DEVELOPMENT OF A HIGH CURRENT HVDC CIRCUIT BREAKER WITH FAST FAULT CLEARING CAPABILITY

B. Pauli, G. Mauthe, E. Russell, G. Ecklin

Abstract: Recent years have seen rapid growth in direct current transmission. This growth increases the need and scope of application for a high voltage direct current circuit breaker.

Significant improvements have been made in a previously developed 500 kV, 2000A HVdc circuit breaker. These improvements have increased the current interrupting capabilities to 4000A dc and more and have decreased the fault clearing time to the order of ac breakers of similar voltage ratings. The improvement was on a HVdc circuit breaker that is built using well proven ac power system components. It is modular in design so as to be suitable for a wide range of system voltages and energy levels.

Introduction

For many years various investigators have explored different approaches to develop a high voltage direct current circuit breaker [1]. Recently a joint effort by the Bonneville Power Administration (BPA), Electric Power Research Institute (EPRI), Brown Boveri Corporation (BBC), and the Electric Power Research Institute (EPRI) has resulted in the successful development and field testing of a practical, 500 kV, 2000A air-blast HVdc breaker [2,3]. The primary focus of all HVdc breaker development has been overcoming the problem of dc systems having no natural current zero. In the familiar high voltage ac circuit breaker, the interruption process depends on the naturally occurring cyclic instances of current zero. The breaker will typically arc through high current periods making no attempt to clear until or about the current zero point, whereupon it will then isolate the circuit. To obtain similar isolation in a dc circuit, it is necessary to create a current zero point. References [1] to [4] describe many of the past methods to accomplish this. Most of these methods create a current zero by active or passive commutation of the direct current.

Active commutation methods have a capacitor, typically precharged, inserted across the main interrupter element through some switching device. The surge current caused by the insertion of this capacitor quickly drives the current in the interrupter to zero.

Current Interruption Methods: The 2000A limit on the current interrupting capability limits the scope of the original breaker's application generally to HVdc systems where the sum of the steady state current ratings of all the rectifiers in a multiterminal system does not exceed 2000A. It was felt that a breaker with interrupting current capability of 4000A would be necessary to meet most of the needs of the near future. Such a breaker would be adequate to meet breaker needs in a multiterminal dc system with two rectifiers rated at 2000A each, or in a ±500 kV or ±600 kV bipolar HVdc system with maximum power flow of 4000-4800 MW. Therefore, one of the objectives of the project was to develop a breaker with capability to
interrupt 4000A direct current. It was also decided that, subject to funding and time constraints, an attempt would be made to determine realistic limits of the maximum current interrupting capability of the breaker as constructed for this application.

Fault Clearing Time: How much of an improvement in fault clearing time is worthwhile depends on the cost of obtaining such improvement and the incremental system benefits derived from it. From the point of view of transient stability performance, three-phase faults on the ac side of the rectifier are typically as severe or worse than dc side faults. Therefore, in most cases, switching time for clearing dc side faults comparable to that on the ac side should be adequate.

For the breaker that was field tested at Celilo, the breaker was tripped only after the fault current was brought down to prefault values. This was to ensure that the breaker was opened only when the current was within its interrupting capability. Even after the trip signal is given, it takes about 20 milliseconds for the breaker contacts to separate before any commutation process can start. The breaker operation and the fault-clearing process can be materially speeded up if the trip signal is given as soon as the fault is detected and without waiting for the current levels to come down in response to converter control action. By this method the breaker contact opening mechanism and the converter controls operate in parallel rather than in series. In this approach the breaker contacts may open before the fault current has been reduced to current levels that the breaker can interrupt. Therefore, for this method to be successful, the breaker may have to sustain higher arc currents and longer arcing time without losing its rated current interrupting capability. Development of a breaker with such capability would have the additional advantage of making the breaker somewhat immune to destructive failure in case of false operation during a fault.

The magnitude of the transient fault current that the breaker would encounter when operated in this manner depends on the system and fault location. For the purpose of this project, the fault current was defined using the example of parallel operation of two 846-mile long, 500 kV, 2000A HVdc lines, each similar to the Pacific HVdc Intertie. This case was simulated by extending the digital simulation of the Pacific HVdc Intertie using the Electromagnetic Transients Program (EMTP) [5]. A schematic of the simulated system is shown in Fig. 1.

![Fig. 1: Schematic of the simulated circuit for determination of transient fault current](image)

DC fault conditions at four points along the line were simulated to determine currents on the line at the points of parallel connection of the lines. Fig. 2 shows the wave forms of the currents with maximum values in these four cases. The peak of the fault current is higher and duration shorter when the fault is closer to the rectifier. Even under the worst case, the magnitude of the transient fault current in dc systems is substantially lower than that of similar faults in ac systems. An envelope of all the fault current waveforms, as shown in Fig. 2, was taken as the transient fault current through the breaker. This is a conservative estimate and more severe than actual fault cases. The initial part of this envelope, for about 20 ms, represents the transient fault current occurring before the breaker contacts separate even if there was no relaying time delay in fault detection. This portion can be ignored for the interruption process since it would have no influence on the breaker arc phenomena. Therefore, the peak value of transient current of interest to the breaker development would be not more than 8 kA. This was taken into consideration in establishing the test current criteria.

![Fig. 2: Line currents for dc line fault in a parallel dc transmission system](image)

(a) Fault at rectifier end; (b) Fault at 1/3 distance away from rectifier; (c) Fault at 2/3 distance away from rectifier; (d) Fault at inverter end; (e) Fault at inverter end line current (d) and inverter end line current (e)

Modularization: The basic design of the breaker consists of series connection of different modules, each consisting of one interrupter with its own L-C commutating circuit and energy absorber as for the basic four module case shown in Fig. 3.

![Fig. 3: Basic four module HVdc circuit breaker with four breaks in series](image)
It is possible to have larger modules with more than one interrupter in one commutating circuit. The impact of having larger modules on commutating time or capacitor size is not obvious, especially when the breaker is configured into one large module with four, six or eight interrupters in series. The obvious advantage of having a breaker with one large module with one commutating circuit is, that in such a case it is not necessary to design the energy absorber elements to accommodate unavoidable spreads in commutation times that different modules might have. Additionally, increasing the number of breaks for a particular voltage and current rating reduces the size of the commutating capacitor that is required. It was considered worthwhile to investigate both of these aspects of modularization under this project.

Therefore, the overall objective was to develop and proof-test a 500 kV air-blast HVdc circuit breaker operating on the principle of passive commutation with continuous and interrupting current capability of at least 4000A dc and also capable of clearing dc faults when tripped with zero time delay from fault initiation. The project consisted of theoretical investigations, design and module testing of the breaker. Backed by the experience of good correlation between factory module testing and full scale field tests in previous development efforts, field testing was not considered in this project. Therefore, the tests were conducted on one or two modules in a basic four-module configuration with maximum interrupter voltage, limited by MO energy absorbers, specified as 200 kV per module. This corresponds to a 500 kV HVdc circuit breaker with maximum interrupter voltage of 800 kV (1.6 pu).

**DESIGN PRINCIPLES**

Basic principle: The basic principle of the breaker operating on passive commutation is explained with the aid of Fig. 4.

**Fig. 4:** Principle of passive commutation circuit

- **I:** commutation switch
- **II:** commutation circuit
- **III:** energy absorber unit MO
- **L:** system inductance
- **I₀:** direct current to be interrupted
- **Iₛ:** current in commutating switch
- **Uarc:** arc voltage of commutating switch
- **Lc,Cc:** inductance and capacitance of commutating circuit
- **Rc:** inherent ohmic resistance of commutating circuit
- **Iₐ:** current in the MO energy absorber
- **MO:** metal oxide energy absorber
- **MO**
- **Lc**
- **Cc**
- **Rc**
- **I₀**
- **Iₛ**
- **Uarc**
- **Lc,Cc**
- **Rc**
- **Iₐ**
- **MO**
- **I₀**
- **Iₛ**
- **Uarc**
- **Lc,Cc**
- **Rc**
- **Iₐ**
- **MO**

The differential equation for the current $Iₛ$ of the opening commutating switch can be written as follows:

$$Lc \frac{d²Iₛ}{dt²} + (Rc + \frac{dUarc}{ds}) \frac{dIₛ}{ds} + \frac{1}{Cc} Iₛ = \frac{I₀}{Cc}$$

An approximate solution of this equation has the form

$$Iₛ = I₀[1 - e^{-2Ic(Rc + \frac{dUarc}{ds})} \cdot \sinh(t)]$$

In the case $Rc(\frac{dUarc}{ds}) > 0$, the exponential term creates an oscillating current with increasing amplitude.

The characteristic arc voltage $U_{arc}$ vs. current in the switch $(U_{arc} = f(Iₛ))$ follows a dynamic pattern dictated by the constants and the frequency of the commutation circuit $Uc = \sqrt{Lc \cdot Cc}$, as well as the parameters and behaviour of the commutating switch $[5]$. When the oscillating current $Iₛ$ in the switch reaches or passes through zero, the commutating switch is able to interrupt it. Consequently the dc current $I₀$ is transferred to the commutation circuit and charges the capacitor $Cc$. Metal oxide energy absorbers across the commutation circuit limit the maximum voltage across the capacitor to their clipping voltage level. When the clipping voltage is reached, the current is transferred to the energy absorbers.

The energy absorbers act in this operating mode as a relatively low ohmic dynamic resistance, dissipating the system energy and thus reducing the dc current to zero. This clipping voltage, which has to be higher than the system voltage, determines how fast the direct current can be reduced to zero.

**Factors influencing dc current interruption**

Commuting switch: For a commuting switch, an air-blast circuit breaker is employed consisting of several interrupter units with a double-blast interrupter-nozzle arrangement.

During the commuting or arcing time, the build-up and prolongation of the arc in the nozzle arrangement as well as repeated break-downs and rebuild-up of the arc voltage are determining factors of the commutation process. This behavior is influenced by the arc characteristic, interrupting media and nozzle geometry.

Commutation circuit: It is essential that the ohmic resistance $Rc$ of the commutation circuit be as low as possible in order to achieve a fast increase of the oscillating current and thus short commutation times. The values of the capacitance $Cc$ and inductance $Lc$ also influence the commutation time. These values, which dictate the inherent natural frequency of the commutation circuit, interact closely with the arc voltage characteristic of the commutating switch.

Energy absorber circuit: The metal oxide energy absorber units do not influence the commutation process. But the choice of the clipping voltage level affects the energy absorption time. This level must be chosen such that the switch overvoltages up to 1.7 p.u. can be dissipated within the energy absorber circuit.

**Theoretical modelling of commutation:** To support the experimental investigations, computer calculations of the commutation process have been carried out using a theoretical model of the commutating switch together with the commutation circuit [7].
The arc in each interrupter unit of the commutating switch is modelled as consisting of two independent parts with different characteristics (see Fig. 5). One of these parts is the arc in the section between the stagnation point of the flow and the corresponding nozzle throat. The other part is the arc between the nozzle throat and the arc root on the surface of the metallic nozzle outlet.

Both parts are described by a modified Mayr equation. The corresponding functions $P_1(g)$ and $T_1(g)$, $g$ being the specific conductivity, have been determined from current and arc voltage measurements near current zero. During the arcing period, the arc roots are blown downstream into the nozzle, which results in an increase of the arc voltage. After a certain time the central sections of the arc form new arc roots, and the arc voltage changes, indicated in Fig. 5 as reignition.

This arc voltage change can stimulate the current oscillation in the commutation circuit. If these arc voltage changes are in phase with the inherent frequency of the commutation circuit, the amplitude of the current oscillation in the commutation circuit increases very quickly.

In reality, the time between successive voltage changes in the interrupter units is not constant. Due to the magnetic fields that are produced by the external current loops, the arc is moved toward the nozzle wall, and after contact with the walls, the voltage drops or voltage changes occur. This radial arc movement together with the arc-diameter modulations in the oscillating current results in statistical fluctuations that are taken into account in the model in the following way. During arc elongation the voltage rises at a constant rate. If the arc voltage has reached a certain value $U'_{arc}$, an immediate voltage drop is assumed in the model. The value of $U'_{arc}$ is determined statistically by the computer model.

The result of such a calculation is shown in Fig. 6. Due to the statistical behaviour, voltage drop and circuit oscillation may get out of phase during the commutation period. Phenomena like beating can occur. These effects are also observed in the measurements as can be seen in Fig. 6.

If the oscillating current amplitude has reached a certain level, then even the possible damping influence of the voltage drop and circuit oscillation being out of phase is not high enough to damp the oscillation. The increase in the magnitude of the current oscillations continues. Thus the effect of statistics of the interaction of the arc behaviour in the nozzle with the commutation circuit allows a very detailed description of the whole commutation period.

As shown later in Fig. 14 calculated and measured commutation times are in good agreement and the theoretical model together with computer calculations proved to be a powerful tool for the development and design of the HVdc circuit breaker.

### BREAKER ARRANGEMENT

**Basic arrangement:** In the arrangement as shown in Fig. 3 a standard four break, 550 kV ac circuit breaker is used as the commutating switch with a commutation circuit connected across each of the four breaks. An alternative arrangement is shown in Fig. 7. In this arrangement an eight-break commutating switch is employed with two breaks in series for each of the four commutation circuits. This eight-break arrangement may be necessary to satisfy the longer creepage distance across the circuit breaker that might be needed for certain HVdc applications. With two breaks in the commutation circuit, the size of the capacitor would be smaller.

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**Fig. 5:** Modelling of the arc in the double nozzle interrupter. $P_0$ and $T_0$ being parameters of the modified Mayr equation.

**Fig. 6:** Comparison of calculated and measured commutation current.

**Fig. 7:** Basic four module HVdc circuit breaker with eight breaks in series.

**Fig. 8:** Basic circuit of the laboratory test set-up.
Fig. 9: 500 kV HVdc circuit breaker

Fig. 9 shows the installation of the test breaker at BBC's Laboratories. Except for the fact that this installation contains only half of the commutation and energy absorber circuits, the basic configuration is that of a commercial 500 kV HVdc circuit breaker.

Commutating switch: It is a standard high voltage air-blast circuit breaker BBC type DLF [8]. However, due to the specified transient current, the switch requires a blasting time after contact separation of approx. 80 ms (40 ms allowed for the transient current to decrease to 4000A, 20 ms for the commutation and 20 ms safety margin).

Commutation capacitor: Tests were carried out with different values of capacitances, by series-parallel connection of the capacitor units. The capacitance of one capacitor unit is 5 uF with a rated test voltage of 60 kV dc. The capacitors are all-film types and are equipped with discharge resistors. The main stressing of the capacitors during opening of the breaker occurs if the contact gap reignites after a preceding current interruption. In cooperation with the supplier, discharge endurance tests have been carried out with a current peak of 12 kA per unit.

Commutation inductor: They are built as single layer coil, fully impregnated with weather resistant epoxy resin. The copper conductor consists of more than one thousand insulated single wires. The inductance is 100 uH. Rated BIL of the inductors is 300 kV. One of the commutation inductors was equipped with taps from 70 uH to 115 uH for test purposes. With these variable commutation elements, a wide variety of commutating circuit conditions could be easily attained.

Energy absorber: In contrast to the prototype breaker tested at Celito, the energy absorbers are not free standing, but are included in the frame of the commutation circuit. Each module is equipped with 2 absorber units in parallel, however any reasonable number of units in parallel is possible. The total energy absorption capability of 1 unit is 3.75 MJ. The clipping voltage at 4000A was fixed to 200 kV per module.

General: One main task of designing the breaker is to reduce the effective resistance of the commutation circuits to a value as small as possible. Short and low resistance connections were used. Special attention was given to the eddy current losses.

TEST RESULTS

Test circuit: Based on the results shown in Fig. 2, it was decided to test the breaker with direct current (curve A in Fig. 10a) and direct current with superimposed transient (curve B in Fig. 10a).

To produce such test currents the test circuit shown in Fig. 10b was developed and installed. DC current values up to 8 kA as well as transient current curves can be simulated using this circuit. The following describes its principle of operation.

A short circuit generator (G) used usually for ac circuit breaker testing serves as the energy source. In this particular case two generators each of 1000 MVA short-circuit power have been applied. The diodes D1 and D2 convert the ac current of the source into the required dc-test current I0. The low loss inductance L acts to store magnetic energy and consequently as current source as well as to smooth the ripple of the test current.

![Diagram of test circuit](image)

Fig. 10: Wave forms a) and circuit b) for breaker test

(Explanation see text)

Point 1: Breaker contact separation 1
Point 2: Breaker contact separation 2

Initially the test breaker TB and auxiliary breakers A1, A2 are closed, the auxiliary breakers MS and A1 are open. When the breaker MS closes, the test current I0 starts to rise exponentially through the test breaker with a time constant T1 = L/R1. It approaches a maximum value I1 which is proportional to V0/R1.
At time \( t_1 \) both auxiliary breakers \( A_2' \) and \( A_2'' \) open and, therefore, the resistors \( R_2' \) and \( R_2'' \) are inserted into the circuit. The test current \( I_0 \) starts to decrease exponentially with a time constant \( T_2 = \frac{L}{R_1 + \left( R_2' // R_2'' \right)} \) and would yield a new steady state dc current value \( I_2' \) proportional to \( V_G / \left( R_1 + \left( R_2' // R_2'' \right) \right) \). At the moment \( t_2 \) the auxiliary breaker \( A_1 \) is closed and the test current remains approximately constant at the momentary current value \( I_2 \).

If \( A_1 \) is closed without opening \( A_2' \) and \( A_2'' \) current waveshape as shown by curve A in Fig. 10a will be obtained. By correct adjustment of the resistors \( R_1 \) and \( R_2, R_2' \) as well as the instant of auxiliary breaker operation any required test current curve within certain limits can be realized. Varying the moment of contact separation of the test breaker (e.g. Point 1 and 2 of Fig. 10a) allows testing the breaker's interrupting behaviour with different duration of the transient current. After current commutation the energy stored in the inductance \( L \) is dissipated by the MO energy absorbers of the test breaker.

The rate of rise of the TRV (transient recovery voltage) across the HVdc circuit breaker is determined by the commutation capacitor of the breaker and the test current \( I_0 \) at the commutation instant

\[
\frac{du}{dt} = \frac{I_0}{C_C}
\]

The peak value of the TRV is limited by the clipping voltage of the energy absorbers.

Test program: Broadly four sequences of tests were conducted:

1. Interruption of steady state direct current with no superimposed transient current
2. Interruption of direct current with superimposed transient current
3. Tests on different module arrangements
4. Tests to explore maximum direct current interruption capability

The tests were carried out with the full voltage of 200 kV per module.

Steady state current tests: Using the basic one-break module tests with different nozzle geometries of the commutation switch were carried out. With the optimum nozzle arrangement the results of a series of tests at various dc current levels and with several capacitance values are exhibited in Fig. 11a and b. Fig. 11a gives mean values whereas Fig. 11b shows the scatter of the commutation time. Fig. 12 shows a typical oscillogram.

For a given capacitance, the commutation time \( t_c \) increases with higher currents as can be seen in Fig. 11. Contributing factors are the higher arc voltage and higher magnitude of \( \frac{du_{arc}}{dt} \) at lower values of direct current. These test results clearly demonstrated that dc breakers with 4000A interrupting capability can be built for commutation times in the range of 10 - 20 ms with reasonably sized capacitors.

Tests for the interruption of direct current with superimposed transient: Tests were performed by gradually raising the value of the transient current superimposed on 4000A direct current to 8000A. Current oscillation in the commutation circuit starts on the descending part of the transient current slope. The time from the instant of relatively fast increase of the magnitude of the oscillating current to the instant of commutation amounts to approximately 15 to 20 ms. Fig. 13 shows an example of current commutation with superimposed transient current. No effect on the commutation process caused by high transient current could be observed.
Fig. 14 shows the comparison of the calculated and measured commutation time exhibiting a very good correlation.

Fig. 14: Comparison of calculated and measured commutation time ($t_c$) for the superimposed transient current.

Fig. 15 summarizes the test results with two transient current curves. The curves were realized with two different contact separation moments of the commutating switch in relation to the transient current shape corresponding to point 1 and 2 of Fig. 10.

These results clearly demonstrate that the concept of operating a dc breaker before the dc circuit current has been reduced to the interrupting current capability of the breaker is quite feasible. The magnitude of the transient fault current seems to have little effect on the breaker's ability to interrupt the direct current.

Tests on different module arrangements: All the results presented so far are for tests on modules with only one break. Tests were also executed on modules with two breaks and four breaks.

Fig. 16 shows the results of tests with two breaks in one module. This may be compared with similar results for one module with one break shown in Fig. 11 b).

Fig. 17 shows the comparison of the test results for two breaks per module and one break per module arrangements. Results confirm that the 500 kV breaker arrangement such as shown in Fig. 7 with eight breaks is quite feasible and the increase in number of breaks is accompanied by reduction in capacitor size.

Transient current tests were also carried out with two current curves on the 2-breaks per module arrangement (see Fig. 18).

Fig. 18: Test results of one module with two breaks. Transient current ($I_0$) vs. commutation time ($t_c$).

Some tests were performed with four breaks in one module. Fig. 19 is a comparison of results of a breaker with 4 breaks configured as one or two modules. Results show no significant difference in commutation time in the two approaches. These results, although not extensive, point to the conclusion that changing the number of modules in a breaker without changing the total number of breaks, capacitor size, natural frequency of commutation and the resistance of the commutation circuit has little effect on commutation time. This conclusion is consistent with the results of the previous project when no significant difference in commutation time was noticed when the breaker was tested at Celilo in two module and four module arrangements.
The new dc breakers are shown to be capable of withstanding transient currents higher than 4000A without 5500A dc could be built. Breakers with current interrupting capability of even lower. With further increase in capacitance, practical

CONCLUSION

A high current HVdc circuit breaker test unit has been built and tested with more than 400 current interruptions. Tests have shown that this circuit breaker is capable of interrupting more than 4000A dc. Compared to the 500 kV, 2000A breaker field tested on the Pacific Intertie in 1984, higher interrupting current capability has been obtained in two ways: by increasing the capacitance value by about fifty percent or by doubling the number of breaks with capacitance value 20 percent lower. With further increase in capacitance, practical breakers with current interrupting capability of even 5500A dc could be built.

The new dc breakers are shown to be capable of withstanding transient currents higher than 4000A without affecting interruption. This transient current withstand capability is greater than is likely to occur during ac faults. Therefore, no time delay is required to allow the HVdc system controls to restore the current to prefault levels before the breaker is tripped. The interrupting time of such dc breakers would then be comparable to the interrupting time of conventional ac breakers for ac faults. The breaker is modular in construction and can be designed for a wide variety of system conditions.

The use of such breakers in dc transmission systems is expected to provide flexibility in system design and contribute to system stability.

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REFERENCES


Fig. 19: Test results

Commutation time (t_0) vs. current (I_0)

Comparison of
- with middle connection (two modules, each with two breaks)
- without middle connection (one module, four breaks)

Current limit test: In determining the current limit for the breaker, the capacitance value was increased. However it was not possible to optimize the commutation circuit frequency or nozzle geometry for the higher current limit test: In determining the current limit for the breaker, the capacitance value was increased. However it was not possible to optimize the commutation time, since neither time nor resources of the test arrangement permitted extensive tests.

Test results are shown in Fig. 20. Direct currents up to 6.5 kA were interrupted with commutation time less than 20 ms. A 7.7 uF capacitor with 2 breaks per module is adequate for this. For currents greater than 5.5 kA the commutation time increases significantly even with higher capacitance values.

Fig. 20: Test results of current limit test with one module, two breaks.

Commutation time (t_0) vs. current (I_0)

The use of such breakers in dc transmission systems is expected to provide flexibility in system design and contribute to system stability.
Karl W. Kanngiesser (Brown, Boveri & Cie, Mannheim, F.R. Germany): The question has been raised by A. Greenwood whether we need a d.c. circuit breaker of 12 kA interrupting capability which I would like to comment as follows.

In all existing HVDC schemes the rectifier station controls the current. In case of a d.c. line-to-ground fault the d.c. side fault current may transiently rise to about 3 times the rated value but within about 30 ms is brought back by the fast acting current control to either zero or the pre-fault value. The advantage of the new breaker design is that one has not to wait until the quasi-steady-state has been reached but at the instant of fault sensing may trip the breaker and by this shortening the fault clearing time.

The need for a d.c. breaker with an interruption capability of, say, 12 kA, may arise with a large multi-terminal HVDC system whose rectifier stations have rated currents summing up to 12 kA. In such a system the sustained commutation failure of an inverter station may lead to a quasi-steady-state d.c. side fault current of that magnitude. Although control modes are available to reduce this current automatically, e.g. the so-called low voltage current limit, one may prefer to have a non-dependent breaking capability of the d.c. breaker.

On the other hand, we have to admit that very likely in the near future no such requirements will arise, necessitating a further upgrading of the existing d.c. breaker.

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B. Pauli, G. Mauthe, E. Ruoss, G. Ecklin, J. Porter, and J. Vithayathil: The authors would like to thank the discussor for the interest in the work presented. To the question of Professor Greenwood and the answer by K. W. Kanngiesser that authors have no additional remarks since it covers the question raised in a comprehensive way.

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