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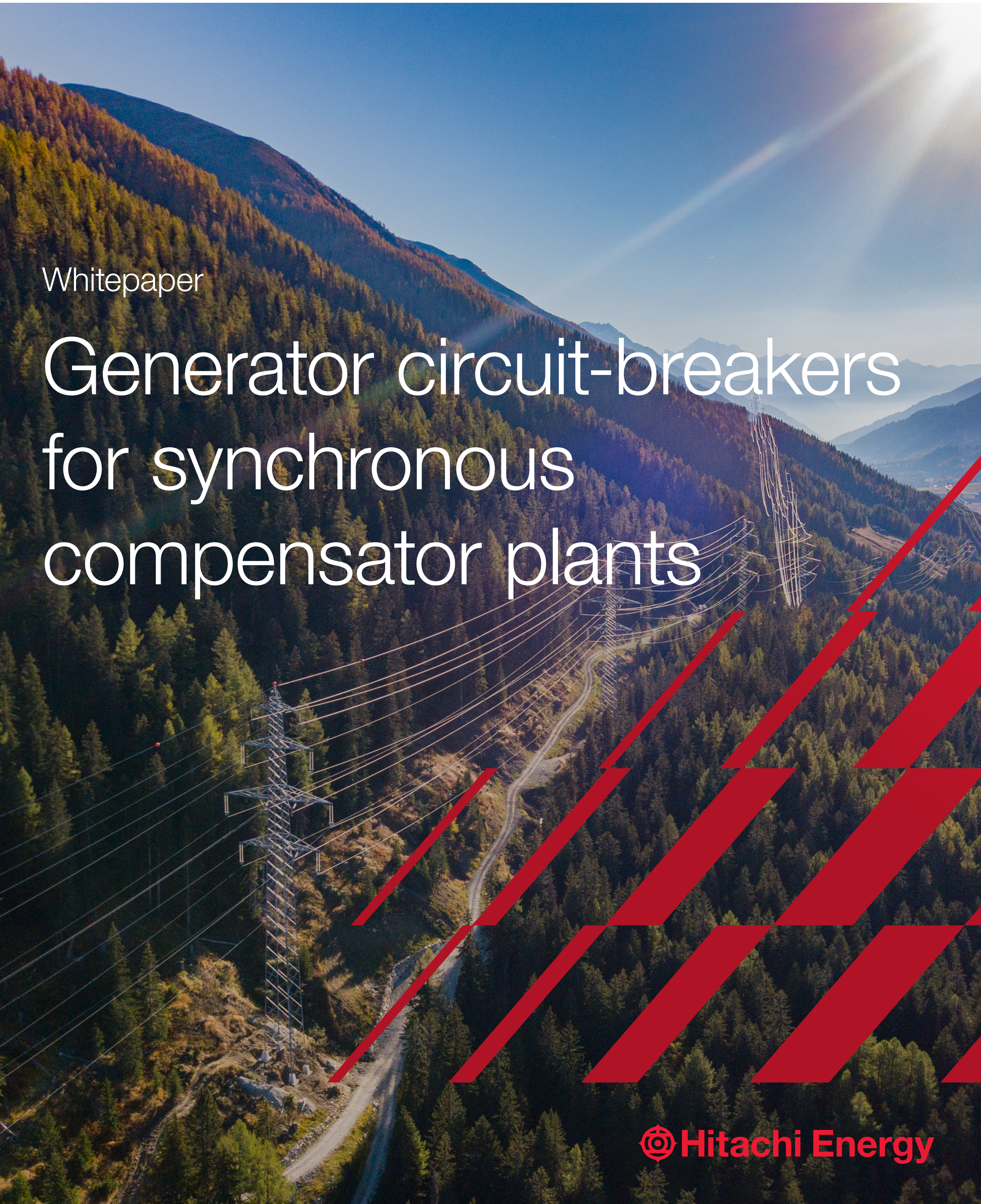


Whitepaper

# Generator circuit-breakers for synchronous compensator plants

Hitachi Energy

# Generator circuit-breakers for synchronous compensator plants

## Energy transition and significance of synchronous compensators

The integration of renewable energy resources such as wind and photovoltaic is promoted worldwide. The “Energiewende” renewable energy act of Germany has ambitious targets such as 80-95% $CO_2$ reduction until 2050, retirement of all nuclear power plant by 2022, 60% stake of renewables by 2050. Similar targets are also set by several other countries.

From the technical perspective, renewables such as wind turbine generators and photovoltaic panels are interfaced to the grid through converters, which naturally do not contribute to the system inertia and have small amount of short-circuit capacity in comparison to the classical synchronous generators. In addition, there is need of high-voltage direct current (HVDC) for the transmission of electricity over long distance due to remote and concentrated renewable generation and aggregated loads in industrial and metropolitan areas. The impact of this changing network configuration has led to the systems with less strength and low inertia affecting the overall system stability and the power supply quality.

To overcome these challenges and facilitate more integration of renewables into the existing network, the robust and well-proven traditional technology of synchronous compensator has regained its importance. It provides short-circuit strength and inertia to the grid, improves system stability in networks with weak interconnection, and can improve the operation of power electronics installations.

Therefore, a detailed understanding of the behavior of a synchronous compensator is essential to define the requirements of other power station equipment. Specifically, the characteristics of the current fed by a synchronous compensator after a three-phase short-circuit at its terminals is of utmost importance to define the requirements of the generator circuit-breaker (GCB) to be installed between the synchronous compensator and the step-up transformer.

# Challenges for generator circuit-breakers in synchronous compensator plants

The requirements imposed on a GCB greatly differ from the requirements imposed on general-purpose transmission and distribution circuit-breakers. Due to their location of installation, high technical requirements are imposed on GCBs 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 GCBs have to deal with are associated with very steep transient recovery voltages (TRVs) and can be characterized by delayed current zeros (DCZ). 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 covered the requirements for GCBs was IEEE Std C37.013-1997 (R2008) with its amendment IEEE Std C37.013a-2007 which is now replaced by the dual logo standard IEC/ IEEE 62271-37-013:2015. The requirements laid down in these standards are based upon applications employing synchronous generators. The question whether these requirements are adequate for the application of GCBs in synchronous compensator plants is considered in the present work.

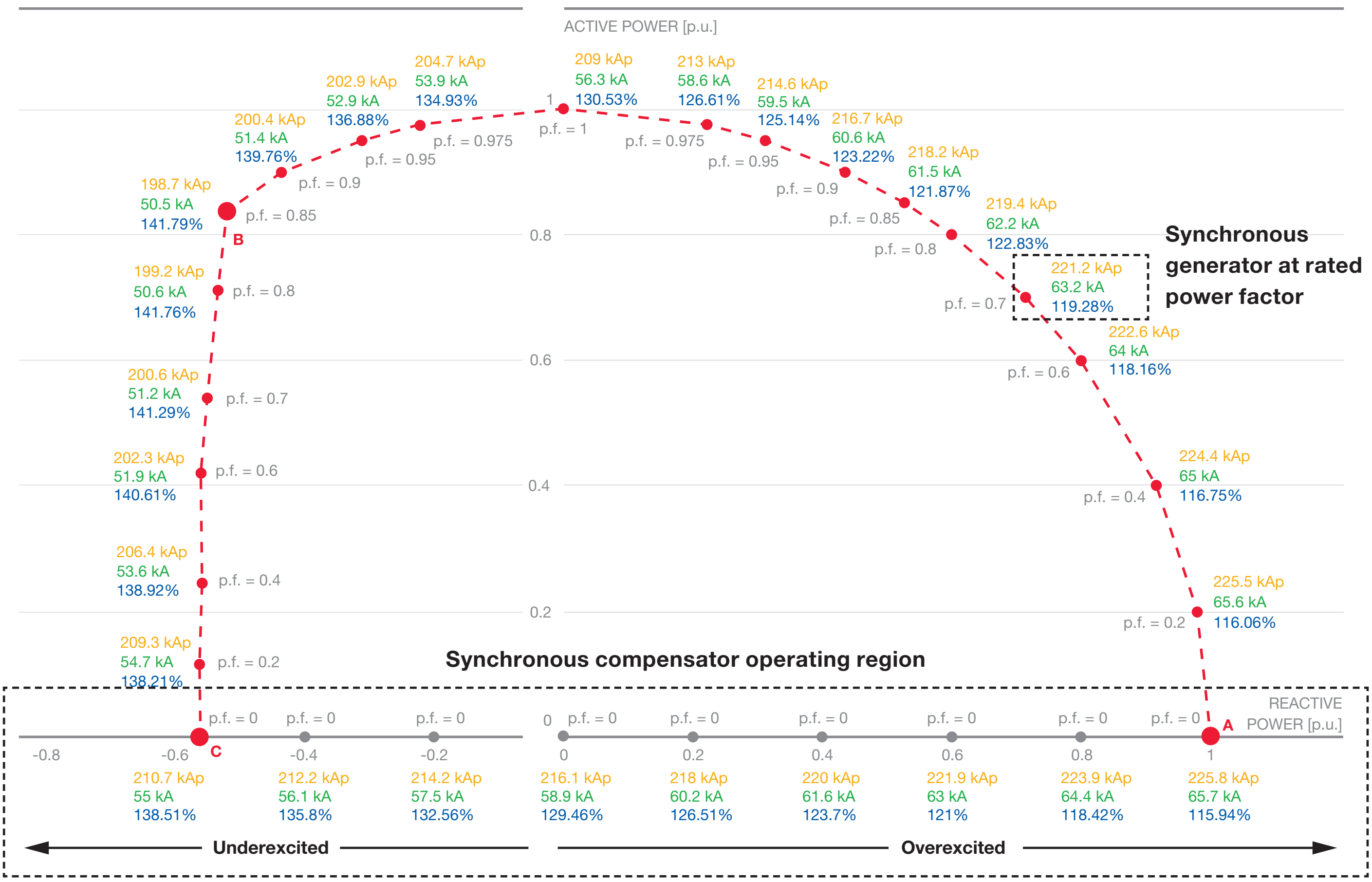
The main difference between a synchronous generator and a synchronous compensator is their operating point during normal operation. Synchronous generators are not meant to be operated at zero power factor, whereas synchronous compensators do so in normal operating conditions. Another important difference is the lower inertia of synchronous compensators due to the absence of a prime mover. These two factors can result in higher stresses on the GCBs in terms of degree of asymmetry (DOA) of the fault current in case of terminal faults and fault currents due to out-of-phase conditions which can lead to DCZ lasting several cycles.

# Generator-source short-circuit current and influence of pre-fault loading conditions

The pre-fault loading condition of a synchronous machine has influence on the characteristics of the generator-source short-circuit current, i.e. the current to be interrupted by the GCB in case of faults between the terminals of the GCB and the low voltage- (LV-) windings of the step-up transformer. For illustration, these characteristics were calculated for each of the specified operating points on the reactive power capability curve of a 250 MVA, 20 kV synchronous machine shown in Figure 1 using the Electromagnetic Transients Program (ATP-EMTP). In all calculations, 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. It has been assumed that the contacts of the circuit-breaker part 40 ms after fault initiation (i.e. a typical contact parting time for GCBs). The sign convention used for synchronous machine in this study is as follows: when overexcited the machine supplies reactive power to the grid and when underexcited it absorbs reactive power from the grid. The magnitude of the symmetrical short-circuit current (green), peak short-circuit current (yellow) and degree of asymmetry (blue) are evaluated at this instant and depicted for each of the operating points on the graph. Three notable points are highlighted on the graph: point A (overexcited, p.f. = 0), point B (armature current limit) and point C (underexcited, p.f. = 0).

Decreasing tendency is observed for the symmetrical short-circuit current and peak short-circuit current while moving from point A to B, whereas the degree of asymmetry is increasing along this path. From B to C and C to A along the graph, the symmetrical short-circuit current and peak short-circuit current increases, whereas the degree of asymmetry decreases.
The highest degree of asymmetry is observed at point B.
This study also emphasizes the importance of the zero power factor loading conditions in overexcited as well as underexcited region. The maximum symmetrical short-circuit current and the maximum peak value is observed at overexcited point and zero power factor condition. Machines operated on their underexcited operating point can lead to a high degree of asymmetry. The degree of asymmetry at underexcited point and zero power factor condition is in the given case above 130%, which confirms the presence of delayed current zeros.

Therefore, the following three pre-fault conditions shall be evaluated when investigating the synchronous compensator-source short-circuit current:
- Synchronous compensator unloaded
- Synchronous compensator in service at rated overexcited operating point at zero power factor
- Synchronous compensator in service at rated underexcited operating point at zero power factor

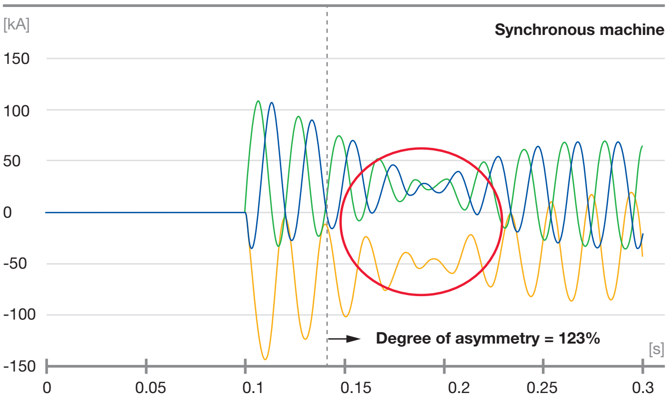



**01** Symmetrical short-circuit current (green), peak short-circuit current (yellow) and degree of asymmetry (blue) at different operating points of reactive power capability curve of synchronous machine (fault initiation at UA = 0)

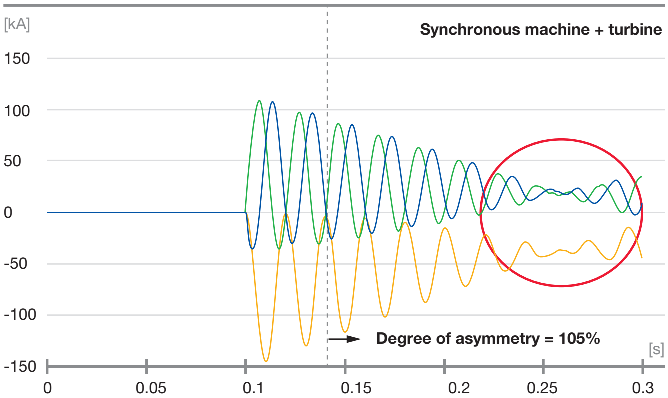
# Out-of-phase switching current and influence of inertia

One of the duties of a GCB is to synchronize the synchronous compensator with the main system. In practical application, out-of-phase synchronizing might occur due to wiring errors when connecting voltage transformers or synchronizing equipment, due to an inaccurate value of the GCB closing time or due to control circuit failure that leads to a faulty synchronization. In such a case, the GCB shall be capable to interrupt the fault currents resulting from out-of-phase angles of up to 180°. The current resulting from out-of-phase synchronizing might show DCZ whose causes are different compared to synchronous compensator terminal faults. The rapid movement of rotor from initial out-of-phase angle δ0 to δ = 0 results in a small a.c. component of the fault current and a dominant d.c. component when the δ = 0 condition is reached. As the instant when the δ = 0 condition is reached depends on the movement of rotor, the total inertia of the turbine, rotor and excitation equipment of the plant have a decisive impact on the waveshape of out-of-phase current.

Synchronous compensators do not have any prime mover, which means the inertia is comparatively lower than the same size of a synchronous generator-turbine set. To understand the influence of reduced inertia, two cases are simulated: (1) synchronous compensator, (2) synchronous generator-turbine set. Figure 2 and 3 show the waveshape of the resulting out-of-phase current in case of an out-of-phase angle δ0 = 90° for case (1) and case (2) respectively. Fault is initiated at voltage zero in phase A. The degree of asymmetry is evaluated at contact parting time of 40 ms. The results show that degree of asymmetry, which is a direct measure of the d.c. component, is higher when only the inertia of synchronous machine is considered. This is due to the fact that smaller total inertia reduces the time to δ = 0, producing a higher d.c. component at the considered GCB contact parting time.




**01** Prospective out-of-phase current (out-of-phase angle δ0= 90°, fault initiation at UA = 0); Inertia of synchronous machine only (Case 1)




**02** Prospective out-of-phase current (out-of-phase angle δ0 = 90°, fault initiation at UA = 0); Inertia of synchronous machine + turbine (Case 2)

# Case study

The electrical layout of the synchronous compensator plant considered for this study is depicted in Figure 4. It consists of a synchronous compensator unit connected to a two-winding step-up transformer via GCB. In such a power plant layout, fault current exhibiting DCZ can usually occur in case of: (a) synchronous compensator terminal faults; (b) out-of-phase synchronizing.

## (a) Synchronous compensator terminal fault

A three-phase fault has been initiated at 100 ms at the terminal of synchronous compensator (F1 in Figure 4.). Fault initiation occurs at voltage zero in phase A. The contacts of the GCB part 37 ms after fault initiation (10 ms minimum tripping delay of the protection system plus 27 ms minimum opening time of the GCB). The magnitude of the a.c. component of the synchronous compensator-source short-circuits current and its degree of asymmetry can vary depending on its loading condition prior to fault. Therefore, three different pre-fault loading conditions of synchronous compensator are simulated: unloaded, at overexcited operating point (250 MVAR/ p.f. = 0) and at underexcited operating point (-140 MVAR/ p.f. = 0). The course of the synchronous compensator-source short-circuit currents in each case is depicted Figure 5. The magnitude of the symmetrical short-circuit current and its degree of asymmetry are evaluated at this instant of contact parting. The calculations carried out brought to the results summarized in Table 1.

The synchronous compensator-source short-circuit current for unloaded, overexcited and underexcited operating points exhibit DCZ (i.e. degree of asymmetry > 100 %). According to IEC/ IEEE 62271-37-013, a type test is not a sufficient proof of the breaking capability of the GCB with currents that exhibit DCZ. The capability of the GCB to interrupt a given current with delayed zero crossings:

- Shall be ascertained by computations that consider the effect of the arc-voltage on the prospective short-circuit current
- Can be considered as being demonstrated if the GCB is capable of forcing the current to zero within its maximum tested arcing time
- Arc-voltage model to be used for this computation has to be derived from the tests

Therefore, calculations are performed in ATP-EMTP taking into account the effect of the arc-voltage of the GCB on the prospective short-circuit current. The arc-voltage model used for the calculation has been derived from tests. The arc-voltage versus current characteristic of the GCB is transferred into a mathematical model and implemented in the ATP-EMTP as a non-linear time-varying resistance. In order to carry out a thorough investigation on the interrupting capability of GCBs, a comparison between $SF_6$ and vacuum extinguishing technologies is provided.

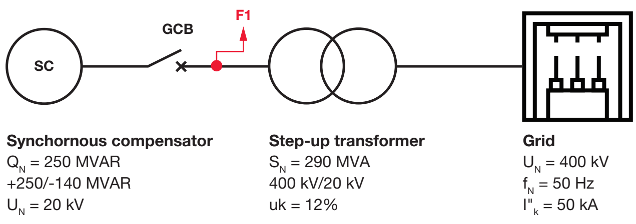
In order to show that the GCB can handle these fault currents, the following two typical situations have been considered:

- Fault initiation at voltage zero in one phase which implies that the current in the corresponding phase exhibits the maximum degree of asymmetry
- Fault initiation at voltage peak in one phase which implies that the current in the corresponding phase is symmetrical

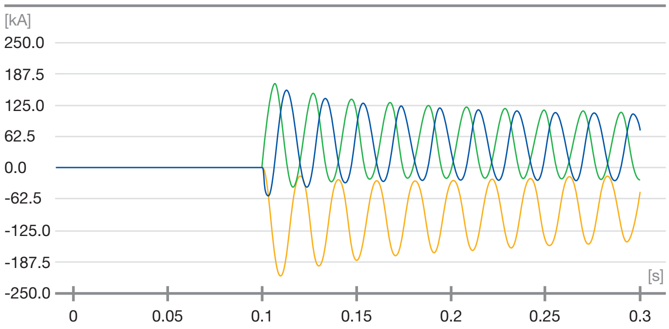
The results of the simulations are summarized in Table 2. The simulation results of interruption of synchronous compensator-source short-circuit current when the synchronous compensator operating at underexcited point with zero power factor prior to fault and the fault initiation at voltage maximum in one phase are shown in Figure 6 where (a) represents the case with a $SF_6$ GCB and (b) shows the case with a vacuum GCB.

In all cases analyzed, the longer arcing time occurs when fault is initiated at voltage maximum in one phase. The arcing time shall not exceed the maximum tested arcing time of the GCB to ensure the successful interruption of short-circuit current. It is evident from the results that the interruption with $SF_6$ GCB leads to very short arcing times which are below the typical maximum tested arcing times of a $SF_6$ GCB. On the other hand, GCB based on the vacuum technology takes several cycles to force the current to zero, leading to arcing times of up to 85.2 ms, that might exceed the maximum tested arcing time of this vacuum GCB.

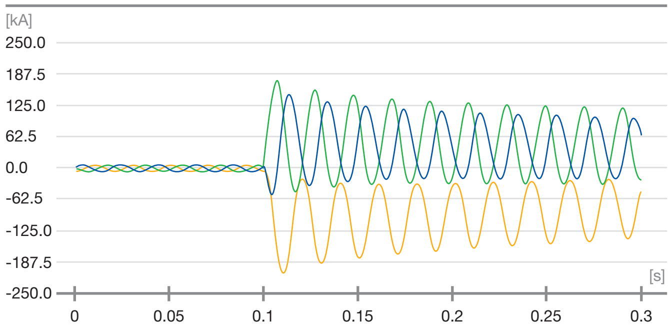
A method sometimes adopted to reduce the arcing time of the circuit-breaker is to introduce an intentional tripping delay. A value in the range of 100 ms – 200 ms is usually sufficient to limit the degree of asymmetry of the fault current at contact separation to values the GCB can cope with. It has to be noted that this solution would lead to longer fault duration and consequently to severe damages to power station equipment with consequent long downtime for repair. For this reason, many power station operators consider the solution of intentionally delaying the tripping as not recommendable. Therefore, the preferred method to handle the DCZ phenomena is to choose a GCB having an arc-voltage magnitude sufficiently high to force current to zero without the aid of any intentional tripping delay.




**04** Single-line diagram of a synchronous compensator plant




**5a**

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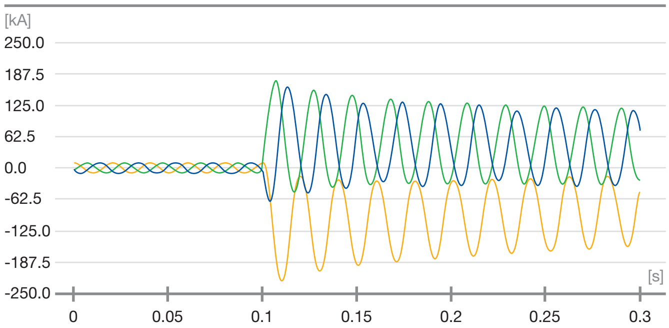



**5b**

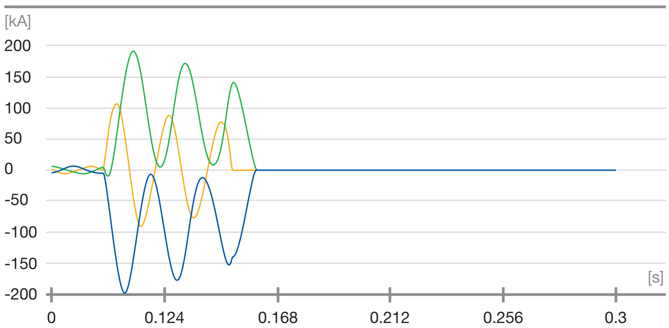
**05** Prospective synchronous compensator-source short-circuit current for three pre-fault loading conditions: (a) unloaded, (b) overexcited (250 MVAR, p.f.= 0), (c) underexcited (-140 MVAR, p.f.= 0) (fault initiation at UA = 0)

## 01 Short-circuit current characteristics

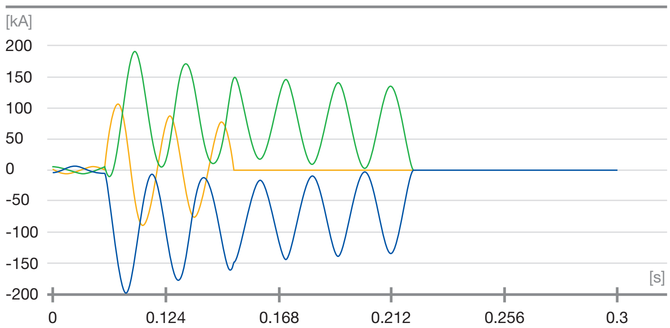
| Pre-fault operating point | Short-circuit current characteristics | | | |
|---|---|---|---|---|
| | Making current [kAp] | Symmetrical short-circuit current [kA] * | Asymmetrical short-circuit current [kA] * | Degree of Asymmetry [%] * |
| **Unloaded** | 216.1 | 59.9 | 123.6 | 127.7 |
| **Overexcited: 250 MVAR, p.f. = 0** | 225.8 | 66.7 | 127.1 | 114.6 |
| **Underexcited: -140 MVAR, p.f. = 0** | 210.6 | 56.0 | 121.8 | 136.5 |

*Contact parting time = 37 ms

**06** Interruption of synchronous compensator-source short-circuit current with (a) a $SF_6$ GCB and (b) a vacuum GCB; pre-fault loading at underexcited point (-140 MVAR, p.f.= 0) (fault initiation at UA = max)




**6a** $SF_6$ GCB (arcing time = 22.8 ms)




**6b** Vacuum GCB (arcing time = 84.0 ms)

## 02 Arcing times in case of interruption of synchronous compensator terminal faults

| Pre-fault operating point | Fault initiation | Arcing times (ms) | |
|---|---|---|---|
| | | $SF_6$ | Vacuum |
| **Unloaded** | UA = 0 | 20.1 | 41.7 |
| | UA = max | 22.8 | 85.2 |
| **Overexcited: 250 MVAR, p.f. = 0** | UA = 0 | 19.8 | 41.6 |
| | UA = max | 22.2 | 84.7 |
| **Underexcited: 140 MVAR, p.f. = 0** | UA = 0 | 20.1 | 41.6 |
| | UA = max | 22.8 | 84.0 |

## (b) Out-of-phase synchronizing

Although the standard for GCB, IEC/ IEEE 62271-37-013, only covers requirements associated with 90° out-of-phase angle, in reality synchronizing with out-of-phase angles of up to 180° can occur. Therefore, fault currents resulting from synchronizing under different out-of-phase angles have been analyzed. For each initial out-of-phase angle δ0, cases when the voltage at the synchronous compensator terminals is either lagging or leading the high voltage (HV) system voltage referred to the LV-side of the step-up transformer are simulated. A negative δ0 means the voltage at the synchronous compensator terminals is lagging the HV system voltage referred to the LV-side of the step-up transformer; while a positive δ0 means the voltage at the synchronous compensator terminals is leading it.

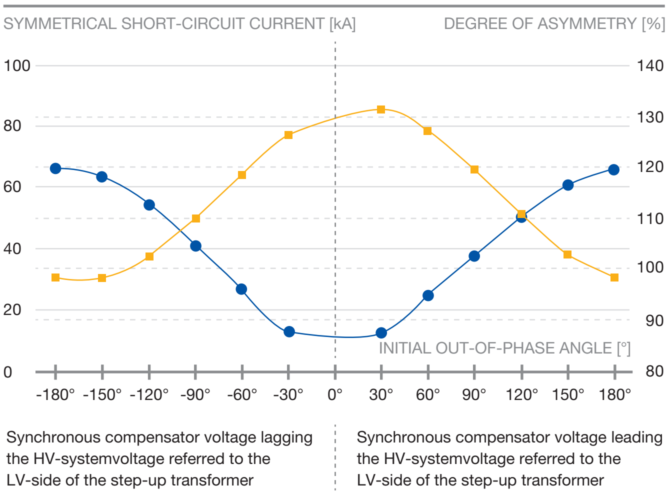
In the simulations fault initiation takes place at the instant when the voltage across the GCB in phase A passes through zero. Contact parting time is considered to be 37 ms after fault initiation. At this instant (t = 137 ms), the magnitude of the symmetrical short-circuit current and its DOA are calculated. As depicted in Figure 7, the DOA of the fault current tends to decrease with increasing out-of-phase angle. Furthermore, for a given |δ0| the DOA is higher when δ0 is positive. The symmetrical short-circuit current and the peak current due to out-of-phase conditions increases with the out-of-phase angle as seen in Figure 7 and 8 respectively. The magnitude of these currents is slightly higher when δ0 is negative. The magnitudes of symmetrical short-circuit current and peak current are maximum in case of |δ0| = 180° compared to all the other cases analyzed.

In almost all the cases analyzed, the DOA is higher than 100% which confirms the occurrence of DCZ in such fault conditions. This can be explained by the rapid decay of the a.c. component of the fault current.

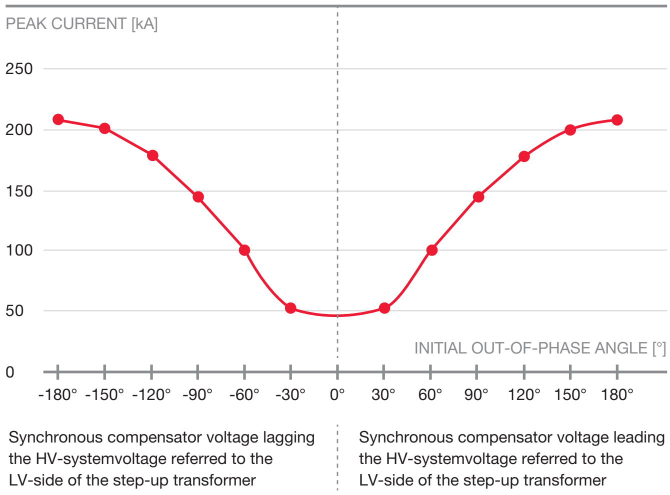
It is consistent with the fact that synchronous compensators do not have any prime mover, therefore inertia constant is comparatively lower than the same size of a synchronous generator-turbine set.

To assess the capability of the GCB to interrupt the calculated out-of-phase fault currents with DCZ, calculations that consider the effect of the GCB arc-voltage on the prospective fault current shall be performed to determine the maximum arcing times achieved during interruption. Due to their high arc-voltage, $SF_6$ GCBs are generally suitable to handle out-phase fault currents with DCZ; on the other hand, due to their considerably lower arc-voltage, the suitability of vacuum GCBs for the application is not always guaranteed. The suitability analysis was performed to verify the interrupting capability of both technologies for the application. The arcing times that resulted from the simulation of the interruption of the fault currents for different out-of-phase angles are shown in Figure 9 for fault initiation at voltage zero and at voltage maximum in phase A.

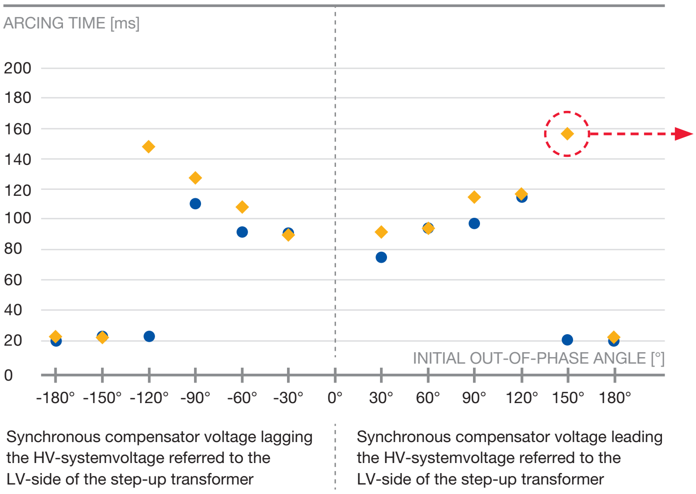
In almost all cases the longer arcing time occurs when fault is initiated at voltage maximum in phase A. The fault current in case of initial out-of-phase angle of 150° leads to the longest arcing time as depicted in Figure 9. Moreover, the arcing time in case of δ0 = -150° and δ0 = +150° are considerably different. In such a fault case the vacuum GCB cannot be considered suitable for the application because in most of the cases analyzed, its arc-voltage is not sufficient to force current to zero within its maximum tested arcing time. Figure 10 shows the interruption of the fault current for both the $SF_6$ and vacuum GCBs for the case of δ0 = +150°. Due to its higher arc-voltage the $SF_6$ GCB is able to interrupt the current in 22.4 ms after the separation of contacts, whereas interruption with the vacuum GCB leads to an arcing time of 156.6 ms.




**07** Symmetrical short-circuit current and DOA of the prospective out-of-phase synchronizing fault current vs. initial out-of-phase angle

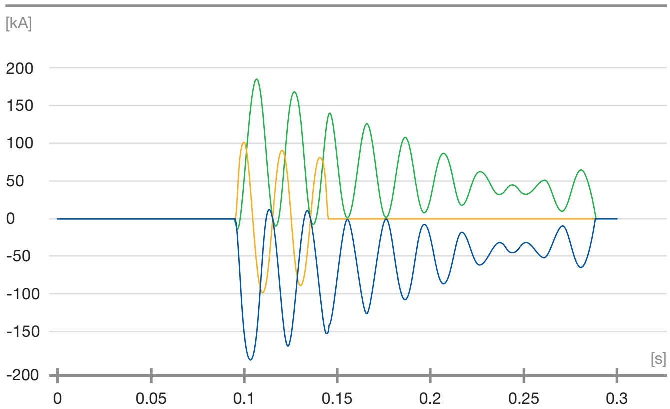



**08** Peak value of the prospective out-of-phase synchronizing fault current vs. initial out-of-phase angle

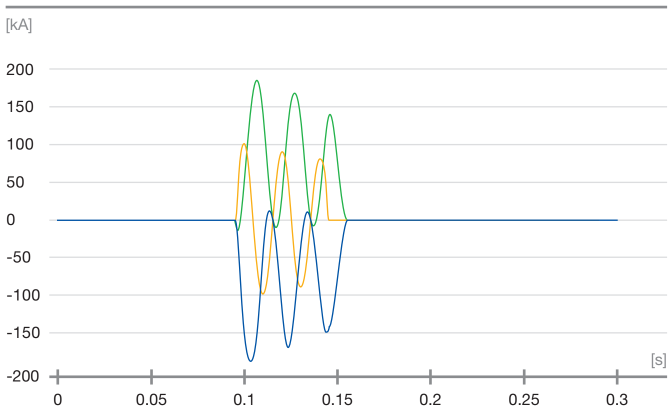



**09** Arcing times resulting from interruption of out-of-phase synchronizing fault current vs. initial out-of-phase angle for both cases: (a) fault initiation at UA = 0, (b) fault initiation at UA = max, considering a vacuum GCB

**10** Interruption of out-of-phase synchronizing fault current (a) a vacuum GCB and (b) a $SF_6$ GCB; (δ0 = 150°, fault initiation at UA = max)




**10a** Vacuum GCB (arcing time = 156.6 ms)




**10b** $SF_6$ GCB (arcing time = 22.4 ms)

# Conclusions

The main difference between a synchronous generator and a synchronous compensator is their operating point during normal operation. Synchronous generators are not meant to be operated at zero power factor, whereas synchronous compensators do so in normal operating conditions. Another important difference is the lower inertia of synchronous compensators due to the absence of a prime mover. These two factors can result in higher stresses on the GCBs in terms of DOA of the fault current in case of terminal faults and fault currents due to out-of-phase conditions which can lead to DCZ lasting several cycles.

The effect of the pre-fault loading and lower inertia of a synchronous compensator on the severity of the fault currents is investigated in this paper and illustrated with a case study. The important conclusions derived from the results of the case study are as follows:

**Synchronous compensator terminal fault**
The fault current in case the synchronous compensator is operating at rated underexcited operating point prior to fault leads to the most severe interrupting conditions with respect to the asymmetry of the current. The fault occurring at voltage maximum in one phase leads to a longer arcing time compared to the case of a fault occurring at voltage zero.

**Out-of-phase synchronizing**
In most cases the longer arcing time occurs in the case of fault initiation at voltage maximum in one phase. The fault current in case of initial out-of-phase angle of 150° has led to the longest arcing times. The standard for GCB covers only requirements for an out-of-phase angle of 90° which is not sufficient to confirm the suitability of the GCB for synchronous compensator applications.

In both the fault cases, application of a vacuum GCB results in longer arcing times compared to the $SF_6$ GCB. It is recommended to choose GCBs having an arc-voltage magnitude sufficiently high to force the current to zero within the maximum permissible arcing time in such applications.

## Learn more

When the challenges are addressed with appropriate expertise and technology, the power system with high penetration of renewables can be operated in safe and reliable environment.

**Application Study Group** supports customers for the proper selection of the generator circuit-breaker for conventional as well as new power plants.

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