D10.5: Document on failure mode analysis of HVDC circuit breakers

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EXECUTIVE SUMMARY

This deliverable provides a generic failure mode analysis of HVDC circuit breakers. The failure modes of various internal components and the subsequent impacts on the overall performance of the HVDC circuit breaker have been discussed for the following technologies of HVDC circuit breakers:

- Capacitor discharge based active current injection mechanical HVDC circuit breaker
- Voltage Source Converter (VSC) assisted resonant current (VARC) HVDC circuit breaker - another realization of active current injection mechanical breaker
- Hybrid mechanical breaker

A failure mode and effect analysis (FMEA) is performed without considering the detection and probability metrics which are usually taken into account in a traditional FMEA approach. The reason for this is that the different components of the DC breakers are used in a non-standardized way since these devices experience DC voltage and current stresses instead of AC, the statistical information of which is not readily available. The failure rates and lifetime estimates proposed by CIGRE could not be used since they refer to AC applications. For this reason, the study was focused on analysis of the failure modes of each individual component of the HVDC circuit breaker along with their associated failure causes and impacts on the operation of the overall circuit breaker. Some components, such as the surge arrester and residual current switch, are common to all DC breaker topologies and their operating principles and failure modes are similar. Thus, to avoid redundancy and duplication of information, the failure analysis of these components is presented in a separate chapter rather than together with different HVDC circuit breakers. Moreover, the vacuum interrupter is common to the two active current injection mechanical HVDC circuit breakers. Similar to the surge arresters, the failure modes and analysis of vacuum circuit breaker is also presented separately. Finally, the failure analysis of all the individual components unique to specific technology of HVDC breakers are presented in separate chapter or subchapters.

Typical failure modes of the various components are failure in open position (fails to close when needed), failure in closed position (fails to open when desired), leakage and overheating. These failures occur due to causes like control or protection system malfunction, high voltage and current stresses, ageing, corrosion, structural damage etc. The impact of these failures on the operation of the HVDC breaker could be inability to interrupt current —both fault and/or load current, compromised operation of the breaker (e.g. reduced fault clearing speed) or negligible. In fact, due to intellectual property related to each technology, the design considerations of different components to enhance the reliability of the overall breaker system and the techniques to address some failure modes and mechanisms to reduce failure probability are not discussed in this document.

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1 INTRODUCTION

1.1 PURPOSE

The purpose of this document is increasing the awareness and understanding of different failure mechanisms and their associated impacts of the different HVDC circuit breaker technologies. For this reason, a generalized failure mode and effect analysis (FMEA) for the following HVDC circuit breaker types is discussed:

- Capacitor discharge based active current injection DC breaker [1]
- Voltage source converter (VSC) assisted active current injection DC breaker (VARC[1]) [2]
- Hybrid DC circuit breaker [3]

In the traditional FMEA method, the failure modes of each component of the system should be identified along with their associated severity, detection and probability metrics. Due to the fact that in HVDC applications, the standard components (switching gaps, MOSA, power electronics) of the HVDC circuit breaker are used in an non-standard way, the last two metrics (detection and probability) are neglected, given that the use of CIGRE failure rates for these components would not be valid because they refer to AC applications. For this purpose, the analysis will be focused on the failure modes of each component of the HVDC circuit breaker, their associated failure causes and impact on the operation of the overall breaker system.

The fault tree method is used for the failure mode analysis of the three DC circuit breaker technologies. A graphical representation of this method is illustrated in Figure 1-1. As can be seen, each DC circuit breaker is decomposed into its components (1, 2,..,M). For each component of the breaker, the possible failure modes are first identified (1, 2,..,N). Then, for each failure mode, the root cause of the failure and the impact on the operation of the breaker need to be identified.

[1] Voltage source converter Assisted Resonant Current

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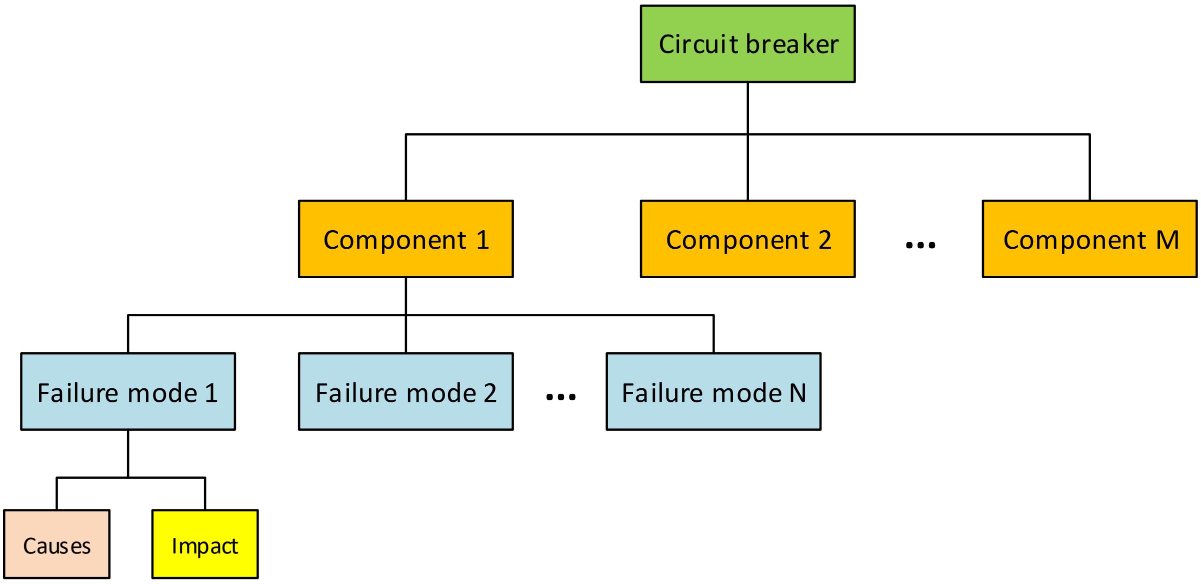

Figure 1-1 Fault tree analysis method

Given the lack of operational experience with this equipment, a lot of detailed information on failure modes of the overall system as well as the internal components is not available. Also, for reasons of confidentiality and competitiveness, project partners are hesitating to disclose this data. Failure experiences from testing the various prototypes of HVDC circuit breakers in PROMOTioN project, again because of confidentiality and competitiveness, cannot be disclosed to support this study. More information about the test procedures of the HVDC circuit breakers, the voltage and current waveforms during fault current interruption and the electrical stresses on the components of the breakers are provided in [4], [5], [6], [7], [8] and [9]. The publicly available deliverables of the PROMOTioN project can be found in [10].

1.2 MOTIVATION

Understanding the failure mechanisms of DC circuit breakers is of paramount importance for the proper design of an HVDC system and its protection schemes. The severity of the impact of each failure mode on the operation of the system is critical for the selection of the appropriate back-up protection systems, and the understanding of the root cause of each component failure is important for estimating the expected lifetime and scheduling the maintenance activities for the HVDC switchgear. For this reason, the main objectives of this deliverable are to identify:

- the potential failure modes of the internal components of different technologies of HVDC circuit breaker
- the failure causes of each failure mode
- the impact of each failure mode on the operation of the system

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1.3 DOCUMENT STRUCTURE

In Chapter 2, an introduction is given to the three DC circuit breaker types and their operating principles. In Chapter 3, the failure analysis of the common components for all three DC breakers is presented. The surge arrester (MOSA) and residual current switch are common in all DC breaker types and their failure modes are presented along with associated failure causes and impact on the operation of the system. Chapter 4 is focused on active current injection DC breakers. The chapter starts with the presentation of the failure analysis of the vacuum interrupter which is a common component in both types of active current injection breakers (capacitor discharge based and VSC assisted/VARC). In the following, the failure analysis of the individual components of each active current injection breaker is presented separately. Finally, the failure analysis of the individual components of the hybrid DC breaker is presented in Chapter 5 and the main conclusions of the failure mode analysis on DC breakers are summarized in Chapter 6.

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2 BRIEF REVIEW OF OPERATING PRINCIPLES OF HVDC CIRCUIT BREAKERS

HVDC circuit breakers used in multiterminal networks are expected to rapidly interrupt any fault current that appears in such a system (within 10 ms) and dissipate the significant amount of energy associated with the fault [7]. In HVDC systems, fault current zeros do not occur naturally; hence, breaker types usually used in AC-System cannot be applied. Thus, an HVDC circuit breaker needs to somehow create a local current zero in order to interrupt fault currents in a system. In addition, an HVDC circuit breaker needs to generate a counter-voltage higher than the system voltage in order to suppress the fault current to zero. To create local current interruption, to generate, limit and maintain the counter voltage and ultimately absorb system's magnetic energy during the fault, HVDC circuit breakers employ several parallel current branches consisting of different components serving different purposes depending on the technology. In case of active current injection HVDC breakers, the fault current commutates to the surge arrester branch by making use of a current injection circuit and a vacuum breaker [1]. In case of hybrid DC breakers, the fault current is commutated to the surge arrester by using semiconductor-based switches (e.g. IGBT or BIGT switches) [3].

In this study, two types of active current injection HVDC breakers are considered: the capacitor discharge based breaker which has been developed by Mitsubishi (MEU) and the voltage source converter (VSC) assisted breaker (VARC type) which has been developed by SCiBreak. The hybrid HVDC breaker type has been developed by ABB. The operating principles of each DC breaker will be described in this chapter.

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2.1 ACTIVE CURRENT INJECTION BREAKERS

2.1.1 CAPACITOR DISCHARGE BASED

The schematic of the capacitor discharge based DC circuit breaker is shown in Figure 2-1.

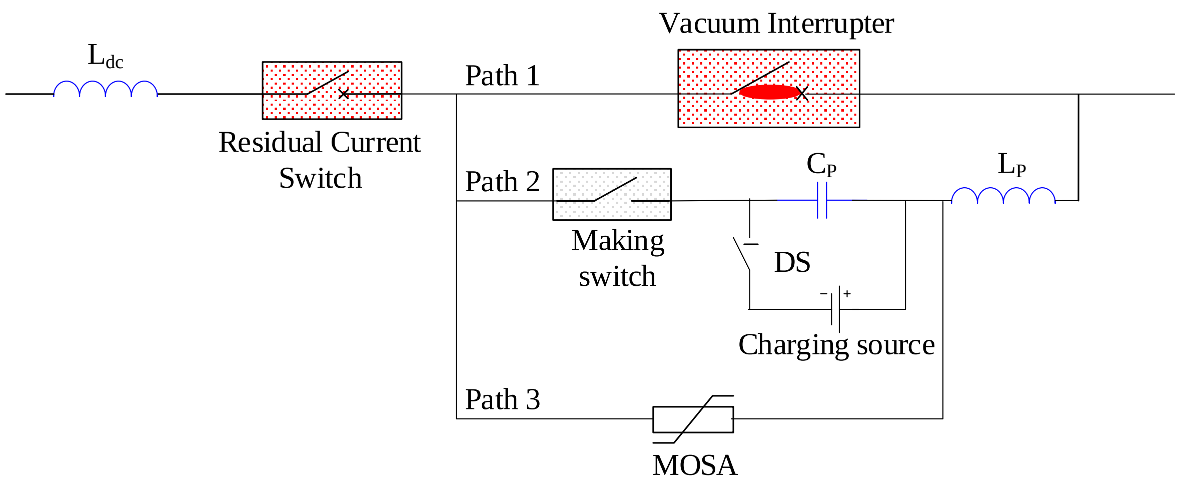

Figure 2-1 Capacitor discharge based DC breaker

During normal operation, the DC current flows though the vacuum interrupter (path 1). After the occurrence of a fault, the protection system detects a fault and sends trip command to the breaker. The breaker takes action; first by opening its vacuum interrupter. Then, after the vacuum interrupter reaches sufficient dielectric strength, a counter current is injected from the pre-charged capacitor (C_P), shown in Figure 2-1, by closing a high-speed making switch to create local current zero through the vacuum interrupter. If the vacuum interrupter succeeds in interrupting current at the created current zero, then the fault current is commutated to path 2 shown in the figure. An interaction of the capacitor and inductor (C_P and L_P) circuit is used in order to inject an oscillating counter-current into the loop created by paths 1 and 2 and force the current flowing through the vacuum interrupter to zero. As soon as the fault current commutates to path 2, the capacitor starts to re-charge, thus, creating counter voltage until the voltage reaches the clamping level of the metal oxide surge arrester (MOSA) in the path 3. Once the counter voltage reaches that level, the current commutates to the surge arrester (path 3) and a counter voltage is maintained to this level until the fault current is completely suppressed.

The rated voltage of the clamping level of the surge arrester is typically 1.5 p.u. Once this value is reached, a negative DC voltage is applied across the inductance L_{dc} and the fault current starts going down. After the fault current is supressed, small leakage current flows through the surge arrester. This leakage current is interrupted by opening the residual current switching device (switch or breaker) and the fault is cleared [1].

2.1.2 VSC ASSISTED (VARC)

A circuit diagram of a VARC DC circuit breaker module is shown in Figure 2-2. The VARC DC circuit breaker is a hybrid breaker in the sense that it relies on both mechanical and power electronic components in its main circuit in order to break current [2]. However, since the power electronics themselves do not interrupt current or withstand high voltage during current interruption, this technology is still categorized as mechanical HVDC circuit breaker. A VSC[2] converter is used to create a HF[3] resonant current with an increasing amplitude until this oscillating current equals or exceeds the fault current to be interrupted. This creates an artificial zero in the arcing vacuum interrupter. When the vacuum interrupter interrupts the current at that current zero, the current commutates first into the capacitor, and very shortly thereafter into the arrester branch. A controlled Voltage Source Converter (VSC), consisting of common off-the-shelf IGBTs and a DC-link capacitor bank, is used to excite the current in the resonant circuit. The advantage of this principle is that the power electronics remain operating at far lower voltage than system voltage.

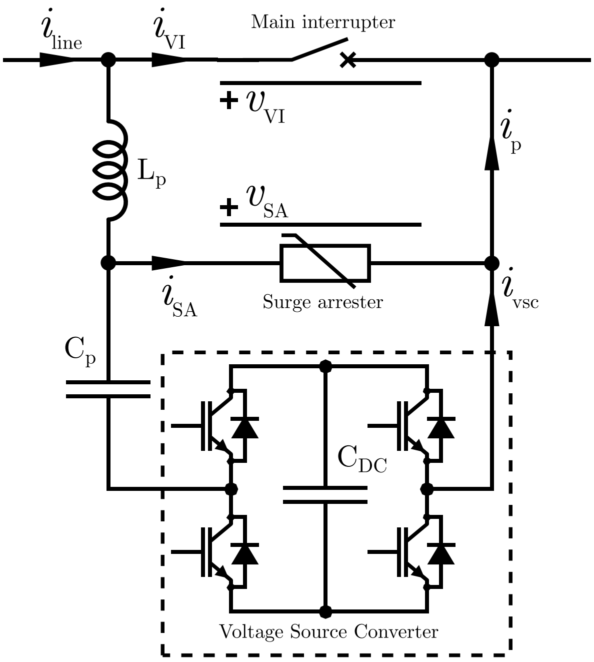

Figure 2-2 VSC assisted (VARC) circuit breaker

The VARC circuit breaker topology can be modularized, in the sense that the part of the breaker that performs the breaking operation is divided into a string of independent, series-connected circuit-

[2] Voltage Source Converter
[3] High Frequency

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breaker modules. The VARC circuit breaker modules that are tested and shown in the PROMOTioN project are designed for 40 kV TIV.

An outline of the full VARC circuit breaker is shown in Figure 2-3. In addition to the circuit breaker modules, the figure contains a separate circuit breaker, labelled as the *Residual Current Breaker* and a current limiting reactor with the label L_{DC}. The residual current breaker provides galvanic separation following a breaking operation and the current limiting reactor limits the rate of rise of the fault current in the case of a fault.

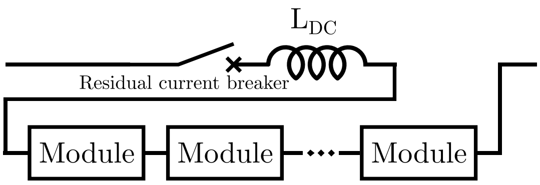

Figure 2-3 VARC DC CB outline

2.2 HYBRID BREAKER

The schematic of the hybrid HVDC circuit breaker is shown in Figure 2-4.

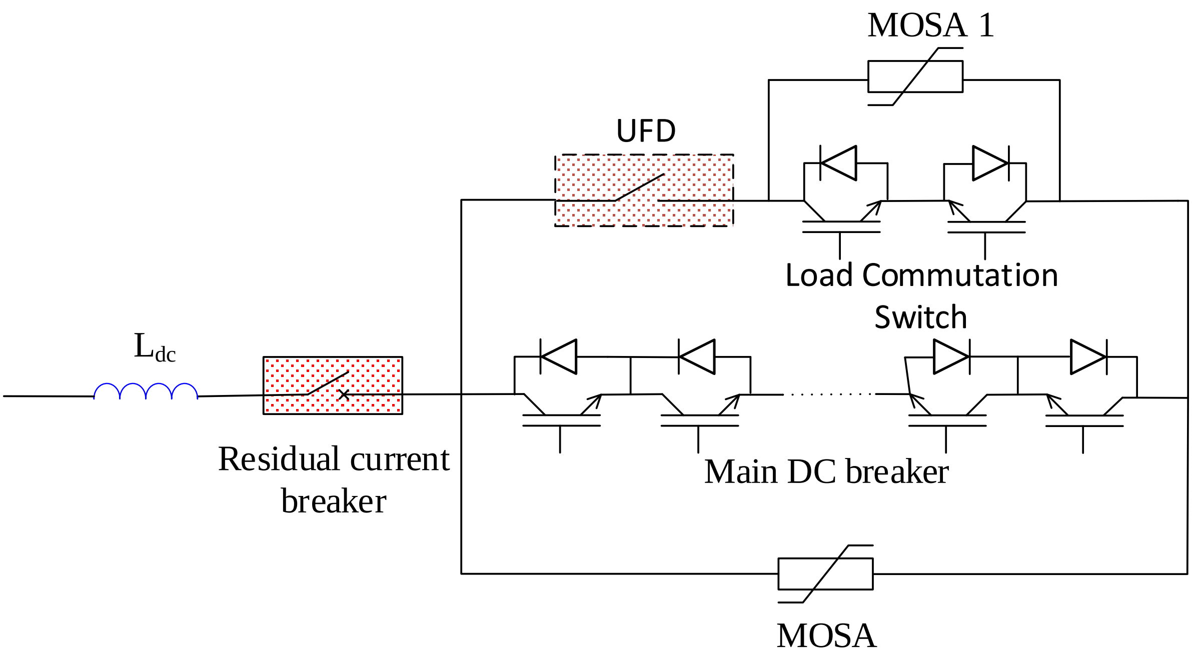

Figure 2-4 Hybrid DC circuit breaker

The hybrid breaker consists of 3 parts: the normal current conduction branch, the commutation branch and the energy absorption branch. During normal operation, the current flows though the normal

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conduction branch which consists of the series connection of the Ultra-Fast Disconnector (UFD) and the Load Commutation Switch. The Load Commutation Switch usually consists of a matrix of series and parallel power semi-conductors and is connected in parallel with a surge arrester which starts to conduct large current as soon as its clamping level is reached. The Ultra-Fast Disconnector is typically an ultra-fast mechanical switch. After the occurrence and the detection of the fault, an opening command is sent to the HVDC circuit breaker. The breaker takes action first by switching the power electronics of the load commutation switch off. Then the fault current commutates into the main breaker realized as power electronic breaker in the commutation branch. The main breaker consists of many series connected power semi-conductors. Usually hundreds of power semi-conductors are required in order to increase the voltage withstand capability of the main breaker and as a result, the conduction losses of this branch are high. After the fault current is commutated into the commutation branch, the contacts of the UFD start moving apart and once they reach a sufficient gap distance, the power electronic switches of the main breaker are turned off. This is followed by a voltage rise by charging some snubber elements which leads to current commutation into the energy absorption branch (MOSA). The commutation branch carries the fault current until the UFD achieves sufficient dielectric strength. In this way, the UFD disconnector gains sufficient voltage withstand capability to endure the counter-voltage which is limited and maintained by the MOSA. Finally, the fault current is going down while the MOSA is absorbing energy from the system. Similar to other HVDC circuit breaker technologies, small leakage current flowing through the MOSA can be interrupted by opening the Residual Current Switching device [3].

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3 FAILURE ANALYSIS OF COMMON COMPONENTS OF ALL DC CIRCUIT BREAKERS

3.1 FAILURE ANALYSIS OF MOSA

The most likely cause of failure of surge arresters in HVDC CB applications is thermal overload; either from a high current during current suppression, or from a low but long-term leakage current after an interruption operation has been completed. For example, this leakage current through the surge arrester stacks would continue to flow if the residual current switching device had failed to open [5] [8].

Failure of the surge arrester during the suppression time is expected to possibly result either from the surge arrester not meeting its design specifications, or from the dissipated energy during operation greatly exceeding the design value. Since the surge arrester stack cools down relatively slowly, with a time constant for cooling in the order of hours, the surge arrester could be overloaded if the breaker is forced to interrupt many times within this time interval. The size of the surge arrester stack should therefore be chosen so that the breaker can perform with certainty a determined minimum amount of operations without significant cooling of the surge arrester between the operations [7] [5] [4].

In case the surge arrester fails, the fault will not be suppressed by the breaker module in which the failed surge arrester is located.

In the following, the different failure modes of the surge arrester will be presented along with their failure causes and the impact on the operation of the breaker. The list of the failure modes of the MOSA is presented in Table 3.1.

Table 3.1 List of failure modes of MOSA

Failure mode of MOSA	Table
Surge arrester burst	**Table 3.2**
Overheating and gradual degradation	**Table 3.3**
Structural damage	**Table 3.4**
External breakdown	**Table 3.5**
Fails into short-circuit	**Table 3.6**
Fails into open circuit (very unlikely to happen for MOSAs)	**Table 3.7**

Table 3.2 Failure of surge arrester: surge arrester burst

Component	Surge arrester
Failure mode	Surge arrester burst
Failure cause	Thermal runaway due to excessive energy dissipation during the suppression time

Impact	• Breaker module does not contribute to fault current suppression • Failure of surge arrester stack and external arcing in the module

Table 3.3 Failure of surge arrester: overheating and gradual degradation

Component	Surge arrester
Failure mode	Overheating and gradual degradation
Failure cause	Failure of residual current switch to open
Impact	• Increased voltage stress on surge arresters in other modules, likely leading to further failures if residual breaker stays closed. • Failure of surge arrester stack • Breaker might fail to open during a repeated switching action

Table 3.4 Failure of surge arrester: Structural damage

Component	Surge Arrester
Failure mode	Structural damage
Failure cause	• Ageing • Mechanical stress in excess of rating (e.g. seismic stresses)
Impact	Breaker fails to interrupt fault current

Table 3.5 Failure of surge arrester: external breakdown

Component	Surge Arrester
Failure mode	External breakdown
Failure cause	Ageing (e.g. degradation of creeping distance insulation)
Impact	Breaker fails to interrupt fault current and external arcing across the device

Table 3.6 Failure of surge arrester: Failure into short-circuit

Component	Surge arrester
Failure mode	Fails into short-circuit
Failure cause	• Mechanical damage in MOSA-block, possibly impacting both the V/I characteristics and the energy absorption capability. • Unequal energy distribution • Exceeding energy absorption capability
Impact	• Assuming that just a part of the MOSA section has failed into short circuit: reduced counter-voltage from the MOSA branch, resulting in longer energy absorption time Consequently more energy will be absorbed, which results in higher stress on the healthy MOSA blocks. • Typically, the MOSA consists of several parallel MOSA blocks. When one of the MOSA blocks fails into short-circuit (one column), that column experience a significant change in its V/I-characteristics, resulting in unequal energy distribution (the short-circuited column will be loaded with the full fault current which should ideally be shared among all the parallel columns). This high energy dissipation could cause the MOSA to fail into open circuit leading to its destruction

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Table 3.7 Failure of surge arrester: Failure into open circuit

Component	Surge arrester
Failure mode	Fails into open circuit (very unlikely to happen for MOSAs)
Failure cause	Very high energy absorption, e.g. from previous “failed into short-circuit”-events
Impact	• In case there is only one MOSA column, no counter (clamping) voltage is generated when the commutation branch of the breaker opens. This would result in an uncontrollable voltage rise across the breaker which could potentially lead to flashover and destruction of the breaker. • In case there are multiple MOSA columns, the healthy columns could be overloaded by the fault current leading to insufficient counter voltage (clamping voltage) generation and consequently to fault current interruption failure

Failure tests of surge arresters are described in PROMOTioN deliverable D10.4 [4].

3.2 FAILURE ANALYSIS OF RESIDUAL CURRENT SWITCH

The purpose of the residual current switch (RCS) is to separate the breaker module from the system voltage after interruption and to interrupt the residual current. This is necessary to protect the DC breaker from the system voltage and its transients and to have a galvanic isolation following a breaking operation. The demands on its breaking capacity are not large; it should be capable of interrupting a small current in the order of a few amperes following the DC fault current interruption. Depending on the (local) system configuration, this may be a DC current or a current having zero crossings. This might have an impact on the type of the switching device which is suitable for this task. The demands on its voltage withstand capability, however, are those of the full breaker and grid. The failure modes of the residual current switch are the same as those of the interrupters / disconnectors in all DC breakers, but the impacts on the operation of the breaker are different.

The failure modes of the residual current switch are presented in the following tables along with their associated failure causes and impacts on the operation of the DC breaker.

Since the residual current switch might be a conventional switching device, the distinction between major and minor failures are made, leading to a more detailed analysis regarding mechanical defects. Nevertheless, quantitative data are not available and AC circuit breaker failure data are not applicable.

The list of the failure modes of the residual current switch is presented in Table 3.8.

Table 3.8 List of failure modes of residual current switch

Failure mode of RCS	Table
Inability to withstand line current in closed position	**Table 3.9**
Failure to interrupt	**Table 3.10**
Failure to withstand system voltage after interruption, (restrike) in stationary position	**Table 3.11**
Does not close on command	**Table 3.12**
Does not open on command	**Table 3.13**
Closes without command	**Table 3.14**
Opens without command	**Table 3.15**
Air or hydraulic oil leakage in the operating mechanism	**Table 3.16**
Small SF6/dry air/ vacuum leakage	**Table 3.17**
Oil leakage of grading capacitors	**Table 3.18**
Change in mechanical functional characteristics	**Table 3.19**
Change in electrical functional characteristics	**Table 3.20**
Change in functional characteristics of control or auxiliary systems	**Table 3.21**

Table 3.9 Failure of residual current switch: Inability to withstand line current in closed position

Component	Residual current switch
Failure mode	Inability to withstand line current in closed position
Failure cause	• Significant long term overcurrents • Damage to contacts or other parts of the interrupter
Impact	• Destruction of the residual current switch

Table 3.10 Failure of residual current switch: Failure to interrupt (reignition)

Component	Residual current switch
Failure mode	Failure to interrupt
Failure cause	• Current zero crossing with accompanying TRV[4] imposed too soon after high charge commutation through the arc and contacts • Damage to contacts or other parts of the interrupter
Impact	• Delayed interruption (in case of oscillating current) in the residual current switch, not severe if the breaker eventually interrupts the current. • If the current is not interrupted by the residual current switch, the leakage current through the MOSA will lead to high energy dissipation and destruction of the MOSA due to thermal overloading

Table 3.11 Failure to withstand system voltage after interruption (restrike) in stationary position

Component	Residual current switch
Failure mode	Failure to withstand system voltage after interruption (restrike) in stationary position
Failure cause	Insufficient contact separation to withstand the system voltage
Impact	Delayed clearing of the current in the residual current switch after interruption, not severe if the switch eventually withstands the system voltage (non-sustained discharge). In case of a sustained discharge, risk of breakdown of circuit breaker components because of continued exposure to the system voltage and its transients.

[4] Transient Recovery Voltage

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Table 3.12 Failure of residual current switch: Does not close on command

Component		Residual Current Switch
Failure mode		Does not close on command
Failure cause		• Malfunction in controller • Mechanical stress in excess of rating • Environmental stresses (other than lightning) in excess of ratings
Impact	During normal operation (in service/load current interruption)	Operation of the system cannot be resumed
	During fault	Not applicable

Table 3.13 Failure of residual current switch: Does not open on command

Component		Residual Current Switch
Failure mode		Does not open on command
Failure cause		• Malfunction in controller • Mechanical stress in excess of rating (e.g. seismic strength) • Environmental stresses (other than lightning) in excess of ratings
Impact	During normal operation (in service/load current interruption)	Residual current not interrupted, thermal overload of arresters and absence of insulation
	During fault	Residual current not interrupted, thermal overload of arresters

Table 3.14 Failure of residual current switch: closes without command

Component		Residual Current Switch
Failure mode		Closes without command
Failure cause		• Malfunction in controller • Mechanical stress in excess of rating (e.g. seismic strength) • Environmental stresses (other than lightning) in excess of ratings
Impact	During normal operation (in service/load current interruption)	Overstressing of arresters (thermal) and other components (dielectrically), no voltage separation function of the breaker system
	During fault	Not applicable

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Table 3.15 Failure of residual current switch: opens without command

Component		Residual Current Switch
Failure mode		Opens without command
Failure cause		• Malfunction in controller • Mechanical stress in excess of rating (e.g. seismic strength) • Environmental stresses (other than lightning) in excess of ratings
Impact	During normal operation (in service/load current interruption)	Contacts will be damaged by the arc, residual current switch not designed to interrupt load current
	During fault	Destruction of the device

Table 3.16 Failure of residual current switch: air or hydraulic oil leakage

Component		Residual Current Switch
Failure mode		Air or hydraulic oil leakage in the operating mechanism
Failure cause		Mechanical or structural damage, Ageing
Impact	During normal operation (in service/load current interruption)	None if taken care of in proper way and time
	During fault	• None if taken care of in proper way and time • If not detected early, this could lead to malfunction of the residual current switch

Table 3.17 Failure of residual current switch: small SF6/dry air/vacuum leakage

Component		Residual Current Switch
Failure mode		Small SF6/dry air/vacuum leakage
Failure cause		Ageing
Impact	During normal operation (in service/load current interruption)	None if taken care of in proper way and time
	During fault	Decrease in dielectric strength which can cause interruption failure

Table 3.18 Failure of residual current switch: oil leakage of grading capacitors

Component		Residual Current Switch
Failure mode		Oil leakage of grading capacitors
Failure cause		Ageing
Impact	During normal operation (in service/load current interruption)	None if taken care of in proper way and time
	During fault	Interruption failure may occur

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Table 3.19 Failure of residual current switch: change in mechanical functional characteristics

Component		Residual Current Switch
Failure mode		Change in mechanical functional characteristics
Failure cause		• Ageing • Mechanical stress in excess of rating
Impact	During normal operation (in service/load current interruption)	None if taken care of in proper way and time
	During fault	Opening speed will decrease which can cause electrical breakdown between the contacts

Table 3.20 Failure of residual current switch: change in electrical functional characteristics

Component		Residual Current Switch
Failure mode		Change in electrical functional characteristics
Failure cause		• Ageing • Electrical stress in excess of rating
Impact	During normal operation (in service/load current interruption)	None if taken care of in proper way and time
	During fault	Interruption failure may occur due to reduction of interruption performance

Table 3.21 Failure of residual current switch: change in functional characteristics of control or auxiliary systems

Component		Residual Current Switch
Failure mode		Change in functional characteristics of control or auxiliary systems
Failure cause		Electrical failure
Impact	During normal operation (in service/load current interruption)	None if taken care of in proper way and time
	During fault	Interruption failure may occur

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4 FAILURE ANALYSIS OF ACTIVE CURRENT INJECTION BREAKERS

4.1 FAILURE ANALYSIS OF VACUUM BREAKER

The vacuum circuit breaker (VCB) is required to fulfil vital roles at all times in an active current injection breaker, both in the capacitor discharge based DC circuit breaker as in the VSC assisted one [1]. For this analysis, the VCB is considered to have as principal components the (high-speed) drive (or actuator) and the vacuum interrupter (VI), the arcing chamber in which current interruption is achieved. Failure modes of both main components are considered. During a breaking operation, the VCB needs to conduct the fault current, successfully interrupt at/around current zero and subsequently withstand the ensuing TIV. Failure during the course of any of these events leads to inability of the affected breaker module to contribute to suppression of the fault current. Possible failures of the vacuum interrupter also include overheating and failure in steady state operation.

The failure modes of the vacuum interrupter are presented in the following tables along with their associated failure causes and impacts on the operation of the DC breaker. The list of the failure modes of the vacuum breaker is presented in Table 4.1.

Table 4.1 List of failure modes of vacuum breaker

Failure mode of Vacuum Breaker	Table
Inability to withstand load current in closed position	**Table 4.2**
Failure to interrupt (consecutive or multiple reignitions which lead to interruption failure)	**Table 4.3**
Failure to withstand TIV (restrike)	**Table 4.4**
Inability to close	**Table 4.5**
Inability to open	**Table 4.6**
Does not close on command	**Table 4.7**
Does not open on command	**Table 4.8**
Closes without command	**Table 4.9**
Opens without command	**Table 4.10**
Breakdown to earth in closed position	**Table 4.11**
Breakdown to earth during an opening operation	**Table 4.12**
Small SF6/dry air/vacuum leakage	**Table 4.13**
Oil leakage of grading capacitors	**Table 4.14**
Change in mechanical functional characteristics	**Table 4.15**

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Table 4.2 Failure of vacuum breaker: Inability to withstand load current in closed position

Component	Main interrupter and its actuator
Failure mode	Inability to withstand load current in closed position
Failure cause	• Significant long term overcurrents • Damage to contacts or other parts of the VI • Insufficient contact force from the actuator
Impact	Destruction of the VI and no current conduction through the breaker Welding of the contacts, no more opening possible

Table 4.3 Failure of vacuum breaker: Failure to interrupt (consecutive or multiple reignitions)

Component	Main interrupter
Failure mode	Failure to interrupt (consecutive or multiple reignitions which lead to interruption failure)
Failure cause	• Current zero crossing with accompanying ITIV[5] and TIV[6] imposed too soon after high charge commutation through the arc and contacts or after too short time to reach adequate contact separation to withstand TIV • Damage to contacts or other parts of the VI • Malfunction of the drive (too slow, not enough gap)
Impact	• No current interruption in the affected module • Long duration arcing in the VI leads to pressure rise and loss of insulation and arc quenching capability

Table 4.4 Failure of vacuum breaker: Failure to withstand TIV (restrike)

Component	Main interrupter
Failure mode	Failure to withstand TIV (restrike)
Failure cause	Insufficient contact separation to withstand the TIV
Impact	• Delay or absence of current interruption in the affected module • VI's have the capability to restore insulation very quickly after breakdown, but this is not guaranteed. It depends on the discharge current magnitude and its frequency

Table 4.5 Failure of main interrupter actuator: Inability to close

Component	Main interrupter actuator
Failure mode	Inability to close
Failure cause	Damaged actuator, or failure in drive circuitry
Impact	All other modules will be required to immediately open again, in order to avoid failure of the surge arrester stack in the module that is unable to close.

[5] Initial Transient Interruption Voltage: the voltage which appears across the switching gap the first microseconds after current interruption
[6] Transient Interruption Voltage

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Table 4.6 Failure of main interrupter actuator: Inability to open

Component	Main interrupter actuator
Failure mode	Inability to open
Failure cause	Damaged actuator, or failure in drive circuitry
Impact	The affected module will not be able to contribute to fault current suppression.

Table 4.7 Failure of vacuum breaker: Does not close on command

Component		Vacuum circuit breaker
Failure mode		Does not close on command
Failure cause		• Malfunction in controller • Mechanical stress in excess of rating • Environmental stresses (other than lightning) in excess of ratings
Impact	During normal operation (in service/load current interruption)	No current conduction through CB
	During fault	Not applicable

Table 4.8 Failure of vacuum breaker: Does not open on command

Component		Vacuum circuit breaker
Failure mode		Does not open on command
Failure cause		• Malfunction in controller • Mechanical stress in excess of rating (e.g. seismic strength) • Environmental stresses (other than lightning) in excess of ratings
Impact	During normal operation (in service/load current interruption)	• Fails to interrupt load current
	During fault	• Fails to interrupt fault current • Possible contact welding because full current passes through closed contacts • Thermal instability

Table 4.9 Failure of vacuum breaker: Closes without command

Component		Vacuum circuit breaker
Failure mode		Closes without command
Failure cause		• Malfunction in controller • Mechanical stress in excess of rating (e.g. seismic strength) • Environmental stresses (other than lightning) in excess of ratings
Impact	During normal operation (in service/load current interruption)	Unexpected restoration of current flow / voltage application in system, safety implications if CB consists of only one module
	During fault	Not applicable

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Table 4.10 Failure of vacuum breaker: Opens without command

Component		Vacuum circuit breaker
Failure mode		Opens without command
Failure cause		• Malfunction in controller • Mechanical stress in excess of rating (e.g. seismic strength) • Environmental stresses (other than lightning) in excess of ratings
Impact	During normal operation (in service/load current interruption)	Contact and CB will be damaged by the arc (too long arc duration)
	During fault	Contact will be destroyed by the arc (long arc duration)

Table 4.11 Failure of vacuum breaker: Breakdown to earth in closed position

Component		Vacuum circuit breaker
Failure mode		Breakdown to earth in closed position
Failure cause		• Ageing • Voltage in excess of rating • Lightning overvoltage in excess of rating
Impact	During normal operation (in service/load current interruption)	• Fails to carry load current • Fault current to earth
	During fault	• Fails to interrupt fault current depending on fault location • Fault current to earth

Table 4.12 Failure of vacuum breaker: Breakdown to earth during an opening operation

Component		Vacuum circuit breaker
Failure mode		Breakdown to earth during an opening operation
Failure cause		• Ageing • Switching overvoltage in excess of rating
Impact	During normal operation (in service/load current interruption)	• Fault current to earth, depending on fault location • No load current conduction
	During fault	• Fault current to earth • Unsuccessful fault clearing

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Table 4.13 Failure of vacuum breaker: vacuum leakage

Component		Vacuum interrupter
Failure mode		Small SF6/dry air/vacuum leakage
Failure cause		• Ageing • Insulation failure
Impact	During normal operation (in service/load current interruption)	Negligible
	During fault	• If leakage is detected on time, interruption process will not be affected • If not detected early enough, it could lead to decrease in dielectric strength which can lead to interruption failure

Table 4.14 Failure of vacuum breaker: Oil leakage of grading capacitors

Component		Vacuum interrupter
Failure mode		Oil leakage of grading capacitors
Failure cause		Ageing
Impact	During normal operation (in service/load current interruption)	Negligible
	During fault	Interruption failure may occur

Table 4.15 Failure of vacuum breaker: Change in mechanical functional characteristics

Component		Actuator of vacuum breaker
Failure mode		Change in mechanical functional characteristics
Failure cause		• Ageing • Mechanical stress in excess of rating
Impact	During normal operation (in service/load current interruption)	Negligible
	During fault	Opening speed will decrease which can cause electrical breakdown between the contacts

The position of the vacuum interrupter in the VARC module circuit diagram is shown in Figure 4-1. Excessive charge commutation or mechanical shocks may cause the vacuum interrupter to permanently reignite more frequently. Reignitions are current zero crossings of the HF (high frequency) injection current[7] at which no interruption takes place [4]. Reignitions are not a failure itself, because experience shows (see PROMOTioN Deliverable D10.4) that after several HF current zero crossings

[7] Frequency of injection current: in the range of 2-3 kHz for the capacitor discharge based breaker (Mitsubishi) and around 20 kHz for the VSC assisted (VARC) breaker (SciBreak) [7].

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the arc interrupts. An example of how two typical reignitions look in the case of the VARC circuit breaker are shown at a magnified scale in Figure 4-2. The first reignition occurs immediately after zero-crossing, at a very low voltage. There is nearly no attempt from the VI to withstand the ITIV, and this type of reignitions has a thermal origin. After the next zero crossing, the VI performs a partial recovery of its voltage withstand capability and then reignites approximately 3 µs after the second zero-crossing. This case therefore shows both a very early reignition, and one that occurs relatively late. The current and voltage signals are unprocessed, and therefore contain some minor artifacts; a combination of offset and capacitive coupling on the Rogowski coil that is used for current measurement, and an inductive component in the VI voltage measurement. The sampling frequency is 150 MS/s, and the sensors used have a bandwidth of 50 MHz for the voltage measurement and 300 MHz for the current measurement.

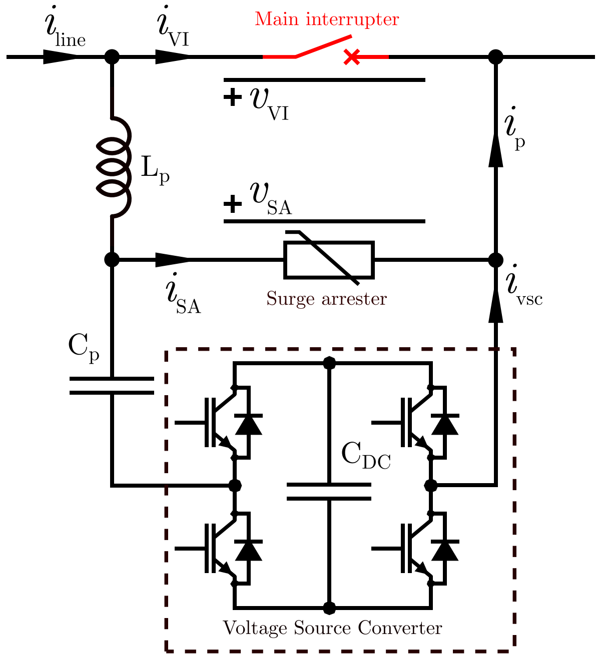

Figure 4-1 The position of the main interrupter in the VARC module circuit diagram.

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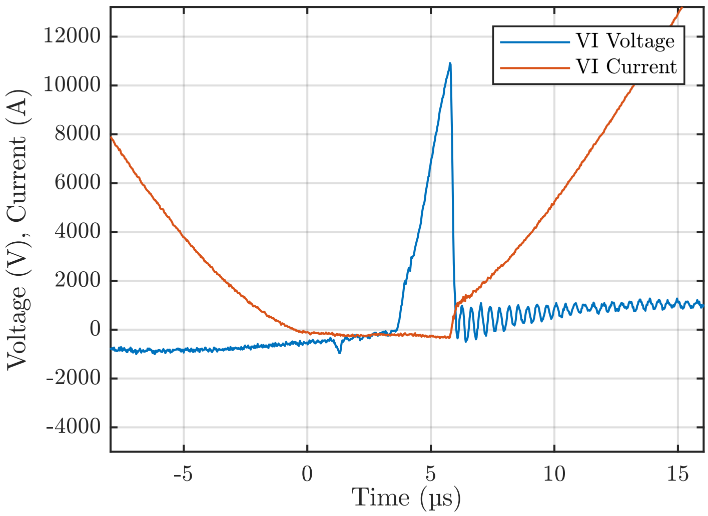

Figure 4-2 Reignition in VI a few hundred ns after a first current zero, followed by another reignition approximately 3 µs after the next current zero. The zero on the time axis is placed approximately at the instant of the first current zero. The VI used for the measurements had mechanical damage in the contacts.

The same interruption typically occurs quite inconspicuously, as shown in

Figure **4-3**. The capability of VIs to interrupt high-frequency currents varies considerably both between different types of VI and between different use cases of the same VI. Care therefore has to be taken when choosing the VI, and the circuits that surround it, in order to provide auspicious conditions for an interruption at the first current-zero to be free from reignitions. However, the occurrence of a number of reignitions of HF injection current before interruption is in principle harmless.

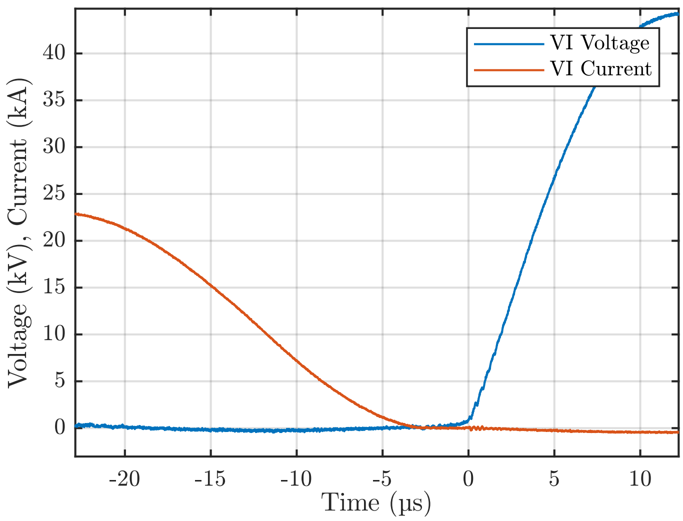

Figure 4-3 An interruption in a similar setting as fig. 4-2 on first zero-crossing, without reignitions, for reference. The zero on the time axis is placed approximately at the instant of the current zero.

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4.2 FAILURE ANALYSIS OF CAPACITOR DISCHARGE BASED BREAKERS

4.2.1 FAILURE OF CURRENT INJECTION CIRCUIT

The position of the current injection circuit in the capacitor discharge based DC breaker is shown in Figure 4-4.

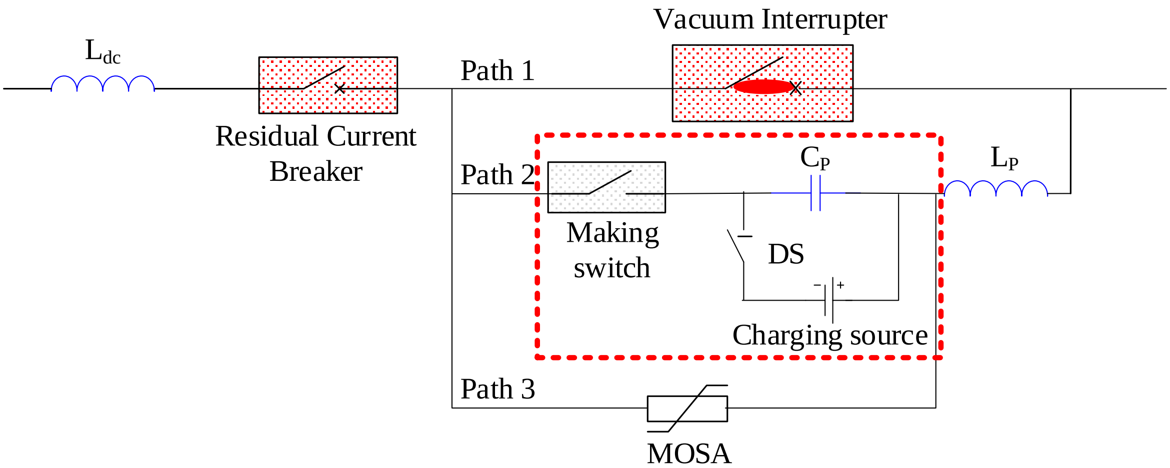

Figure 4-4 The position of the current injection circuit in the capacitor discharge based mechanical DC breaker circuit diagram

The failure modes of the current injection circuit along with their failure causes and impacts on the operation of the DC breaker are presented in the following tables. A list of the failure modes of the current injection circuit is presented in **Table 4.16**.

Table 4.16 List of failure modes of current injection circuit

Failure mode of current injection circuit	Table
High-speed making switch: Does not close on command	**Table 4.17**
High-speed making switch: Does not open on command	**Table 4.18**
High-speed making switch: Closes without command	**Table 4.19**
High-speed making switch: Scatter in discharge of injection current	**Table 4.20**
Mechanical switching gap: Does not close on command	**Table 4.21**
Gaps (commutation): Closes without command	**Table 4.22**
Gaps (commutation): Scatter in discharge of resonant current	**Table 4.23**

Table 4.17 Failure of high-speed making switch: Does not close on command

Component		High-speed making switch
Failure mode		Does not close on command
Failure cause		• Malfunction in controller • Mechanical stress in excess of rating (e.g. seismic strength) • Environmental stresses (other than lightning) in excess of ratings
Impact	During normal operation (in service/load current interruption)	Failure to interrupt load current
	During fault	Failure to interrupt fault current because of the absence of current zero crossing in the vacuum interrupter

Table 4.18 Failure of high-speed making switch: Does not open on command

Component		High-speed making switch
Failure mode		Does not open on command
Failure cause		• Malfunction in controller • Mechanical stress in excess of rating (e.g. seismic strength) • Environmental stresses (other than lightning) in excess of ratings • Malfunction in drive / controller • Contact welding
Impact	During normal operation (in service/load current interruption)	• Injection circuit capacitor cannot be charged • Failure to interrupt load current
	During fault	• Injection circuit capacitor cannot be charged • Failure to interrupt fault current

Table 4.19 Failure of high-speed making switch: Closes without command

Component		High-speed making switch
Failure mode		Closes without command
Failure cause		• Malfunction in controller • Mechanical stress in excess of rating (e.g. seismic strength)
Impact	During normal operation (in service/load current interruption)	• Injection capacitor gets discharged • Load current cannot be interrupted
	During fault	• Injection capacitor gets discharged • Fault current cannot be cleared

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Table 4.20 Failure of high-speed making switch: Scatter in discharge of injection current

Component		High-speed making switch
Failure mode		Scatter in discharge of injection current
Failure cause		• Ageing (change in electrical characteristic) • Malfunction in controller
Impact	During normal operation (in service/load current interruption)	• May fail to interrupt, depending on degree of scatter • Prolonged interruption • In case of cascaded breaker design with each cascaded unit having its own discharge circuit, scatter between units causes unsynchronized interruption
	During fault	Interruption failure may occur

Table 4.21 Failure of gaps of high-speed making switch: Does not close on command

Component		Mechanical switching gap[8]
Failure mode		Does not close on command
Failure cause		Malfunction in controller
Impact	During normal operation (in service/load current interruption)	• No injection of resonant current • Failure to interrupt load current
	During fault	• No injection of resonant current • Failure to interrupt fault current

Table 4.22 Failure of gaps of high-speed making switch: Closes without command

Component		Gaps (commutation)
Failure mode		Closes without command
Failure cause		• Malfunction in controller • Mechanical stress in excess of rating (e.g. seismic strength)
Impact	During normal operation (in service/load current interruption)	• Injection capacitor will get discharged untimely • No impact on the normal operation of the system. The injection of the resonant current might create voltage oscillation for a short period of time
	During fault	• No resonant current injection • Injection capacitor will get discharged • Failure to interrupt fault current

[8]The mechanical making switch can be a switch with either moving contacts or with stationary contacts (triggered spark gap). Mitsubishi employs mechanical switching gap.

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Table 4.23 Failure of gaps of high-speed making switch: Scatter in discharge of resonant current

<table>
<tr><td colspan="2">Component</td><td>Gaps (commutation)</td></tr>
<tr><td colspan="2">Failure mode</td><td>Scatter in discharge of resonant current</td></tr>
<tr><td colspan="2">Failure cause</td><td>• Ageing (change in electrical characteristic)
• Malfunction in controller</td></tr>
<tr><td rowspan="2">Impact</td><td>During normal operation (in service/load current interruption)</td><td>No load current interruption in case of insufficient injection current amplitude</td></tr>
<tr><td>During fault</td><td>Interruption failure will occur in case of insufficient injection current amplitude</td></tr>
</table>

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4.2.2 FAILURE OF CAPACITOR AND ITS CHARGING SYSTEM

The position of the capacitor in the capacitor discharge based DC circuit breaker is shown in Figure 4-5.

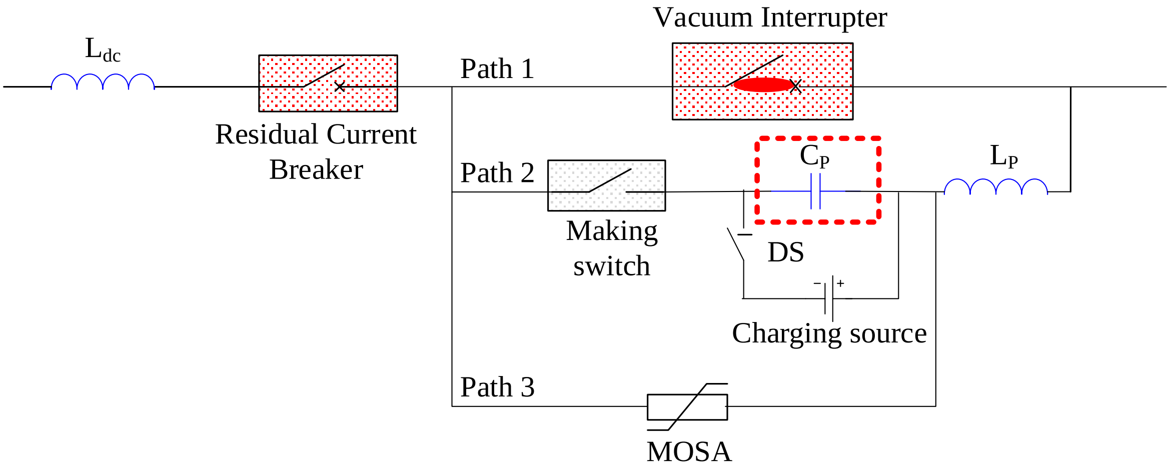

Figure 4-5 The position of the capacitor in the capacitor discharge based mechanical DC breaker circuit diagram

The failure modes of the capacitor are presented in the following tables along with their failure causes and impacts on the operation of the DC breaker. The list of the failure modes of the capacitor is given in Table 4.24.

Table 4.24 List of failure modes of capacitor

Failure mode of capacitor	Table
Cannot charge	**Table 4.25**
Small change in capacitance	**Table 4.26**

Table 4.25 Failure of capacitor: Fails to charge

Component		Capacitor (Commutation branch)
Failure mode		Cannot charge
Failure cause		Ageing, control failure
Impact	During normal operation (in service/load current interruption)	• No injection of resonant current • Failure to interrupt load current
	During fault	• No injection of resonant current • Failure to interrupt fault current

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Table 4.26 Failure of capacitor: Change in capacitance

Component		Capacitor (Commutation branch)
Failure mode		Small change in capacitance
Failure cause		Ageing
Impact	During normal operation (in service/load current interruption)	Load current interruption failure may occur due to high frequency of injection current
	During fault tolerance	Fault interruption failure may occur due to high frequency of injection current

4.2.3 FAILURE OF REACTOR

The position of the reactor in the capacitor discharge based mechanical DC breaker is shown in Figure 4-6.

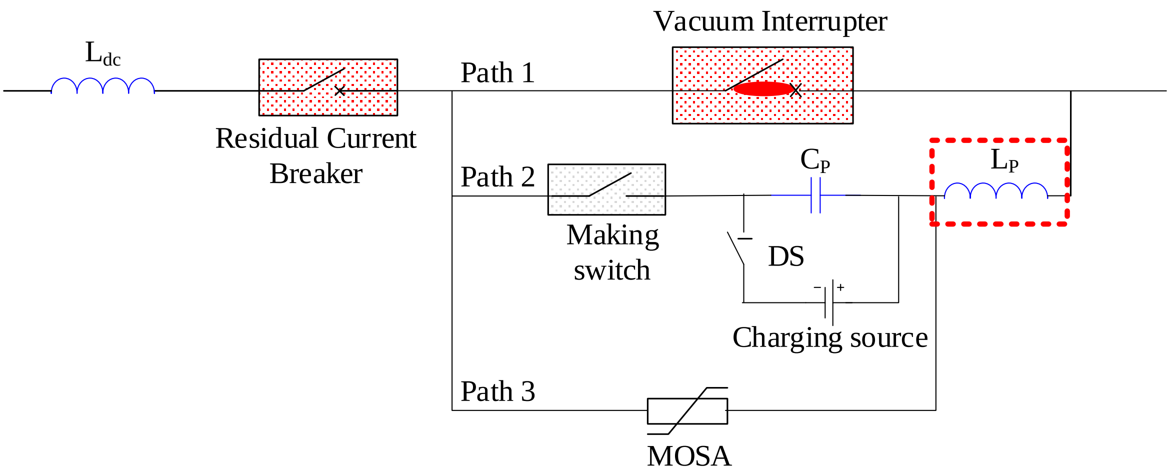

Figure 4-6 The position of the reactor in the capacitor discharge based mechanical DC breaker circuit diagram

The failure modes of the reactor along with their associated failure causes and impacts on the operation of the breaker are presented in the following tables. The list of the failure modes of the reactor is presented in Table 4.27.

Table 4.27 List of failure modes of reactor

Failure mode of reactor (Commutation Branch)	Table
Flashover to earth	**Table 4.28**
Small change in reactance	**Table 4.29**

Table 4.28 Failure of reactor: Flashover to earth

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<table>
<tr><td>Component</td><td>Reactor (Commutation Branch)</td></tr>
<tr><td>Failure mode</td><td>Flashover to earth</td></tr>
<tr><td>Failure cause</td><td>Ageing</td></tr>
<tr><td>Impact</td><td>No resonant current injection
Failure to interrupt load current
Earth fault</td></tr>
</table>

Table 4.29 Failure of reactor: Change in reactance

<table>
<tr><td colspan="2">Component</td><td>Reactor (Commutation Branch)</td></tr>
<tr><td colspan="2">Failure mode</td><td>Small change in reactance</td></tr>
<tr><td colspan="2">Failure cause</td><td>Ageing</td></tr>
<tr><td rowspan="2">Impact</td><td>During normal operation (in service/load current interruption)</td><td>Change in the waveshape of the resonant injection current
This could lead to load current interruption failure</td></tr>
<tr><td>During fault tolerance</td><td>Change in the waveshape of the resonant injection current
This could lead to fault current interruption failure</td></tr>
</table>

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4.3 FAILURE ANALYSIS OF VARC DC CIRCUIT BREAKER

This chapter will discuss and analyse the possible failure modes of the subcomponents of a VARC DC CB module and of the full breaker consisting of series-connected VARC modules. Some of the components in the VARC breaker have failure modes that are expected to be very similar to failure modes of components in other DC circuit breaker topologies. Primarily, the surge arrester stack failure modes are likely to be very similar across all DC circuit breaker topologies, since the surge arrester stack is utilized in the same way in all topologies (see subsection 3.1). The operating principles of the residual current switch are also the same in all DC breaker types (see subsection 3.2). The failure modes of these components were presented in chapter 3. The functionality of the vacuum interrupter is the same in both active current injection breaker types and it was presented in subsection 4.1.

4.3.1 REDUNDANCY OF THE VARC CIRCUIT BREAKER MODULES

Since the VARC DC circuit breaker consists of a string of independent modules, failure in one of the breaker modules to commutate into the surge arrester and create a counter-voltage does not imply failure of the full breaker to neutralize the fault or to suppress the fault current. In order to suppress the fault current, the TIV of the breaker needs to be large enough, and the surge arresters need to be able to dissipate the energy resulting from the interruption. Both these conditions are naturally met with a 12-module VARC DC circuit breaker, even in the case that one module fails to contribute to the suppression of the fault current.

If the circuit breaker consists of N breaker modules, of which one fails during a breaking operation, the other $N-1$ modules will be required to generate their TIV independently of the failed one. The TIV of the breaker during suppression will therefore change by a factor $\frac{N-1}{N}$. This amounts to a reduction in TIV by 8% if $N=12$, which still is larger than a system voltage at 67% of the TIV by a large margin. The dissipated energy in the circuit breaker is the integral of the TIV of the breaker times the current through it during the suppression time. With a constant breaker operating time, the fault current at the time of fault neutralization is also constant. The two things that change if one module is left out during the suppression are therefore:

- the slope of the current during suppression
- the duration of the suppression, and the TIV of the full breaker.

The slope of the current during suppression depends on the change in difference between TIV of the breaker and the system voltage. The ratio between the breaker TIV and system voltage is taken as 1.5, but will be denoted as k, in order to make the impact of the parameter clear. For the case when there is a strong driving voltage and a constant series inductance, the total dissipated energy during an operation per module changes by a factor $\left(1-\frac{k}{k-1}\frac{1}{N}\right)^{-1}$ when an N-module breaker is forced to

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operate as an N-1-module breaker. In particular, a breaker consisting of 12 modules will require an overdesign of the surge arrester by 33% in order to stay within a safe area of operation in the case that one module fails. HVDC converter voltage drop during the fault amounts to a temporary increase in the factor k, and therefore decreases the overload on the surge arresters, so that the expression above corresponds to a severe case for the breaker. Since failures of a module are expected to occur extremely rarely, a 33% energy margin could well coincide with a design margin that is already in place, so that the redundancy comes without additional component cost of the breaker. For a breaker with a lower number of modules, the redundancy could, if desired, instead be accomplished by means of an additional module in the breaker that normally does not operate. Such a module can give the ability to reduce the energy stress on the functioning modules, at the expense of a slightly longer suppression time in the case of a module failure. It should also be noted that if the breaker is designed to operate several times in quick succession, the 33% becomes an even smaller part of the rated energy dissipation capability of the surge arrester stack.

4.3.2 FAILURE MODES OF THE VOLTAGE SOURCE CONVERTER

The failure modes of the VSC include failures in the control system of the VSC, hardware failures in the IGBT modules, failures in the IGBT gate drivers and failures in the capacitor bank in the VSC DC-link.

Failures of the VSC in most cases lead to inability of the affected module to contribute to fault current suppression. From the outside of the VSC compartment, there would be few or no signs in the case of a failure.

The IGBT switches can fail both in open and closed mode. The closed mode (latch-up or flashover in busbar package) is more severe, since it could lead to short-circuit of the DC-link capacitor in the VSC if it is not detected. The open modes (bond-wire lift-off or corner-cracking) likely lead to inability to create a current zero-crossing in the VI of the affected module, but the consequences are typically less severe. The causes for failures of the IGBTs themselves are expected to be related to manufacturing errors. The busbar system that connects the IGBTs together to form a VSC is a sensitive part of the VSC as a whole, since the distances between the positive and negative plates of the DC-link are very small, physically separated by dielectric. The distances need to be small in order to reduce the loop inductance in the converter to acceptable levels. Small particles in the busbar system could therefore cause a short circuit if they puncture the dielectric layer. There are also creepage distances in the busbar system that need to be kept free of grease or dirt in order to prevent tracking and flashover. These challenges are not, however, specific to the VSC in the VARC circuit breaker, but rather a natural part of the design of any high power VSC. The number of semiconductors used in the VARC DC circuit-breaker is, however, comparatively low. compared to a leg of a converter station connected

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to the same line as the circuit breaker. The full circuit breaker will contain at least ten times fewer IGBT modules. The lower number of semiconductors significantly reduces the risk of semiconductor related failures but at the same time, it increases the significance of a single IGBT failure. The failure modes of the voltage source converter are presented in the following tables along with their associated failure cases and impacts on the operation of the DC breaker. The position of the IGBTS in the VSC and VARC module is indicated with red color in Figure 4-7. The list of the failure modes of the VSC is presented in Table 4.30.

Table 4.30 List of failure modes of the VSC

Failure mode of VSC	Table
IGBTs in the VSC: Short-circuit in the DC-link	**Table 4.31**
IGBTs in the VSC: One module fails in open position	**Table 4.32**
DC-link capacitor bank: Short circuit	**Table 4.33**
DC-link capacitor bank: No charging power	**Table 4.34**
DC-link capacitor bank: Insufficient capacitance in DC-link	**Table 4.35**

Table 4.31 Failure of IGBTs in the VSC: Short-circuit in the DC link

Component	IGBTs in the VSC
Failure mode	Short-circuit in the DC-link
Failure cause	• Static latch-up of one of the switches in the VSC (caused by high temperature rise close to the gate structure) • Grease or dirt in the busbar package that connects the IGBTs together in the VSC • Failure of gate driver or incorrect control of the VSC
Impact	• Breaker module does not contribute to fault current suppression, current oscillation does not ensue • Failure of VSC, damages to VSC compartment

Table 4.32 Failure of IGBTs in the VSC: One module fails in open position

Component	IGBTs in the VSC
Failure mode	One module fails in open position
Failure cause	Bondwire lift-off, corner-cracking etc.
Impact	VSC operates as half-bridge, with a lower rate of rise of oscillating current, which leads to more than two times longer ramp-up time of the counter injected current. Fault current suppression in the affected module could still be possible but is not guaranteed per design.

The capacitors that are suitable for the DC-link in the VSC are typically metallized film polypropylene (MKP) power electronics capacitors. Their failure modes and failure rates are relatively well known, because of their widespread use in industrial power electronics. A publicly available report, written by the capacitor expert Roland Gallay for CERN, provides a good summary of the relevant failure modes in [11]. The DC-link capacitor bank does not normally carry any current, and the voltage across it is very well controlled, so, many of the failure modes described in the report will not appear. The failure

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modes of MKP capacitors that depend on manufacturing and application, and are quite relevant for the VARC application are:

- Uncontrolled self-healing
- Corona
- Corrosion

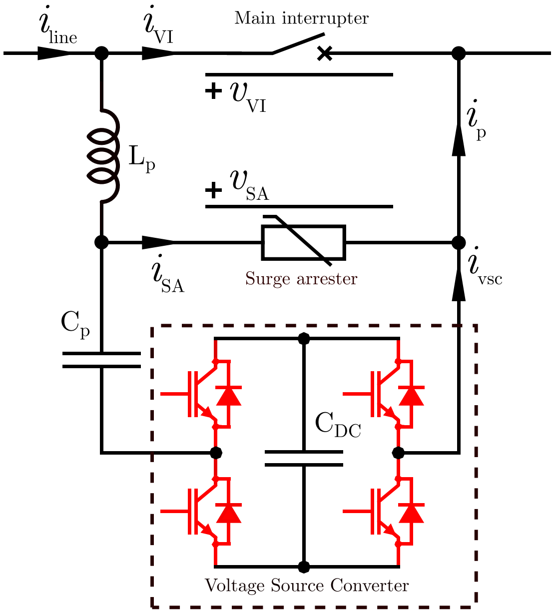

Figure 4-7 The position of the IGBTs in the VSC and the VARC module circuit diagram.

Problems during manufacturing or poor environmental conditions can cause corona, which over time, can lead to wear on the metallizations and therefore loss of capacitance. Poor environmental conditions, primarily humidity, also causes corrosion. Corrosion causes both loss of capacitance and increased losses in the capacitor. The position of the DC-link capacitor in the VSC and VARC circuit diagram is indicated with red color in Figure 4-8. Its failure modes, failure causes and impact on the operation of the breaker are described in the following tables. The list of failure modes of the DC-link capacitor bank is presented in

Table 4.33 Failure of DC link capacitor bank: Short circuit

Component	DC-link capacitor bank
Failure mode	Short circuit
Failure cause	Long term degradation of capacitors due to humidity or other environmental factors.
Impact	Failure of affected module to contribute to fault current suppression

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Table 4.34 Failure of DC link capacitor bank: No charging power

Component	DC-link capacitor bank
Failure mode	No charging power
Failure cause	Failure of DC-link charging supply or lack of power from auxiliary power system
Impact	Failure of affected module to contribute to fault current suppression

Table 4.35 Failure of DC link capacitor bank: Insufficient capacitance in the DC link

Component	DC link capacitor bank
Failure mode	Insufficient capacitance in DC-link
Failure cause	Loss of capacitance due to long term effects of corona and/or corrosion
Impact	Failure of affected module to contribute to fault current suppression

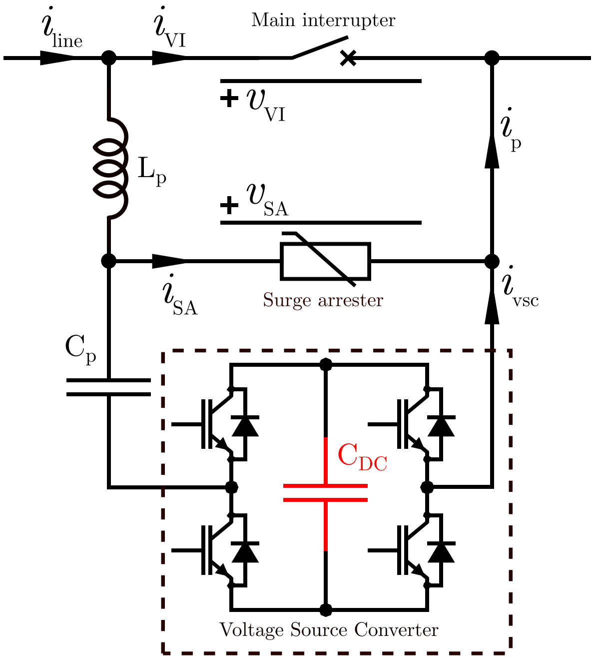

Figure 4-8 The position of the DC-link capacitor in the VSC and the VARC module circuit diagram.

4.3.3 FAILURE MODES OF THE RESONANT CIRCUIT CAPACITOR

This subsection treats the failure modes of the components constituting the capacitance in the resonant branch of the VARC circuit breaker. This component is normally discharged at ambient temperature. The capacitor type is typically a wound film capacitor with polypropylene dielectric. Depending on the ratings of the breaker, there might need to be several capacitors connected together to fulfill the function of the capacitance in the current injection branch. Each capacitor also has a discharge resistor connected across it, both as a safety measure and in order to have a passive means to dissipate residual capacitor energy after a breaker operation. The position of the resonant circuit capacitor in the VARC module is indicated by red color in Figure 4-9. The listed possible failure modes are full short circuit and intermittent internal connection. These failures modes and their associated failure causes and impacts on the operation of the DC breaker are presented in the following tables.

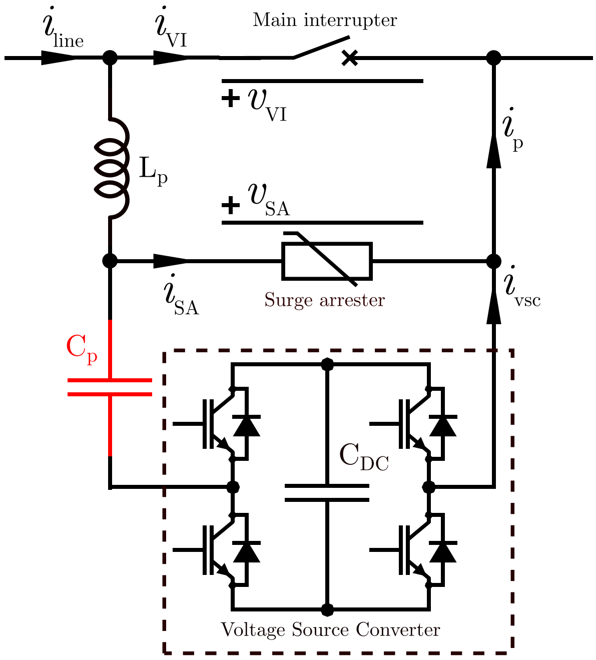

Figure 4-9 The position of the resonant circuit capacitor in the VARC module circuit diagram.

The list of the failure modes of the resonant circuit capacitor is presented in Table 4.36.

Table 4.36 List of failure modes of resonant circuit capacitor

Failure mode of resonant circuit capacitor	Table
Full short-circuit of capacitor	**Table 4.37**
Intermittent function	**Table 4.38**

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Table 4.37 Failure of capacitor in current injection branch: Full short-circuit of capacitor

Component	Capacitors in current injection branch
Failure mode	Full short-circuit of capacitor
Failure cause	• Flashover due to grease or dirt on components • Failure of external discharge resistor • Reduction of dielectric withstand capability due to one or several of the following: increased ambient temperature, overcurrent, ingress of contaminants into capacitor enclosure
Impact	• The affected module will not contribute to the suppression of the fault current • If this main breaker is also in an open state, the VSC will carry part of or all of the DC-current, possibly leading to overheating over time.

Table 4.38 Failure of capacitor in current injection branch: Intermittent function

Component	Capacitors in current injection branch
Failure mode	Intermittent function
Failure cause	Thermal shocks due to overcurrents in combination with a high temperature environment, leading to change of internal geometry in capacitor
Impact	Too low amplitude of resonant current, possibly no fault current interruption will occur in the affected module. A later dielectric failure could also result.

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5 FAILURE ANALYSIS OF HYBRID DC CIRCUIT BREAKER

Hybrid HVDC circuit breakers, as the other designs, usually comprise of three functional units or four main components, electrically connected according to Figure 5-1.

- **Main current branch:** formed by a series combination of a mechanical switch (ultra-fast disconnector) and a low voltage semiconductor switch.
- **Commutation branch:** built of a high-voltage semiconductor switch whose function is to carry the fault current, providing a low impedance path for a short time while the mechanical switch of the main branch is opening.
- **Energy absorption branch:** built of Metal Oxide Surge Arresters (MOSAs) that carry the fault current after the commutation branch has turned off, providing the needed counter voltage (TIV) to drive the fault current to zero and absorb the inductive stored energy (see section 3.1).
- **Residual current switch** (see section 3.2)

After the fault clearance, the residual current switch interrupts the residual current and isolates the faulty line from the HVDC grid to protect the arrester banks of the hybrid HVDC breaker from thermal overload [3].

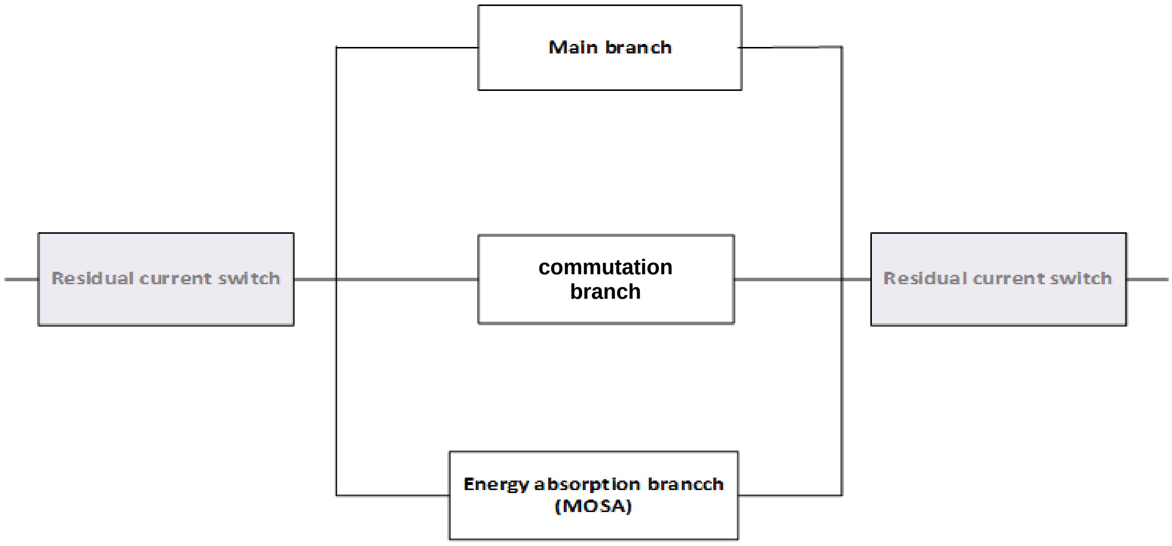

Figure 5-1 – Simplified circuit diagram of the Hybrid HVDC Circuit Breaker.

The possible failure modes of hybrid HVDC circuit breakers, that are independent of the internal design of the main components, are summarized in the following sections. Additional failure modes that depend on the internal design are not included herein, because of reasons of intellectual property protection.

5.1 FAILURE OF LOAD COMMUTATION SWITCH

The position of the load commutation switch in the hybrid DC breaker circuit diagram is indicated by the red dotted line in Figure 5-2.

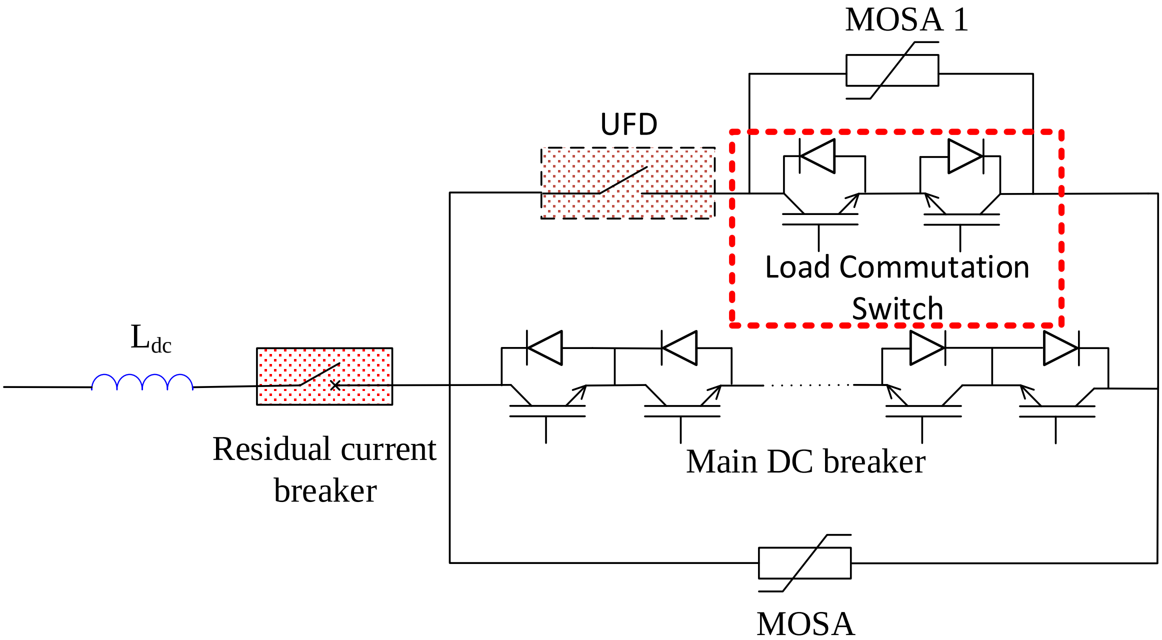

Figure 5-2 Position of load commutation switch in hybrid DC breaker circuit diagram

The Load Commutation Switch (LCS) may be of modular design and is rated based on project specific requirements on continuous loading, withstand capability and reliability level [3]. If the LCS is designed in a matrix topology, the current and voltage capability can easily be increased, as well as the redundancy, by adding parallel paths and series positions. Limiting factors are for instance the available footprint and price. With a suitable level of redundancy and by utilizing the internal protection system, the LCS should only be operated if safe operation can be assumed. The failure modes of the LCS as a whole unit along with their related failure causes and impacts on the operation of the breaker are listed below. The list of the failure modes of LCS is presented in Table 5.1.

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Table 5.1 List of failure modes of Load Commutation Switch

Failure mode of Load Commutation Switch	Table
Failure to close	**Table 5.2**
Goes into high-resistive mode during current conduction	**Table 5.3**
Provides too low voltage when opening	**Table 5.4**
Fails to open (stays in low-resistive mode)	**Table 5.5**

Table 5.2 Failure of load commutation switch: Failure to close

Component	Load Commutation Switch
Failure mode	Failure to close
Failure cause	• Control- or protection failure • Hardware failure
Impact	• Energization/connection of the DC line is not done properly. • Commutation branch needs to open again, and MOSA might need time to cool down from the attempted energization. • The functional unit cannot be put in service.

Table 5.3 Failure of load commutation switch: high resistive mode during current conduction

Component	Load Commutation Switch
Failure mode	Goes into high-resistive mode during current conduction
Failure cause	• Control- or protection failure • Hardware failure • Thermal runaway due to cooling system failure
Impact	• Possibly violent failure, as high current is pushed through a high resistance, causing high power dissipation. • If no bypassing of high-resistive part is possible, an unscheduled maintenance might be needed. • Back-up breakers might need to actuate

Table 5.4 Failure of load commutation switch: LCS does provides insufficient voltage in order to provide commutation into the main DC breaker (commutation branch)

Component	Load Commutation Switch
Failure mode	Provides too low voltage when opening
Failure cause	Part of series-connected devices in the LCS stay in low-resistive mode
Impact	• Current cannot commutate properly to the commutation branch, so the breaker cannot interrupt the fault current • Back-up breakers need to actuate

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Table 5.5 Failure of load commutation switch: fails to open

Component	Load Commutation Switch
Failure mode	Fails to open (stays in low-resistive mode)
Failure cause	• Control- or protection failure • Hardware failure
Impact	• The fault cannot be cleared by the breaker • Very high current, up to withstand level, through the main branch (LCS). • Overheating of the LCS due to uncontrollable increase of the fault current and eventual destruction of the DC breaker. Back-up protection should be actuated.

5.2 FAILURE IN COMMUTATION BRANCH

The position of the main DC breaker, building the commutation branch, in the hybrid DC breaker circuit diagram is indicated by the red dotted line in Figure 5-3.

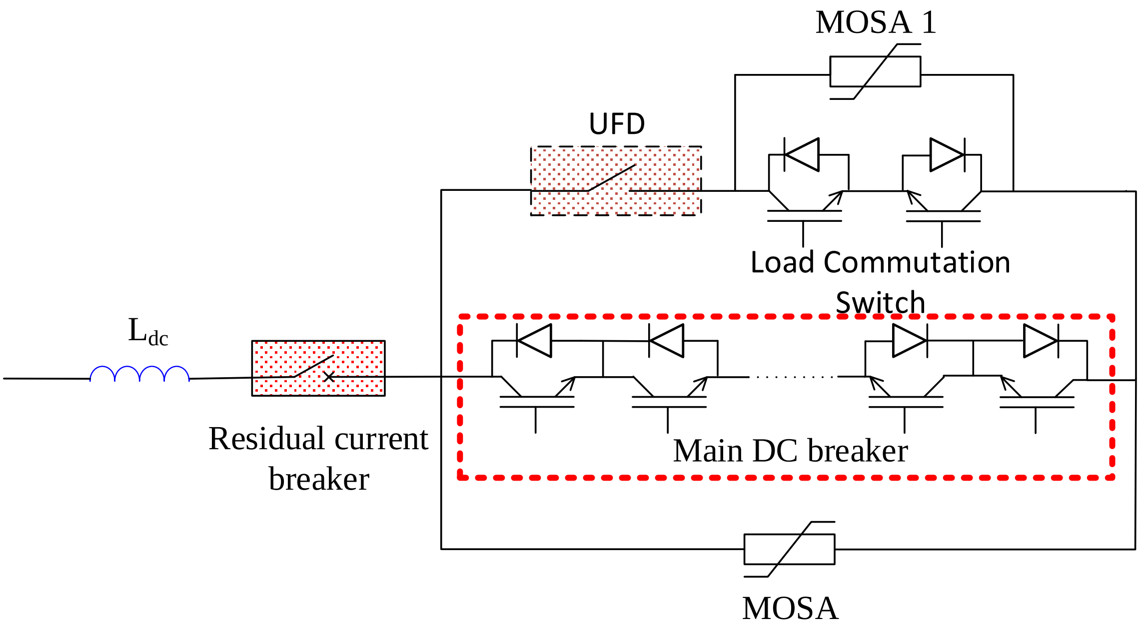

Figure 5-3 Position of the main DC breaker in the hybrid DC breaker circuit diagram

The function of the commutation branch is to carry the fault current safely while the mechanical switch (UFD) is opening. Once the mechanical switch is fully open, the commutation branch can safely break the fault current and start to provide the high counter voltage necessary to reach the clamping voltage of the surge arrester and from that point on divert the fault current into the surge arrester [3].

To increase the reliability, availability and meet the specific project or market requirements, the commutation branch shall be designed in such a way that it includes the required redundancy levels. Hence safe operation of the commutation branch shall be assumed as long as the redundancy levels

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are not used. An online supervision and control are recommended and to avoid further damage, the main breaker (commutation branch) should only be operated if safe operation can be assumed.

The failure modes of the commutation branch along with their failure causes and impacts on the operation of the DC breaker are described below. The list of the failure modes of the commutation branch is presented in Table 5.6.

Table 5.6 List of failure modes of Commutation Branch

Failure mode of Commutation Branch	Table
Fails to close	**Table 5.7**
Goes into high-resistive mode while HVDC circuit breaker is operating in closed mode	**Table 5.8**
Goes into high-resistive mode during normal operation (when load current flows through the Main branch)	**Table 5.9**
Fails to open (stays in low-resistive mode)	**Table 5.10**

Table 5.7 Failure of commutation branch: Fails to close

Component	Commutation branch
Failure mode	Fails to close
Failure cause	• Control- or protection failure • Hardware failure
Impact	• Energization/Connection of the DC line is not done properly. • Commutation branch needs to open again, and MOSA might need time to cool down from the attempted energization (if e.g. part of the commutation branch successfully closed). • The functional unit cannot be put in service.

Table 5.8 Failure of commutation branch: Goes into high-resistive mode while DC breaker is operating in closed mode

Component	Commutation branch
Failure mode	Goes into high-resistive mode while HVDC circuit breaker is operating in closed mode
Failure cause	• Control- or protection failure • Hardware failure
Impact	• Possibly violent failure, as high current is flowing through a high resistance, causing high power dissipation. • If no bypassing of high-resistive part is possible, an unscheduled maintenance might be needed. • Commutation might not be possible • Commutation branch might need to open again, and MOSA might need time to cool down from attempted energization. • Back-up breakers might need to actuate • Possibly delayed commission.

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Table 5.9 Failure of commutation branch: Goes into high-resistive mode during normal operation

Component	Commutation branch
Failure mode	Goes into high-resistive mode during normal operation (when load current flows through the Main branch)
Failure cause	• Control- or protection failure • Hardware failure
Impact	• Possibly violent failure during current commutation, as high current will be flowing through a high resistance, resulting in high power dissipation. • Fault current might not commutate properly to the commutation branch, so the breaker may not be able to interrupt the load current. • Possibly very high current through the main branch (if e.g. commutation is not possible) • Possibly very high current through the commutation branch (if e.g. commutation is slow, such that the UFD is not allowed to open until it is too late) • If no bypassing of high-resistive part is possible, an unscheduled maintenance might be needed. • Back-up breakers might need to actuate.

Table 5.10 Failure of commutation branch: Fails to open

Component	Commutation Branch
Failure mode	Fails to open (stays in low-resistive mode)
Failure cause	• Control- or protection failure • Hardware failure
Impact	• Very high current through the commutation branch, leading to damage of the semiconductors • The fault cannot be cleared by the breaker • Back-up breakers need to actuate

5.3 FAILURE OF ULTRA FAST DISCONNECTOR

The position of the Ultra-Fast Disconnector (UFD) in the hybrid DC breaker circuit diagram is indicated by the red dotted lines in Figure 5-4.

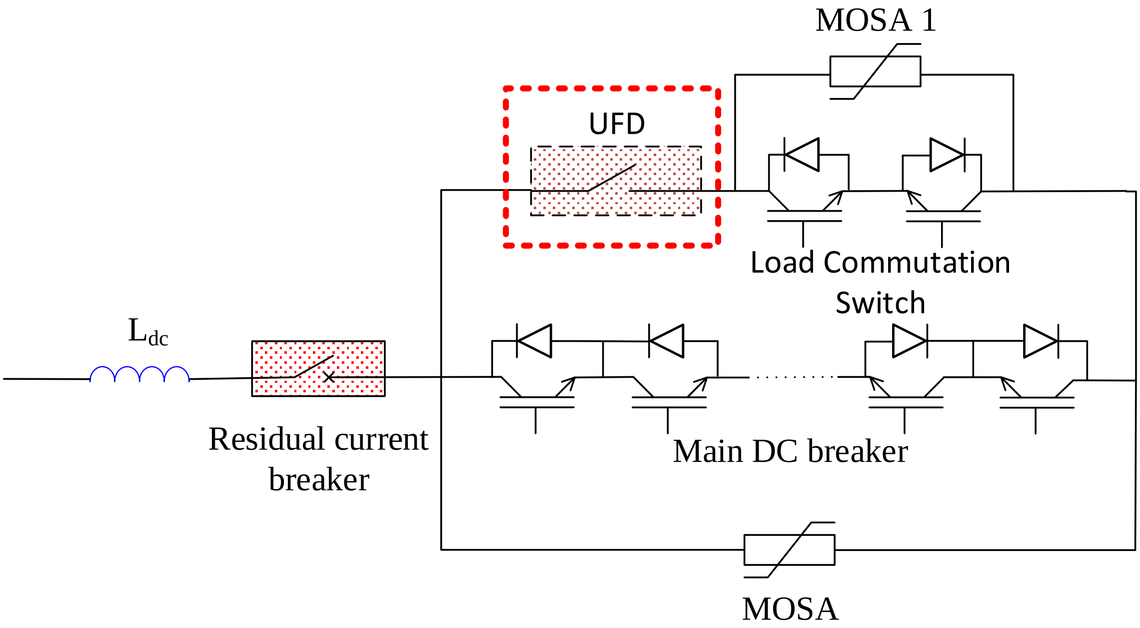

Figure 5-4 Position of the UFD in the hybrid DC breaker circuit diagram

Besides providing low impedance conduction path, the main function of the mechanical switch is to withstand the full voltage of the DC breaker and isolate the load commutation switch from the voltage across the commutation branch during current breaking [3]. When a fault has been detected and the current is commutated to the commutation branch, the fault current continues to rise steeply until the mechanical switch opens, hence the operating speed of the mechanical switch is critical when deciding the ratings of all the components of the breaker. The mechanical switch shall be designed in such a way that it insures extra high capability and reliability. If for any reason the UFD fails to secure its functionality, the backup breaker in the HVDC system, shall be activated.

The failure modes of the UFD along with their associated failure causes and impacts on the operation of the DC breaker are described below. The list of the failure modes of the UFD is presented in Table 5.11.

Table 5.11 List of failure modes of Ultrafast Disconnector

Failure mode of Ultrafast Disconnector	Table
Fails to close	**Table 5.12**
Reduced insulation strength	**Table 5.13**
Fails to open	**Table 5.14**

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Table 5.12 Failure of Ultra-Fast Disconnector: Fails to close

Component	Ultra-Fast Disconnector
Failure mode	Fails to close
Failure cause	• Control-or protection failure • Hardware failure
Impact	• Energization/Connection of the DC line is not done properly. • Commutation branch needs to open again, and MOSA might need time to cool down from the attempted energization. • The functional unit cannot be put in service.

Table 5.13 Failure of Ultra-Fast Disconnector: Slow opening speed or gas leakage

Component	Ultra-Fast Disconnector
Failure mode	Reduced insulation strength
Failure cause	• Failure in driving mechanism • Mechanical damage/wear of moving parts • SF6 gas leakage
Impact	• Increased current breaking time. • Higher energy absorption in MOSA due to higher peak value of the fault current. • Back-up breakers might need to actuate.

Table 5.14 Failure of Ultra-Fast Disconnector: Fails to open

Component	Ultra-Fast Disconnector
Failure mode	Fails to open
Failure cause	• Control- or protection failure • Hardware failure
Impact	• TIV is applied across LCS instead of UFD, considering that an opening signal is sent to the commutation branch. • Electrical breakdown of LCS if main DC breaker (commutation branch) opens • No fault current interruption • Back-up breakers need to actuate

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6 SUMMARY

In this deliverable failure modes of three different technologies of HVDC circuit breaker have been discussed based on available (although limited) information. The HVDC circuit breaker technologies which were included in the analysis are the following:

- Capacitor discharge based active current injection mechanical breaker (Mitsubishi)
- Voltage Source Converter (VSC) assisted active current injection mechanical breaker (VARC-SCiBreak)
- Hybrid mechanical breaker (ABB)

A failure mode and effect analysis (FMEA) is performed without considering the detection and probability metrics which are usually taken into account in a traditional FMEA approach. The reason for this is that the different components of the DC breakers are used in an unstandardized way since they experience DC voltage and current stresses instead of AC. Moreover, there is no field data available, and no detailed failure mode scenarios. Thus, the failure statistics estimates as proposed by CIGRE could not be used since they refer to AC applications. For this reason, the study was focused on analysis of the failure modes of each individual component of the DC breaker along with their associated failure causes and impacts on the operation of the system.

Some components which are common to all HVDC circuit breaker technologies are discussed in separate chapter in order to avoid redundancy and duplication of information. These components include the MOSA and the residual current switch. The operating principles and failure modes of these components are principally similar in all DC breaker technologies. For this reason, one common failure analysis is performed for these components and it is presented in a separate chapter. Moreover, the vacuum interrupter is common in both active current injection mechanical DC breaker technologies. The failure analysis of vacuum interrupter in both technologies is thus presented in a common subsection. Finally, the failure analysis of all the individual sub-systems of the breakers is also included.

Typical failure modes of the components are failure in open position (fails to close when commanded), failure in closed position (fails to open when commanded), leakage and overheating. These failure modes could occur due to causes like control or protection system malfunction, high voltage and current stresses during a fault, ageing, corrosion, structural damage etc. The impact on the operation of the breaker could be malfunction of the breaker (no fault/load current clearing), compromised operation of the breaker (e.g. reduced clearing speed) or negligible. It could not be taken into account how the design considerations of the different components of the breaker affect their reliability, failure

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modes and failure probability since this data was not provided by the manufacturers for confidentiality reasons.

The failure modes of flashover both to earth and between various parts of the breakers are almost all severe, but high voltage insulation coordination in air can be designed with very high confidence if space is not a significant constraint. These flashover failure modes are therefore associated with a high severity, but one can also have a high confidence in their prevention. The combination of properties places the flashover failure modes in the periphery of interest in a failure mode analysis, and they are therefore left out from this study.

Finally, all sub-units included in the HVDC breaker are designed in such a way that they ensure reliability both on unit as well as on system level. In the worst-case scenario, if any of the HVDC breaker units fails to secure its reliability, the backup breaker in the HVDC system, or the AC breaker on the AC side of the HVDC system, shall be activated. This is a common scenario in protection of HVDC systems. To detect faults in the right time, on-line supervision and monitoring of the HVDC units is recommended.

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