground at each side of the transformer and coupling capacitances between the high-voltage and the low-voltage sides. Moreover, the frequency dependence of damping has been considered by paralleling the inductances of each module by a resistance. Additional details about this model can be found in [8]. The windings of each power transformer have been connected according to the vector group of the machine. The grounding of the neutral of the power transformer has been considered too.

For both the generator and the power transformer the inductance elements determine the short-circuit current. The models of generator and power transformer described before have been adopted (and therefore the study has been carried out) only for those power stations for which all the relevant machine parameters have been made available by the manufacturers.

The busduct has been modelled with its surge impedance and propagation velocity.

The GenCB has been modelled as an ideal switch (i.e. neither the arc-voltage nor the wave-slowing capacitors have been taken into account).

Voltage and current transformers have been modelled with an equivalent capacitance.

The HV-system has been modelled with its positive and zero sequence equivalent impedance (see Fig. 4). A shunt capacitance with the corresponding series resistance is considered too. The impedances of the HV-system are determined by its maximum short-circuit power. The capacitance at the HV-busbar and the corresponding series resistance have been calculated on the basis of the RRRV given in [9] for test duty T100s. For each power station analysed the HV-system data of that particular bus have been used. The HV-system feeding the step-up transformer will have a considerably smaller natural frequency than the transformer, leading to an equivalent circuit with two natural frequencies. It has to be mentioned that the approach followed in [10] considers the HV-system having an infinite short-circuit power. This assumption is too conservative and not realistic. For this reason, in the present work, it has been decided to consider actual values of HV-system short-circuit power for each power station analysed.

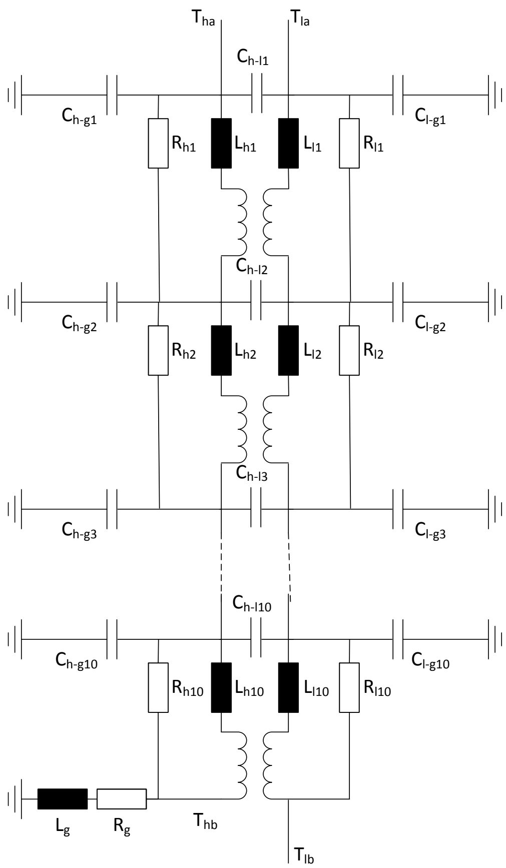

Fig. 3. Model of power transformer

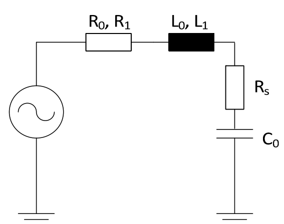

Fig. 4. Model of HV-System

III. System-Source Short-Circuit Currents

The prospective TRV (i.e the TRV not influenced by the arc-voltage and the capacitors of the GenCB) appearing across the contacts of the GenCB immediately after the interruption of the system-source short-circuit current has been calculated for each power station analysed. In accordance with [1], the TRV is determined for the first-pole-to-clear in case of a three-phase grounded fault between the generator and the GenCB. The three-phase fault for GenCB applications leads to higher current magnitude and to higher RRRV compared to single- and two-phase faults. This is due to the fact that the step-up transformer windings at the generator side are generally delta connected. On the other hand, the RRRV in case of three-phase grounded faults is somewhat smaller than the RRRV in case of isolated faults [10].

The studies have been performed by considering a pre-fault voltage equal to the maximum operating voltage of the HV-system.

In all simulations, the TRV resulting from the interruption of a symmetrical current has been considered.

The results of this investigation are shown in Table I, where the power stations analysed have been grouped in 4 classes depending upon the rated power of the step-up transformer (S_{Tn}). Following the approach described in [10], the prospective TRV parameters E_2, RRRV and t_d for each class are expressed as a fixed number. The 70th percentile of each parameter of the prospective TRV is displayed. The peak value E_2 is normalised to the rated maximum voltage of the GenCB (V), which is equal to the maximum operating voltage of the generator (U_{gm}). This approach is aligned to that used in [1]. The statistical treatment of the obtained TRV parameters has been done following the underlying methodology described in [11].

The analysis shows that E_2/V and RRRV are less severe compared to those laid down in [1], whereas t_d can be even shorter than 1 μs. The parameter RRRV seems to be slowly increasing with S_{Tn}. In [10] a similar trend is shown but the proposed values of RRRV are somewhat higher than those listed in Table I. It is important to highlight that in [10] the HV-system has been modelled assuming an infinite short-circuit power. This conservative assumption is unrealistic because the equivalent impedance of the HV-system is normally not negligible compared to the step-up transformer short-circuit impedance.

TABLE I
Results of the Survey of TRV Parameters in case of System-Source Short-Circuit Currents

Class	S_{Tn} (MVA)	E_2/V	RRRV (kV/μs)	t_d (μs)
1	$S_{Tn} \leq 200$	1.8	3.7	1.0
2	$200 < S_{Tn} \leq 400$	1.8	4.4	1.0
3	$400 < S_{Tn} \leq 600$	1.7	5.0	0.8
4	$S_{Tn} > 600$	1.8	5.2	1.0

This fact is acknowledged in [10], which states that, by taking into account the actual short-circuit power of the HV-system, RRRV would be 5% to 15% smaller in practical cases. In the present analysis the higher observed value of RRRV is 5.89 kV/μs which is close to the maximum value laid down in [1], i.e. 6 kV/μs. It is remarkable that very small values of t_d have been observed, with the minimum value being 0.56 μs.

IV. Generator-Source Short-Circuit Currents

The prospective TRV appearing across the contacts of the GenCB immediately after the interruption of the generator-source short-circuit current has been calculated for each power station analysed. In accordance with [1], the TRV is determined for the first-pole-to-clear in case of a three-phase grounded fault between the GenCB and the step-up transformer. The three-phase fault for GenCB applications leads to higher current magnitude and to higher RRRV compared to single- and two-phase faults. This is due to the fact that the star point of the generator stator winding is generally grounded via an equivalent high resistance.

The studies have been performed by considering a pre-fault voltage equal to the maximum operating voltage of the generator.

In all the simulations, the TRV resulting from the interruption of a symmetrical current has been considered.

The results of this investigation are shown in Table II, where the power stations analysed have been grouped in 4 classes depending upon the rated power of the generator (S_{Gn}). Again the prospective TRV parameters for each class are expressed as a fixed number. The 70th percentile of each parameter of the prospective TRV is displayed. The peak value E_2 is normalised to V.

The natural frequency of the generator is normally much smaller than that of the step-up transformer; therefore, in contrast to what has been observed for the TRV in case of system-source short-circuit currents, the capacitance of the components installed between the generator and the GenCB does not have a substantial influence on the prospective TRV. The values found for the parameter E_2/V are more severe than those laid down in [1] for each class of S_{Gn}. On the other hand, less severe values of RRRV and t_d have been observed. The parameters RRRV and t_d in case of generator-source faults are respectively smaller and longer than the corresponding parameters for system-source faults. This is due to bigger equivalent capacitance of the generator compared to that of the step-up transformer. The parameter RRRV seems to be slowly increasing with S_{Gn}. Again similar findings are shown in [10]. In the present analysis the highest observed value of RRRV is 2.12 kV/μs which is close to the maximum value laid down in [1], i.e. 2.2 kV/μs. It is remarkable that values of t_d much longer than 0.5 μs (i.e. the value laid down in [1]) have been observed. Even the minimum observed value (i.e. 0.7 μs) is less severe than the requirement imposed by [1].

TABLE II
RESULTS OF THE SURVEY OF TRV PARAMETERS IN CASE OF GENERATOR-SOURCE SHORT-CIRCUIT CURRENTS

Class	S_{Gn} (MVA)	E_2/V	RRRV (kV/μs)	t_d (μs)
1	$S_{Gn} \leq 200$	2.0	0.8	2.0
2	$200 < S_{Gn} \leq 400$	1.9	1.1	1.7
3	$400 < S_{Gn} \leq 600$	1.9	1.1	2.0
4	$S_{Gn} > 600$	1.9	1.6	1.5

V. FAULT CURRENTS RESULTING FROM OUT-OF-PHASE CONDITIONS

After interruption of the fault current resulting from out-of-phase conditions, both sides of the GenCB remain energised. The magnitude of the interrupted current determines the voltage drop across power station equipment located at each side of the GenCB. The power frequency recovery voltage appearing across the open contacts of the GenCB consists of the sum of the voltage variations on each side of the GenCB following current interruption. After current interruption, voltage oscillations occur at each side of the GenCB dictated by the parameters of the generator and of the step-up transformer. The TRV across the first-pole-to-clear is therefore a dual frequency oscillatory curve with the natural frequency of the transformer higher than that of the generator.

Even though [1], [2] cover only requirements for an out-of-phase angle of 90° el., it is recognized that synchronising with different out-of-phase angles up to 180° el. might occur. The current magnitude in case of 180° el. out-of-phase conditions can attain very high values (approximately 89% of the a.c. component of the system-source short-circuit breaking current according to [11]) and the associated TRV can exhibit very high values of E_2 and RRRV. An analysis of fault currents resulting from 30° el., 60° el., 90° el., 120° el., 150° el. and 180° el. out-of-phase conditions has been carried out.

The phase angles of the two voltage sources have been set in order to obtain the required phase displacement of the power frequency voltages at each side of the open GenCB. The prospective TRV appearing across the contacts of the GenCB immediately after the interruption of the fault current resulting from 30° el., 60° el., 90° el., 120° el., 150° el. and 180° el. out-of-phase conditions has been calculated for each class of S_{Gn} listed in Table II.

The TRV is determined for the first-pole-to-clear in case of a three-phase fault current. The studies have been performed considering the generator terminal voltage equal to U_{gm}. In all the simulations the TRV resulting from the interruption of a symmetrical current has been considered.

The results of this investigation are shown in Tables III to VIII. The power stations analysed have been grouped in 4 classes depending on S_{Gn}. The peak value E_2 is normalised to V.

TABLE III
TRV PARAMETERS IN CASE OF FAULT CURRENTS RESULTING FROM 30° EL. OUT-OF-PHASE CONDITIONS

Class	S_{Gn} (MVA)	E_2/V	RRRV (kV/μs)	t_d (μs)
1	$S_{Gn} \leq 200$	0.9	1.0	1.0
2	$200 < S_{Gn} \leq 400$	0.9	1.3	1.0
3	$400 < S_{Gn} \leq 600$	0.9	1.4	0.8
4	$S_{Gn} > 600$	0.9	1.6	1.0

TABLE IV
TRV PARAMETERS IN CASE OF FAULT CURRENTS RESULTING FROM 60° EL. OUT-OF-PHASE CONDITIONS

Class	S_{Gn} (MVA)	E_2/V	RRRV (kV/μs)	t_d (μs)
1	$S_{Gn} \leq 200$	1.8	2.0	1.0
2	$200 < S_{Gn} \leq 400$	1.7	2.4	1.0
3	$400 < S_{Gn} \leq 600$	1.7	2.7	0.8
4	$S_{Gn} > 600$	1.6	3.1	1.0

TABLE V
TRV PARAMETERS IN CASE OF FAULT CURRENTS RESULTING FROM 90° EL. OUT-OF-PHASE CONDITIONS

Class	S_{Gn} (MVA)	E_2/V	RRRV (kV/μs)	t_d (μs)
1	$S_{Gn} \leq 200$	2.5	2.8	1.0
2	$200 < S_{Gn} \leq 400$	2.5	3.5	1.0
3	$400 < S_{Gn} \leq 600$	2.4	3.8	0.8
4	$S_{Gn} > 600$	2.3	4.4	1.0

TABLE VI

TRV PARAMETERS IN CASE OF FAULT CURRENTS RESULTING FROM 120° EL. OUT-OF-PHASE CONDITIONS

Class	S_{Gn} (MVA)	E_2/V	RRRV (kV/μs)	t_d (μs)
1	$S_{Gn} \leq 200$	3.0	3.4	1.0
2	$200 < S_{Gn} \leq 400$	3.0	4.2	1.0
3	$400 < S_{Gn} \leq 600$	2.9	4.6	0.8
4	$S_{Gn} > 600$	2.8	5.4	1.0

TABLE VII

TRV PARAMETERS IN CASE OF FAULT CURRENTS RESULTING FROM 150° EL. OUT-OF-PHASE CONDITIONS

Class	S_{Gn} (MVA)	E_2/V	RRRV (kV/μs)	t_d (μs)
1	$S_{Gn} \leq 200$	3.4	3.8	1.0
2	$200 < S_{Gn} \leq 400$	3.4	4.7	1.0
3	$400 < S_{Gn} \leq 600$	3.3	5.1	0.8
4	$S_{Gn} > 600$	3.2	6.0	1.0

TABLE VIII

TRV PARAMETERS IN CASE OF FAULT CURRENTS RESULTING FROM 180° EL. OUT-OF-PHASE CONDITIONS

Class	S_{Gn} (MVA)	E_2/V	RRRV (kV/μs)	t_d (μs)
1	$S_{Gn} \leq 200$	3.5	3.9	1.0
2	$200 < S_{Gn} \leq 400$	3.5	4.9	1.0
3	$400 < S_{Gn} \leq 600$	3.4	5.4	0.8
4	$S_{Gn} > 600$	3.3	6.2	1.0

The analysis shows that E_2/V and RRRV increase with the out-of-phase angle. The parameter RRRV seems to be also increasing with S_{Gn}. On the other hand, t_d seems to be somewhat constant with the out-of-phase angle and with S_{Gn}.

VI. COMPARISON OF TRVS OBTAINED WITH LUMPED AND DISTRIBUTED PARAMETERS MODELS

The use of models with distributed parameters is important to reproduce accurately the behaviour of power station equipment during transient events.

Fig. 5 shows the TRV waveform corresponding to the first-pole-to-clear in case of three-phase grounded fault occurring at the generator terminals. The generator model adopted shows a very good behaviour regarding the TRV [8]. It should be noted that even the bend during the first rise of the TRV typical for three-phase grounded faults is correctly reproduced by this model [8]. In contrast, the TRV of ungrounded faults would show a straight line up to the peak. For this reason, it is of utmost importance to use a complex model based on distributed parameters to assess the TRV for different fault scenarios.

The use of models with lumped parameters would lead to a simplified procedure to assess TRV parameters. The drawback is that the resulting TRV will be substantially different from that obtained with distributed parameters.

As an example, the TRV in case of fault currents resulting from 180° el. out-of-phase conditions has been simulated with lumped parameter models. The comparison of this TRV with that obtained with distributed parameters models is depicted in Fig. 6 for the first-pole-to-clear. Despite RRRV and t_d of the two curves appear to match well, the peak value obtained with distributed parameters models is considerably higher. The TRV in this case is a dual frequency oscillatory waveform. The natural frequency of the step-up transformer is higher than that of the generator. The TRV across the GenCB for the first-pole-to-clear obtained with distributed parameters models and the corresponding generator-side and step-up transformer-side voltage waveforms are depicted in Fig. 7.

VII. INFLUENCE OF THE GENCB CAPACITORS ON THE PROSPECTIVE TRV

SF_6 GenCBs are usually equipped with capacitors in order to mitigate the prospective TRV. These capacitors are usually installed phase to ground between the step-up transformer and the GenCB. In some cases they are also installed between the generator and GenCB.

To effectively prove the interrupting capability of a GenCB, the TRV that would appear across the open contacts of the GenCB after current interruption shall be reproduced in test circuits.

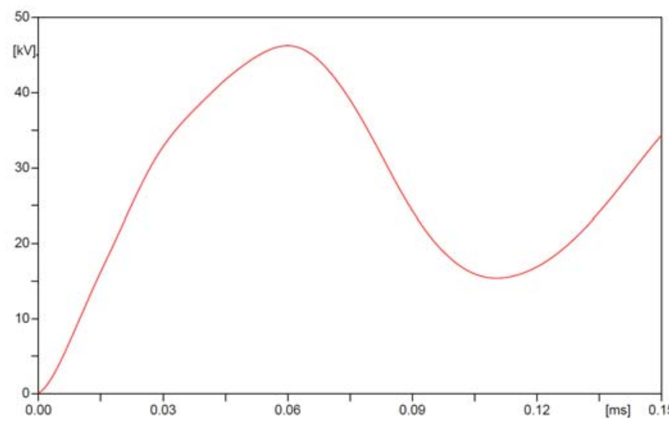

Fig. 5. TRV waveform corresponding to the first-pole-to-clear in case of a three-phase grounded fault occurring at the generator terminals

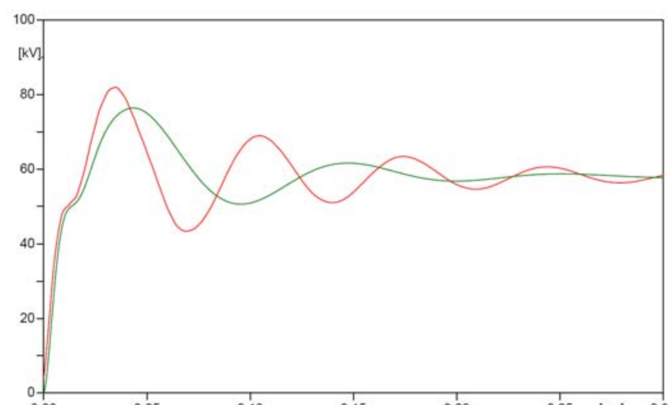

Fig. 6. TRV waveforms in case of fault currents resulting from 180° el. out-of-phase conditions for the first-pole-to-clear obtained with distributed (red curve) and lumped (green curve) parameters models

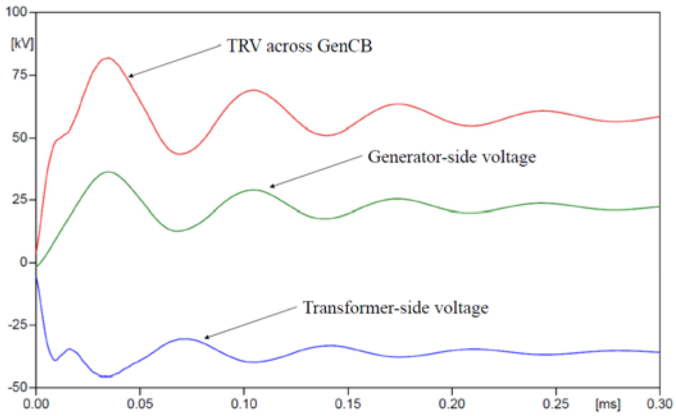

Fig. 7. Voltage waveforms in case of fault currents resulting from 180° out-of-phase conditions for the first-pole-to-clear obtained with distributed parameters models

Appropriate test circuits need to be designed for this purpose. To reproduce the prospective TRV, power testing laboratories normally use only one voltage source. Such a solution can reproduce the same effects of actual system-source and generator-source faults, where one side of the GenCB is short-circuited. For load current and out-of-phase current switching tests, however, by short-circuiting one side of the GenCB also the capacitor (if installed) on that side gets shorted and its influence is nullified. The equivalent TRV measured across the open contacts of the GenCB is therefore not realistic. To overcome this problem the TRV modified by the capacitors has to be calculated. The calculated TRV is then applied and the GenCB is tested without the additional capacitors. The same approach is sometimes followed for testing the capability of a GenCB to handle system-source and generator-source short-circuit currents.

The installation of wave-slowing capacitors results in the beneficial effect of reducing RRRV and increasing t_d of the TRV waveform. This is due to the fact that the additional capacitance decreases the natural frequency of the circuit. On the other hand, E_2 slightly increases. For this reason, in order to endorse the suitability of a GenCB for a specific application, the following conditions shall be met:

- the amount of equivalent capacitance required for breaking tests shall be given in the test report and on the nameplate of the GenCB of concern;
- the same capacitance value shall be used for all breaking tests;
- capacitors of the same capacitance value as used during those tests shall be installed in the GenCB system delivered for a specific project (any other capacitance values nullify the test).

Numerical examples about the influence of wave-slowing capacitors on the prospective TRV are provided in [12].

VIII. Conclusions

In case of system-source faults, the parameters E_2/V and RRRV are less severe compared to those laid down in IEEE Std C37.013-1997 (R2008) and in IEEE Std C37.013a-2007 whereas t_d can be more severe. The parameter RRRV seems to be slowly increasing with S_{Tn}. The highest observed value of RRRV is 5.89 kV/μs; this value is close to the maximum value laid down in IEEE Std C37.013-1997 (R2008), i.e. 6 kV/μs. Very small values of t_d have been observed, with the minimum value being 0.56 μs.

In case of generator-source faults the values obtained for the parameter E_2/V are more severe than those laid down in IEEE Std C37.013-1997 (R2008). On the other hand, less severe values of RRRV and t_d have been observed. The parameters RRRV and t_d in case of generator-source faults are respectively smaller and longer than the corresponding parameters for system-source faults. This is due to bigger equivalent capacitance of the generator compared to that of the step-up transformer. The parameter RRRV seems to be slowly increasing with S_{Gn}. The highest observed value of RRRV is 2.12 kV/μs which is close to the maximum value laid down in IEEE Std C37.013-1997 (R2008), i.e. 2.2 kV/μs. Values of t_d much longer than 0.5 μs (i.e. the value laid down in IEEE Std C37.013-1997) have been observed. Even the minimum observed value (i.e. 0.7 μs) is less severe than the requirement imposed by the IEEE standard.

The TRV parameters in case of out-of-phase fault currents have been investigated for different out-of-phase angles. The analysis shows that E_2/V and RRRV increase with out-of-phase angle. The parameter RRRV seems to be also increasing with S_{Gn}. On the other hand, t_d seems to be somewhat constant with the out-of-phase angle and with S_{Gn}.

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