DC VACUUM CIRCUIT BREAKER

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ABSTRACT

In the last years the progressive increase of distributed and non-programmable energy sources arise the interest in the use of DC for medium voltage distribution systems.
The paper focus on the design considerations of the apparatus required to support the management and protection of these applications.
The fault handling techniques in DC distribution system is introduced and the definition of the main requirements for the circuit breakers is supported by computer simulations of short circuit current interruptions.
A medium voltage DC circuit breaker designed for 12 kV and 2.5 kA nominal current and 15 kA interrupted short circuit current is presented. The functionalities and the performances are illustrated by means the experimental results obtained from high power tests.

INTRODUCTION

The transmission and distribution power distribution system is facing new requirements in term of efficiency, flexibility in the power flow management and robustness and quality of the service. The availability of new technologies and apparatus opens to DC as an alternative to AC when is required an easy integration of electrification areas (microgrids) or in case of heavy penetration of renewable sources [1]. Additional examples of DC distribution system are found in railway applications and in urban electrical mobility where along the traditional wired supply of the vehicles new systems with fast charging of electric buses and cars and energy storage systems are facing the market [2].
In order to support these new applications a complete portfolio of protection systems and apparatus is required The paper introduces the design of DC circuit breakers and their performances related to what is asked for by the power system perspective.
In fact, even small changes in the performance and specifications concerning the handling and fault clearance may have large impacts on the concept, technology and cost of the circuit breaker.
The most profitable solution would require a combined design of the power distribution architecture and of the apparatus taking in consideration the requirements needed for the power management.

One purpose of the presented paper is to initiate a dialogue on the circuit breaker requirements for future DC distribution systems.

DC SHORT CIRCUIT CURRENT

The short circuit current in a DC distribution system could look very different depending on the characteristic of the different sources supplying the fault. Contributions to the DC short circuit current could come from a rectifier connected to the AC grid or from wind power or photo voltaic converters. The short circuit current contribution from each converter is most likely limited, but contributions from several converters in a system will sum up to higher currents. However, the main difference compared to AC short circuit currents is the lack of current zero crossings, which support the fault clearance in standard circuit breakers used in distribution system voltages of above 10 kV. The DC short circuit current and the limitation of the rate of rise of the short circuit current will be illustrated using a simple DC system (**Figure 1**) fed by a 3-phase AC system through one passive diode rectifier per phase [3]. This could be the case when a three phase AC generator is connected to a DC grid.

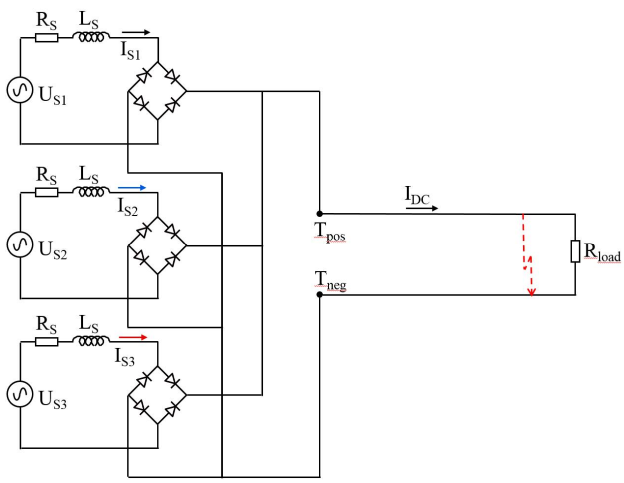

Figure 1. Short circuit in a DC system fed by a 3-phase AC source through passive rectifiers.

The DC system in **Figure 1** has one positive “T_{pos}” and one negative terminal “T_{neg}” and one resistor “R_{load}”

representing a load. A short circuit indicated by the red arrow in the DC system is selected to occur close to the terminals and one consequence is that the resistance and inductance of the DC system between the fault and the terminals are neglected.
The amplitude of the AC source voltages "U_{S1} to U_{S3}" is $\frac{12kV}{\sqrt{3}} = 6.93\,kV$. The source inductance "L_S" is 0.884 mH giving a short circuit current of 25 kA_{RMS}. The source resistance "R_S" is selected to 17.5 mΩ giving a time constant of the AC short circuit current of 50 ms.

The short circuit currents on the AC side of each phase are shown in the upper diagram in **Figure 2** and the DC short circuit current is shown in the bottom diagram. The DC load resistor is selected to give a load current prior to the fault of 2.5 kA. The DC short circuit current is the sum of the rectified AC short circuit currents and the steady state current reaches 70 kA which is twice the AC peak current of 35 kA. The DC short circuit current is given by the AC short circuit inductance since there is not any resistance in the DC system in this example.
The DC short circuit current shows a 50 Hz frequency component before the steady state DC current is reached. The transient 50 Hz component increases the DC short circuit current.
The rate of rise of the DC short circuit current is given by the rate of rise of the AC short circuit current in this case when the DC short circuit current is given by the AC short circuit current and not by the DC system resistance.

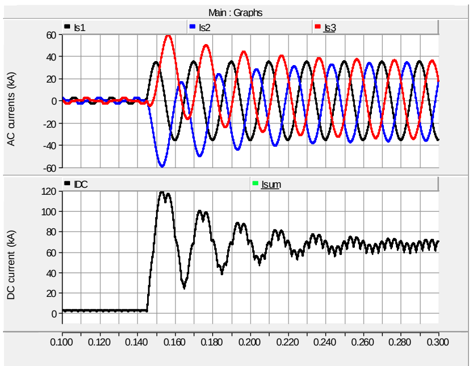

Figure 2. Upper diagram: 3-phase short circuit currents through the AC sources. Bottom diagram. DC short circuit current.

Limiting inductor

Short circuit currents in DC systems rise to high steady state currents without current zero crossings. Interrupting the high steady currents have large impact on the DC circuit breaker requirements and design. It is preferred to interrupt the short circuit current before the steady current is reached enabling a lower current to be interrupted. This could be achieved by a faster operation of the circuit breaker or by reducing the rate of rise of the short circuit current or by a combination of both measures. Current limiting inductors are used in AC systems to limit the amplitudes of short circuit currents. An inductor in the DC system will reduce the rate of rise of the DC short circuit current as well as the 50 Hz oscillations in the DC short circuit current. The inductor will however not limit the steady state short circuit current. This function of the DC-side inductor is illustrated in **Figure 4** when an inductance of 3.5 mH marked as "L_{DC}" is inserted on the DC side of the system (**Figure 3**). The inductor could represent the natural line inductance in combination with a physical inductor.

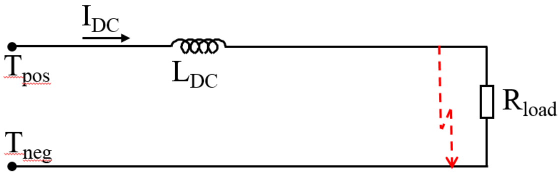

Figure 3. Short circuit in a DC system with a limiting inductor.

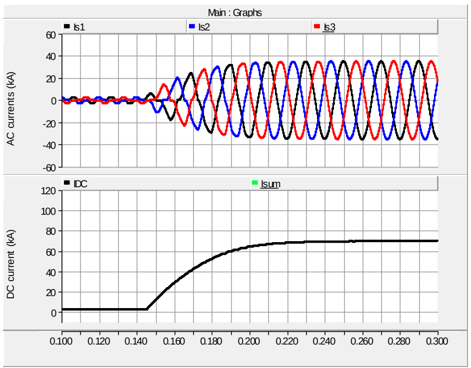

Figure 4. Short circuit in a DC system fed by a 3-phase AC source through passive rectifiers and a smoothing DC inductor.

DC VACUUM CIRCUIT BREAKER

Different concepts of DC circuit breakers with different properties and technology readiness levels have been proposed in literature, in order to cope with the whole voltage range from low voltage to high voltage. A forced increase of the arc voltage across the opening interrupter contacts is utilized for low voltage applications such as traction and photovoltaic, but unfortunately not applicable for distribution system voltages.
Hybrid concepts utilising a combination of mechanical and power electronic switches have been proposed and tested for both medium voltage [3] and high voltage [6] networks. The mechanical switch is used for carrying the nominal current with low losses and the power electronic switch is used for current interruption.
A high voltage DC vacuum circuit breaker for HVDC transmission systems [5] utilizing current injection from pre-charged capacitors has been proposed and tested at 80 kV. This concept when scaled down to distribution system voltage is regarded as the most suitable technology for distribution system applications [4] and [7] among the different technology approaches addressed to handle DC

interruptions.

The DC circuit breaker shown in **Figure 5** and **Figure 6** is based on a single pole operated 3-phase AC circuit breaker with an added active resonant injection circuit consisting of pre-charged capacitor.

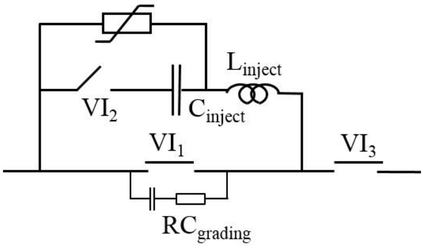

Figure 5. Electrical diagram of the vacuum DC circuit breaker.

One of the 3 vacuum interrupter (VI) poles of the vacuum circuit breaker is used for carrying the nominal current and for interruption of the short circuit current, VI_1. The second pole, VI_2, is used as closing switch to connect the pre-charged capacitor for current injection. The third pole, VI_3, is used as disconnecting switch.

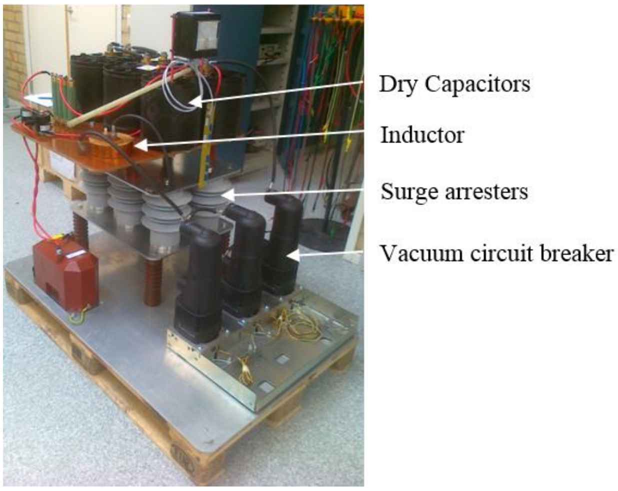

Figure 6. Vacuum DC circuit breaker with current injection.

High power testing

Testing the short circuit current interruption of DC circuit breakers is a challenge due to the lack of DC short circuit current sources giving both the correct high short-circuit current and the correct recovery voltage across the circuit breaker. However, the critical parameters of the recovery voltage i.e. di/dt, the voltage peak and du/dt, are given by the DC circuit breaker design itself and not by the network as explained in detail below. This is valid for at least the tested vacuum circuit breaker. The exception is the surge arrester energy absorption capability, which depends on the system inductance. With this in mind, the high power tests of the DC circuit breaker were performed with an AC short-circuit generator (**Figure 7**). The timing was set to achieve a full asymmetry of the short circuit current providing nearly 10 ms of current flow to reach the peak of the 50 Hz short-circuit current.

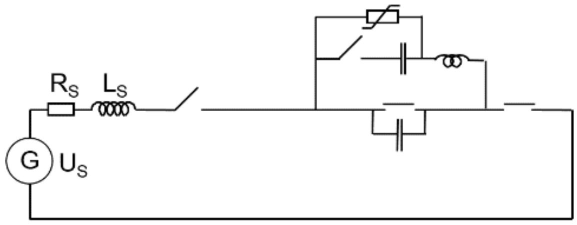

Figure 7. High power DC short-circuit current testing utilizing an AC short circuit generator.

One example taken from interruption testing at 15 kA is shown in **Figure 8**. Explanations are given by coloured arrows depicting currents and voltage.

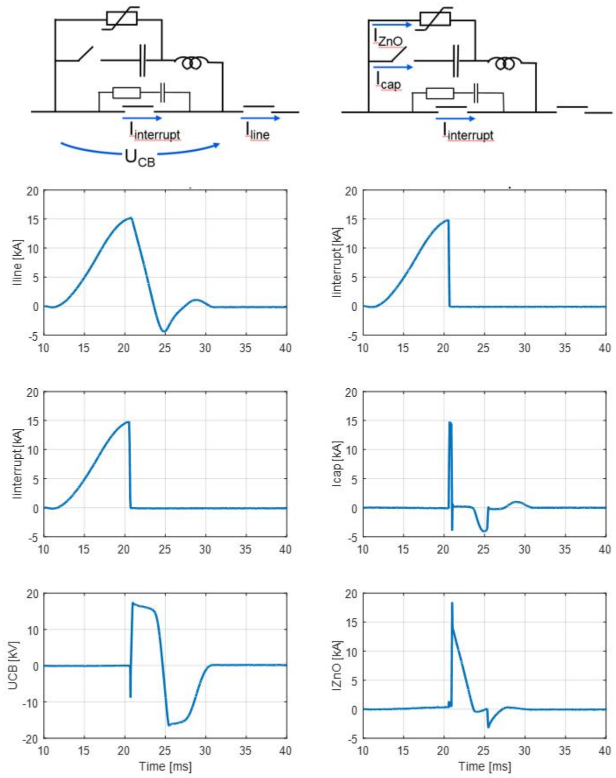

Figure 8. Interrupting 15 kA.

Circuit breaker functionality

The opening sequence of the DC vacuum circuit breaker is illustrated by an example of recorded branch currents and the voltage across the circuit breaker when interrupting 15 kA as shown in **Figure 8**.

The vacuum interrupters VI_1 and VI_3 are in closed position carrying the nominal current, and the VI_2 is in open position to allow charging of the injection capacitor (**Figure 5**). The fault is assumed to occur at time = 11 ms in **Figure 8**. The line current shown in the upper left diagram of **Figure 8** start to increase as well as the current through VI_1 shown in the left middle diagram. The circuit breaker is tripped when the current reaches 5 kA at time = 15 ms. Tripping of the circuit breaker will cause VI_1 to start to open and VI_2 to start to close. Opening VI_1 will ignite an arc in the vacuum interrupter. VI_1 will be fully open when VI_2 is closed assuming the same contact speeds and strokes of the two vacuum interrupters. Closing of VI_2 occurs at time 20 ms in the oscillogram and causes the injection capacitor to be discharged through the injection inductor and VI_1. The injected current has to be higher than the momentary line current to be interrupted to ensure a current zero crossing in VI_1. The upper right diagram shows the current through VI_1. The injected current is an oscillating current with relative high frequency and makes the current interruption at a value of 15 kA look like instantaneous. The line current will be commutated into the branch of VI_2 as soon as the current is interrupted in VI_1. This will charge the injection capacitor very fast up to 18 kV, which is the voltage limited by the surge arrester. The current through VI_2 and the injection capacitor is now commutated in to the surge arrester branch. The surge arrester will limit the overvoltage caused by the magnetic energy trapped in the system short circuit inductance. The current through the surge arrester will decrease when the surge arrester absorbs and dissipates the magnetic energy. The VI_3 can be opened after the surge arrester has sufficiently decreased the current. VI_3 is required to prevent thermal overstressing of the surge arrester due to the current through the surge arrester which is higher than for the normal and transient over voltage protection application of surge arresters.

Circuit breaker design

The circuit breaker design is based on extensive high power testing for this new application of vacuum interrupters. The design of the vacuum DC circuit breaker and the selection of components is given by the following parameters:

1. current to be interrupted
2. injected current
3. di/dt of the interrupted current
4. capacitors and inductor
5. recovery voltage and du/dt
6. opening and closing times
7. surge arrester (SA) energy

Current to be interrupted

The current to be interrupted and the energy dissipated into the arc from the instant of contact separation until current interruption is critical for the DC circuit breaker. The higher the current the larger the current interruption capability of the used interrupter and the more critical are other parameters such as the permissible di/dt of the interrupted current. The interrupted current also has an impact on the injection capacitor and SA. The higher the interrupted current the larger the injected current and therefore the size of the capacitor and the larger the surge arrester since the trapped magnetic energy is higher.

Injected current

The injected current has to be higher than the highest interrupted current the circuit breaker is designed for to ensure current zero crossings in the interrupting vacuum interrupter VI_1. The injected current is a function of the charging voltage of the capacitor and the ratio between the injection capacitance and inductance.

$$I_{inject} = U_{charge}\sqrt{\frac{C_{inject}}{L_{inject}}} \tag{1}$$

Time derivative (di/dt) of the interrupted current

The time derivative of the injected current (di/dt) is one limiting condition for a successful current interruption. The maximum di/dt is a function of the resonance frequency of the injection circuit and amplitude of the injected current.

$$\frac{dI}{dt} = \omega_I I_{inject} \tag{2}$$

The resonance frequency is given by the capacitance and inductance of the injection circuit.

$$\omega_I = \frac{1}{\sqrt{L_{inject}C_{inject}}} \tag{3}$$

The maximum di/dt occurs at the current zero crossing of the injected current, which is not occurring at the same instant as the current zero crossing through interrupting vacuum interrupter VI_1. The current through VI_1 is the sum of the line current and the injected current. Therefore, the actual di/dt at the first current zero crossing of the current through VI_1 is lower than the maximum value taken from (2). The higher the interrupted current the lower the di/dt at the current zero crossing assuming a constant amplitude of the injected current. One example for an interruption at 15 kA is shown in **Figure 9**. The right diagram shows the time expansion of the measured current. It can be observed that the di/dt is slightly decreasing towards current zero.

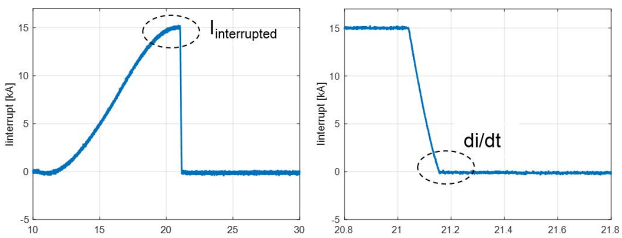

Figure 9. Current through VI_1.

Capacitors and inductor

The capacitance, C_{inject}, and the inductance, L_{inject}, for the injection circuit can be calculated by combining the equations (1), (2) and (3).

$$C_{inject} = \frac{1}{di/dt}\frac{I_{inject}^2}{U_{charge}} \tag{4}$$

$$L_{inject} = \frac{U_{charge}}{di/dt} \tag{5}$$

Recovery voltage and time derivative (du/dt)

The recovery voltage and the rate of rise of the recovery is determined by the circuit breaker design and not by the system properties which is the case for AC circuit breakers. This makes the circuit breaker design more predictable and simplifies the testing of the circuit breaker. The voltage across the vacuum interrupter VI_1 will increase after current interruption from zero to the momentary voltage of the injection capacitor. The voltage increase will also charge the grading capacitor across VI_1 (**Figure 10**). The charging circuit is determined by series connection of the injection capacitor and the grading capacitor through the injection inductance. Since the grading capacitance is much smaller than the injection capacitance, the resonance frequency of the circuit can be calculated from:

$$\omega_U = \frac{1}{\sqrt{L_{inject} \cdot C_{grading}}} \quad (6)$$

The rate of rise of the recovery voltage directly after current zero is calculated from (6) times the momentary voltage of the injection capacitor, U_{cap}, which depends on how far the capacitor has been discharged at the instant of current interruption

$$dU/_{dt} \approx \omega_U U_{cap} \quad (7)$$

After the first transient rise of recovery voltage, the voltage across the VI_1 will continue to rise until the surge arrester protective voltage is exceeded. The du/dt is lower and caused by the charging of the injection capacitor by the interrupted line current.

$$dU/_{dt} = \frac{1}{C_{inject}} I_{interrupted} \quad (8)$$

One example of the recovery voltage when interrupting 15 kA is shown in **Figure 10** in two time scales. The left diagram shows the voltage across VI_1 in a larger time scale limited to about 18 kV by the surge arresters. The right diagram is a time expansion and the two time windows with different du/dt are easily recognized and in agreement with equations (7) and (8).

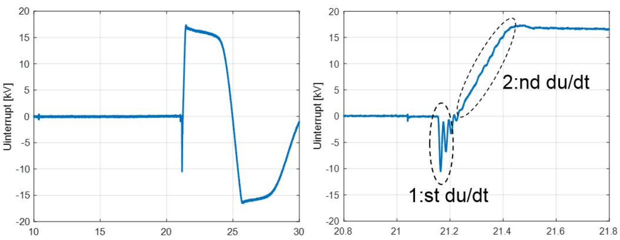

Figure 10. Recovery voltage across VI_1. Right diagram indicates two time windows with different du/dt according to equations (7) and (8).

Is has to be remarked that the vacuum interrupters used in the DC breaker are hardly sensitive to the parameter dU/dt within the applied range, which could be different for other kind of interrupters e.g. SF_6 interrupters.

Opening and closing times

Finally, the opening and closing times of the interrupters in the DC breaker are important parameters. As described above, the design of the breaker very much depends on the size of the short-circuit current to be interrupted, which is small if the breaker has short reaction times. Available mechanical breakers have opening and closing times of between 30 and 40 ms. Electro-magnetic actuators are able to operate within 20 ms, but only Thomson drives utilizing coils with high repulsion currents achieve opening times of less than several milliseconds [8]. Unless the rate of rise of the DC short-circuit current is reduced by the use of larger inductors, the reaction time of the DC circuit breaker needs to be below 5 ms. The speed of the interrupter contacts is also a decisive parameter and normally related to the opening and closing times. The speed determines the shortest arcing time till current interruption in order to achieve a sufficiently large contact gap that can withstand the recovery voltage across the interrupter.

Surge arrester (SA)

The energy to be absorbed by the SA depends on the system short-circuit inductance and the interrupted current and the SA protective voltage in relation to the system voltage. Also, the operating sequence of the DC breaker has to be considered.

SUMMARY

One concept for a DC distribution circuit breaker has been designed and successfully tested for 12 kV and interrupting 15 kA 5 ms after trip. It is the hope of the authors that the distribution system operators will find the results useful when evaluating DC as an alternative to AC in their systems. We are looking forward to study future papers on DC distribution systems.

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