New Requirements for the Application of Generator Circuit-Breakers

M. Palazzo, M. Delfanti

Abstract-- **The requirements imposed on generator circuit-breakers greatly differ from the requirements imposed on general purpose 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 current, short-circuit currents, fault currents due to out-of-phase conditions and transient recovery voltages. The question whether the 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 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*: Arc-voltage, delayed current zeros, fault currents, generator circuit-breaker, three-winding step-up transformer.**

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 current, 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).

The stresses imposed on GenCBs in case of fault currents 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 zeros;
- the rate-of-rise of the TRV 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 as short as 1 μs;
- the rate-of-rise of the TRV appearing after the interruption of a generator-source short-circuit current may be as high as 2.2 kV/μs and the corresponding time delay 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 test quantities given for general purpose transmission and distribution circuit-breakers for the 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 (DCZ).

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] and in [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 139 power stations has been performed. Generators ranging from 16 MVA to 2,002 MVA have been surveyed. Technical parameters of power station equipment have been collected from combined cycle (CC), gas turbine (GT), conventional thermal (TH), nuclear (NU), conventional hydro (HY) and pumped storage (PS) power stations.

The fault transients simulations have been performed by means of the Electromagnetic Transients Program (EMTP) [3]. The peak values, the a.c. and the d.c. components of the system-source and generator-source short-circuit currents as well as of the fault currents resulting from synchronising under different out-of-phase angles have been analysed. The degree of asymmetry of those fault currents has been studied too. It is defined as the ratio of the d.c. component to the peak value of the a.c. component and it is usually expressed in percentage.

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The TRV is the voltage appearing across the open contacts of the GenCB immediately after current interruption. The characteristics of the generator and of the associated step-up transformer dictate the waveform of the prospective TRV for various duties. In all practical applications the TRV imposed on GenCBs follows an oscillatory waveform. The interruption of a symmetrical current leads to the most severe TRV. A three-phase fault is the most severe case and gives the highest current magnitude. Under these conditions the peak value and the rate-of-rise of the TRV can be extremely high. This is especially true in case of interruption of fault currents due to out-of-phase conditions. As far as the requirements for the application of GenCBs is concerned, a detailed analysis of the TRV parameters is out of the scope of the present paper.

II. Power Station Equipment Models Adopted for the Simulations

The synchronous machine has been modelled with armature time constant, direct-axis and quadrature-axis subtransient and transient short-circuit time constants and direct-axis and quadrature-axis subtransient, transient and synchronous inductances. The inertia constant of the rotating mass has been taken into account as well.

The power transformers have been modelled with winding resistance and series inductance. The equivalent winding parameters have been obtained from the short-circuit impedances. The windings of each power transformer have been connected according to the vector group of the machine.

The HV-system has been modelled as equivalent voltage source and impedance. The equivalent impedance is determined by the maximum short-circuit power of the HV-system. For each power station analysed the HV-system data of that particular power station have been used.

III. System-Source Short-Circuit Current

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.

A typical power station layout used for this investigation is depicted in Fig. 1. Fault location is identified by "Fsys". Some power stations are equipped with a three-winding step-up transformer (see Fig. 2). In such a layout in case of a fault located in Fsys the fault current to be interrupted by GenCB1 would have the additional contribution of generator G2. Some power station layouts employ one two-winding step-up transformer for two generators (see Fig. 3). In this case both the a.c. component and the degree of asymmetry of the fault current to be interrupted by GenCB1 could attain very high values.

Depending upon the specific layout the possible contribution to the fault current of the motors connected to the LV-side of two-winding and three-winding unit auxiliary transformers has been taken into account (refer to the dotted lines in Fig. 1, Fig. 2 and Fig. 3).

In all the simulations fault initiation takes place in the moment when the voltage in one phase passes through zero, thus leading to the highest degree of asymmetry in that phase. The calculations have been based on the maximum service voltage of the HV-system. In the simulations it has been assumed that the contacts of the GenCB part 40 ms after fault initiation (i.e. a typical contact parting time for GenCBs). The magnitude of the a.c. component of the short-circuit current and its degree of asymmetry are evaluated at this instant.

The results depicted in Fig. 4 show that the a.c. component of the system-source short-circuit breaking current (I_{SCsys}) tends to increase with generator rated power. No specific influence of the type of the power station upon this trend is observed. The maximum observed value of I_{SCsys} is 248 kA.

The degree of asymmetry of the system-source short-circuit current at contact separation (DOA_{sys}) seems to be less dependent upon generator rated power and shows an average value of 72.2% (see Fig. 5). No currents exhibiting DCZ are observed (i.e. DOA_{sys} is never higher than 100%).

The ratio of the peak value of the system-source short-circuit current (I_{Psys}) to I_{SCsys} is somewhat constant with generator rated power and its average value amounts to 2.73 (see Fig. 6). This value is aligned to the factor 2.74 reported in [1]. In a few cases the ratio I_{Psys}/I_{SCsys} exceeds 2.83 (i.e. $2\cdot\sqrt{2}$). This can happen when more generators are connected to one step-up transformer and it is due to the contribution of those generators to the system-source short-circuit current.

The a.c. component of the fault current fed by generators decays with time and as a consequence the ratio of the peak value of the fault current (occurring 0.5 cycles after fault initiation) to the a.c. component of the fault current calculated at the time of contact separation (i.e. the breaking current) can exceed $2\cdot\sqrt{2}$. More information about this phenomenon are given in [4]. The maximum value of the ratio I_{Psys}/I_{SCsys} which has been observed is 3.28.

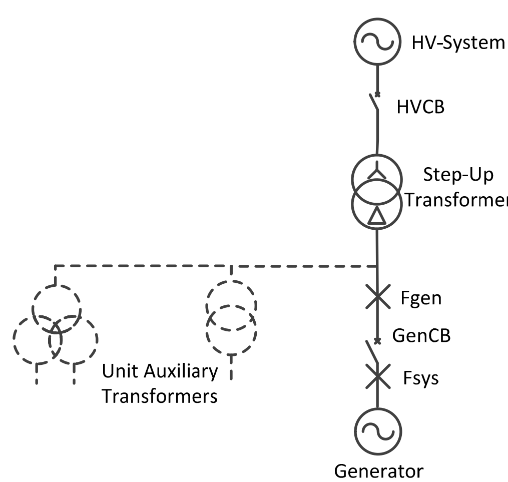

Fig. 1. Power station layout with one generator connected to a two-winding step-up transformer

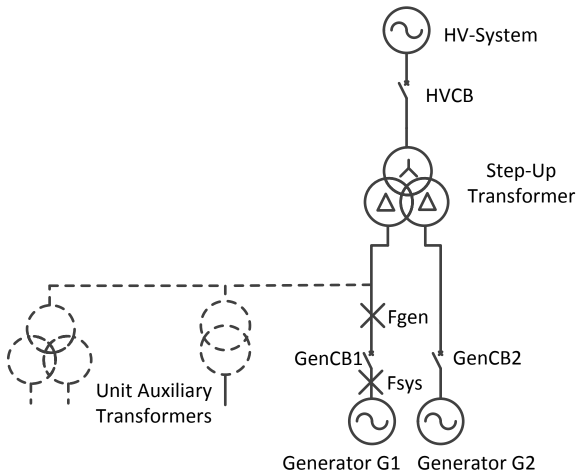

Fig. 2. Power station layout with two generators connected to a three-winding step-up transformer

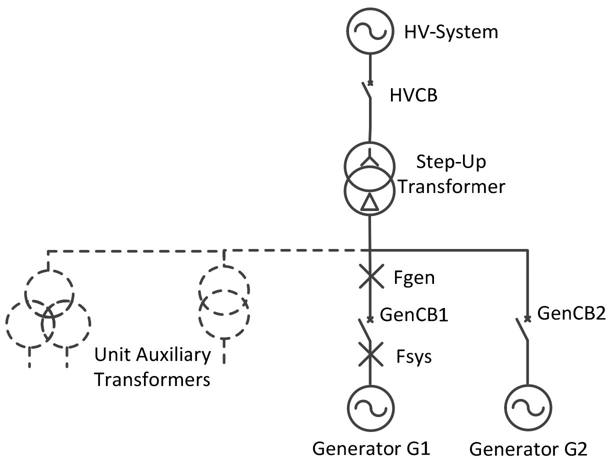

Fig. 3. Power station layout with two generators connected to a two-winding step-up transformer

IV. Generator-Source Short-Circuit Current

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. Fault location is identified by "Fgen" in Fig. 1, Fig. 2 and Fig. 3. The a.c. component of the generator-source short-circuit current decays with the subtransient and transient time constants of the machine; the d.c. component decays with the armature time constant. As a consequence the magnitude of the generator-source short-circuit breaking current (I_{SCgen}) is usually lower than I_{SCsys} but the degree of asymmetry at contact separation (DOA_{gen}) can be considerably higher than DOA_{sys}. If the a.c. component of the fault current decays faster than the d.c. component, it can happen that, for a certain period of time following the initiation of the fault, the magnitude of the d.c. component of the fault current is bigger than the peak value of its a.c. component. In such a case the degree of asymmetry of the fault current is higher than 100%, thus leading to DCZ. In the simulations fault initiation takes place in the moment when the voltage in one phase passes through zero, so that the highest degree of asymmetry is obtained in that phase. The calculations have been based on the maximum operating voltage of the generator. It has been assumed that the contacts of the GenCB part 40 ms after fault initiation. The magnitude of the a.c. component of the short-circuit current and its degree of asymmetry are evaluated at this instant.

The results depicted in Fig. 7 show that the ratio I_{SCgen}/I_{SCsys} does not seem to be dependent upon generator rated power. Very low values of the ratio I_{SCgen}/I_{SCsys} are observed when several generators are connected to one step-up transformer. In such a case the system-source short-circuit current would have the additional contribution of those generators thus leading to a total system-source short-circuit current of much higher magnitude compared to the generator-source short-circuit current which is fed by one generator. In 9% of the surveyed generators a value of I_{SCgen} higher than I_{SCsys} is observed.

DOA_{gen} is generally higher than 100% thus confirming that generator-source short-circuit currents typically exhibit DCZ (see Fig. 8). Only 7% of the surveyed generators lead to a value of DOA_{gen} lower than 100%. DOA_{gen} of especially higher values are observed for GT generators rated up to 300 MVA. In those cases DOA_{gen} can attain very high values and even exceed 150%. This is mainly due to the long armature time constant and to the relatively short subtransient time constants which are typical for this type of generators. For generators rated above 1,600 MVA values of DOA_{gen} between 110% and 120% have been observed. Further investigations have shown that DOA_{gen} is somewhat constant within a practical range of contact parting times.

The ratio of the peak value of the generator-source short-circuit current (I_{Pgen}) to I_{SCgen} is generally much higher compared to the ratio I_{Psys}/I_{SCsys} because the a.c. component of the fault current fed by generators decays with time; this decay is dictated by the subtransient and transient time constants of the machine. The faster is the decay of the a.c. component of the fault current fed by the generators the higher is the ratio I_{Pgen}/I_{SCgen}. In the survey an average value of the ratio I_{Pgen}/I_{SCgen} of 3.5 has been obtained. The maximum value observed is 4.6. The higher values are generally observed in GT applications and can be again explained by the long armature time constant and to the relatively short subtransient time constants which are typical for this type of generators. The average value of the ratio I_{Pgen}/I_{Psys} amounts to 0.96. In 46% of the surveyed generators I_{Pgen} is higher than I_{Psys} (see Fig. 9). The maximum value of the ratio I_{Pgen}/I_{Psys} which has been observed is 1.7.

V. Fault Currents Due to Out-Of-Phase Conditions

Out-of-phase synchronising occasionally occurs in power plants [5]. The main reasons for out-of-phase synchronising are wiring errors made during commissioning or during maintenance when connecting voltage transformers and synchronising equipment. Any value may be caused by inadequate settings of the synchronising equipment, e.g. due to an incorrect value of the closing time of the GenCB or due to manual synchronisation. The current resulting from out-of-phase synchronising may show DCZ; their causes are totally different compared to generator-source short-circuit currents. The rapid movement of the rotor from initial out-of-phase angle δ_0 to $\delta = 0$ results in a very small a.c. component of the fault current and a dominant d.c. component when the condition of $\delta = 0$ is reached. Because the instant when the $\delta = 0$ condition is reached is determined by the movement of the rotor, the inertia constants of turbine, rotor and excitation equipment of the generator are of special importance [4]. 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. Therefore an analysis of fault currents resulting from out-of-phase synchronising with angles of 30° el., 60° el., 90° el., 120° el., 150° el. and 180° el. has been carried out. For each initial out-of-phase angle δ_0 it has been assumed that the voltage at the generator terminals is either leading or lagging the HV-system voltage referred to the LV-side of the step-up transformer.

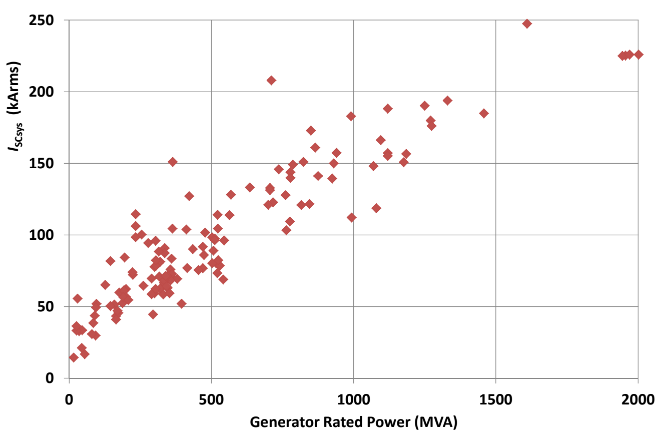

Fig. 4. A.C. component of the system-source short-circuit breaking current as a function of generator rated power

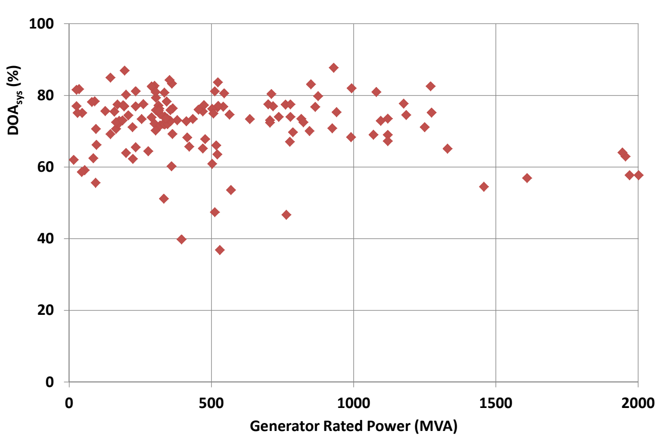

Fig. 5. Degree of asymmetry of the system-source short-circuit breaking current as a function of generator rated power

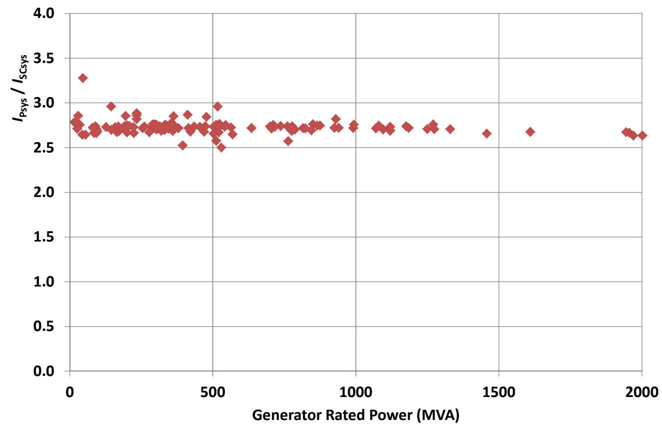

Fig. 6. Ratio of the peak value of the system-source short-circuit current to the system-source short-circuit breaking current as a function of generator rated power

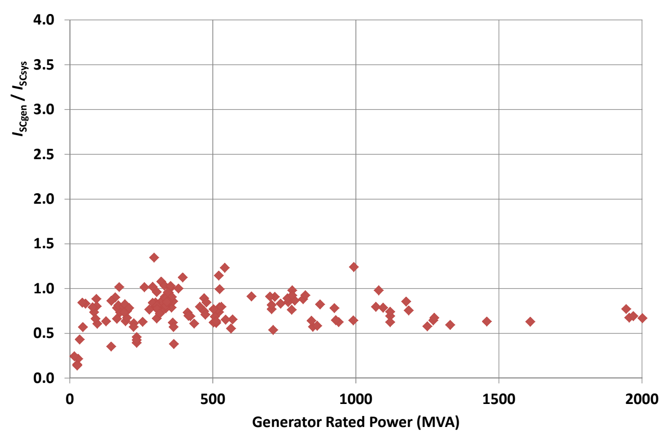

Fig. 7. Ratio of the a.c. component of the generator-source short-circuit breaking current to the a.c. component of the system-source short-circuit breaking current as a function of generator rated power

If the voltage at the generator terminals is lagging the HV-system voltage referred to the LV-side of the step-up transformer the out-of-phase angle is considered negative; if the voltage at the generator terminals is leading the HV-system voltage referred to the LV-side of the step-up transformer the out-of-phase angle is considered positive. In the simulations fault initiation takes place in the moment when the voltage across the open contacts of the GenCB in one phase passes through zero. Moreover it has been assumed that the contacts of the GenCB part 40 ms after fault initiation. The magnitude of the a.c. component of the fault current and its degree of asymmetry are evaluated at this instant.

The results depicted in Fig. 10 show that the ratio of the a.c. component of the out-of-phase breaking current (I_{OOP}) to I_{SCsys} tends to increase with the out-of-phase angle. Furthermore I_{OOP} is higher when δ_0 is negative (i.e. when the generator terminal voltage is lagging the HV-system voltage referred to the LV-side of the step-up transformer). The ratio I_{OOP}/I_{SCsys} for each out-of-phase angle analysed is somewhat constant with generator rated power.

It is remarkable that for an initial out-of-phase angle of -90° el. the average value of the ratio I_{OOP}/I_{SCsys} is 0.52 and for an initial out-of-phase angle of +90° el. the average value of the ratio I_{OOP}/I_{SCsys} is 0.50. Those values match quite well with the value laid down in [1], [2], i.e. 0.5.

The degree of asymmetry of the out-of-phase fault current at contact separation (DOA_{OOP}) tends to decrease with the out-of-phase angle (see Fig. 11). DCZ are observed with any initial out-of-phase angle. Furthermore DOA_{OOP} is higher when δ_0 is positive (i.e. when the generator terminal voltage is leading the HV-system voltage referred to the LV-side of the step-up transformer). DOA_{OOP} can attain much higher values compared to DOA_{gen}. This can be explained by the fast decay of the a.c. component of the out-of-phase fault current due to the movement of the rotor from initial out-of-phase angle δ_0 to the condition of $\delta = 0$.

The peak value of the fault current due to out-of-phase conditions (I_{POOP}) is normally lower than I_{Psys} (see Fig. 12). The ratio I_{POOP}/I_{Psys} tends to increase with the out-of-phase angle and it can be higher than 1.

The ratio I_{POOP}/I_{OOP} tends to decrease with out-of-phase angle and at lower values of δ_0 it is much higher than the ratio I_{Pgen}/I_{SCgen}. This reflects the impact of the rapid movement of the rotor on the decay of the a.c. component of the out-of-phase fault current (see Fig. 13).

VI. Statistical Analysis

Because all the parameters described before for system-source and generator-source short-circuit currents as well as for out-of-phase fault currents have been analysed for generators of different rated power, it is of interest to study the degree of linear interrelation between each of those parameters and generator rated power. This study can be performed by means of correlation analysis. The accuracy of a linear model between two variables depends on the correlation between them, measured by the sample correlation coefficient *r*. The sample correlation coefficient ranges from −1 to 1. A value of *r* close to ±1 indicates a strong linear relationship between two variables and that a linear regression analysis is adequate. A value of *r* equal to 0 implies that there is no linear correlation between the variables.

If the correlation analysis shows a strong linear relationship between the two variables, the relationship between those variables can be represented by the following model:

$$y_i' = \alpha + \beta s_{ni} \qquad (1)$$

where

y_i' is the estimated value of the general parameter of the fault current as a function of generator rated power;

s_{ni} is the observed value of generator rated power;

α and β are two constants which can be found by minimizing the sum of the squared errors:

$$\Delta^2 = \sum_{i=1}^{n}(y_i - y_i')^2 = \sum_{i=1}^{n}(y_i - \alpha - \beta s_{ni})^2 \qquad (2)$$

where

Δ^2 is the sum of the squared errors;

y_i is the observed value of the general parameter of the fault current;

n is the sample size (i.e the number of pairs of observed values for the two variables Y and S_n).

The least-squares estimates of α and β are the values which identify the line with the least total error and can be obtained by calculating the derivatives of Δ^2 with respect to α and β and setting them equal to 0.

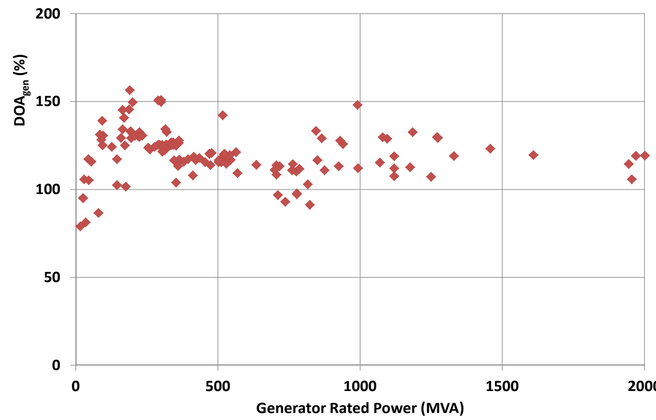

Fig. 8. Degree of asymmetry of the generator-source short-circuit breaking current as a function of generator rated power

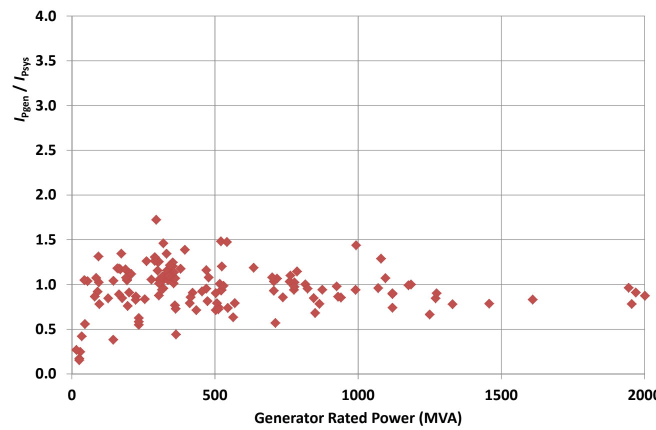

Fig. 9. Ratio of the peak value of the generator-source short-circuit current to the peak value of the system-source short-circuit current as a function of generator rated power

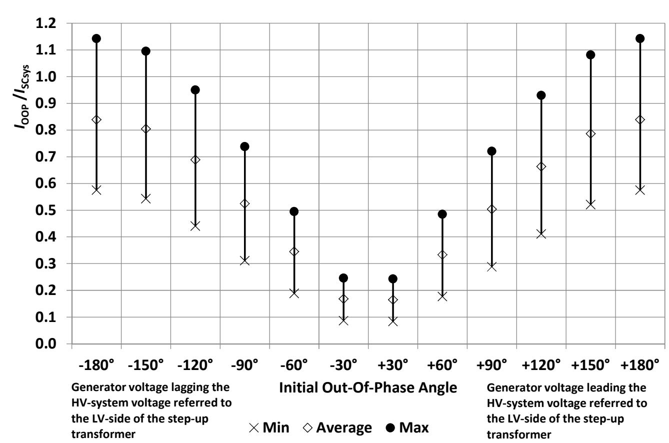

Fig. 10. Ratio of the a.c. component of the out-of-phase breaking current to the a.c. component of the system-source short-circuit breaking current as a function of initial out-of-phase angle

The obtained regression line is valid over the range of values of S_n for which data have been observed and it can be expressed by the following formula:

$$E[Y|S_n = s_n] = \hat{\alpha} + \hat{\beta} s_n \quad (3)$$

where $\hat{\alpha}$ and $\hat{\beta}$ are the least-squares estimates of α and β respectively. The effect of the linear regression of Y on S_n can be measured by the reduction of the sample variance of Y obtained by taking into account the linear dependency of Y on S_n. Specifically the larger the value of $|r|$ the greater is the reduction of the sample variance of Y if the relationship between Y and S_n is taken into consideration [6]. In case the linear model obtained with (3) does not adequately represent the relationship between the two variables in a specific range of values of the variable S_n a multiple linear regression model is employed. Extending (1) to a larger number of predictors the following model is obtained:

$$y_i' = \alpha + \sum_{j=1}^{p} \beta_j (s_{ni})^j \quad (4)$$

The adequacy of the number of predictors used for this model is confirmed by analysing the adjusted R^2, i.e. the adjusted proportion of variation in the response that is explained through the regression on all the predictors in the model. Higher adjusted R^2 indicates a better fitting model.

In order to set the requirements to cover the majority of GenCBs applications the following formula is employed:

$$y_{i-70\%} = \hat{\alpha} + \sum_{j=1}^{p} \hat{\beta}_j (s_{ni})^j + k \quad (5)$$

where $y_{i-70\%}$ is the line below which 70% of observations of the variable Y fall and k is a constant which identifies the line below which 70% of the observations of the variable Y fall. When the condition $|r| < 0.3$ is fulfilled, a low linear relationship between the two variables exists. In such a case (5) is replaced by the 70th percentile for the variable Y.

The results are summarized in Table I and Table II.

A. System-Source Short-Circuit Current

The relationship between I_{SCsys} and S_n is represented by the model shown in Table I. A time constant of 133 ms as well as a value of 2.74 for the ratio I_{Psys}/I_{SCsys} seem to be adequate to cover the requirements for most applications irrespectively of S_n. Nevertheless special attention should be paid to applications in those power station layouts where more generators are connected to one step-up transformer.

B. Generator-Source Short-Circuit Current

A value of I_{SCgen} equal to 80% of I_{SCsys} and a value of DOA_{gen} equal to 130% would cover the requirements for the majority of applications. Additional investigations have shown that DOA_{gen} is somewhat constant within a practical range of contact parting times. In case of GT applications with generators rated power up to 300 MVA values of DOA_{gen} higher than 150% can be expected. For generators rated above 1,600 MVA values of DOA_{gen} between 110% and 120% are representative. According to [1], [2], demonstrating the capability of a GenCB to interrupt short-circuit currents with DCZ may be difficult and limited in high power testing stations. Considering that various designs of generators behave differently it can be impossible to reproduce the required current waveform in the testing station [7]. Therefore the capability of a GenCB to interrupt a fault current with DCZ has to be ascertained by calculations that take into account the effect of the arc-voltage of the GenCB on the prospective short-circuit current. The arc-voltage model to be used for this purpose has to be derived from tests [1]. The GenCB's arc-resistance is an additional resistance which forces the d.c. component of the short-circuit current to decay faster. It is of utmost importance that the magnitude of the arc-voltage is high enough to force a fast decay of the d.c. component of the fault current, so that current zeros are produced within the maximum permissible arcing time of the GenCB. The arc-voltage of a GenCB depends on different physical quantities, e.g. the instantaneous value of the current and the type of the extinguishing medium, its pressure, the intensity of its flow and the length of the arc. In order to investigate the behaviour of the GenCB during the interruption of fault currents with DCZ, the arc-voltage versus current characteristics has to be transferred into a mathematical model. From the arc-voltage and the current the arc-resistance is obtained. A non-linear time-varying resistance has to be inserted into the simulation at the time of the separation of the contacts of the circuit-breaker to model the behaviour of the GenCB. Investigations have shown that SF_6 GenCBs are generally providing a better performance compared to vacuum GenCBs to handle fault currents which exhibit a very high degree of asymmetry [4].

A value of I_{Pgen} equal to I_{Psys} would cover the requirements for the majority of applications. Nevertheless in approximately 30% of the surveyed cases a value higher than 1.07 for the ratio I_{Pgen}/I_{Psys} is observed.

C. Fault Current due to Out-Of-Phase Conditions

Considering that fault currents due to out-of-phase conditions can occur in real applications with any out-of-phase angle, the selection of an out-of-phase angle of 90° el. on which the test requirements laid down in [1], [2] are based appears arbitrary. A value of I_{OOP} equal to 89% of I_{SCsys} for an out-of-phase angle of 180° el. would cover the requirements for the majority of applications. In some applications a ratio I_{OOP}/I_{SCsys} even higher than 1 has been observed.

Values of DOA_{OOP} much higher than 100% have been observed. Because DOA_{OOP} is higher in case of generator terminal voltage leading the HV-system voltage referred to the LV-side of the step-up transformer whereas I_{OOP} is higher in case of generator terminal voltage lagging the HV-system voltage referred to the LV-side of the step-up transformer, the capability of a GenCB to interrupt out-of-phase fault currents under both conditions has to be ascertained by calculations that take into account the effect of the arc-voltage of the GenCB on the prospective fault current. Because the decay of the magnitude of the a.c. component of the out-of-phase fault current is determined by the movement of the rotor, the inertia constants of turbine, rotor and excitation equipment of the generator are of special importance and need to be taken into consideration in the analysis. A value of I_{POOP} equal to I_{Psys} would cover the requirements for the majority of applications.

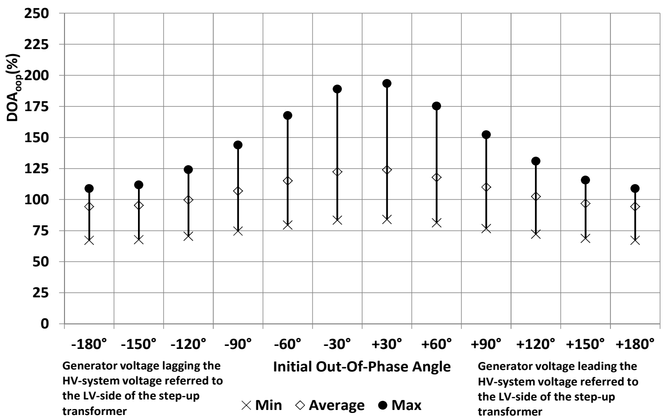

Fig. 11. Degree of asymmetry of the out-of-phase breaking current as a function of initial out-of-phase angle

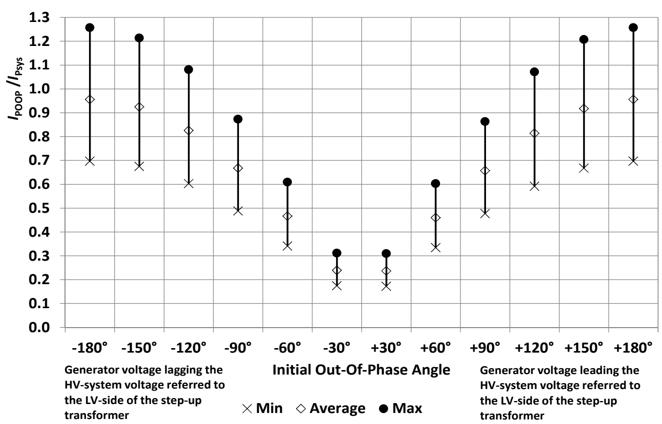

Fig. 12. Ratio of the peak value of the out-of-phase fault current to the peak value of the system-source short-circuit current as a function of initial out-of-phase angle

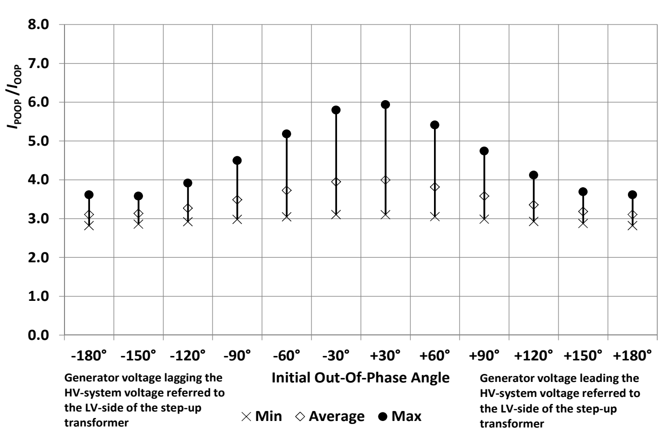

Fig. 13. Ratio of the peak value of the out-of-phase fault current to the out-of-phase breaking current as a function of initial out-of-phase angle

TABLE I
RESULTS OF THE SURVEY OF SYSTEM-SOURCE AND GENERATOR-SOURCE SHORT-CIRCUIT CURRENTS

Variable Y	r	$y_{i-70\%}$
I_{SCsys} (kA_{rms})	0.91	$37.426+0.147s_{ni}-0.00002386(s_{ni})^2$ s_{ni} expressed in MVA
DOA_{sys}	-0.18	76.9%
I_{Psys}/I_{SCsys}	-0.23	2.74
I_{SCgen}/I_{SCsys}	0.04	0.8
DOA_{gen}	-0.14	130%
I_{Pgen}/I_{Psys}	-0.02	1.07

TABLE II
RESULTS OF THE SURVEY OF OUT-OF-PHASE FAULT CURRENTS

Variable Y	Initial out-of-phase angle δ_0	r	$y_{i-70\%}$
I_{OOP}/I_{SCsys}	-30° el.	-0.2	0.18
DOA_{OOP}	-30° el.	0.04	132%
I_{POOP}/I_{Psys}	-30° el.	-0.27	0.25
I_{OOP}/I_{SCsys}	+30° el.	-0.2	0.18
DOA_{OOP}	+30° el.	0.04	133%
I_{POOP}/I_{Psys}	+30° el.	-0.27	0.25
I_{OOP}/I_{SCsys}	-60° el.	-0.23	0.37
DOA_{OOP}	-60° el.	0.04	122%
I_{POOP}/I_{Psys}	-60° el.	-0.28	0.49
I_{OOP}/I_{SCsys}	+60° el.	-0.22	0.36
DOA_{OOP}	+60° el.	0.04	124%
I_{POOP}/I_{Psys}	+60° el.	-0.28	0.49
I_{OOP}/I_{SCsys}	-90° el.	-0.24	0.57
DOA_{OOP}	-90° el.	0.02	112%
I_{POOP}/I_{Psys}	-90° el.	-0.28	0.71
I_{OOP}/I_{SCsys}	+90° el.	-0.23	0.55
DOA_{OOP}	+90° el.	0.02	115%
I_{POOP}/I_{Psys}	+90° el.	-0.29	0.7
I_{OOP}/I_{SCsys}	-120° el.	-0.25	0.74
DOA_{OOP}	-120° el.	-0.02	104%
I_{POOP}/I_{Psys}	-120° el.	-0.29	0.88
I_{OOP}/I_{SCsys}	+120° el.	-0.25	0.71
DOA_{OOP}	+120° el.	-0.01	108%
I_{POOP}/I_{Psys}	+120° el.	-0.29	0.86
I_{OOP}/I_{SCsys}	-150° el.	-0.25	0.86
DOA_{OOP}	-150° el.	-0.05	100%
I_{POOP}/I_{Psys}	-150° el.	-0.29	0.98
I_{OOP}/I_{SCsys}	+150° el.	-0.25	0.84
DOA_{OOP}	+150° el.	-0.05	102%
I_{POOP}/I_{Psys}	+150° el.	-0.29	0.98
I_{OOP}/I_{SCsys}	-180° el.	-0.25	0.89
DOA_{OOP}	-180° el.	-0.06	99%
I_{POOP}/I_{Psys}	-180° el.	-0.29	1.01
I_{OOP}/I_{SCsys}	+180° el.	-0.25	0.89
DOA_{OOP}	+180° el.	-0.06	99%
I_{POOP}/I_{Psys}	+180° el.	-0.29	1.01

VII. CONCLUSIONS

The results of the survey show that the requirements laid down in IEEE Std C37.013-1997 (R2008) and in IEEE Std C37.013a-2007 with respect to the system-source short-circuit currents are still adequate whereas the requirements concerning the generator-source short-circuit currents and the out-of-phase fault currents do not properly represent the stress imposed on GenCBs. A model to represent the relationship between I_{SCsys} and S_n has been proposed. The maximum observed value of I_{SCsys} is 248 kA. A time constant of 133 ms as well as a value of 2.74 for the ratio I_{Psys}/I_{SCsys} seem to be adequate to cover the requirements for most applications. A value of I_{SCgen} equal to 80% of I_{SCsys} and a value of DOA_{gen} equal to 130% would cover the requirements for most applications. In case of GT applications with generators rated power up to 300 MVA values of DOA_{gen} higher than 150% can be expected. For generators rated above 1,600 MVA values of DOA_{gen} between 110% and 120% are representative. DOA_{gen} is somewhat constant within a practical range of contact parting times. A value of I_{Pgen} equal to I_{Psys} would cover the requirements for most applications. I_{OOP} tends to increase with the out-of-phase angle whereas DOA_{OOP} tends to decrease with the out-of-phase angle. A value of I_{OOP} equal to 89% of I_{SCsys} for an out-of-phase angle of 180° el. would cover the requirements for the majority of applications. DCZ are observed with every initial out-of-phase angle and DOA_{OOP} can attain much higher values compared to DOA_{gen}. Because DOA_{OOP} is higher in case of generator terminal voltage leading the HV-system voltage referred to the LV-side of the step-up transformer whereas I_{OOP} is higher in case of generator terminal voltage lagging the HV-system voltage referred to the LV-side of the step-up transformer, the capability of a GenCB to interrupt out-of-phase fault currents under both conditions has to be ascertained by calculations that consider the effect of the arc-voltage of the GenCB on the prospective fault current.

VIII. References

[1] IEEE Standard for AC High-Voltage Generator Circuit Breakers Rated on a Symmetrical Current Basis, IEEE Std C37.013-1997 (R2008).

[2] IEEE Standard for AC High-Voltage Generator Circuit Breakers Rated on a Symmetrical Current Basis – Amendment 1: Supplement for Use with Generators Rated 10-100 MVA, IEEE Std C37.013a-2007.

[3] Canadian/American EMTP User Group: ATP Rule Book, 1987-1992.

[4] M. Palazzo, D. Braun and M. Delfanti, “Investigation on the Occurrence of Delayed Current Zeros Phenomena in Power Stations and Related Stress Imposed on Generator Circuit-Breakers”, *International Conference on Power Systems Transients – IPST 2011*, Delft, The Netherlands, 2011.

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[7] I. M. Canay, “Comparison of Generator Circuit-Breaker Stresses in Test Laboratory and Real Service Condition”, *IEEE Transactions on Power Delivery*, Vol. 16, No. 3, July 2001.