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Vacuum Circuit Breakers – Promising Switching Technology for Pumped Storage Power Plants up to 450 MVA

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***Abstract*—Vacuum as switching medium has been established widely in the distribution systems for more than 30 years. Well known for its outstanding and reliable interrupting capability of fault and load currents of all possible nature, the vacuum switching technology is now dominating the medium voltage level up to 52 kV. Technical advancements in the field of vacuum physics in last decades made it possible to implement vacuum switching technology also for generator applications. Well known for their demanding requirements on interrupting devices such as high fault currents with high degree of asymmetry or higher and steeper transient recovery voltages, the standards IEC/IEEE 62271-37-013 (2015) & IEEE C37.013 (1997) were introduced to address such requirements on circuit breakers used in generator applications. Circuit breakers employing vacuum technology fulfil all defined requirements to be qualified as Generator Circuit Breakers (GCBs) according to the above mentioned standards. Especially for Pumped Storage Power Plants (PSPPs), the Vacuum Generator Circuit Breakers (VGCBs) in compared with GCBs with gas quenching medium offer distinctive advantages such as fast dielectric recovery strength that eliminate the need of surge capacitors for switching duties, significantly higher number and frequency of possible switching operations, lower maintenance cost and environmental-friendly (GWP is 0). The VGCBs, due to their design flexibility & interrupting capabilities, are ideal for PSPPs for both motor and generator operation, back-to-back starting which are typical in such plants. A case study on a typical pump storage power plant is presented here by simulating various fault scenarios showing that a VGCB is fully suitable due to their reliability and economic profitability.**

***Index Terms*—vacuum generator circuit breaker, generator application, pump storage power plant, NETOMAC simulation**

I. INTRODUCTION

Over the last decades Vacuum Circuit Breakers (VCBs) are the most preferred switching devices in the medium voltage levels up to 52 kV. More than 80% of today's new installation employs vacuum switching technology [1]. The strongest argument for vacuum switching technology is its great advantage in terms of installation, maintenance, long life cycle and operation in comparison to other switching technologies. Generator applications are considered high demanding for medium voltage circuit breakers and require their own standard. Special test parameters in terms of breaking and TRV withstanding capability were introduced to meet such high demands. Vacuum Generator Circuit Breakers (VGCBs) have successfully passed all mandatory tests and are fully qualified as Generator Circuit Breaker since the first introduction of the generator breaker standards IEEE C37.013

in 1997. Extensive developments were made in the field of vacuum physics that pushed the range of the nominal current carrying capability of VGCB with natural cooling up to 12,500 A and the short-circuit breaking capability up to 100 kA. Further investigations and developments are on going to enable the full potential of VGCB.

The following chapters will show the challenges on generator circuit breakers (GCB) in general, followed by the explanation about VGCB's capability to face all of them. This paper will also include the most recent findings in the vacuum switching technology to highlight the significant enhancements between today's technology and the early days of the vacuum technology. In the end a case study is presented showing VGCB's capability to meet all the high demands by generator applications. Simulations of various short-circuit scenarios were carried out using the EMTP software PSS ® NETOMAC.

II. CHALLENGES ON GCBS

The generator circuits are considered highly inductive with a very small resistive component leading to fault current with a very high degree of asymmetry in case of a sudden short-circuit at the generator terminals. Being installed directly between the Generator and Generator Step-up Transformer (GSUT) as shown in Figure 1, the GCB is facing the direct impact of such high asymmetrical current in case of a terminal short-circuit.

The generator breaker standards introduce the terms *system-source* and *generator-source* fault according to source of the short-circuit current across the GCB. Each current have different challenges due to its origin of the fault current.

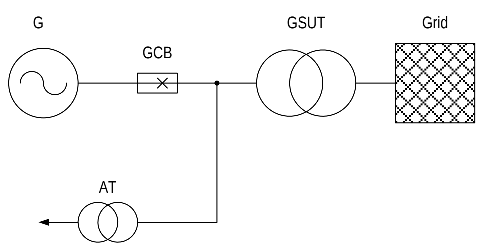

Fig 1. Typical layout of a generator circuit

A. *System-source short-circuit current*

If a short-circuit occurs at the generator terminal of the GCB, the source of the current across the GCB is from the grid through the GSUT as shown in Figure 2.

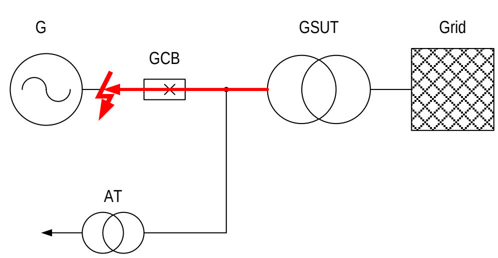

Fig 2. System-source short-circuit

Typically, as shown in Fig 3. , the fault current in case of a system-source short-circuit is high with constant symmetrical component (AC) due to the small transformer impedance. Since the resistive component is relatively small in case of highly inductive electrical equipment such as transformer, the aperiodic fault current component (DC) decays relative slowly. The degree of asymmetry at the contact separation of a GCB is therefore quite high which is in the range of 60% to 75%.

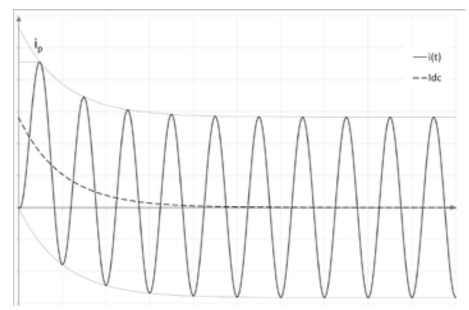

Fig 3. Typical current curve of a system-source fault

B. *Generator-source short-circuit current*

In case of a fault at the transformer terminal of the breaker, the fault current across the GCB is now fed by the generator as shown in the Figure 4.

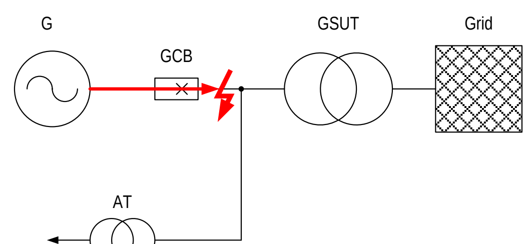

Fig 4. System-source short-circuit

Contrary to the transformer with just one main winding, generator can have up to three windings which interact differently in case of a sudden short-circuit, leading to the below characteristic current curve (Figure 5). The AC component is no longer constant but decays and the DC component decays as well but much slower in comparison to a system-source fault current. Depending on the generator's characteristics, the AC decaying can happen much faster than the DC component for certain machine parameter combinations. Since the current offset is now higher than the oscillating component, the total current can show missing zero crossings which means a degree of asymmetry of more than 100%. It usually lies in the range of 110% to 130%.

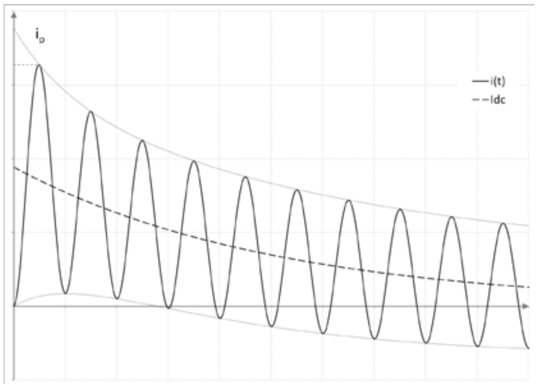

Fig 5. Typical current curve of a generator-source fault

Medium voltage breakers employ the principle of current-zero-interruption; means a zero crossing is required for the breaker to interrupt the current. In case of unfavourable generator parameters, the current zero crossings can delay for several cycles. The opening of a GCB in such cases can lead to a very high thermal stress on the contacts because of the very long arcing time.

C. *Out-of-phase switching capability*

One of the main tasks of a GCB is to synchronize the generator with the HV grid. Wiring errors of voltage transformers during commissioning or after maintenance can lead to false synchronisation. In few cases the out-of-phase current can show delayed current zeroes. However the reason is significantly different than in case of the generator-source fault. The fast decaying of the AC component is primarily caused by the rapid change of the angular displacement of the rotor. Hence the inertia constant of the machine set has a significant influence on the fault current behaviour during false synchronization. The amplitude, however, is determined by the system and machine parameter and also by the out-of-phase angle. The generator standards IEC/IEEE 62271-37-013 and IEEE C37.013 defined only the out-of-phase angle of 90° as a mandatory test duty [2]. When the out-of-phase angle is greater, the amplitude of fault current will be higher but less critical in terms of asymmetry. Technically a false synchronization angle of 180° creates a higher fault current than a 90°. Even though the above standards don’t define a test for 180°, the VGCBs are tested in house and proved to handle the stresses successfully.

D. *Low frequency switching*

One of the special requirements of PSPPs is running the machine in both pump mode and turbine mode. In order to bring the machine from turbine mode to pump mode, several starting methods are possible of which back-to-back start is commonly preferred due to its higher efficiency and reduced equipment cost. During the process of starting, if a fault occurs in the circuit, the installed GCB must be able to interrupt the currents with low frequency which is in the range of 20 Hz. However, the vacuum switching technology have been extensively used in German railway networks with a frequency of 16.7 Hz which further ensures the suitability of this technology for PSPP switching applications.

E. *Transient recovery voltage*

Immediately after the current interruption the contact gap of every circuit breaker must be able to withstand the fast rise of the transient recovery voltage (TRV). Generator circuits are highly inductive with relatively small capacitance which leads to very steep TRV with high amplitude which is even more challenging for a GCB. Also that the connection between GCB and generator/GSUT is usually very short, thus the system capacitance is very low when compare to other distribution applications. This has an even worse impact on the steepness of the TRV.

TABLE I. COMPARISON BETWEEN IEC 62271-100 AND IEC/IEEE 62271-37-013 (EXTRACT) [2][3]

Test parameter	**IEC 62271-100 Distribution breakers**	**IEC/IEEE 62271-37-013 Generator breaker**
Breaking capability	✓ (rated rating) n.a. (generator-source)	✓ (rated rating) ✓ (generator-source)
Degree of asymmetry (at e.g. 50 ms)	33% (τ = 45 ms) n.a. (generator-source)	69% (τ = 133 ms) 130% (generator-source)
Amplitude of TRV	$U_r \cdot 1.72$	$U_r \cdot 1.84$
Rate of rise of recovery voltage (RRRV)	e.g. 0.47 kV/µs	e.g. 4.5 kV/µs
Out-of-phase breaking capability	$I_{sc} \cdot 0.25$	$I_{sc} \cdot 0.5$
Out-of-phase RRRV	e.g. 0.35 kV/µs	e.g. 4.1 kV/µs

The comparison of the test parameters between circuit breakers used for distribution application and generator application in Table 1 shows which requirements a circuit breaker must be able to fulfil to be qualified as a type tested GCB.

III. SWITCHING CHARACTERISTICS OF VGCBS

Generally the interruption process of the vacuum switching technology is quite simple. At the opening of the breaker molten metal bridges start to form between the contacts. The vacuum arc is then initiated when the molten metal bridges break. The vacuum arc is characterized as a metal vapour and stays in diffuse mode up to ~10 kA [4] and becomes constricted at higher current levels. Various contact geometries are developed to either keep the constricted arc rotate on the contact surface (RMF – radial magnetic field) or to ensure that the arc stays diffuse even at higher current level up to 100 kA (AMF – axial magnetic field). Diffuse arcs tend to have much less erosion impact on the contact surface thus AMF contact type is mostly preferred for high current application such as generator applications.

Further vacuum has a very fast recovery strength in the range of >10 kV/µs [1] and therefore can easily withstand the required high TRV and RRRV of generator applications. Other gaseous switching technologies such as SF_6 have much lower TRV withstand capability and require additional surge capacitors to be suitable at all for generator applications. However VCBs are often falsely associated with high current chopping levels which are no longer relevant due to the change of contact materials. In the past, where the chopping current is > 10 A, which is the consequence of using Cu contacts high overvoltages can occur. Modern contact system use CuCr material and significantly reduce the chopping current level to less than 5 A [5], which will no longer produce any impermissible overvoltages.

In addition, the VGCBs for generator applications are often falsely projected that the vacuum arc voltage is too low to influence the delayed current zeros. Although the arc voltage is considered low for VGCB, it does have a noticeable effect on the DC decaying behaviour of short-circuit current in generator circuits, especially the generator-source current. Recent measurements show that the arc voltage for AMF contact types (diffuse arc) is in the range of 80 – 120 V while 120 – 150 V is considered average for RMF (constricted arc) contact geometry. The resistive character of an arc can reduce the DC time constant after the contact parting leading to a positive effect on the decaying of the DC offset and reducing the arcing time significantly. Specific simulations were performed with 100 V of arc voltage and presented in [6]. Apart from this, the lower arc voltage further offers another advantage – lower contact erosion. Due to the lower arc voltage in vacuum (~ 100 V) the thermal impact (erosion) on the vacuum breaker contacts is much less than SF_6 breaker contacts (at ~ 1500 V), leading to significantly higher number of possible switching operations – both load current (maintenance-free up to 10,000 CO operations and more) and short-circuit current (maintenance-free > 50 operations at full short-circuit current rating). This makes VGCBs as ideal switching device for applications with very high amount of switching operations such as pump storage, where load current is switched very often; at least twice a day.

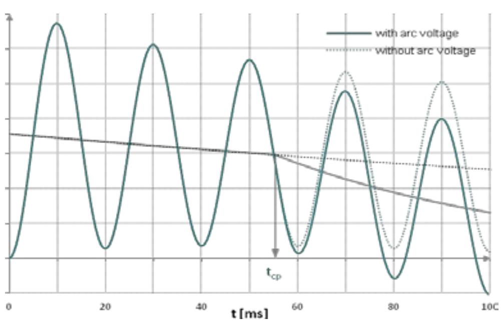

Fig 6. Principle effect of arc voltage at contact parting

In addition to high number of switching operations, the VGCBs have various distinctive advantages over other technologies which are explained in detail in reference [7].

IV. CASE STUDY

In the following section a case study showing the maximum possible fault current stresses based on a typical pump storage power plant configuration (Fig 1.) is presented. The simulations are performed with an EMTP software PSS ® NETOMAC taking into account the breaking behaviour and capability of a 100 kA VGCB.

TABLE II. SYSTEM DATA

Grid	
Rated voltage U_{rQ}	330 kV
Three-phase short-circuit power S''_k	14.4 GVA
Impedance ratio R/X	0.09 pu
System frequency f_s	50 Hz
GSUT	
Rated power S_{rT}	250 MVA
Rated voltage U_{rTHV} / U_{rTMV}	330 / 15.75 kV
Short-circuit impedance u_k	11%
Short-circuit losses P_k	240 kW
Synchronous generator	
Rated apparent power S_{rG}	249 MVA
Rated voltage U_{rG}	15.75 kV
Rated speed n	136.4 min^{-1}
Saturated synchronous reactance $x_{d/q}$	103 % / 71.7%
Saturated transient reactance $x''_{d/q}$	39.3% / 71%
Saturated subtransient reactance $x''_{d/q}$	24.7% / 24.4%
Saturated leakage reactance x_l	22%
Transient time constant $T'_{d/q}$	4.076 s / 0.5 s
Subtransient time constant $T''_{d/q}$	0.05 s / 0.05 s
Armature time constant T_a	0.4 s
Moment of inertia J	40,000 tm^2

Various fault scenarios have been considered in this case study. The following fault initiation conditions are taking into account to simulate the highest stress on a GCB.

- A three-phase, bolted (fault resistance R_F = 0) short-circuit produces the maximum fault current, since generator circuits are mostly high-impedance grounded [8].
- The short-circuit is initiated at voltage zero to simulate the maximum DC offset of the fault current and at voltage maximum the show the effect when the first pole to clear is symmetrical [7].
- The generator at various operating modes i.e. no load, lagging ($\cos_\varphi$ = 0.8 pu) and leading ($\cos_\varphi$ = 0.95 pu) in prior to the short-circuit initiation. It is important to mention that it is practically not possible to generate a low-resistant three-phase short-circuit while the generator is in service (lagging or leading). The only possibility is via an arc fault which is clearly stated in standards [2] and [3].
- Out-of-phase synchronization at 90° as required by the standards
- Out-of-phase switching at 180° to show the highest level of fault current on the VGCB.

The contact separation shall take place at 55 ms after the short-circuit initiation, including 10 ms protection relay and 45 ms mechanical opening time of the VGCB. Simulation results for both generator-source and systems-source fault currents are presented in Table III. In ANNEX A 1. to A 5. the current curves of generator-source fault and out-of-phase synchronization are showed in order to analyze the possible delayed current zeros.

TABLE III. SIMULATION RESULTS – SHORT-CIRCUIT CURRENTS

	System - source fault	**Generator-source fault**			**Out-of-phase synchronization**	
		No load	***Lag-ging***	***Lea-ding***	***90°***	***180°***
$\mathbf{I_{ac,rms}}$	70 kA	28 kA	36 kA	24 kA	26 kA	41 kA
$\mathbf{I_{dc}}$	74 kA	45 kA	49 kA	44 kA	39 kA	56 kA
DC%	74%	114%	95%	127%	105%	97%
$\mathbf{i_p}$	199 kA	100 kA	115 kA	94 kA	92 kA	132 kA

The system-source fault current, as expected, is high in amplitude with higher degree of asymmetry when compared with distribution networks which reflects the testing parameters (τ = 133 ms) showed in TABLE I.

Before analysing the generator source fault it is important to understand the peculiarity of the generators used in PSPPs. The generators used in these plants have slightly different short-circuit parameters than generators used in conventional power plants. Their short-circuit reactances and also the ratio of subtransient to transient reactances are comparatively small; further the decaying time constants T'_d and T''_d are very long. Due to these characteristics short-circuit current level in case of a generator-source fault is mostly higher than in other power plant configurations of the same power rating.

Based on the results in TABLE III. and the curves in ANNEX the generator-source fault current at leading power factor (A 3.) shows the most severe behaviour in terms of delayed current zeros. The arcing time of about two cycles is obtained here. Nevertheless the fault current is completely interrupted within five cycles under the consideration of moderate 100 V of a VGCB. Fault current in case the generator is in lagging power factor is higher in the amplitude but less critical due to its smaller degree of asymmetry (A 2.). However as mentioned earlier, the calculation of a bolted three-phase short-circuit when the generator is in service (lagging or leading power factor) is only possible theoretically since such faults cannot be occurred in reality. According to the standards [2] and [3] an arc voltage of at least 300 V for a free-burning arc in air has to be taken into account in the simulations for generator in service. By including this arc voltage, the arcing time will be reduced drastically and the fault current will be interrupted completely in less than 4 cycles.

Another important phenomenon to be analyzed is out-of-phase switching currents which are mainly dependent on moment of inertia of the machine and the out-of-phase angle. Typically the generators used in pump storage power plants tend to have a very large moment of inertia, thus the change of the angular displacement occurs much slower. As already explained in chapter II section C generator parameters and mainly the machine inertia have a major influence on the AC decaying of the out-of-phase current: the larger the machine inertia, the slower the AC decaying. This can be reflected in the calculation results showed in TABLE III. The current amplitude increases with increased out-of-phase angle. The degree of asymmetry of the fault current at 90° is slightly above 100% which however can be covered by the generator-source breaking capability (up to 130% for GCB class G2). At 180° the asymmetrical breaking current is higher but much less critical since no delayed current zeroes can be obtained.

V. CONCLUSION

Generator circuits in general are high demanding in terms of breaking capability and TRV withstand capability. Further the PSPPs have even special requirements when compared with conventional power plants like high number of switching operations at load current rating per day or switching low frequency currents while back-to-back starting. The VGCB fulfil all the above necessary requirements and as defined by the generator breaker standards IEEE C37.013 & IEC/IEEE 62271-37-013. They offer many distinctive advantages over any other gaseous GCBs like withstanding the TRV and RRRV requirements without any additional surge suppressors. And lower contact erosion enable a very long and maintenance-free electrical life cycle of at least 10,000 operating cycles, which is a huge cost saving for power plant operators, especially pump storage power plants. It is proved in this paper that the vacuum arc voltage of 100 V does have a positive and non-negligible impact reducing the arcing time significantly while switching the generator-source fault currents. Further this technology offers a wider range of design flexibilities make them the best choice for the modernisation of the power plants.

Thus the VGCBs, with their distinctive advantages and unique characteristics, are considered as a reliable and cost efficient solution for switching pumped storage power plants.

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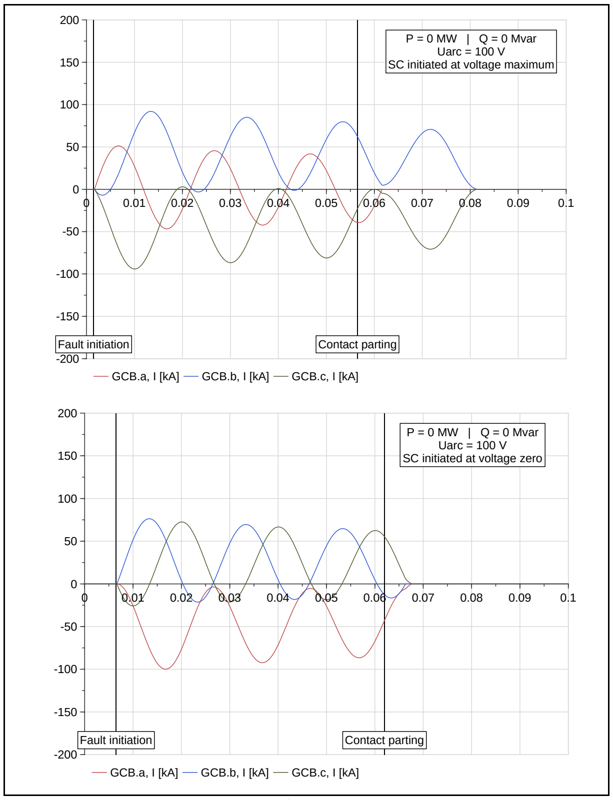
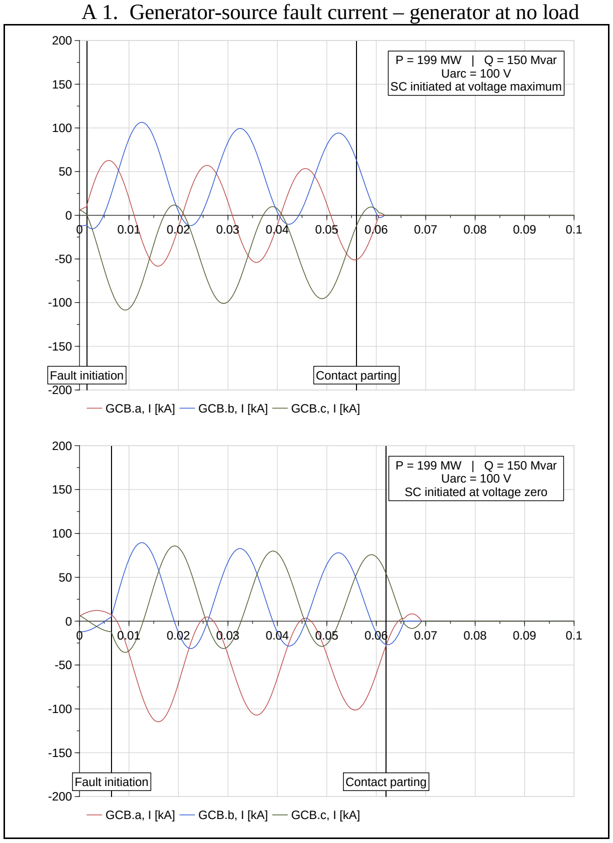
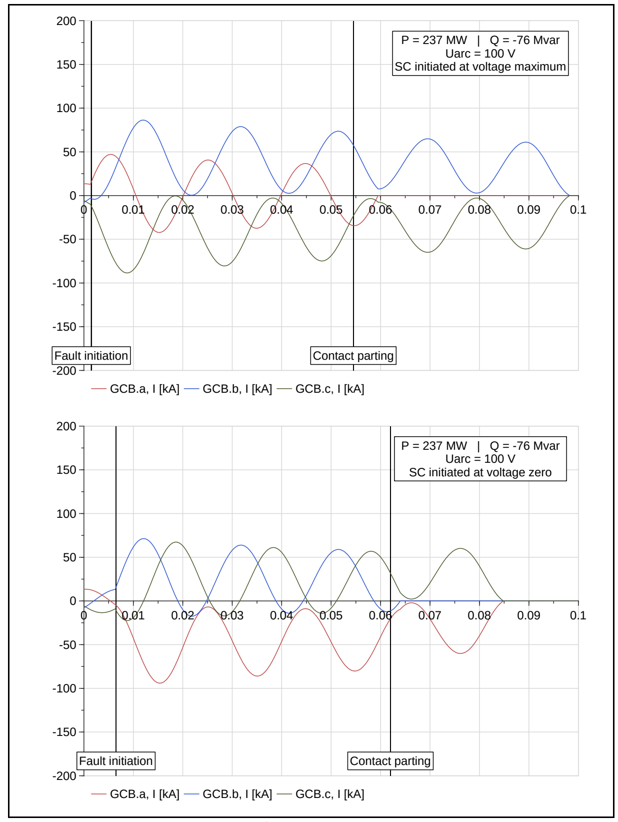
ANNEX



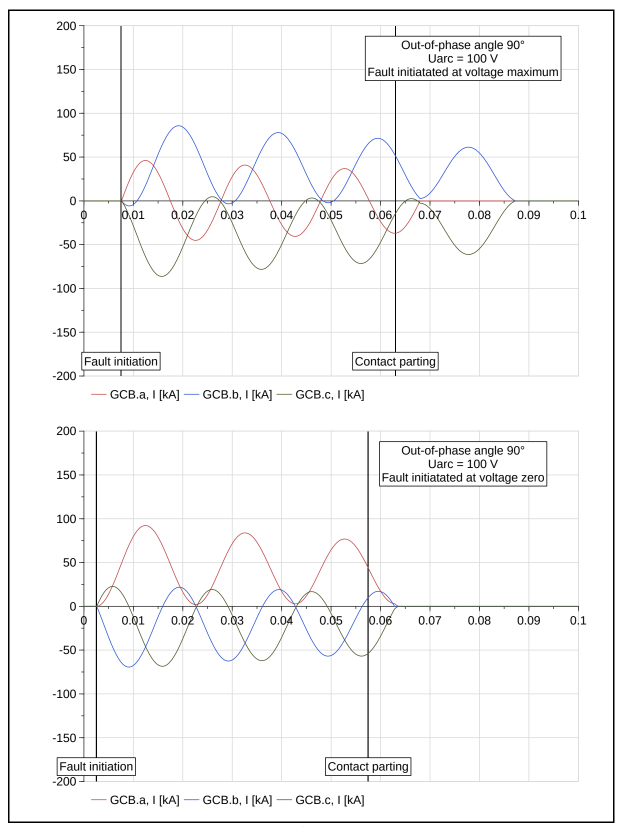
A 1. Generator-source fault current – generator at no load



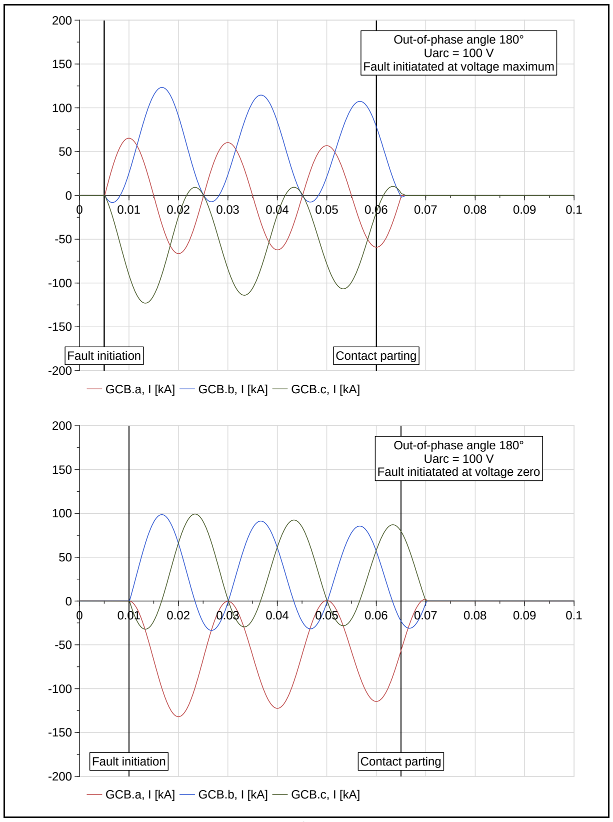
A 2. Generator-source fault current – generator in lagging mode



A 3. Generator-source fault current – generator in leading mode



A 4. 90° out-of-phase synchronization



A 5. 180° out-of-phase synchronization