21, rue d'Artois, F-75008 PARIS
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420kV AIS circuit-breaker performance comparison for shunt reactor application

Guilhem Blanchet
Statnett, Norway

Trond Magne Ohnstad
Statnett, Norway

Dag Petter Lysheim
Statnett, Norway

Magne Runde
SINTEF Energy Research, Norway

SUMMARY

Circuit-breaker manufacturers develop and produce in general only one circuit-breaker model that is supposed to meet the IEC requirements for all types of applications (line, cable, transformer, capacitor bank, SVC, shunt reactor and short-circuit capability up to 63 kA). Switching of shunt reactors has for long been recognized as a particularly challenging switching duty for such general purpose circuit-breakers. Overvoltages generated by de-energization of shunt reactor may be harmful to all the components in the grid, including the circuit-breaker itself. Such overvoltages are generated by two different phenomena: Current chopping and re-ignitions.

This report presents a technical comparison of the shunt reactor switching behaviour of five different 420 kV AIS circuit-breakers on the market. The considered breakers can be classified into three categories according to short-circuit rating and technology: 50 kA self blast, 63 kA self blast and 63 kA puffer type. The properties on which the comparison is based on are: i) Width of the re-ignition free arcing window, ii) current chopping number, and iii) rate of rise of the dielectric strength. Considering economical, safety and technical aspects, 50 kA self blast circuit-breakers with composite insulator housings come out best and should be selected for shunt reactor switching applications.

KEYWORDS

Circuit-breaker, shunt reactor, current chopping, chopping number, inductive load switching, rate of rise of dielectric strength, IEC 62271-110, arcing window, chopping overvoltages, re-ignition, etc.

Guilhem.Blanchet@statnett.no

1. INTRODUCTION

Statnett, the Norwegian TSO, has many years of experience with building and upgrading high voltage substations and are currently developing the next generation power grid. To compensate capacitive reactive power several shunt reactors (25) have been installed in the Norwegian 420 kV system. These reactors are mostly of variable shunt reactor (VSR) type with a reactive power rating of 90 – 200 MVAR, and are normally switched in and out every day. De-energizing shunt reactors, (i.e., interrupting small inductive currents) has always been a big challenge for circuit-breakers.

Over the last few years, several reactor breakers in Statnett's 420 kV grid have failed suddenly during de-energisation. The present article reports on the failure investigations and compares the interrupting properties of five circuit-breaker models on the market. Current chopping, re-ignition phenomena and other characteristics associated with shunt reactor switching are reviewed. Recommendations are given with regard to how to assess and compare these breakers for shunt reactor de-energisation, as seen from a grid owner perspective.

2. REACTOR CIRCUIT-BREAKER INCIDENTS

2.2 Porcelain insulated circuit-breaker explosion during commissioning

Figure 1: Fragmentation of 420 kV porcelain insulated circuit-breaker.

The first incident occurred in 2013 during the first opening operation during commissioning of a 420 kV breaker for a 90 - 200 MVAR, 50 Hz shunt reactor. The circuit-breaker was a new 50 kA self-blast SF_6-breaker with two interrupting chambers with porcelain housing. As can be seen from Figure 1, the housings of both chambers of one of the three single-phase units exploded.

The recorded current and voltages oscillograms showed that the normal load current of 120 A was not interrupted in the failed pole. The arc was burning for more than one half-cycle (>10 ms), then quenched and then re-ignited immediately afterwards when the contacts were in fully open position. This circuit-breaker is a double motion type, implying that in fully open position, the main contacts are covering the arcing contacts. More interruptions and re-ignitions have followed until the arc commuted from the arcing to the main contacts. Since the burning arc virtually short-circuits one of the interrupter units, the other unit got all the voltage, and immediately suffers a dielectric breakdown across its main contacts. Hence, both interrupters ended up with an arc burning across their main contacts. This lasted for more than 1 min until the disconnector switch in series with the circuit-breaker cleared the shunt reactor load current.

Some 10 s after opening of the circuit-breaker, signal indicating low SF_6 pressure was received by the station control system, indicating fragmentation of both porcelain insulators. Fortunately, no persons were injured by the porcelain fragments that were thrown more than 50 meters away. However, parts of the surrounding high voltage equipment insulators were damaged by the fragments.

This shunt reactor breaker was equipped with Controlled Switching Device (CSD) supplied by a different manufacturer. The settings of the CSD were correct.

A comprehensive investigation was carried out, but the root cause of the failure was not found. The manufacturer was not able to provide an IEC 62271-110 type test on an identical circuit-breaker model. However, such test reports for other models were available.

2.3 Composite insulated circuit-breakers perforation after 1100 operating cycles

The two other incidents happened with circuit-breakers from another manufacturer within a two months period in two different substations. In both cases CSD was installed. The breakers were both put into service in 2009 and had around 1100 close-open cycles.

Figures 2 and 3 show external parts of one of these failed circuit-breakers. As can been seen, the interrupter housings were still in place, but one of them was punctured. The internal parts of both interrupter units were heavily burned and melted. The other failed circuit-breaker had similar damages. Compared to the case in Figure 1, this clearly illustrates the benefit of using composite housing instead of porcelain.

Figure 2: Perforation of composite circuit-breaker.

Figure 3: Perforation of the composite insulator.

Analyses showed that during the CSD commissioning the circuit-breaker`s opening times were incorrectly set. This resulted in a too short arcing time, leading to re-ignition in almost every open operation, giving a significant wear on the circuit-breaker chamber insulating materials. Hence, 1100 operations (in these cases corresponding to 5 years of service) seem to be the expected lifetime for this circuit-breaker model when all opening operations have re-ignitions.

3. TYPE TEST IEC 62271-110: INDUCTIVE LOAD SWITCHING AND SITE TEST

Reactor switching is an operation where small differences in circuit parameters can produce large differences in the severity of the duty. In spite of this, IEC 62271-110 proposes a standard test circuit intended to cover interruption of different kinds of inductive loads. It is well established that tests using the standardized circuit give valuable information usable for estimating the switching over-voltages in different networks. This general type test may also be used for assessment of certain circuit-breaker properties such as chopping performance and re-ignition level.

The type test outcome can be grouped as follows:

Proving the interrupting capability of the breaker:
- To prove the ability of the breaker to interrupt the reactor current
- To prove that re-ignitions are not harmful to the breaker.

Investigation of the breaker`s behaviour mainly with regard to overvoltage generation:
- To achieve an estimate of the maximum chopping current
- To study the statistical distribution of the chopping currents (and any dependence on arcing time)
- To investigate the re-ignition probability or determine the range in CSD setting giving re-ignitions.
- To get an estimate of the dielectric strength characteristic of the contact gap.

An additional field test should be performed to correctly assess the performance of a certain circuit-breaker in a specific situation. The test results, even though only valid for that specific substation, can be extended to other installations only with the utmost care.

In other words, only field tests with a specific reactor can fully demonstrate the switching performance of a circuit-breaker under these particular conditions. Therefore, it is very important during commissioning of a circuit-breaker to take the time to test and verify the settings and limits of re-ignition free window.

4. COMPARISON STUDY

As mentioned above, a standard IEC laboratory type test must be performed in order to obtain general information about the circuit-breaker behaviour. It also provides a good basis for comparing the reactor current interrupting capabilities and the behaviour of different circuit-breakers models for the same circuit configuration, currents, voltages, transient recovery voltages, etc.

Interruption of small inductive currents is a very interactive process between the circuit-breaker and the shunt reactor. Different circuit-breaker technologies and models have different current chopping levels, arcing windows, rate of rise of dielectric strength (RRDS) and behave differently under re-ignitions. Circuit-breaker design greatly influences the overvoltages that may occur during interruption of shunt reactors. Small differences in the circuit parameters can produce large differences in the severity of the duty.

For economic reasons, some type tests were performed by some manufacturers only on one breaking chamber. Other manufacturer have done the test with both chambers. Values presented in this paper are reported for a 420 kV two chamber pole live tank circuit-breaker. Moreover, the circuit-breaker test object shall be as close as possible to the "real life conditions", which is at the most probable rated pressure of the extinguishing medium (corresponding to test duty 2 of IEC 62271-110).

4.1 Re-ignition free arcing window

The time from the instant of contact separation of the circuit-breaker contacts to the current zero crossing is the arcing time. This parameter is essential for shunt reactor de-energisation behaviour.

If the arcing time is too short (for example 2 ms), the circuit-breaker contacts are too close to each other (yielding a low dielectric strenght) at current zero crossing. When the transient recovery voltage (TRV) rises between the contacts, this will lead to a re-ignition, and therfore the breaker is not interupting the current as expected. In such a case the current is interupted one half cycle later, (at the next zero crossing). The prospective arcing time was 2 ms and the real arcing time, due to this re-ignition becomes 12 ms (2 ms + 10 ms). This phenomenon of re-ignition generates severe overvoltage stresses across the circuit-breaker terminals and in the surrounding network (including the shunt reactor).

In case of long arcing time (> 5 ms), the TRV will appear at a much larger contact gap with a higher dielectric strenght and the breaker will clear the current without any re-ignition.

Each circuit-breaker model has an arcing time window that can be divided in two regions: re-ignition free (withstand) and re-ignition arcing window. The wider the re-ignition free arcing window is, the better it is for the network and for the breaker itself. The arcing windows of five circuit-breaker models are compared and presented in Figures 4 – 9.

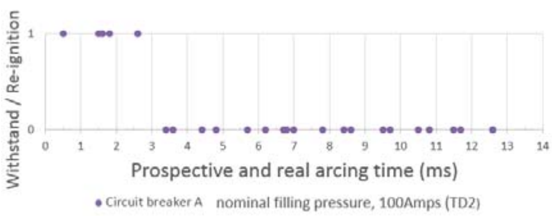

Figure 4: Circuit-breaker A arcing window.

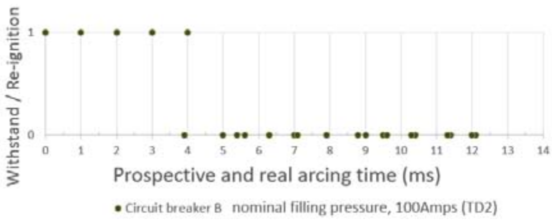

Figure 5: Circuit-breaker B arcing window.

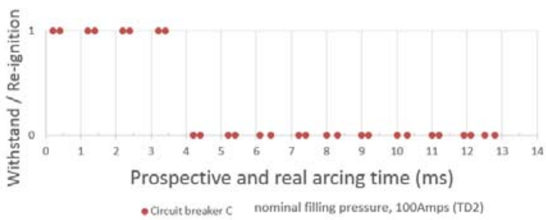

Figure 6: Circuit-breaker C arcing window.

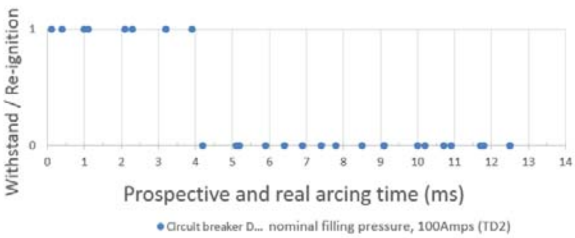

Figure 7: Circuit-breaker D arcing window.

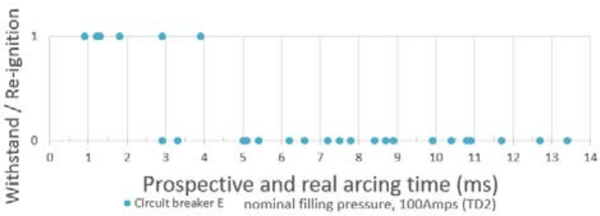

Figure 8: Circuit-breaker D arcing window.

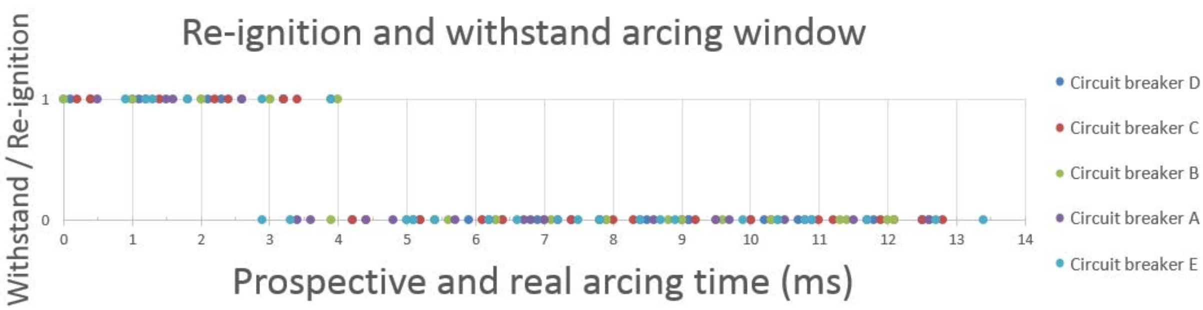

Figure 9: Comparisons of all five circuit-breaker`s arcing window

The transition between the re-ignition free region to the region where re-ignitions occur, takes place between arcing times of 3 and 4 ms for all the 420 kV live tank circuit-breakers considered here. Most of the breakers need arcing time exceeding 4 ms to avoid re-ignitions. Circuit-breaker A has a slightly wider re-ignition free arcing window (3.5 to 10 ms) than the others, i.e., 65% of the half cycle is re-ignition free.

For shunt reactor applications, arcing time settings of CSD equipment should for these breakers be above 4.0 ms. A safety margin, e.g. 2.0 ms due to mechanical discrepancy and temperature effects should be added. Consequently, an appropriate arcing time programmed into the CSD should be minimum 6.0 ms.

4.2 Current chopping

The current amplitude in shunt reactor switching is usually in the range from a several tens of amperes to several hundred amperes.

Most circuit-breaker vendors develop and manufacture only one circuit-breaker model. This model is supposed to be usable for all switching duties and fulfil all the corresponding IEC type test requirements: line, transformer, cable, capacitor bank, SVC, shunt reactor and short circuit making and breaking. In SF6 high-voltage circuits-breakers, the arc is subjected to intense blasting to be able to interrupt large short-circuit currents (up to 63 kA). Such a circuit-breaker has, therefore no difficulties with interrupting small shunt reactor currents. The shunt reactor current is usually forced to a premature zero, prior to a natural current zero. The phenomenon is known as current chopping and may give rise to severe overvoltages.

Since the current has a specific value at the instant of current chopping, there is certain magnetic energy stored in the shunt reactor. This energy can only be transferred to the stray capacitances, parallel to the inductance of the shunt reactor, in an oscillatory way, typically at a few kilohertz. Consequently, the energy trapped in the inductance at the instant of current chopping will oscillate between the two circuit elements, resulting in an overvoltage referred to as the suppression peak overvoltage. The maximum voltage occurs at the instant when all the trapped energy is stored in the stray capacitances. The maximum suppression peak voltage may occur on the second and third pole to clear, since these have longer arcing times and thus a higher chopping current amplitude.

Since the current chopping level was not provided in the type test documentation from the manufacturers and since it was not possible to measure with enough accuracy, this value was determined from the suppression peak overvoltage, the circuit parameters and the numbers of chambers, see Figure 10.

The main characteristic evaluated by shunt reactor current switching tests is the chopping number (λ).

By chopping number approach a circuit breaker is characterized by a simple relation between the chopping current (I0), the number of breaks in series (N), the capacitance seen from the circuit breaker terminals (C) and a constant specific for this circuit breaker named chopping number K:

$$I_0=K\sqrt{(C*N)}$$

The chopping number is an inherent characteristic of the circuit-breaker and is usually independent of the circuit. The chopping number can therefore be used to estimate the behaviour of the circuit-breaker in other circuits than the test circuit.

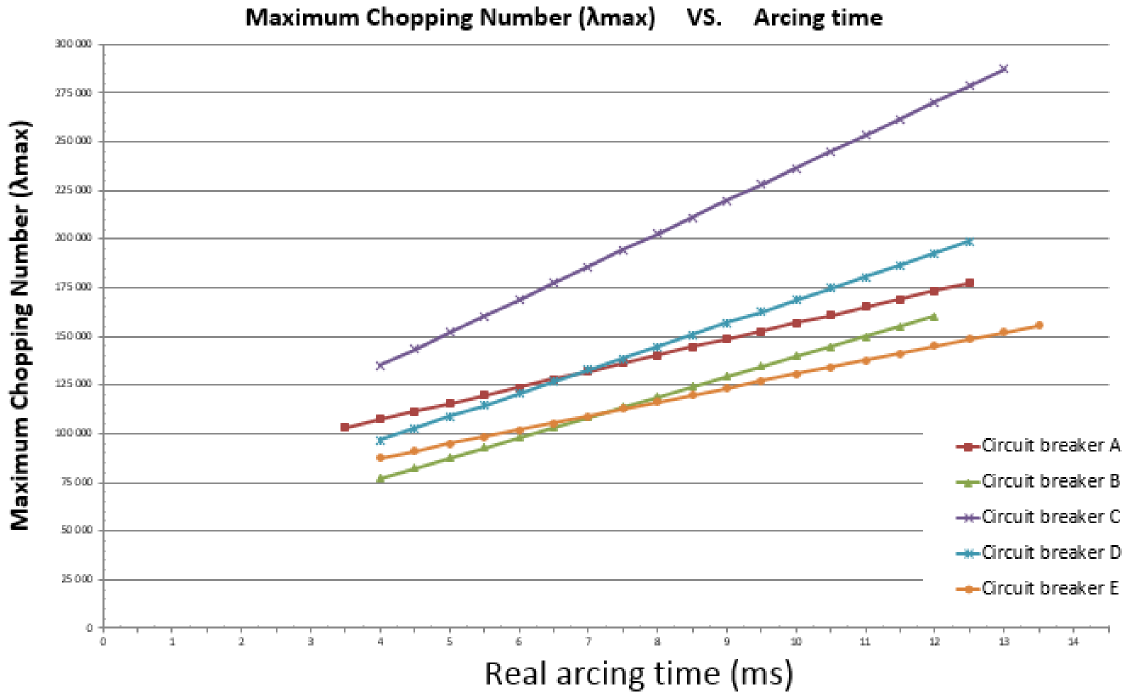

Figure 10: Maximum chopping number versus arcing time for the five circuit-breakers considered.

As shown in Figure 10, a linear relationship between chopping number and arcing time exists. The chopping number of a circuit-breaker depends on the breaker ratings and the interrupting chamber technology used (self blast or puffer).

A higher chopping number means a higher amplitude of the chopped current, and thus higher and potentially more harmful overvoltages being generated, and a greater risk for re-ignition. A breaker with a 63 kA short-circuit capability has a stronger blast on the arc than a 50 kA circuit-breaker. Consequently, a 63 kA circuit-breaker normally has a higher chopping number than a 50 kA breaker.

Against this background, the circuit-breakers considered in this study can be split into three categories:
- 50 kA self blast (circuit-breakers B and E)
- 63 kA self blast (circuit-breakers A and D)
- 63 kA puffer (circuit-breaker C)

From the perspective of current chopping/chopping number, a 50 kA self blast technology circuit-breaker is favourable. Using the 63 kA puffer type for shunt reactor switching should be avoided (unless extremely large short-circuit currents may occur).

4.3 Rate of rise of dielectric strength

Based on the re-ignition window (<4 ms for 50 Hz application) and the re-ignition voltage value (U_w: voltage across the circuit-breaker at re-ignition), it is possible to estimate the rate of rise of dielectric strength (RRDS) of each circuit-breaker as a function of time. A breaker with a high RRDS has a lower risk of re-ignitions. From a dielectric point of view, this is a better circuit-breaker, see Figure 11.

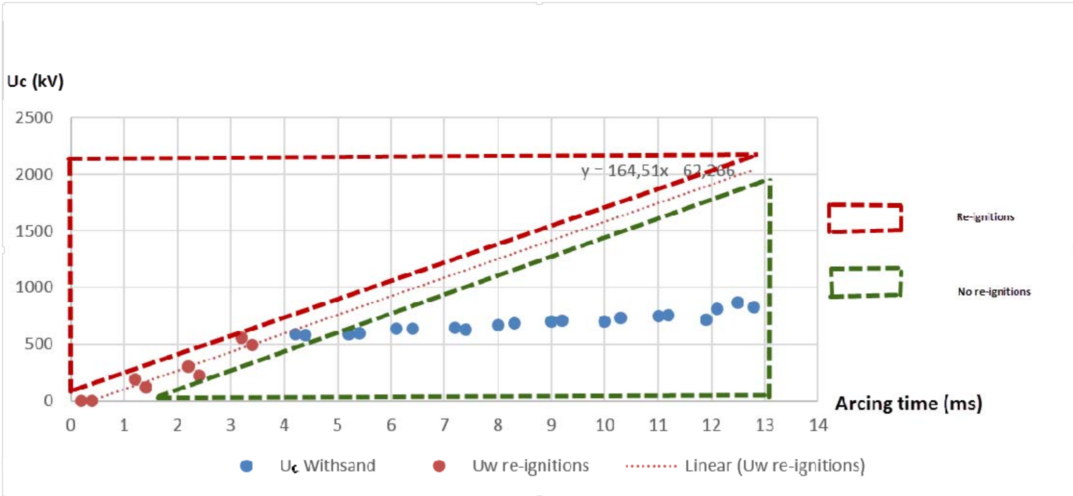

Figure 11: Dielectric strength versus time for circuit-breaker C.

The transient recovery voltage peak (U_c) for 420 kV circuit-breaker for shunt reactor applications is 652 kV, with a time to peak of 380 µs (ref. IEC 62271-110). This gives an average rate of rise of 1.72 kV/µs or 1720 kV/ms.

This parameter depends on the manufacturer's circuit-breaker design (dielectric profile, insulation materials, SF6 pressure, contact gap distance, speed etc.), but assuming a linear relationship is considered sufficiently accurate at least up to 10 ms after contact separation.

The dielectric strength as a function of time has been determined for the five AIS 420 kV circuit-breakers and is presented in Figure 12.

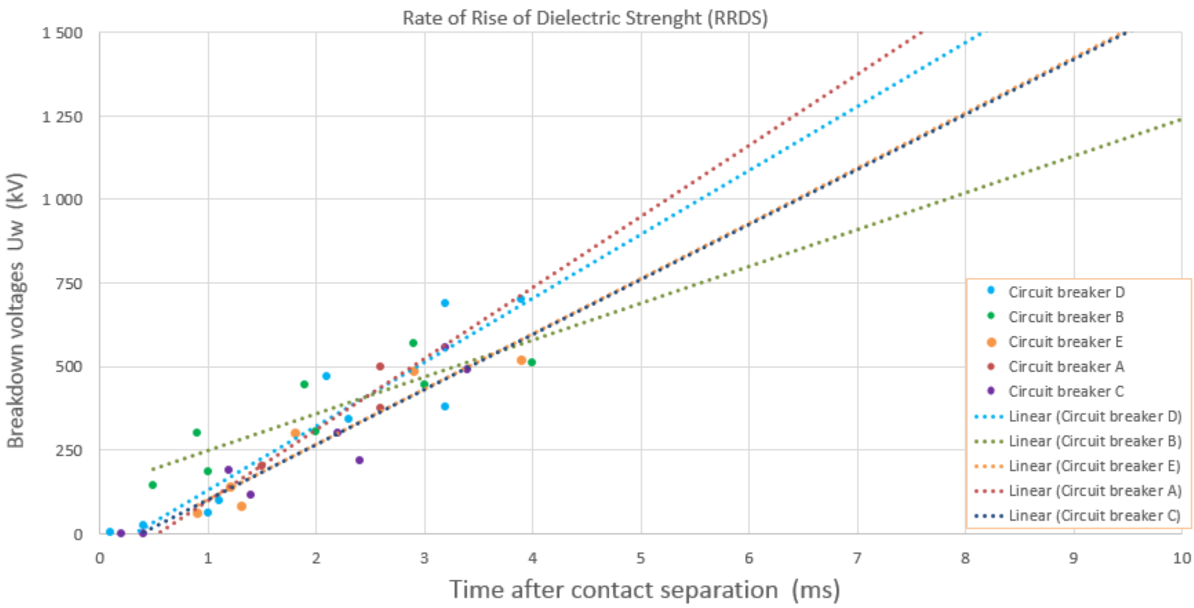

Figure 12: Estimate dielectric strength versus time for the five circuit-breakers.

After interruption of a small inductive current of 100 A (low thermal effect), self-blast 63 kA circuit-breakers (A and D) have the highest RRDS, approximately 190 and 210 kV/ms, respectively. The self blast 50 kA and the puffer 63 kA (C and E) have the same RRDS behaviour, with an RRDS of approximately 160 kV/ms. Finally, circuit-breaker B which is a self blast 50 kA model, has the lowest RRDS, approximately 110 kV/ms.

Hence, the self blast 63 kA breaker has the best performance with regard to the RRDS. This can be explained by their higher short-circuit-breaking capability compared to the 50 kA breaker.

5. CONCLUSION

The ideal circuit-breaker for de-energizing shunt reactors should have a large re-ignition free arcing window, low chopping number and high rate of rise of dielectric strength (RRDS). Since the re-ignition behaviour is related to the amplitude of the chopping current, the chopping number criterion should be emphasised. Table I summarizes the outcome of a comparison of the five circuit-breakers in this regard.

Table I. Summary of comparison between five circuit-breakers.

Rating and technology Criteria	50 kA self blast Circuit-breakers B and E	63 kA self blast Circuit-breakers A and D	63 kA puffer Circuit-breaker C
Re-ignition free arcing window	0	0	0
Chopping number	++	-	--
RRDS	-	+	0

The first conclusion is that, unfortunately, no circuit-breaker in this study is optimised for shunt reactor de-energization.

Concerning the re-ignition free arcing window criterion, there are no major differences among the studied circuit-breakers. RRDS and chopping number requirements are somehow contradictory. Circuit-breakers that have a high blasting effect, also have high current chopping numbers and a relatively high RRDS.

The 63 kA puffer breaker technology is less suited than the others for interrupting small inductive currents, due to very high chopping number and medium range RRDS.

The 63 kA self blast breakers considered also have a high chopping number which leads to high suppression peak or chopping overvoltages. However, the RRDS is better than for the 63 kA puffer and the 50 kA self blast breakers.

The 50 kA self blast circuit-breakers have a low chopping current compared to the others. The RRDS is somewhat lower than the 63 kA self blast breakers, and therefore causes a higher risk for re-ignitions and corresponding overvoltages.

From an economical perspective, 50 kA self blast circuit-breakers come out favourable compared to the others.

Hence, considering economical, HSE and technical aspects, it is concluded that 50 kA self blast circuit-breaker technology with composite insulator housings should be selected for shunt reactor switching applications.

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