A THREE-PHASE GENERATOR VACUUM CIRCUIT BREAKER BASED ON VACUUM INTERRUPTER TECHNOLOGY HAS BEEN ESTABLISHED FOR THE APPLICATION IN GENERATOR CIRCUITS UP TO 15 KV-50 KA

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ABSTRACT

Vacuum interrupters are serving worldwide in distribution circuits, meeting the electrical and mechanical requirements specified in the IEC and / or ANSI standards especially for low and medium voltage applications.

Generator circuits require adapted generator circuit breakers and are tested according to ANSI / IEEE C37.013.. Traditionally generator circuit-breakers have been used as huge units based on air- or SF6- blast interruption technology.

Over the last 35 years, the short circuit interruption performance of vacuum interrupters has been dramatically increased due to the continuous development, especially in the view of contact system design and materials. Today it is obvious that also the vacuum interrupter technology can be applied to generator circuit-breakers.

A new three-phase vacuum circuit-breaker has been established for the application in generator circuits up to 15 kV-50 kA-4000 A. To reach the required short circuit interruption capability, an improved vacuum interrupter with transverse magnetic field (TMF) contact system has been developed. A fast clock spring mechanism was designed to actuate these interrupters. The results of power tests are presented with the main focus related to vacuum technology: The influence of the arcing time duration before current zero (CZ) and mechanical characteristic, the transferred charge I x dt, di/dt steepness at CZ, and finally the transient recovery voltage (TRV).

Key words: *Circuit-breaker, Generator circuit-breaker, Contact system based on TMF, Vacuum Interrupter (VI), Delayed Current Zero (DCZ), Out of Phase (OoP), mechanical spring drive.*

INTRODUCTION

In low, medium and high voltage applications the short-circuit interrupting capability of vacuum interrupters VI´s has been increased significantly over the past years. The short circuit interrupting ability was mainly developed for the requirements of low and medium voltage range. Further research and development of VI-physics, e.g. more detailed understanding of the plasma arc behaviour under vacuum and the interaction between the arc, the contact material and the mechanical actuation mechanism, led to the development of a safe system based on “transverse magnetic field“ (TMF) contact systems for generator circuit-breaker applications. The constricted arc column is forced by the self-generated TMF – field to reduce the time at which the arc-root is acting on the contacts.

The VI´s are based on an optimized TMF contact system and are designed to interrupt high short circuit current ratings of a short-current of 50kA with a compact design. This design is able to meet all requirements and covers all

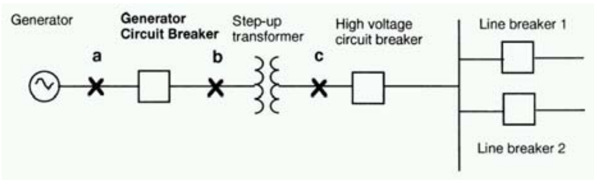

Fig. 1: Basic single line diagram of a generator circuit, on the left the generator and the generator circuit breaker, on the right the transformer to feed the power into the high voltage network [**1**].

needs in generator circuits, both to protect the generator and the connected grid.

Compared to the well-known applications in low and medium voltage range, in generator circuits the VI has to cope with high short-circuit currents with high asymmetrical components at long time constants. This can cause long arcing times and is accompanied with steep Rates of Rise of Recovery Voltage (RRRV) and a high TRV peak values after current interruption.

A three-phase vacuum circuit-breaker with a fast clock spring drive actuator is designed to actuate these interrupters and tested to cover all demands to single and three phase tests according to ANSI/IEEE C37-013-1997 and the IEC 62271-37.013 currently in CDV state [1,2].

This paper focuses on the properties of the VI in combination with the drive actuator design itself and on the impacts from VI testing under those severe conditions especially when the short circuit interruption ability is tested at 50Hz [3]. The high power tests presented here were carried out at KEMA High Power Laboratory.

Fig. 2: Compact three phase **vacuum generator circuit breaker type: VD4G-50** (15kV-50kA-3150 … 4000A-50/60Hz). Dimensions: pole center distance 210mm; height 636mm; depth 459mm; width 750mm and the weight of 210kg.

GENERATOR CIRCUIT BREAKER (GCB) AND CIRCUIT CONFIGURATIONS

The basic design of the generator circuit configuration is displayed in Fig. 1. Generator circuit-breakers (GCB) Fig. 2 are essentially located between the generator and the step-up transformer of the high voltage network.

In generator circuits two different faults are possible with a combination of high short-circuit current at high asymmetrical components: The system-source fault (fault on generator side, Fig.1 a) and on system-source fault (fault on the transformer side, Fig.1 b).

In case of a “bad” synchronisation between the network and the generator circuit breaker may close into a condition that is known as “out-of phase” (OoP). If this occurs with a phase angle of up to 90°, the generator circuit-breaker has to interrupt short-circuit current values nearly as high as the system source fault (see [**2**] and Table 1, incl. the test duties (TD)). This is in contrast to the values of the short-circuit current under OoP-conditions according IEC 62271-100, which is 25 % of the rated short circuit current.

If a **system-source fault** occurs, the short-circuit current is established at high magnitudes and the breaker is located close to the generator. The energy of the system feeds the fault from the system through the transformer. Only the impedance of the transformer and the impedance of the short bus conductor connection limit the current. The asymmetrical component during arcing can be up to 75 % at short-circuit current (Table 1, step B).

TABLE 1: Main test values of the generator circuit breaker (GCB) assembly meet all requirements for the rating 15kV / 50 kA according to the both mentioned standards [**1,2**] (in brackets (*) the values for the 63kA short circuit interruption current rating).

VD4G-50 15kV - 50kA (63kA)	**step A)**	**step B)**
System-source interrupting capability	TD1 ↓	TD2 ↓
Symmetrical [kA]	50 (63)	50 (63)
asymmetrical component	0 %	75 %
TRV_{peak} [kV]	27.6	27.6
Rate of rise of recovery voltage RRRV [kV/µs]	3.5	3.5
t_{delay}	< 1µs	< 1µs
time constant τ	133ms	133 ms
Generator-source (DCZ) interrupting capability	TD4/5 ↓	TD6 ↓
Symmetrical [kA]	31.5 (55)	23.5 (55)
asymmetrical component	- /110 %	130 %
TRV_{peak} [kV]	27.6/32.2	31.5
RRRV [kV/µs]	3.4/1.84	1.84
t_{delay}	< 0.5 µs	< 0.5 µs
time constant τ	133 ms	133 ms
Out of Phase (OoP 90°) interrupting capability	OP1 ↓	OP2 ↓
Symmetrical [kA]	25 (31)	25 (31)
asymmetrical component	- %	75 %
TRV_{peak} [kV]	39	39
RRRV [kV/µs]	3.3	3.3
t_{delay}	< 1 µs	< 1 µs
time constant τ	133 ms	133 ms

The values are displayed for the GCB – VD4G-50 for a rated short circuit current of 50kA. To interrupt the current, the generator circuit breaker must be tested at the asymmetrical current combined with long arcing times and with a faster Rate of Rise of Recovery Voltage (RRRV) than usual in medium voltage distribution circuits tested according to IEC62271-100.

In case of **generator-source fault,** the fault occurs between the circuit breaker and the transformer. The short circuit current coming from the generator-source produces nearly 31.5 (Table 1; TD5) respectively 23.5 kA (TD6). However, the asymmetrical component of the short circuit current can be considerably higher, reaching up to 110 % (step A; TD5) or 130 % (step B; TD6). This fault characteristic with high asymmetrical currents is due to the type of generator, operating conditions and the complex short-circuit impedance of the generator. This can lead to superimposed DC component with more than 100% of the peak value of the related AC current. The short-circuit current becomes that high that no current zero crossing (CZ) will occur during the first several tens of milliseconds. In case of an arc voltage generated by the contact system based on "transverse magnetic field" (TMF) in a range of 150 to 200V by applying the time constant ($\tau = L/R$) of the network is decreased and the first CZ is forced to happen earlier → this is valid for all types of generators.

Out of phase condition is a short-circuit interruption producing the high stress for the generator circuit-breaker and especially for the VI. If the generator and the circuit will be closed at phase opposition (90° electrical) the short circuit current in the circuit is increased.

The test results of OoP testing are based on a phase difference of 90° according to the IEC 62271-37.013 OoP with the specified test duties OP1 and OP2.

The needed values to perform all three fault conditions are presented in Table 1 according to the standard. In order to reduce the device volume and to reduce power losses, a compact breaker design with low resistance and a short bus conductor connection is preferable.

GENERATOR BREAKER, RESULTS OF SHORT CIRCUIT INTERRUPTION TESTS

The VI´s are equipped with an optimized TMF contact system [**3**]. Three phase vacuum circuit-breakers are available for application in generator circuits at 50/60 Hz. To fulfil the required short circuit interruption ability, the test has to be performed at 50Hz for IEC markets and at 60Hz for ANSI markets.

When the short circuit interruption ability is tested at 50Hz the transferred charge after contact separation is investigated by a simulation of a three phase direct generator circuit. The chosen generator is a cylindrical rotor machine with a power of 198MVA and an excitation current of 828A (Fig. 3). The simulation was done at 50kA allows a direct comparison of the short circuit current interruption under the severe condition of the three phase direct "delayed current zero" (DCZ) and the test duty TD4 [4]. This gives information regarding the resulting arcing time and the occurrence of the transferred charge following the equation:

$$\boldsymbol{C = \int I \; x \; \partial t}$$

Coulomb C: [As] and the current I: [A] and the arcing time t: [s].

After contact separation the arc voltage inside the vacuum interrupter is taken into account with 50V (simulation) at the current interruption operation. When a higher arc voltage of 150 … 200 V is applied, the simulated current zero crossing will occur earlier during the current interruption operation. During the short circuit interruption at 50Hz and under the above mentioned condition of Fig. 3 A), phase L2 has the

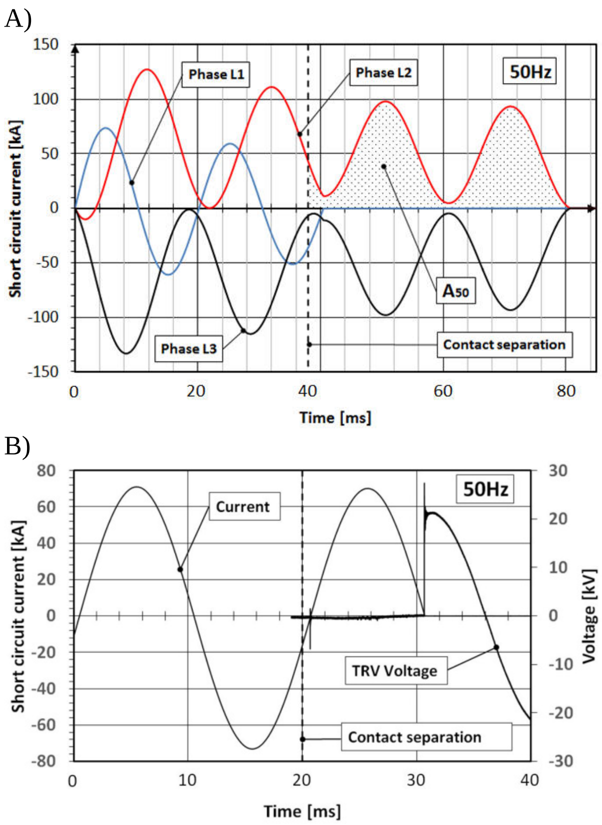

Fig. 3: The chosen generator has two poles with a power of 198MVA with an excitation current of 828A. Three phase direct DCZ interruption simulation: 50kA short circuit current and 110% DC:
A) Done for 50Hz frequency. The transferred charge during arcing is shown as the area according to A), at A_{50} the transferred charge equals to [C] = 1281As. B) Test duty: TD4 – Single phase testing: TRV 27.6kV; RRRV 3.5kV/μs; Current 50kA, 50Hz done at KEMA laboratories, the transferred charge during arcing is [C] = 495As.

maximum transferred charge at the vacuum interrupter of about 1281As according to the area A50 the integral of I x dt after the contact separation. The interruption is done under the test duty TD4 condition according to Fig. 3; B) with standard test condition according to IEC62271-37.03. The arc duration time during the interruption operation is much shorter at TD4, with the result that the integral I x dt is about 495 As.

At current zero the "transient recovery voltage" (TRV) across the vacuum interrupter can be withstood more easily with less transferred charge which results in a temperature heating up effect inside the VI of the GCB. This was observed during a large number of interruption validation tests of VI´s and the connected actuation mechanism done at high power laboratories. The vacuum circuit breaker VD4G-50 actuation mechanism is based on the stored-energy spring type.

The necessary operating energy is stored by manually or motorized charging of a clock spring.

The stored-energy spring mechanism essentially consists of drum containing the clock spring, the charging system, the latching and operating mechanism and the linkages which transmit the force to the breaker poles. This includes the charging motor, releases, auxiliary switches and the control elements located in the front panel. The operating mechanism is fundamentally suitable for auto-reclosing and, due to the short charging times, also for multi-shot auto-reclosing. A series of interlocks such as truck interlocking, earthing switch interlocking, etc. are provided to prevent dangerous situations and any malfunctions. The vacuum circuit breaker operating mechanism is tested up to 12,000 mechanical operations.

At the short circuit interruption operation the current crosses the point of "current zero" for interruption at that time where the contacts are actuated from the mechanical drive mechanism to the nominal – here the maximum

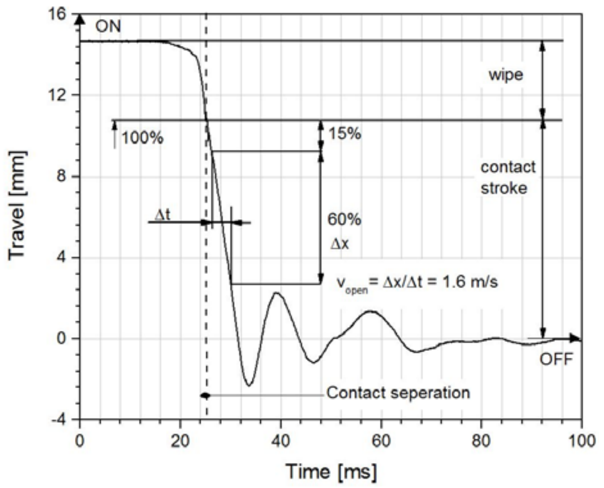

Fig. 4: Vacuum circuit breaker travel curve of the mechanical actuator installed inside the type VD4G-50 mechanism at the short circuit interruption operation. The opening velocity has a value of 1.6m/s measured as a mean value between 15% and 75% of the total contact stroke.

contact stroke after nearly 6 ms – the travel curve is displayed in Fig. 4 – with the di/dt – steepness of the RRRV with more than 3.4kV/µs and the TRV value up to 27.6kVpeak → 10 ms after the contact separation.

CONCLUSIONS AND DISCUSSION

The newly developed generator circuit breaker (GCB) developed with its VI´s and actuation mechanism are able to fulfil the requirements based on the presented simulation results and a number of type test which are performed on same vacuum interrupter according to [3].

The GCB is able to interrupt the required short circuit current of up to 50kA at a voltage rating of 15 kV (50Hz) according to the requirements IEC 62271-37.013 (CDV) / ANSI/IEEE C37.013. All test duties were passed with robustly.

- Typical simulation result is presented in Fig. 3 displaying a three phase short circuit interruption for a generator source fault with long arcing times and high values of asymmetry, "delayed current zero" (DCZ) Fig. 3; A). In Fig. 3; B) an interruption operation DCZ of a 50kA short circuit current with an asymmetrical component of about 110 % at contact separation and a long arcing time of 40ms (see step A of Tab. 1) is shown.
- The ability to withstand those long arcing times until the first current zero appears, and to interrupt under these conditions is demonstrated at the corresponding part the electrical and the mechanical mechanism.
- Displaying short circuit interruption under the test duty TD4 condition, respectively.
- After arcing up to 10.1ms, the VI saw TRV values up to 27.6kVpeak. The steepness of the RRRV is observed with more than 3.4kV/µs.

Under that condition and the arcing period at current zero the TRV can be withstood more easily due to the full open gap at the contact system with reduced overshoot and back-travel provided by the actuation mechanism.

- A compact design of the VD4G-50 circuit-breaker with an optimized arrangement at high efficiency and low impedance is feasible. Vacuum circuit-breakers enable such a compact design, and are able to carry continuous currents up to 4000A and higher on demand.
- A robust mechanical actuation system for GCB ratings is available in a compact design.

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