NAME : Priyanka Gugale, Mirko Palazzo (Hitachi Energy)
Alexander Schwery (GE Renewable Energy)
COUNTRY : Switzerland
REGISTRATION NUMBER : 6322

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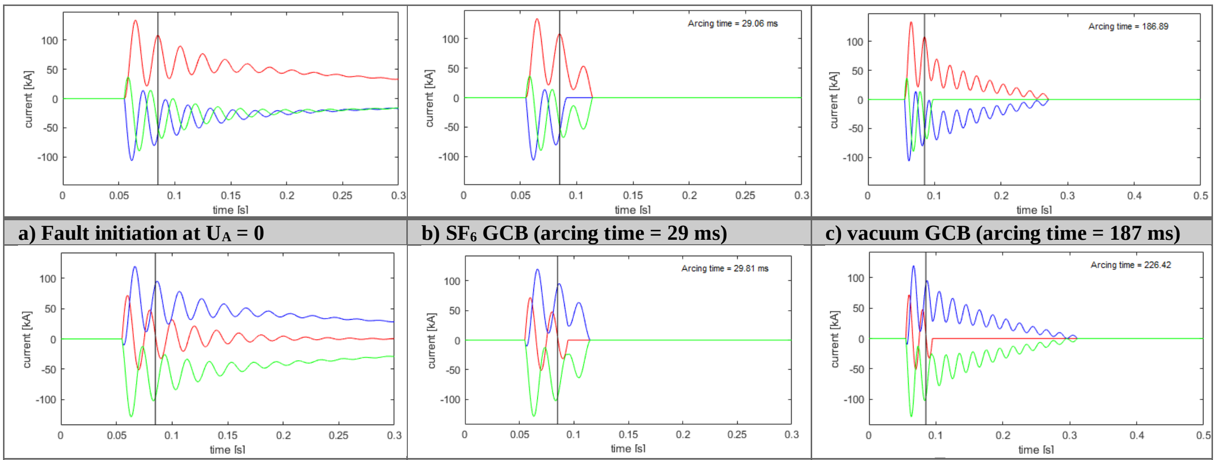
**Delayed current zero in doubly-fed induction generator applications**

From a GCB viewpoint, a major drawback with DFIGs is their behavior during faults. In a DFIG, to protect the rotor-side converter, it is a common solution to short-circuit the rotor via so-called crowbar resistors once the maximum current permissible by the converter is exceeded. This additional resistor provided by the connection of the crowbar decreases the time constant of the a.c. component of the current. The a.c. component of the current will therefore decay faster and depending on the crowbar's resistance value can decay much faster than the d.c. 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. A GCB with a sufficiently high arc-voltage is required to limit the resulting arcing time within the maximum tested arcing time of the circuit-breaker. These conditions are extremely severe for a GCB to cope with and must be thoroughly investigated when assessing the suitability of a GCB for a given application.

As stated in IEC/IEEE 62271-37-013:2021, Annex H: "Considering that various designs of generators behave differently, it may not be possible to simulate the required current shape in the test laboratory. Therefore, the capability of a generator circuit-breaker to interrupt a short-circuit current with delayed current zero crossings shall be ascertained by calculations (see 9.103.6.3.6.3) taking into account results derived from a limited number of appropriate tests (see 7.105)." The arc-voltage model used for this purpose has to be derived from tests (IEC/IEEE 62271-37-013 cl. 9.103.6.3.6.4) and a DCZ test is not a sufficient proof of the capability of the GCB. Moreover, to avoid unrealistically optimistic results when simulating the behavior of the GCB during the interruption of currents with DCZ, IEC/IEEE 62271-37-013 states that the arc-voltage versus current characteristic of the GCB can be used to model the GCB.

In power stations with two-winding step-up transformers, fault currents exhibiting DCZs can usually occur in case of generator terminal faults and out-of-phase synchronizing. This contribution highlights the challenges for GCB connected with DFIG and verifies the capability of GCB to interrupt currents which show DCZ considering $SF_6$ and vacuum arc-extinguishing technologies.

The course of the generator-source short-circuit current is depicted in Figure 1. A bolted fault has been assumed (i.e., that there is no arc-voltage at the fault location). This case may occur when GCB is closed into a bolted fault such as a closed earthing switch. Figure 1a represents the case with fault initiation at voltage zero in one phase, and Figure 1b and 1c show the corresponding interruption with the arc-voltage of SF6 GCB and vacuum GCB respectively. Figure 1d shows the case with fault initiation at voltage maximum in one phase and Figure 1e and 1f, the interruption with SF6 and vacuum GCB respectively. The value of crowbar resistor used in this case is 11.4 mΩ (referred to stator). The contacts of the GCB part 30 ms after fault initiation which happens t = 55 ms. The arc-voltage model of SF6 GCB used for the calculation has been derived from the tests. Whereas a constant arc-voltage of 100V is used for vacuum GCB.




| a) Fault initiation at $U_A = 0$ | b) $SF_6$ GCB (arcing time = 29 ms) | c) vacuum GCB (arcing time = 187 ms) |
|---|---|---|
| d) Fault initiation at $U_A$ = max | e) $SF_6$ GCB (arcing time = 30 ms) | f) vacuum GCB (arcing time = 226 ms) |

**Figure 1: Interruption of generator-source short-circuit current with $SF_6$ GCB and vacuum GCB; (generator unloaded prior to fault initiation)**

To illustrate the effect of pre-fault loading condition on generator terminal fault, cases of generator in service with leading power factor are investigated considering the arc-voltage at the fault location starting at the fault initiation, and the arc-voltage of the GCB starting at contact separation. Fault arc-voltage is considered as recommended in IEC/IEEE 62271-37-013. Also cases of 90°out-of-phase fault current interruption are simulated. The simulation results are summarized in Table I.

TABLE I. ARCING TIMES IN CASE OF INTERUPPTION OF GENERATOR TERMINAL FAULTS AND 90° OUT-OF-PHASE FAULT CURRENT

| Fault type | Fault initiation | Arcing times (ms) | |
|---|---|---|---|
| | | $SF_6$ | vacuum |
| Generator terminal fault, generator unloaded prior to fault initiation | $U_A = 0$ | 29 | 187 |
| | $U_A$ = max | 30 | 226 |
| Generator terminal fault, generator at rated leading p.f. prior to fault initiation | $U_A = 0$ | 24 | 62 |
| | $U_A$ = max | 26 | 65 |
| 90° out-of-phase fault current | $U_A = 0$ | 27 | 164 |
| | $U_A$ = max | 28 | 184 |

Due to the high magnitude of arc-voltage, $SF_6$ GCB is able to interrupt the current within 30 ms after contact parting, whereas the vacuum GCB led to arcing times up to 226 ms which might exceed the maximum tested arcing time of this GCB and result in an unsuccessful interruption. A fault clearing time in range of 200 ms could also lead to undesirable consequences on all connected power system assets and might cause transient instability in the network.

## Summary and conclusion

The generator-source short-circuit current in case of generator unloaded prior to fault leads in the studied case to the most severe interrupting conditions with respect to the asymmetry of current and the arcing time. Also out-of-phase conditions lead to very long arcing times for vacuum GCB. These arcing times might exceed the maximum tested arcing time and might lead to unsuccessful interruption.

Annex K of IEC/IEEE 62271-37-013 does not specify any test duty related to DCZ. The wrong question is being asked in the special report for SC A3. Annex K provides adequate guidance to verify the suitability of GCBs for application with DFIGs covering the possible influence of crowbar resistor, rotor's slip, and pre-fault loading conditions on the stator currents.

In case of faults which exceed the overvoltage and/or overcurrent handling capability of rotor-side converter, crowbar is immediately activated to protect rotor-side converter. Remote grids faults which result in smaller voltage dip on LV-side of step-up transformer might be handled by converter control without triggering the crowbar, but these are typically not the worst-case conditions for sizing a GCB which is intended to interrupt the worst-case generator-source short-circuit current, system-source short-circuit current and out-of-phase fault current.

In conclusion, GCB with higher arc-voltage (e.g. $SF_6$) are normally suitable for DFIG application whereas GCBs with relatively lower arc-voltage (e.g. vacuum) are sometimes not suitable.