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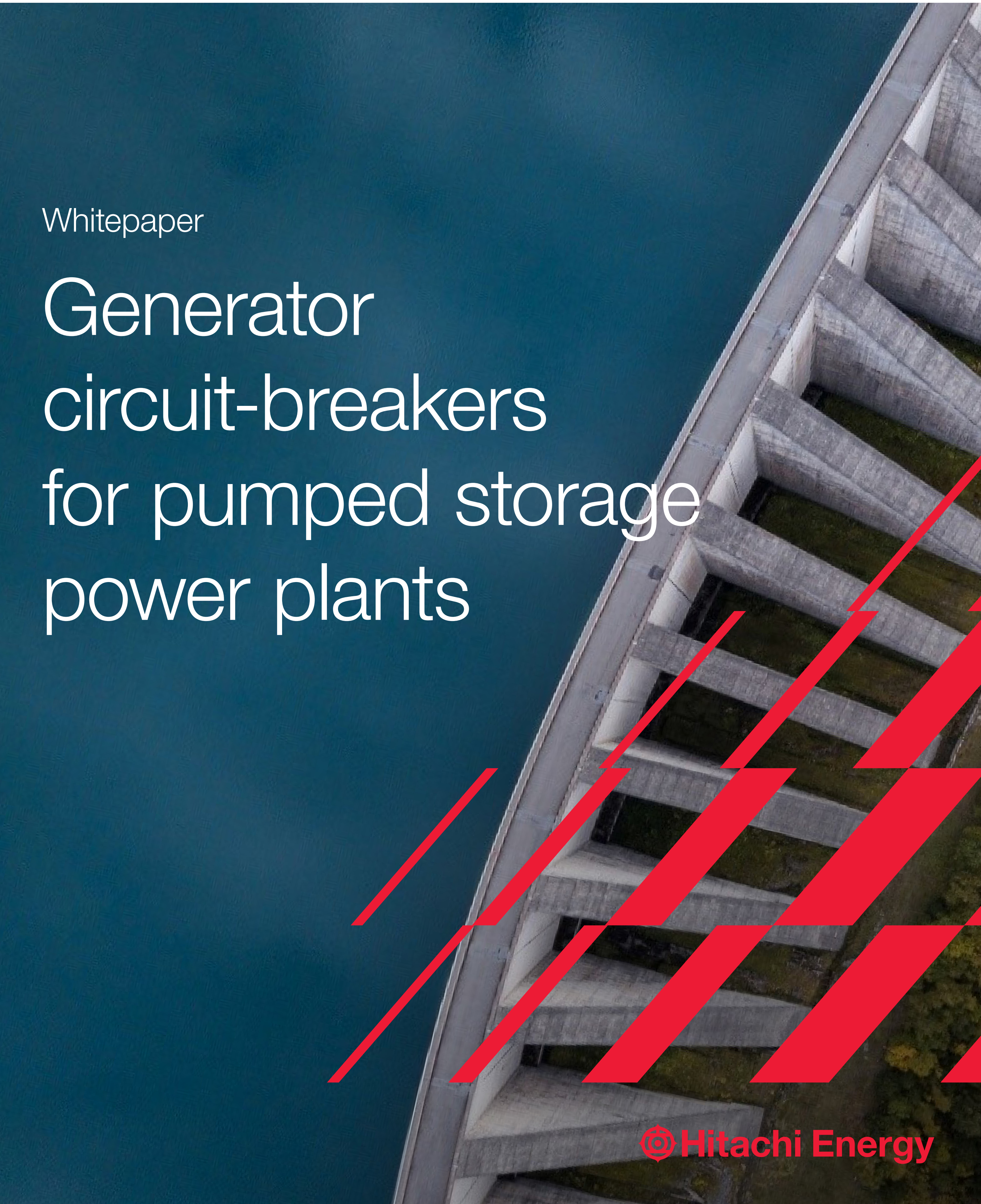


Whitepaper

Generator circuit-breakers for pumped storage power plants

Hitachi Energy

Generator circuit-breakers for pumped storage power plants

Employing doubly-fed induction machines

Variable speed turbines have gained increasing importance in pumped storage power stations (PSPP) since they present big advantages compared to the classical topology with a synchronous generator. Within the variable speed solutions, the one employing a doubly-fed induction generator (DFIG) has become the preferred solution for large installations since it provides the advantages of variable speed operation and four-quadrant active and reactive power capabilities, using converters rated only a small fraction of the rated power.
Fault currents fed by a DFIG differ substantially from the typical current fed by a synchronous generator and can impose very severe stresses for a circuit-breaker to cope with.

The only standard that covered the requirements for generator circuit-breakers (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 this standard are based upon applications employing synchronous generators. The question whether these requirements are adequate for the application of GCBs in pumped storage power stations employing DFIGs is considered in this article.

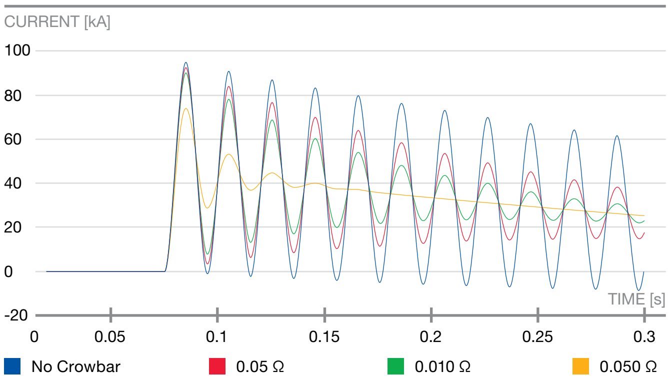
Generator-source short-circuit current and influence of Crowbar resistance

A major drawback with DFIGs is their behavior during grid faults. Faults in the power system cause a voltage dip at the connection point of the machine, which induces very large currents in the windings due to the direct magnetic coupling between stator and rotor. To protect the rotor-side converter, the most common solution is to short-circuit the rotor via so-called crowbar resistors once the maximum current permissible by the converter is exceeded. Large rotor currents flow through the crowbar instead of the converter and the thermal breakdown of the power electronic converter is avoided. This additional resistor, Rcb, provided by the connection of the crowbar decreases the time constant of the a.c. component of the current. The symmetrical component of the current will therefore decay faster, and depending on the crowbar's resistance value, can decay much faster than the DC component. When this occurs, the resulting current waveform can exhibit delayed current zeros (DCZ), meaning that there is no natural zero-crossing of the current for several cycles. These conditions are extremely severe for a GCB to cope with and must be thoroughly investigated when assessing the suitability of a circuit-breaker for a given application.

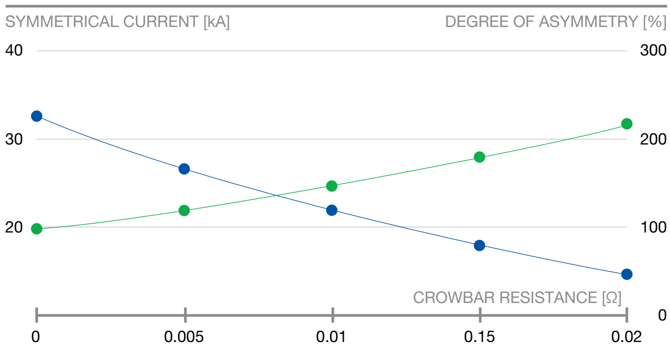
Figure 1 shows the current fed by a DFIG after a three-phase short-circuit at its terminals when different values of crowbar resistance are used to protect the rotor converter. It was assumed that fault initiation takes place in the moment when the voltage in one phase passes through zero, so that the highest degree of asymmetry is obtained in that phase. For illustration purposes, only the phase with maximum asymmetry is shown. The DC component is equal for all cases, while the AC component decays more rapidly when the value of Rcb is increased. In contrast with the current fed by synchronous generators where the AC component decays in steady state to a limited value due to the synchronous reactance, the AC component of the current fed by a DFIG decays to zero, leading to a very highly asymmetrical fault current. If the crowbar resistance is high enough, the symmetrical component of the current can decay to very small values within few milliseconds leading to very severe conditions for a GCB to cope with, as can be seen for Rcb = 0.02 Ω ca. 125-150 ms after fault initiation. Under these circumstances, the current has no natural zero-crossing for several hundred milliseconds.

Figure 2 depicts the magnitude of the symmetrical component and the degree of asymmetry of the fault current assuming that the contacts of the GCB part 40 ms after fault initiation (the symmetrical component and degree of asymmetry are evaluated at this instant). Due to the rapid decay of the AC component, the degree of asymmetry can attain very high values. With Rcb = 0.02 Ω the degree of asymmetry exceeds 200%, value that is higher than the maximum values usually achieved by currents fed by synchronous machines in case of three-phase terminal faults. For synchronous machines the degree of asymmetry of generator-fed faults rarely exceeds 150%.

According to GCB standard IEC/ IEEE 62271-37-013, demonstrating the capability of a GCB to interrupt fault 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. Therefore, the capability of a GCB 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 circuit-breaker on the prospective fault current. The arc-voltage model to be used for this purpose has to be derived from tests. The arc-voltage of the GCB is an additional resistance which forces the DC component of the short-circuit current to decay faster. It is therefore of utmost importance that the magnitude of the arc-voltage of the GCB is high enough to force a fast decay of the DC component of the fault current. The magnitude of the arc-voltage of SF_6 GCBs is normally higher than that of vacuum devices. For this reason, SF_6 GCBs are generally adequate to handle currents which exhibit DCZ, whereas vacuum circuit-breakers might show unsuccessful interruptions.



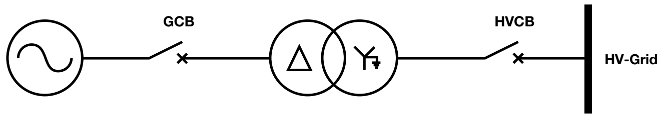
01 Prospective short-circuit current with different values of crowbar resistance



02 Symmetrical component and degree of asymmetry at contact separation

Interruption of fault current with HVCB and GCB

In this section, the capability of a high-voltage circuit-breaker (HVCB) to interrupt fault currents due to symmetrical voltage dips near pumped-storage power plants employing DFIGs investigated. The electrical layout of the PSPP considered for this study is depicted in Figure 3. It consists of one DFIG connected to a two-winding step-up transformer by means of a GCB. A HVCB connects the HV-side of the step-up transformer to a 400 kV grid. Both GCB and HVCB employ SF_6 as extinguishing technology.



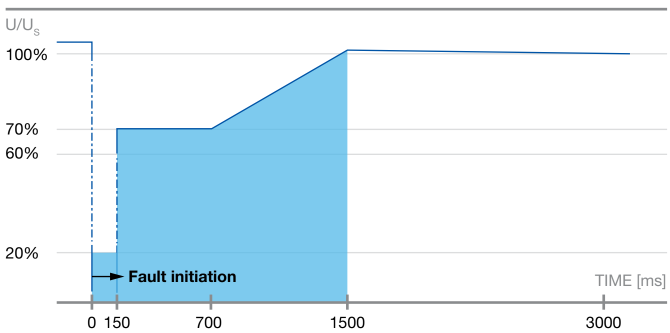
03 Electrical layout of PSPP employing DFIG

Fault ride-through requirements

In order to enhance grid stability many countries approved grid codes that oblige DFIGs to remain connected to the grid so that they can support the voltage and frequency of the grid after the fault has been cleared. The grid code defines the properties of the voltage dip during which the generating unit must maintain operability as shown by Figure 4. This curve shows, for example, that the DFIG can be immediately disconnected in case of full voltage dips, whereas it must remain connected for a minimum of 150 ms in case of voltage dips in the range of 20-70%. As an example, a case of a 0% voltage dip at the HV-busbar is presented. In the simulations it has been assumed that the DFIG is delivering a power of 255.6 MW/ 290 MVA at 470 U/min prior to the voltage dip, and that fault takes place at the moment when the voltage in one phase passes through zero.

Figures 5a and 5b show the prospective short-circuit currents to be interrupted by the HVCB and GCB in the case of fault initiation at voltage zero. Figures 5c and 5d show the effect of the arc-voltage of the HVCB and GCB on the prospective short-circuit current. Simulation results show that the HVCB fails to force the current to zero for several cycles, leading to arcing times of 408 ms. A HVCB might not be able to manage such long arcing time. This condition could again lead to an unsuccessful interruption. On the other hand, the GCB is able to force the current to a zero crossing within its maximum permissible arcing time, with an arcing time of 20.3 ms.

The capability of a circuit-breaker to interrupt currents which exhibit DCZ depends upon whether the magnitude of its arc-voltage is high enough to force a fast decay of the DC component of the fault current. Although the magnitude of the arc-voltage of the HVCB is higher than the one of the GCB, its effect on the prospective short-circuit currents is less favorable. This is because its generator-side value is reduced by the transformer turns ratio. The capability of a circuit-breaker to interrupt currents which exhibit DCZ is determined by the magnitude of the arc-voltage Varc with respect to the system-voltage Vsys. Specifically, a higher Varc/ Vsys ratio means the circuit breaker is more capable to handle these fault currents. From this point of view, a SF_6 GCB is generally more adequate than a SF_6 HVCB to handle currents which exhibit DCZ. Similar results are obtained when considering a 20% voltage dip at the HV busbar and when considering fault initiation taking place when the voltage in one phase is at its maximum. The results of all simulations are summarized in Table 1.



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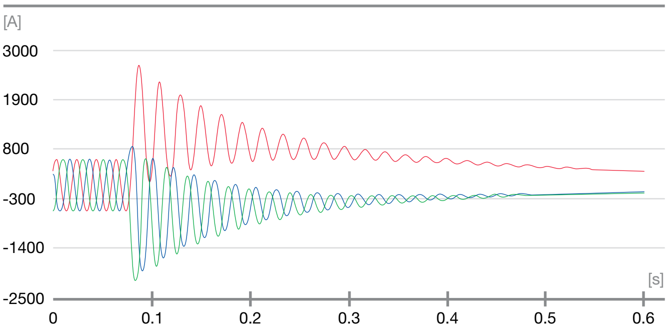
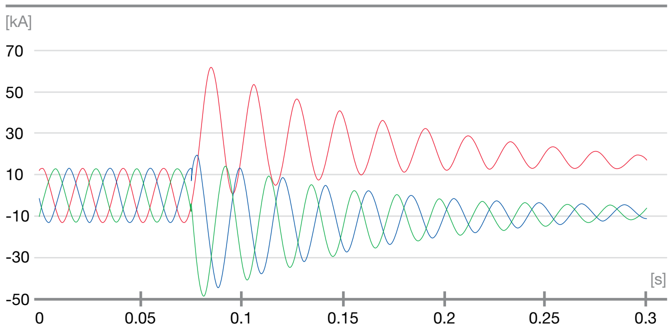
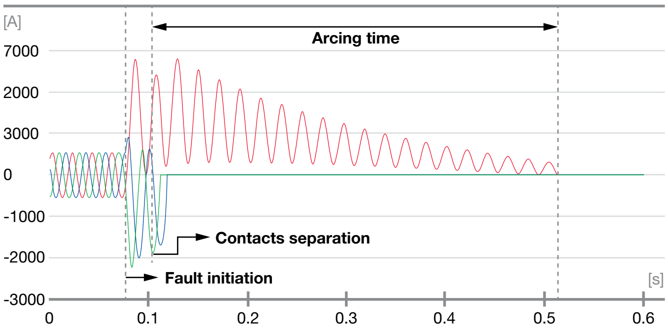
05 Interruption of fault current with SF_6 HVCB and SF_6 GCB (fault Initiation at UA = 0)



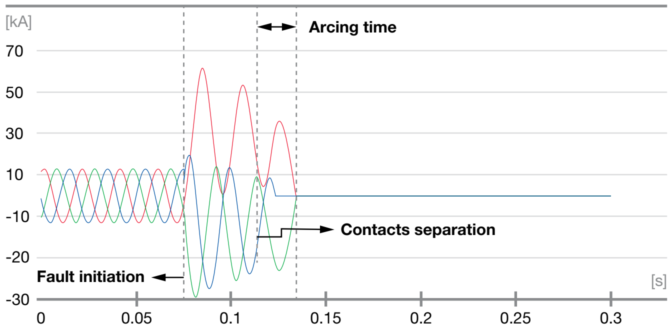
5a Prospective fault current to be interrupted by SF_6 HVCB



5b Prospective fault current to be interrupted by SF_6 GCB



5c Effect of arc-voltage of the SF_6 HVCB, Arcing time = 408 ms



5d Effect of arc-voltage of the SF_6 GCB, Arcing time = 20.3 ms

01 Arcing times in case of full and 20% voltage at HV-busbar

Fault case	Applied voltage at fault initiation	Arcing time (ms)	
		SF_6 HVCB	SF_6 GCB
Full voltage dip at HV-busbar	UA = 0	408	20.3
Full voltage dip at HV-busbar	UA = UAmax	326	23.4
20% voltage dip at HV-busbar	UA = 0	171	18.3
20% voltage dip at HV-busbar	UA = UAmax	109	15.5

Conclusions

Faults currents fed by a DFIG clearly differ from the typical current waveform fed by a synchronous generator and can impose very severe stresses for a GCB to cope with. Due to the crowbar resistance these fault currents can exhibit a much higher degree of asymmetry than the one obtained for terminal faults in case of synchronous machines. The requirements for GCBs laid down in IEC/ IEEE 62271-37-013 are based upon applications employing synchronous generators and might not fully cover the requirements for applications employing a DFIG. Special attention and additional studies are required in order to prove the suitability of a GCB for this type of applications.

The capability of a HVCB to interrupt fault currents due to symmetrical voltage dips near pumped-storage power plants employing DFIGs has been investigated. Simulations show that fault currents in the case of a full voltage dip at the HV-busbar are highly asymmetrical and exhibit DCZ. The stresses imposed by this phenomenon are not adequately covered by the relevant standard for HVCBs. The obtained results demonstrate that the HVCB might fail to interrupt the currents with DCZ in all cases analyzed, since its magnitude of arc-voltage is not high enough to force a fast decay of the DC component of the current. The incapability of the HVCB to interrupt such fault currents represents a problem for power plant operators since in order to be able to connect to the grid they must prove the capability to disconnect the generating units upon request from the grid operator. A HVCB may not guarantee a successful interruption. A feasible solution to overcome this problem is to operate the GCB instead. Simulation results show that the GCB is always capable of interrupting the fault currents within its maximum permissible arcing time. Although its magnitude of arc-voltage could be lower than that of the HVCB, its ratio of arc-voltage with respect to the system voltage is higher. From this point of view, a SF_6 GCB is generally more adequate than a SF_6 HVCB to handle currents which exhibit DCZ. The use of the GCB to disconnect the DFIG in case of symmetrical voltage dips can therefore guarantee the compliance with grid operator regulations which could be difficult (or impossible) to be met otherwise. The preferred scheme is consequently one that includes a GCB in addition to the HVCB.

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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