PROMOTioN
PROGRESS ON MESHED HVDC OFFSHORE TRANSMISSION NETWORKS

Deliverable 9.2
DC grid protection testing procedures and guidelines

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Contents

Document info sheet i
Distribution list i
Approvals i
Document history i

List of Contributors ii

1 Introduction 1

2 New challenges and requirements 3
2.1 Challenges and comparsion 3
2.1.1 General comparison between AC and DC protection 4
2.1.2 Measurement comparison 5
2.1.3 Protection function comparison in general 6
2.1.4 Communication comparison 6
2.1.5 Circuit breaker comparison 7
2.1.6 Interoperability 8
2.2 Requirements of DC protection 8
2.2.1 The requirements/constraints from the AC/DC systems and expectations 8
2.2.2 The requirements of DC protection 9
2.2.3 The requirements of DC protection testing 16

3 Test procedures for DC grid protection testing 18
3.1 Test objectives and factors 18
3.1.1 The operation objectives of DC grid protection 18
3.1.2 The objectives based on DC constraints 19
3.1.3 The objectives based on system performance requirements 19
3.2 Test circuits and faulty scenarios 19
3.2.1 Test circuits 19
3.2.2 Test scenarios 20
3.3 Test procedures 26
3.3.1 DC grid protection algorithms 27
3.3.2 The testing procedures for DC grid protection 28

4 Suggestions on technical guidelines for DC protection testing 45
4.1 Introduction 45
4.2 Definition of testing environment and scenarios 45
4.3 System level assessment of DC protections 45

5 Conclusion 49

6 Bibliography..... 50

Executive Summary

The objective of this deliverable is to develop DC grid testing procedures and guidelines for system level testing of future multi-terminal HVDC grids. This deliverable and work package WP9 uses the IEDs with protection algorithms developed in WP4. The protection strategies are tested in real-time environment utilising hardware-in-loop testing methods.

The document identifies challenges for system level testing of protection and makes recommendations based on the developed procedures. The document exploits the already available standard procedures for ac system testing and applies the knowledge of dc protection testing to make recommendations for testing of MTDC grid protection.

The document is organized in four chapters. The First chapter refers to the core objective of WP9 and explains the relations between tasks defined in WP9. The Second chapter, based on existing literature survey such as Cigré reports and information from work packages WP4 and WP6, introduces the challenges to DC protection considering general protection principles, DC circuit breaker interruption times, measurement technologies, bandwidth of instrument transformers, and interfaces between IEDs and acting equipment such as DC circuit breakers and converters. The constraints to DC protection is also related to stability of the AC grids, the stability of the control systems in the DC grid and the limitations of grid components.

In the Third chapter, general and functional requirements of the DC protection systems are defined and possible future protection philosophies are discussed. The performance requirements for successful testing of protection devices need to conform to the accuracy of protection characteristics, the operation time and the functional requirements including sensitivity, selectivity, speed, reliability, seamlessness and robustness. In this chapter, test procedures are described for both primary and backup protection. Fault scenarios are selected using various critical testing parameters i.e. series line inductors, fault types, fault resistances, and fault locations etc. These test scenarios are then used to evaluate requirements for DC protection by applying statistical analysis.

In the Fourth chapter, suggestions on DC protection testing procedures are proposed for the assessment of the functional requirements, operation times and accuracy. Finally, Chapter 5 presents Conclusion of the work.

1 INTRODUCTION

The objective of WP9 is to demonstrate the operation of the DC grid protection systems in RTDS simulation environment by using hardware in the loop testing methods. This WP will integrate the knowledge from DC circuit breakers (DCCB) modelling (WP6 and WP10) and the DC protection hardware prototypes of Intelligent Electronic Devices (IEDs) in WP4. The demonstration activities are performed at National HVDC Centre in Scotland and SuperGrid Institute at Lyon, France.

The related core project objectives can be seen from Table 1:

Table 1 The core project objectives related to WP9.

#	Core project objectives	Associated WP
1	To establish interoperability between different technologies and concepts by providing specific technical and operational requirements, behaviour patterns and standardization methods for different technologies	WP 1, WP 2, WP 3, WP 4, WP 5, WP 6
2	To develop interoperable, reliable and cost-effective technology of protection for meshed HVDC offshore grids and the new type of offshore converter for wind power integration	WP 2, WP 3, WP 4, WP 5, WP 6
3	To demonstrate different cost-effective key technologies for meshed HVDC offshore grids and to increase their technology readiness level by investigating and overcoming early adopter issues and pitfalls	WP 8, WP 9, WP 10

The specific tasks of WP9 are:

- T9.1 Integrate DC relays from WP4 and DCCB models from WP6 in RTDS environment (M30-M36)
- T9.2 Develop DC grid benchmark RTDS models for RTDS simulation environment (M30-M36)
- T9.3 Develop DC grid protection testing procedures and guidelines environment (M30-M36)
- T9.4 Demonstrate DC grid protection using hardware in the loop real-time testing (M36-M42)
- T9.5 Demonstrate protection interoperability (M42-M46)
- T9.6 Demonstrate primary and back-up protection and system level consequences of protection failure (M42-M46)

In order to provide reasonable testing procedures and guidelines in T9.3, several significant subtasks are needed:

- The basic framework of AC-grid protection testing procedures will be adopted

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- New challenges and requirements applicable to testing of DC grid protection will be concluded.
- The testing procedures for DC protection testing are defined utilising dc protection requirements and standard practices used for AC protection testing.
- The suggestions for the guidelines of DC protection testing will be prepared in accordance with the above considerations.

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2 NEW CHALLENGES AND REQUIREMENTS

Due to historical reasons, most power transmission and distribution grids are based on Alternating Current (AC) technology. The fast developments of Direct Current (DC) technology, especially HVDC, have led to an increasing interest about the application of DC based power transmission, which may provide benefits when connecting remote offshore wind farms and interconnectors.

As an indispensable part of the electrical power system, the protection system is responsible for the security and reliability of power system operation. AC circuit breaker (ACCB) technology and AC protection schemes have already been developed and standardized to a large extent. However, DC based power transmission technology brings many challenges related mostly to the new development of DCCB and DC protection schemes. Fundamentally, the DC protection should be operated with much faster operation speed, and therefore, stringent requirements for the measurements, data processing and communication are imposed.

2.1 CHALLENGES AND COMPARSION

According to the International Electrotechnical Vocabulary with reference to IEC 60050, a meshed grid has one main property: the disconnection of a single branch should not lead to loss of the transmission capacity within the DC grid. The function of the lost branch is taken over by other branches in such a way that these branches possess sufficient transmission capacity. This is the main difference compared to point-to-point systems and multi terminal systems. In these systems, the transmission capacity is reduced or even completely lost in case of a fault in the main branch, which may depend on the fault clearing strategy.

A dedicated protection system is needed to detect and clear faults within a defined time duration in order to maintain the required reliability and availability of the DC grid. The purpose of a protection system is to isolate the faulted element of the transmission system from service, e.g. during a short circuit or when it operates under abnormal conditions, which might cause damage or interfere with the effective operation of the rest of the system. The choice of specific DC grid protection philosophy fundamentally determines the size of the grid that will be isolated from the rest of the grid during a fault at particular location.

Since the protection of DC grids needs to deal with complex fault scenarios, support fast operational performance, and cooperate with measurements and DCCBs, the system level protection of DC grids is regarded as one of the most important and difficult remaining technical challenges in the power system. Some considerations on challenges for future DC applications can be also listed in Table 2 [1]:

Table 2 The challenges on future DC protection compared to the present AC protection

Challenges	Present AC protection	Future DC protection

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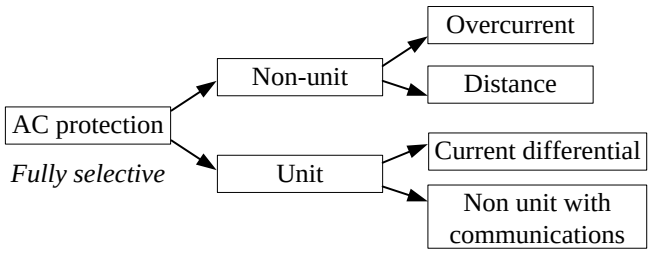
1	AC protections are multi-vendor solution with the consideration of interoperability	Present DC protections are single vendor and related project requirement while future DC protections need to be multi-vendor solution with the consideration of interoperability
2	Conventional AC protection systems: a fully selective philosophy, i.e. only isolate the faulty power component and keep power flow in the rest of the grid uninterrupted.	DC grid protection: The speed is expected to be one order of magnitude faster than that of AC systems The absence of zero-crossings during DC fault current interruption is much more challenging.
3	Well established methods for testing AC protection systems. No DC Grid protection standards.	Development and implementation of DC protection testing methods based on compared differences between AC and DC protection systems.

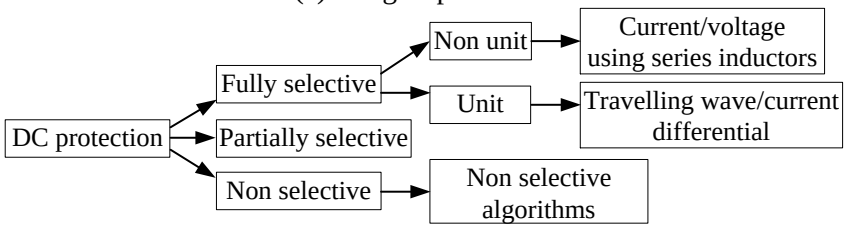
2.1.1 GENERAL COMPARISON BETWEEN AC AND DC PROTECTION

The principle of operation of AC protection is based on the protection zone design of the specific power system. The protection zones are associated with breakers, which are typically overlapping and coordination between protection zones is used to minimize the section of the power system to be disconnected in case of a fault. Closed protection zones can be realized by unit protection algorithms (e.g. current differential), or by non-unit protection principles using telecommunication (e.g. permissive overreaching/under reaching transfer trip). As for the fault clearing time in AC transmission systems, 4 cycles (80 ms) for 50 Hz system, including 2 cycles (40 ms) relay tripping time and 2 cycles (40 ms) circuit breaker operation time, are regarded as the typical values of the fault clearing time [1] [2]. The related categories and time sequences can be observed in Fig. 1 (a) and Fig. 2.

In DC grids, protection zones are also expected to be used to define the sections that should be disconnected in case of faults. However, the affected section of the grid depends on the applied technology for fault current interruption [1]. Moreover, fault clearing speeds of both primary and backup protection in DC grids are typically one order of magnitude faster compared to those in AC grids. For example, the fault clearing time of the primary protection is typically in the range of several milliseconds, from which 2 ms are allocated for relay processing time and several milliseconds for the DC circuit breaker operation time [2]. The related categories and time sequences can be observed in Fig. 1 (b) and Fig. 2.



(a) AC grid protection



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(b) DC grid protection

Fig. 1 Categories of protection philosophies and examples of algorithms (adapted from [1])

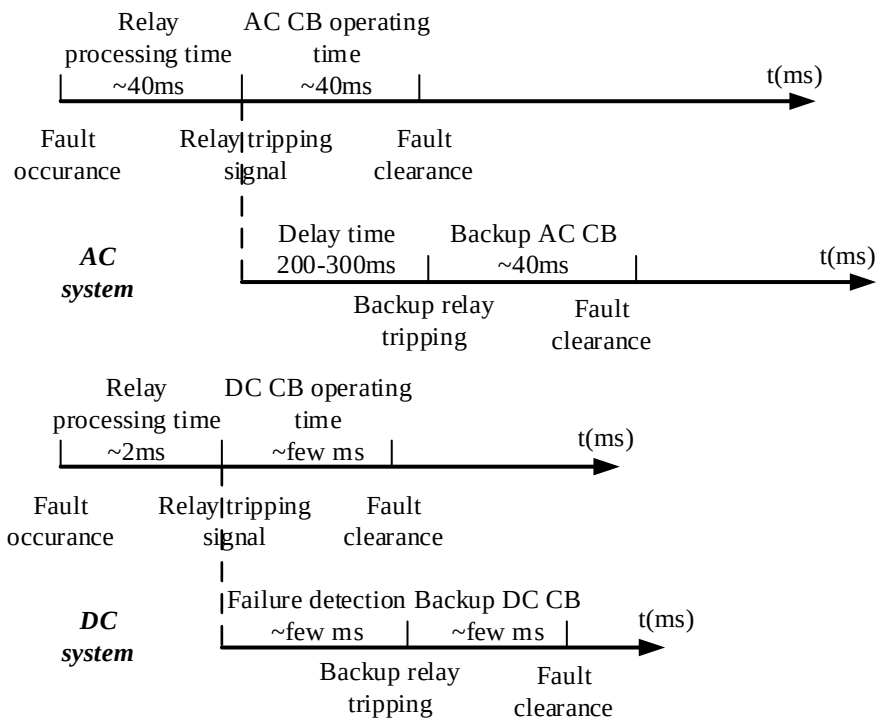

Fig. 2 Typical fault clearing times of primary and backup protection in AC and DC systems (adapted from [1])

2.1.2 MEASUREMENT COMPARISON

The digital interface of instrument transformers for both AC and DC applications is specified in IEC 61869-9. In order to do general measuring and protective data processing, the typical sampling rates for AC and DC measurements are 4.8 ksa/s and 96 ksa/s, respectively. The main technologies and the bandwidth of instrument transformers today have been summarized in Table 3.

Table 3 Technologies and bandwidth of instrument transformers (adapted from [1])

Type	Technology	Bandwidth	Application
CT	Electromagnetic (iron-core)	few kHz	AC
	AC Hybrid electro-optical (combined shunt and Rogowski coil)	few MHz	AC and DC

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	Fibre optic current sensor (magneto-optic effect)	few MHz	AC and DC
	Zero-flux (Direct Current Current Transformer)	few hundred kHz	DC
	DC Zero-flux (Hall-effect current transformer)	few hundred kHz	DC
	Rogowski coil	few hundred MHz	AC and DC
VT	Inductive voltage transformer	few kHz	AC
	Capacitor voltage transformer	few kHz	AC
	Compensated RC-divider	few MHz	AC and DC
	Fibre optic voltage sensor (magneto-optic effect)	few MHz	AC and DC

2.1.3 PROTECTION FUNCTION COMPARISON IN GENERAL

One the key difference between AC and DC IEDs is the interfaces between IEDs and acting equipment, e.g., the interfaces between IEDs and DC breakers [1]. At the AC side, the copper-wired links and related I/O ports between IEDs in power substations since several years, have been changing from analogue signal to digital signal communication. The interface of a DC protection IED should be capable to communicate with the DC breakers and the converter. The protection coordination is expected to be not only between local/remote line protection IEDs, but also to include DC circuit breaker internal protection and converter protection.

DCCBs are required to have more intelligent functions such as self-diagnostics so that the breaker state should be communicated to the local IED for different coordinated protection functions (such as backup protection, breaker failure detection) apart from the pick-up or start signals used to trip the DCCB [1].
Based on the IEC 60255 standards, the typical operation time of AC relay/protection has been specified as the median value of the statistical distribution of operation times assessed over a long series of standardized tests [1] [3]. It has been noted that the typical protection operation time is a parameter that is system dependent, which is hold for both AC and DC protection. While some impact factors (fault current amplitudes, fault location, grounding, etc.) are relevant for AC and DC protection, other factors like (series line inductor size, converter topology, applied DC CB technology etc.) are relevant only for DC protection.

2.1.4 COMMUNICATION COMPARISON

For digital substation concepts, the IEC standard 61850 defines the structure of substation automation and communications inside the substation for data acquisition, protection and data exchange between IEDs. Merging units provide the interface between measurement equipment and control on one side, and protection functions on the other side. For AC protection functions considering fundamental AC cycles (50/60 Hz), the merging units send 80 samples/cycle in 80 messages/cycle via peer-to-peer communication (IEC 61850-9-1) or multicast to multiple subscribers (IEC 61850-9-2) [4]. The performance of the communication speed is specified in IEC 61850-5 into six classes, three for control and protection and three for metering and power quality. For transmission bay level, the total transmission time for both GOOSE message and sampled values (SV) should be below 3 ms [4].

Ideally, similar standards as IEC 61850 together with IEC 61869 and IEC 60834 could also be adapted for DC protection applications. However, the requirements on the communication speed and bandwidth for DC protection needs to be higher than those of AC protection, and could have different classes for fully selective, partially selective and non-selective protection.

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Fully selective DC grid protection is likely to have the highest requirement on communication speed in order to clear a local fault. The traditional communication ways of AC substations are: Power line carrier communication (PLCC) techniques and radio, pilot wires and channels, optic fibres. Based on IEC 60834-1, the comparison of communication time consideration can be seen in the following table:

Table 5 Comparison on communications of AC relay and DC relay adapted from [1]

AC relay	DC relay
• The nominal transmission time delay excluding the propagation time is **2 ms - 45 ms** • The speed requirement on both SV and GOOSE messages should below **3 ms in AC substations** • Maximum actual transmission time of digital teleprotection under noisy conditions for non-unit protection using communication is **10 ms** • Most current differential relays operate at 64 kbps over multiplexed systems such as SONET (Synchronous Optical NETwork) in North America or SDH (Synchronous Digital Hierarchy) in Europe. At TenneT SDH will be phased out and after a few years MPLS (Multiprotocol Label Switching) is the standard.	• The speed requirement on both SV and GOOSE messages within a DC substation is likely to be much shorter than **3 ms in AC substations**. • In the fully selective DC grid protection, the total time delay including SV acquisition, relay time and sending a trip signal is likely to be restricted in the order of **1 ms for non-unit protection**. • In partially selective DC grid protection strategies, the same order of speed as in fully selective protection is required. • If non-selective protection strategy is employed in the faulty sub-grid, **fault identification** within the faulty sub-grid might **have lower requirements** on communication speed. .

Thus, various non-unit protection using communication and differential protection could be viable solutions using direct fibre optical links in non-selective DC grid protection.

2.1.5 CIRCUIT BREAKER COMPARISON

High-voltage ACCB are broadly classified according to the medium used for arc extinguishing between the interrupter contacts, e.g. bulk oil, air blast, vacuum, SF6 breakers, etc. Today the preferred option is to use vacuum circuit breakers especially for medium voltage applications, since SF6 is a greenhouse gas and insulating oil spills cause high environmental and cost concerns [5].

On the other hand, due to the absence of natural current zero crossing, the DCCB needs to be carefully designed and additional branches are needed to interrupt DC fault currents. Based on the diverse technologies used in the additional branch, high-voltage DCCB can be classified as passive resonance, active resonance, hybrid and power electronic breakers [6], [13].
For all DCCB technologies, during the current interruption process, three stages can be defined for both AC and DC circuit breakers: (1) contacts opening (2) arcing or energy dissipating stage (arcing and energy dissipating stage for passive and active resonance types) (3) fault interrupted [1].

However, a DCCB has to endure both high voltage and high current during the fault current suppression time, which is different from AC current interruption process [1]. The comparison between ACCB and DCCB can be seen from the following table [1] [11].

Table 6 Comparison between ACCB and DCCB [1], [11]

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ACCB	DCCB
IEEE C37.06, AC circuit breakers can be classified based on rated voltage (e.g. 362/500/800 kV) and rated short-circuit current (40/50/63 kA).	In point of view of speed and breaking capability, DC circuit breakers can be classified into two large groups: low performance (low speed and low breaking current capability, passive resonant type) and high performance (high speed and high breaking current capability, such as active resonant and hybrid types).
Rated breaking time is 2 or 3 cycles (of a 50/60 Hz waveform) for voltages up to 362 kV and 33 ms for voltage above 500 kV.	Passive resonance circuit breakers rated up to 5.3 kA with interruption time within 20 ms have already been used as transfer switches in point-to-point HVDC links. Recent development on active resonance breakers demonstrates interruption can be achieved within 5-8 ms with breaking capability of 10.5-16 kA. The breaker opening time of hybrid breakers is in the range of 1.2-3 ms.
The standard operation sequence of an AC circuit breaker is O-t-CO-t'-CO, where O = Open; CO = Close-Open; t' = 3 min; t = 0.3 s for circuit breakers rated for rapid reclosing duty	Rapid reclosing of a DCCB might be required in these events: 1) DC breaker located at the healthy lines in the open-grid protection strategy 2) primary protection for self-clearing fault on overhead lines in fully selective protection.

2.1.6 INTEROPERABILITY

Standardization of the HVDC systems is still in at initial stage because historically HVDC systems have been developed as a turnkey projects by a single manufacturer. Recently, the necessity to implement a multi-vendor approach has driven several international standardization bodies in Cigré and CENELEC to work on guidelines and standards for HVDC systems [12]).

2.2 REQUIREMENTS OF DC PROTECTION

2.2.1 THE REQUIREMENTS/CONSTRAINTS FROM THE AC/DC SYSTEMS AND EXPECTATIONS

In order to develop a DC grid and associated protection schemes, similar considerations about the operation performance, security, reliability and cost aspects as with AC systems and AC protections are needed [2].

The grid topologies of both AC and DC systems can give the capability to get increased flexibility and reliability at a lower cost by sharing resources. However, in the DC grid, the control of the power flow and the DC voltage is a big challenge. As for the development of DC protection, it is difficult to provide very fast protection functions and HVDC CBs, which is due to fast fault dynamics and response time. On the other hand, VSC technology in HVDC systems is becoming more and more mature, which is the way forward to the development of DC grids. The most important and difficult remaining technical challenge is the system level protection of DC grids, which considers the coordination between distributed relays, DC breakers and converters to secure the operation of a large meshed DC grid.
As for LCC converter based HVDC, when a DC fault occurs in an existing thyristor-based multi-terminal DC link, the current is forced to zero by the converter control to allow fast disconnection in order to isolate the fault. This approach will not be suitable for a VSC-based DC grid, since the fault current control capability of VSC converters becomes topology and

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control design dependent. Thus in VSC based of DC grids, the need for a DC breaker which can avoid the collapse of the DC voltage and big power swings in the grid is therefore very stringent with the consideration of sufficient selective protection.

The development and investment of DC grid protection is a trade-off between cost and availability. Constraints on the DC grid protection are imposed by [13]:

- The limits of components

The acceptable maximum time for DC fault clearing is mainly limited by overcurrent capability of power electronics of the HVDC converters, and also depends on the converter topology. The protective controls of converters protect their IGBTs and related components before their overcurrent limit is exceeded.

If the converter topology is not the fault blocking type, the converter blocks IGBTs and the current is commutated to the IGBT anti-parallel diodes or protective thyristors. From that moment, the DC fault current is supplied by the AC side through the converter. The time of DC fault clearance is limited by the surge current withstand capability of these anti-parallel diodes. If the converter is the fault blocking type, i.e. full bridge converters [14], the converter can completely block the DC fault current or reduce the DC fault current to an acceptable level. For IGBT based DCCBs, the fault current must be interrupted before the IGBT operation limits are violated. Furthermore, the DCCBs applied to high voltage levels must be able to absorb the energy stored in the system after the fault current interruption.

- Stability of control systems in the DC grid

The limit on the DC grid protection is influenced by converter and DC voltage control as well. The related criteria and stability limits have been discussed in Cigré brochure 657 [15].

- Stability of AC grids

At the AC side, two types of constraints are imposed, i.e.,

  - Maximum loss of power infeed

The loss of power due to a DC fault should not exceed the maximum loss of infeed as designed according to the AC grid codes of specific power systems. The higher power losses may be acceptable when shorter outage durations are guaranteed. This leads to a maximum loss of power infeed that becomes time dependent [15].

  - Transient stability constraints

The fault at the DC side should be cleared timely to avoid loss of synchronism of the AC generators. Instability issues in the AC grid can be result of re-distribution of power flow within the DC grid related power transfer corridors, which is due to the DC fault clearing or the persistence of the DC fault for long period. Moreover, in the latter case, the constraints imposed by the converter power electronics are probably first met.

2.2.2 THE REQUIREMENTS OF DC PROTECTION

The general and functional requirements of DC protection system are described below.

2.2.2.1 GENERAL REQUIREMENTS

The requirements on equipment such as measuring, detecting as well as acting equipment will be determined according to the extent the system can sustain a particular disturbance.

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The DC grid protection philosophy is fundamentally determined by the selectivity of the protection devices and the way of DC fault current interruption to isolate the faults. It should be noted that within a single meshed DC grid, different protection philosophies may exist. Three main fault clearing philosophies are proposed in [13]:

- Non-selective fault clearing
- Partial selective fault clearing
- Full selective fault clearing

In this context, selectivity is related to the objects that are operated to clear the fault. On the other hand, fault detection is the ability to identify the faulty section and/or faulty pole(s) of a HVDC power system. Even in a non-selective fault clearing strategy, it is needed to identify the fault. Table 7 gives an overview of the protection philosophies and possible implementations [13]. The choice of protection philosophy and associated fault clearing strategy depends on the objectives of HVDC grid protection.

Table 7 An overview of the protection philosophies for DC grids [13]

Protection philosophy	*Fully selective*	*Partially selective*	*Non-selective*			
Fault Clearing Strategy	Line or zone	Grid-Splitting	ACCB	with fault blocking converters	with HVDC circuit breakers at converters	Open Grid
HVDC grid protection zones	Lines and converters as separate zones	Small parts of the grids as zones	Entire HVDC grid as one zone	Entire HVDC grid as one zone	Entire HVDC grid as one zone	No protection zones are defined for fault clearing
Faulted zone isolation method	HVDC circuit breakers	HVDC circuit breakers, DC/DC converters	AC circuit breakers	Fault blocking converters	HVDC circuit breakers at converter terminals	HVDC circuit breakers at line ends
Fault clearing time	5 – 10 ms	Depends on fault clearing method (see non-selective methods)	~60 – 80 ms	~5 – 10 ms	~5 – 10 ms	~5-10 ms
DC line switching equipment	HVDC circuit breakers	HVDC circuit breakers, and/or DC/DC converters and DC switches	DC switches	DC switches	DC switches	HVDC Circuit Breakers

The objective of the HVDC protection is both to ensure the HVDC grid is protected (from damage) and the HVAC grid is protected (from transient instabilities and other disturbances). To achieve this objective, a selective protection philosophy, using fast protective algorithms and HVDC circuit breakers is needed. When the focus of the HVDC grid protection is on minimizing disturbances in the AC system, the time constraints on fault clearing can be less stringent because only the loss of power to the AC system, either fixed or time dependent, needs to be considered. Consequently, a partially selective or non-selective protection philosophy can be used. In such a philosophy, a larger part of the HVDC grid (i.e., multiple

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elements such as lines and converters) is disconnected before the faulty element is removed and the system is restored [18].

2.2.2.2 FUNCTIONAL REQUIREMENTS

Any protection system, AC or DC, must have the following properties [16]:

- Sensitivity: The protection system should detect every fault including high impedance faults
- Selectivity: The protection system should only operate after a fault (not during normal operation), and only if the fault is in its own coverage domain
    - Identify the faulty section and/or faulty pole(s) of a HVDC power system
- Speed: The protection system should be fast enough to interrupt faults before they may damage equipment or can no longer be interrupted by the breakers
    - In the DC grid, time constraints are extremely stringent, typically in the order of milliseconds. Some critical time parameters could be considered:
        - Fault clearing time: The time interval between the fault inception and the fault clearance
        - Protection operation time: The time interval between fault inception and the receiving of the trip signal by the relevant circuit breaker.
        - Breaker operation time: The time interval between the receiving instant of the trip signal by the circuit breaker and the elimination of the fault current [1] [17]

- Reliability: The ability that a protection can perform a required function under given conditions for a given time interval. A good protection system is reliable and has a backup system in case the primary protection system fails
    - Security: The probability for a protection of not having an unwanted operation under given conditions for a given time interval
    - Dependability: The probability for a protection of not having a failure to operate under given conditions for a given time interval
- Robustness: the protection system should have the ability to detect faults in normal mode as in degraded mode, and to discriminate faults from any other operation occurring (set-point changes, operations)
- Seamlessness: after the fault clearance, the remaining part of the system should continue operation in a secure steady state

These general principles have consequences on each element of the detection and action chain. For instance, if it is necessary the individual line will be removed in case of a fault (as it is the case with AC grids), DC breakers are needed at both ends of each cable or overhead line (OHL).

2.2.2.3 THE COMPARISON BETWEEN AC PROTECTION AND DC PROTECTION

Normally, for low impedance earth faults, any derivative protection might be suitable. For high impedance faults, with relatively slow rate of change of the voltage and current, a DC under-voltage protection and a telecommunication dependent DC line longitudinal differential protection might be suitable. The comparisons between AC protection and DC protection can

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be generally seen in Table 9 [13] [18]. During an earth fault on one of the DC transmission lines for a symmetrical monopolar transmission, the voltage collapse on the faulty line, and the voltage will increase on the other transmission line, i.e. an asymmetrical voltage. In this case, voltage unbalance protection and overcurrent protection can be applied.

Table 9 Comparison between AC protection and DC protection [13] [18]

Protection types and concepts	Applicability to AC and DC systems
Overcurrent	Mainly applied in radial AC systems, where fault currents are mainly supplied from one side. Its application in meshed AC systems is difficult for selective operations due to its sensitivity of source impedance variations and the fault impedance itself.
	This problem is similar for meshed DC systems.
Distance protection	It is mainly used in meshed AC systems due to its insensitivity to source impedance variations
	In DC grids, distance protection is not readily applicable • During the transient, no fundamental frequency component for the impedance calculation. • In steady-state, only a resistance can be calculated. The fault location must be based on the comparison of the calculated resistance with a threshold instead of the comparison of two dimensional impedance.
Conventional differential protection	Based on comparison of currents at both ends of the protective zone in AC system. Communication between both ends is necessary and data synchronization has to be provided, for longer distances.
	• As HVDC lines are quite long compared with HVAC line lengths, the communication delay in the signal transmission links might take several milliseconds to the other end of a line. • The differential protection in DC grids can only be applied for short lines or busbar protection, as the high rate of rise does not allow a long time for fault detection. In this case the differential protection can be used to compare all local current measurements going into the busbar so telecommunication is not needed.
Under voltage protection	• Similar to overcurrent algorithm application in AC and DC. • In point to point transmissions, the protection operates, whenthe DC voltage persists below a threshold level for a pre-defined time. • In meshed HVDC grids, this type of protection is not readily applicable as a stand alone protection. The lack of selectivity in a meshed network is a disadvantage for this protection.
Voltage balance concept	This concept is used in AC system for an unbalance fault.
	• Similarly in DC system, it compares the positive and the negative voltage of the poles. If the difference is greater than a threshold level for a predefined time, the protection will operate. • The disadvantage of this protection is the lack of selectivity in a meshed network.
Travelling wave differential protection	• Since the waves which are compared from both ends of the line are obtained at different times (due to the propagation delay), the communication delay has only a small impact on the performance of the protection. • For cables, in which the propagation velocity of the waves are about the same as the speed of light in optical fibers, the protection principle can essentially detect internal faults with the same performance as single-ended methods which does not require communication.
	• In AC system, this concept is used just for fault detection.

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Voltage derivative concept	• A fault on the DC line is characterized by the fact that the direct voltage collapses to a low level at a certain comparatively high rate of change (derivative). • The protection response time is very fast and provides fault detection within a few milliseconds.
Combined voltage and current derivative	• In AC system, these concepts are used just for fault detection.
	• The DC current derivative can be combined with a DC voltage derivative to enhance the DC protection performance. Assuming the definition of current direction is positive into the transmission line from each station, the rate of changes of an external fault will be positive. • A negative DC current derivative indicates an external fault, while a positive DC current derivative therefore indicates that the fault is within the protection zone.
Breaker failure protection	In AC networks, in case of current still flowing through the AC breaker after stated fault clearing time, a failed fault clearing is assumed and next breaker(s) in line is tripped to clear the fault.
	• In case of a DCCB failure, backup breakers can be activated almost instantaneously, based on e.g. remaining current after normal fault clearing time. This avoids major disturbances in the HVDC grid, and keeps the required current-breaking capability of the backup breaker at reasonable values. • In case of breaker failure during a busbar fault, all HVDC circuit breakers in the remotely connected stations already measure a current increase from the beginning. So a proper protection co-ordination can assure a time delayed trip of the remote DCCB.

The above table summarises the applicability of existing AC types of protection and concepts that can be applied to DC. Whilst there is some AC protection based on which similar DC protection can be developed (undervoltage, overcurrent, traveling wave based protection), others, like distance and line differential because of stated reasons cannot be used.

2.2.2.4 IMPACTS OF GROUNDING AND CONFIGURATION OPTIONS ON HVDC FAULT BEHAVIORS

The location of the most severe fault condition is determined by several factors, e.g. whether a fault is on OHL or a cable, the number of feeders at the bus to which the faulted line is connected, the distance of fault from the DC bus and fault impedance. For VSC HVDC, several options exist regarding configuration (with/without DC capacitors) and grounding. These include a low impedance grounded asymmetric monopolar, a high impedance grounded symmetric monopolar, or a low or high impedance grounded bipolar configuration. For a meshed HVDC grid, it is currently not clear, which configuration and grounding type must be chosen. However, these choices have a large impact on system cost, protection system design, and grid extensibility [19]. The transient fault current in low-impedance grounded systems is largely influenced by the grounding configuration. Due to the high rate of rise, protection schemes for low-impedance grounded grids must act on a very short timescale. For a symmetric configuration, the transient fault current is mainly delivered by the discharge of DC capacitors and cables. The grounding impedance has an impact on the maximum fault current. A main factor affecting the maximum voltages on each component is whether the neutral point in the symmetrical system is low or high impedance grounded. Since grounding of the converter is a determining factor for the first transient, it is important to adapt settings for the protection scheme whether the converter is grounded or not [19].

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Besides the grounding type, the number and location of grounding points in the dc grid is an important factor. For different configuration of HVDC grids, the fault dynamic performance and protection requirements can be seen from the following Table 10 [19].

Table 10 An overview of HVDC grid configurations [19]

	Asymmetric monopolar grid	Symmetric monopolar grid	Bipolar grid	
Operating voltages[a]	$0, U_n$	$-U_n/2, U_n/2$	$-U_n, 0, U_n$	$-U_n/2, 0, U_n/2$
Cables/P[b]	2	2	3/2	3
Grounding type	Low impedance	High impedance[c]	Low impedance	High impedance
Grounding points	Single grounding point Multiple grounding points[d]	Multiple grounding points	Single grounding point Multiple grounding points[d]	Multiple grounding points
Cable Voltage Rating	$0, U_n$	$-U_n, U_n$	$U_n, 0, U_n$	$-U_n, \pm U_n/2, -U_n$
Steady-state fault current	Large	Zero	Large	Zero
Protection requirements	Fast acting protection	Less stringent time constraints	Fast acting protection	Less stringent constraints
Extensibility	Asymmetric monopoles	Symmetric monopoles	Low impedance grounded bipoles	High impedance grounded bipoles
	Upgrade to bipolar grid	High impedance grounded bipoles	Asymmetric monopoles between metallic return and pole	Asymmetric monopoles between metallic return and pole
Post-fault flexibility after loss of cable	Low	Low	High	High

[a] Pole-to-ground voltage (U_{ptg}) [b] Converter power P ~ U_{ptg} [c] Grounded through DC capacitors or resistors [d] Earth currents possible

2.2.2.5 REQUIREMENTS ON PROTECTION SYSTEM COMPONENTS

The speed requirements of fault clearing or in other words to what extent the system is allowed to be disturbed by a DC fault, will determine the requirements on related system components such as measuring, detecting as well as acting equipment [13].

- Requirements on protection system measuring equipment

Protection systems can only work successfully when they obtain precise information about the actual voltages and currents in the system that needs to be protected. In the HVDC protection system, the bandwidth of the measuring system is particularly important. On one side, the DC currents and voltages need to be measured, while on the other side a high bandwidth is needed to measure the rate of change with a high accuracy. Table 3 summarized main technologies and the bandwidth of instrument transformers today, which gave the choices for DC application [13]. For example, with the consideration of IEC 61869 standard, the bandwidth of sampled values in DC protection should be adequate to transfer 96 k samples/s. The data type for sampled values is defined as 32 bits integer or floating numbers. If 4 bytes are used to represent each sampled data, the bit rate is 3,072 Mbps (4 bytes/sample * 8 bits/byte * 96 k samples/s) for one sampled DC value as compared to 0,128 Mbps (4 bytes/sample * 8 bits/byte * 80 * 50 samples/s) for AC protection. Thus, only those non-conventional instrument transformers can provide sufficient sampling rates and bandwidth for DC protection [1].

- Requirements on protection system detection equipment [13]

With the consideration of reliability, redundant protections prefers to have separate measuring inputs to allow use of separate measuring units for the redundant system together with separate tripping circuits.
The protection IED may execute different fault clearing actions, which are depended on the fault types, e.g. 1) Trip of HVDC CBs, 2) Block of a converter, 3) Trip of ACCBs.
The physical implementation methods will differ according to the different location of protection IEDs, thus the requirements will differ as well, e.g.: 1) Stand-alone protection hardware, 2) Integrated in a converter control and protection system, 3) Integrated in the HVDC CB control and self-protective system. Based on the facts provided in [13], the

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requirements of different physical implementation solutions and protection hardware are summarised in Table 11 and 12.

Table 11 The requirements of different protection physical implementation

Stand-alone protection hardware	• The bandwidth of the measuring equipment and rise time of trip signals will be essential • The interface for the trip signal needs to be coordinated between the acting fault clearing equipment and the protection system • An acting fault clearing equipment can be a DCCB, ACCB or the converter itself • Non-electrical signals might be preferred to minimize the risk of interference, e.g. optical fibres
Integrated in a converter control and protection system	• The bandwidth of the measuring equipment and rise time of trip signals will be essential • A high speed interface with any of the acting fault clearing equipment is required • The interface for the trip signal needs to be coordinated between the acting fault clearing equipment and the protection system • Non-electrical signals might be preferred to minimize the risk of interfere, e.g. optical fibres.
Integrated in the HVDC CB control and self-protective system	• Any measuring equipment needed for the self-protective functions can also be utilized for protections that could protect other network sections as well; e.g. the DC bus, line or cable. • Another advantage is that the interface for the trip signal will be handled internally by the HVDC CB control system; i.e. easier to optimise by any manufacturer.

Table 12 The requirements of protection IED hardware

Binary inputs	• For less time critical protections, the general AC standards defined binary signals might still be an option; e.g. DC side equipment SF6 guards. • For the time critical binary inputs, general requirements for voltage levels and anti-bounce filter might still be applicable. Due to the fact that the speed is essential, optical fibres for the signals might be considered.
Binary outputs	• Binary signals of fundamental frequency (50 or 60 Hz) cannot be considered as an option even for the time critical binary outputs. • For the time critical binary outputs, general requirements for voltage levels might still be applicable. It is required to have extreme fast tripping signal output to trip HVDC CBs. Thus, optical fibres for the signals might be considered.
Analogue inputs	• Especially for earth faults in the DC grid, the most critical issues are time and the fault current limitation, therefore the bandwidth of the analogue measurement is one of the most critical issues. • The bandwidth of the measuring equipment in combination of the detecting equipment input bandwidth will together result in a delay of the measured signal. This time delay needs to be considered in the protection system design.
EMS	• It is not foreseen that DC grid applications require any additional requirement than what would be the case for a traditional point to point transmission. • Error-free operation during system faults requires a high level of protection against electrical disturbances, so the Electro-Magnetic Compatibility needs to be guaranteed.
Power supply	• A major disturbance in a DC grid will have a larger impact in the surrounding AC network than a traditional point to point DC transmission. • A system designed for minimised impact of auxiliary power disturbances is recommended; i.e. redundancy of the power supply is recommended.

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- Requirements on acting equipment

Some general overviews of the current status in the development and detailed information about operating principles of HVDC CBs and other types of disconnectors and switches are given in a Cigré brochure that was prepared by JWG A3/B4-34 with reference [20] and reports from WP6 in PROMOTioN [17].

There have been several main concepts in the design of the HVDC CBs, and each has its positive and negative properties, mainly with respect to losses and speed. The pure semiconductor based HVDC CB has the speed but generates large losses; and the hybrid HVDC CB, which combines a mechanical breaker with a semiconductor breaker in parallel and which has low losses, is slower than the pure semiconductor based HVDC CB. Other designs are based on resonance mechanisms without semi conductive devices [13] [17].

- Requirements on fault location equipment [13]

Even though there is reserve transmission capacity existing in both AC and DC grids, an unscheduled outage or downtime should be as short as possible. The downtime of a single connection is dependent on following:

  - Fault detection and clearance time
  - Fault position location time
  - Fault position inspection time
  - Fault repair time
  - Testing and re-commissioning time

Both inspection and repair need the related knowledge of the location of the faults. Therefore, the fault location should be as accurate as possible to minimise the length of line that needs to be inspected. The fault repair time can last from hours to several months, which depends on the type of connection, OHL or underground cables.

Given a certain desired measurement accuracy (δx), the overall accuracy is dependent on the length of the DC connection line (L). This is given by the following formula:
Acceptable error (%)= $\delta x / L \cdot 100\%$

So for a DC line with a length of 200 km and an desired accuracy of ± 50 m the acceptable measurement error is $\pm 2.5*10^{-4}$. This accuracy is difficult to achieve but not impossible, when using standard measuring equipment.

2.2.3 THE REQUIREMENTS OF DC PROTECTION TESTING

Due to different considerations of DC protection design requirements, the challenges and requirements when testing DC grid protection will be different than those for AC. Even though challenges and requirements are different, the infrastructure remains the same and could be three layered:

- Hardware platform; e.g. Hardware in the Loop testing platform based on RTDS, relays, physical interfaces and connections. This will be introduced in WP4 testing environment and IED unit testing.
- Software platform; i.e. power system and control function models, reasonable test cases, protective function algorithms and DCCB. The related information can be found in WP4, WP6 and other deliverables in WP9.

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- Communication; it could be hardware or software defined data transmission network for the links between the hardware platform and software platform. At present, it is out of scope of this report.

The testing procedures and algorithms will be a part of software platform, which is the focus of this report and will be introduced in Chapter 3.

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3 TEST PROCEDURES FOR DC GRID PROTECTION TESTING

Since this task is also related to T4.3, T4.4, WP6 and other tasks in WP9, the related test procedures will focus on the specific protection components and real-time test environment.

The basic concept of DC grid protection is presented in Fig. 3. Based on measured (by sensors) values of voltage and currents and the system requirements, a protection system will decide to operate a DCCB or block converter. The protection system contains a wide set of protection algorithms based on (possibly) different fault detection methodologies including backup protection.

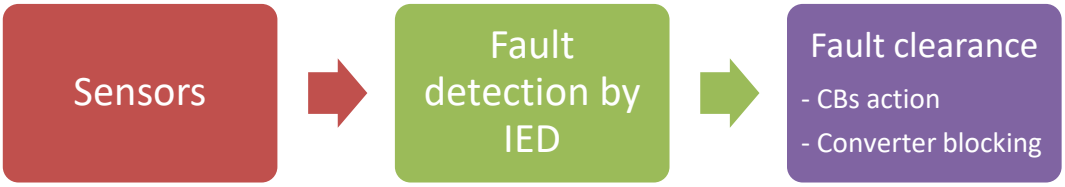

Fig. 3 HVDC grid protection concept

3.1 TEST OBJECTIVES AND FACTORS

The document presents various tables with the AC system constraints parameters. At this stage, the values of these parameters are typically given as indicative values based on either literature survey or experience from existing projects, however, they will definitely require further studies by the involved parties when actual systems are considered.

Furthermore, the document presents the DC system constraints such as DC switchgear constraints, DC converter constraints, DC cable/OHL constraints, surge arrester constraints. Also, for the DC system constraints and the DC component constraints, the emphasis is defining the requirements rather than providing actual values. Additionally, the document introduces key non-functional requirements such as reliability / availability and multi-vendor philosophy.

3.1.1 THE OPERATION OBJECTIVES OF DC GRID PROTECTION

As discussed in section 2.2, the functional requirements are based on AC and DC systems constraints. The objectives of feasible DC grid protection system designs are discussed here, which are related to what the protection system should do. The development of the best protection system is not merely a technical problem, but a techno-economic problem, which attempts to find a balance between the detection and clearing of all faults and the impact of those faults.

In an integrated DC and AC power system, the protection system must fulfil specific requirements and realize corresponding objectives, as they should protect the safety of operating personnel, protect the equipment and confine the consequences to the system. Thus, the reasonable consequences of different faults in the power system and the expected

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performance of the protection system need to be carefully investigated and defined in specifications before such a system can be implemented in practice.

Based on the functional requirements of the DC grid protection, the fundamental objectives of the DC grid protection can be described. Besides, according to the requirements, the boundary conditions under which the protection system operates can be roughly defined.

3.1.2 THE OBJECTIVES BASED ON DC CONSTRAINTS

Steady DC voltage is important for the operation of DC grids. In a DC grid, the significance of DC voltage can be defined by two effects: (i) equilibrium of infeed and offtake and (ii) normal power flow in the grid. Thus, the first objective of DC grid protection is to keep the DC voltage level within the permissible margins.

As for the requirements based on the component level considerations of DC systems, every component in the DC system has its own operational constraints. As an example, when the required speed of fault clearance and the required size of the additional DC side reactors are under defining and designing, the system designers and the equipment designers will have different considerations [12].

Thus, the protection system design will be different with the considerations of different operational range of many components. The mainly involved DC components will include switchgear related protective equipment, e.g. DC circuit breakers and their surge arresters, high speed DC switches, converters and their fault ride through characteristics, cables/OHL, DC current limiting reactors and surge arresters used for overvoltage protection in the grid level. The DC current and voltage ranges will be different based on the different combinations of the DC components.

3.1.3 THE OBJECTIVES BASED ON SYSTEM PERFORMANCE REQUIREMENTS

From the viewpoints of protection engineers, the system level performances of protection schemes should be verified and tested based on some general criteria, in order to make sure the protection schemes can satisfy all the critical requirements and objectives [12]. Since the converter self-protection scheme is vendor-dependent, the scope of the future DC grid protection for meshed DC grids has been considered to exclude converter protection. The general criteria, i.e. system level objectives of DC protection, are listed as follows [21] [22] and elaborated in section 2.2.2.2.

3.2 TEST CIRCUITS AND FAULTY SCENARIOS

The reasonable consequences of different faults in the power system and the expected performance of the protection system need to be carefully investigated and defined by testing with specific test environment, before such a system can be implemented in practice.

3.2.1 TEST CIRCUITS

According to the objectives of DC protection design, there are three test systems (benchmark networks) and the relevant test cases proposed in D4.1 [12], representing small, medium and large impact grids:

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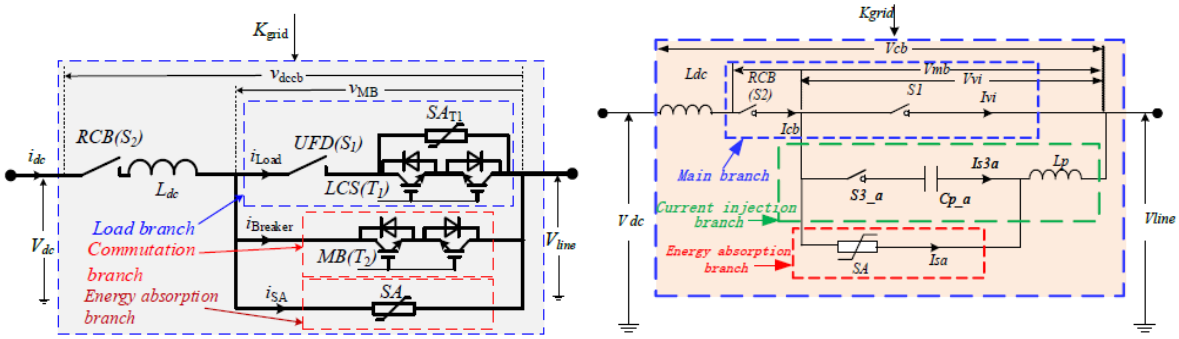
- Small impact grid: the loss of the whole HVDC grid will only have limited impact on the AC grids, seen as small voltage and frequency variations which are quickly restored. Loss of the system has an impact comparable to an "N-1" event.
- Medium impact grid: the loss of the whole HVDC grid will cause significant voltage, rotor angle and frequency transients seen by the AC grid; AC grids are able to recover from the contingency, without having a black-out, but possible load shedding should take place in some parts of the system.
- Large impact grid: The DC grid forms the backbone of the transmission system and the loss of this system likely leads to a blackout.

In this deliverable, typical HVDC network models will be adopted, some standard models can be improved and utilized with the consideration of different structures on DC lines/cables/reactors/converters [21] [23]. The available models have been listed as follows:

- Point to point DC system (Cigré DCS1)
- 3 terminal DC grid system (from RTDS Co.)
- 4 terminal DC grid system (Cigré DCS2)
- 4 terminal DC grid test system (TU Delft)
- 5 terminal DC grid test system (from RTDS Co.)
- 4 terminal DC grid test system (from D.4.1)

And the fourth test system will be mainly used in this report. Typical DC CB models developed in WP6 will be implemented with those chosen HVDC network models [17], e.g.



(a) Hybrid DC CB (b) Mechanical DC CB

Fig. 5 Structure of DCCBs

3.2.2 TEST SCENARIOS

In order to do DC protection testing in a reasonable test environment with the acceptable fault development progress, the critical test scenarios should be defined and developed before the related protection algorithms can be tested.

3.2.2.1 A FAULT CURRENT DEVELOPMENT WITH CONSIDERATION OF THE DC SYSTEM COMPONENTS

Fig. 6 shows an example of a prospective DC fault current in the four-terminal meshed HVDC grid [21] [23]. The fault current is measured by selected DCCBs at the end of lines at converter A1, A2, C1 and C2. The four-terminal meshed HVDC grid is a cable-based system, where each cable is terminated by series inductors. The converters in the system are half-

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bridge modular multilevel converters. The mechanical DCCB proposed in D6.9 is adopted here.

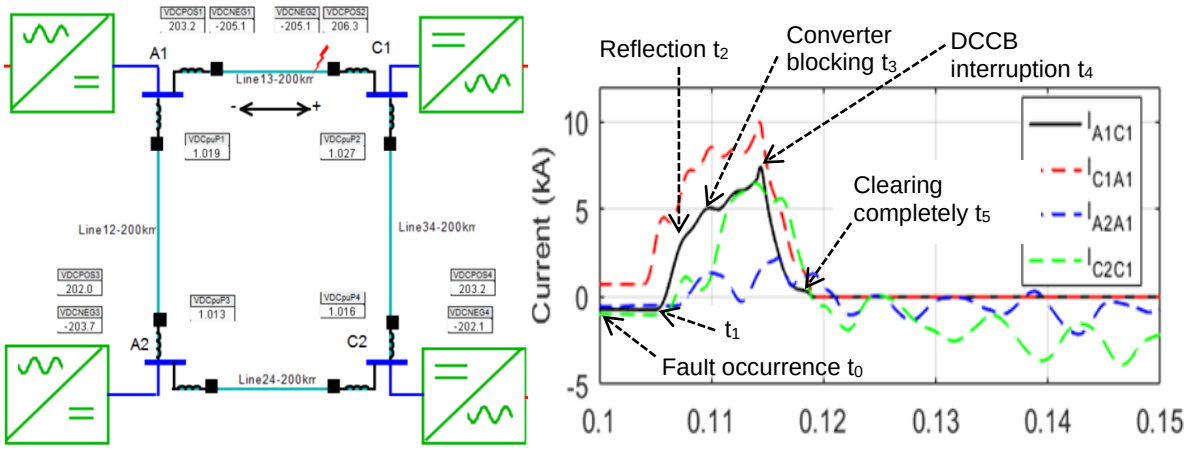
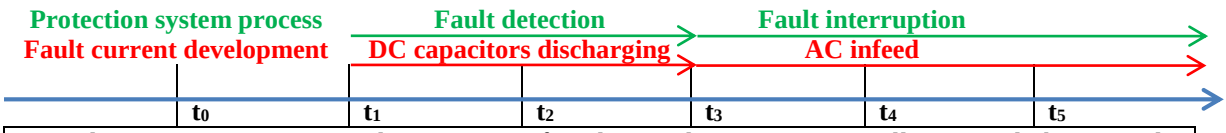


Fig. 6 Fault interruption in a 4-terminal HVDC grid

The fault occurs at the end of the link between converter A1 and C1 at time t_0=0.1s, and the associated travelling waves reach the terminal A1 at t_1=0.1056s. The time delay between t_0 and t_1 is caused by the finite speed of a wave traveling over the cable. After the instant t_1, the DC fault current quickly increases, and its rate of rise is limited by the series inductors. In the first milliseconds, successive reflections (e.g. at t_2) occur, caused by waves traveling over the line between the fault location and the protection system location. Furthermore, other terminals start to feed in fault current. At t_3, converter A1 blocks its IGBTs and the fault current is fed by the AC side. Then, all converters in the system are blocked subsequently. At t_4, the mechanical DCCB located at A1 opens to interrupt the fault current increment. Eventually, after t_5, the fault has been cleared completely by DCCBs on the faulty line between A1 and C1. A detailed overview of the phenomena which occur during the fault is given in Fig. 7.



t_0: Fault inception at transmission line. Creation of a voltage and current wave travelling towards the terminals.
t_1: The travelling waves reach the terminal A1 and continue propogations. The capacitors of the converter at related terminal start to dischange.
t_2: In the first milliseconds, successive reflections and transmission of waves occur between fault location and protection system location.
t_3: IGBTs of converter A1 are blocked for its own protection. Fault current is now contributed by the AC side through converter antiparallel diodes.
t_4: The mechanical DCCB located at A1 opens to interrupt the fault current increment.
t_5: Fault is cleared completely by DCCBs and the system starts to recover.

Fig. 7 The progress of fault clearance

As discussed in [12], the additional DC reactors/inductors play an important role in the beginning stage of fault current development. Since the initial rate of increase of fault current (di/dt) is directly proportional to the voltage difference ΔV across the current rise limiting reactor L ($\Delta V/L$). The di/dt limiting reactor values should be chosen to limit the fault current rise within the operating time of the DCCB to a value which is below the maximum interruptible current.

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It should be noted that terminal faults do not provide the highest possible rate of rise of the current in the cables. The worst case current (considering both di/dt and magnitude) is dependent on the travelling velocity and the operation time of the DCCB. The highest initial peak fault current through a DCCB occurs when a cable fault is located at a distance equal to the distance that the fault transient travels in half of the operating time of the DCCB. A method to determine the worst-case current was given as following [13]

1. For cables, the largest possible fault current for a given DCCB should be determined by:
    a. Prefault condition should be at the highest possible operating voltage and operating current
    b. Simulating pole-to-pole faults
    c. At a distance D_{crit} from the DCCB (This distance, D_{crit}, can be calculated by the half of the production of DCCB operating time T_{op} and the traveling velocity v_{travel} of the fault-generated surges: $v_{travel} \cdot T_{op}/2$)
2. For the OHL, worst case current should be determined by:
    a. Prefault condition should be at the highest possible operating voltage and operating current
    b. Simulating pole-to-pole faults
    c. Simulated at the terminals of the DCCB (The reason for this difference is the higher travelling wave impedance leading to lower initial currents for faults further down the line.)

Thus the critical parameters which influence the DC fault current and should be considered are given in Table 13 [12] [18]:

Table 13 The critical parameters influencing the DC fault current

1	Transmission line type	The characteristic impedance of OHL is larger than for cables, which causes current waves to be smaller in amplitude. The traveling wave speed of OHL is about the speed of light, whereas for cables this is half of to 2/3 the speed of light.
2	Fault resistance	An increasing fault resistance leads to a smaller prospective steady-state fault current.
3	DC side inductance	Increasing the DC side inductance decreases the rate of rise of the current but does not make impact to the prospective steady-state fault current.
4	DC side capacitance	A DC side capacitance (as e.g. used in two-level topologies) initially provides a large discharge current.
5	Converter blocking instant	The converter blocking instant determines the amount of discharge of submodule capacitors. Delaying the converter blocking instant increases the capacitor discharge.
6	AC system strength	The AC system strength mainly determines the value of the prospective steady-state current. An increased AC system strength leads to an increased value of the prospective steady-state current only limited by the short circuit impedance of the connecting equipment such as transformers.
7	System earthing	An overview of the types of system earthing and their associated fault currents and voltages is given in chapter 6 of D4.1 in WP4
8	Converter topology	A treatment of the converter topology and the associated fault currents is given in chapter 3 of D4.1 in WP4

3.2.2.2 CRITICAL FAULT CATEGORIES

The most appropriate protection system design needs to be risk-based. This will lead to similar considerations (rules) as currently used in AC systems.

Power system planning (including the protection system) should evaluate each possible (type of) event, the probability of its occurrence and its impact on the remaining system. Based on

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these two measures, a decision is made whether this impact and probability are acceptable or not, and what necessary design changes are required. Generally, a risk-based analysis by using an economic evaluation with taking into account all the benefits and associated costs [12] [18].

The choice of protection philosophy and its implementation in terms of protection algorithms and equipment is a trade-off between the allowable impact of a certain fault case on the system and the associated costs of the protection system and its implementation. To make this trade-off, the following questions should be considered:

- The occurrence probability of an event (DC fault).
- The impacts of the HVDC system design and the converter technology on fault clearing.
- The impact of the fault on the HVDC grid and connecting AC system, both for cleared and uncleared faults.
    - Affected system components
- The fault duration and its impacts
- The associated costs (including expected energy not served (EENS))
- The impact of the chosen protection philosophy on overall power system reliability
- From the perspective of the HVDC grid users, HVDC grid operators and AC transmission operators, the scope of accepted power interruption.

Based on these questions, some case studies and analysis have been conducted on fault transients and related impacts in Cigré B4. 59, D4.1 and D4.2 [12] [13] [18]. An approach proposed by RTE in the Memento of power system reliability [12] [24] has been adopted to define faulty events by the impact severity (in MW lost) and the probability of occurrence, which can be seen in Fig. 8. When analysing all possible events in the DC grid, the system operator will need to address those events which are located outside of zone 1 and 4 through appropriate actions. In this way, the protection system can be adapted to diverse probability of events and their impacts. The corresponding thresholds and solutions for the events in different zones are listed in Table 14. The balance between different solutions for the specific fault event zone should be based on a cost-benefit analysis of the options.

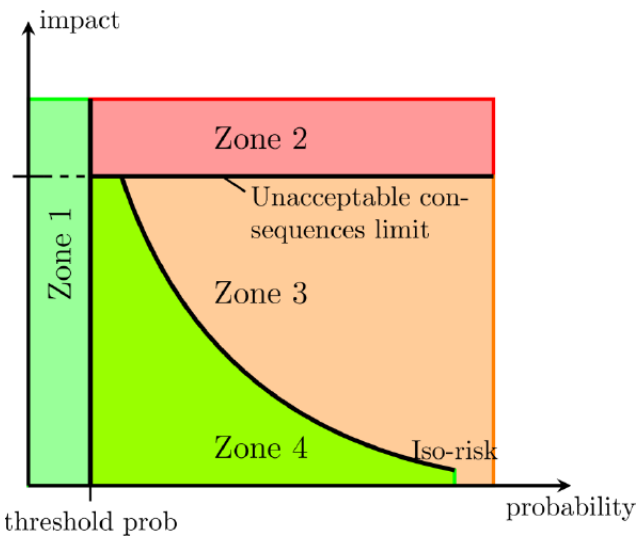

Fig. 8 Categories of different faults based on probability and impact

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Table 14 The definitions and protection considerations of the zones in Fig. 8 adapted from [12] [24]

Categories	Definitions of categories	Protection considerations on thresholds and solutions
Zone 1: Out of norm events	These events are so unlikely that there is no necessity to address them.	**Out of scope**, it is considered too expensive to invest in methods to mitigate these events.
Zone 2: Unacceptable consequence zone	These events are of high impact to the system, while they are with a significant probability to not be able to ignore them. The zone 2 events need to be addressed by suitable design of the system so that these events can be restricted.	***Minimum considered probability or threshold probability*:** identifying the minimum likelihood an event needs to be in order to take particular measures (e.g. an N-k event with k a large number). Events with a lower probability are considered unlikely. ***Solutions:*** investing in new equipment, applying different protection system settings.
Zone 3: Unacceptable risk zone	The events in this zone are of medium impact, and are sufficiently likely to occur. The operator needs to manage these risks.	***Unacceptable consequences limit:*** identifying the limit which the consequences are so serious that any likely event requires adequate protection. This limit relates to the maximum loss of power defined by the system operator. ***Solutions:*** investing in new equipment, applying different protection system settings or by applying new operational rules. It is also acceptable to address this issue through operational decisions, e.g. through preventive actions.
Zone 4: Acceptable risk zone	These events are below a given risk profile which is considered acceptable by the system operator.	**Acceptable risk level:** iso-risk [24] curve identifying the risk which a system operator is willing to take in his system **Solutions:** The decisions on protection are only taken if they are the outcome of a technical and economic analysis.

Furthermore, in WP4, a questionnaire based analysis is given for the evaluation of different types of faults, in order to find the critical faults to be considered in a general DC protection system design, which have been summarized in Table 15 [13] [18]. The related approximate location and occurrence-severity relationships can be seen in Fig. 9.

Table 15 The critical fault types, related information and categories [adapted from [13] and [18]

For OHL	Fault type	Occurrence	Severity	Cause	Categories
1	Pole-to-ground (self clearing)	High probability	Low	Direct Lightning strike on a conductor; back flashover across an insulator; conductor contact by a foreign object; pollution;	Zone 3
2	Pole-to-pole (self clearing)	Low probability	High	Conductor galloping;	Zone 3
3	Pole-to-ground (permanent)	Very rare	High	Insulator failure; Broken conductor	Zone 3
4	Pole-to-pole (permanent)	Very rare	High	Tower failure	Zone 3 or Zone 4
5	Physical disconnection	Low probability	High		Zone 4

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6	Metallic return to ground	Low probability	Low		Zone 4
For Cable	**Fault type**	**Occurrence**	**Severity**	**Cause**	**Categories**
1	Pole-to-ground (self clearing)	Low probability	High	Bushing flashover	Zone 3
2	Pole-to-ground (permanent)	Most probability	High	Insulation failure due to an internal defect, installation damage or external damage;	Zone 2
3	Pole-to-pole (permanent)	Very rare	High		Zone 1 or Zone 4
4	Physical disconnection	Very rare	High		Zone 1
s5	Metallic return to ground	Low probability	Low		Zone 4
For Busbar	**Fault type**	**Occurrence**	**Severity**	**Cause**	**Categories**
1	Pole-to-ground	Low probability	High	Insulation failure due to an internal defect in a AC device or DC device	3 or 4
2	Pole-to-Pole	Low probability	High		3 or 4
Others	**Fault type**	**Occurrence**	**Severity**	**Cause**	**Categories**
1	Loss of grounding	Low probability	Low		Zone 4

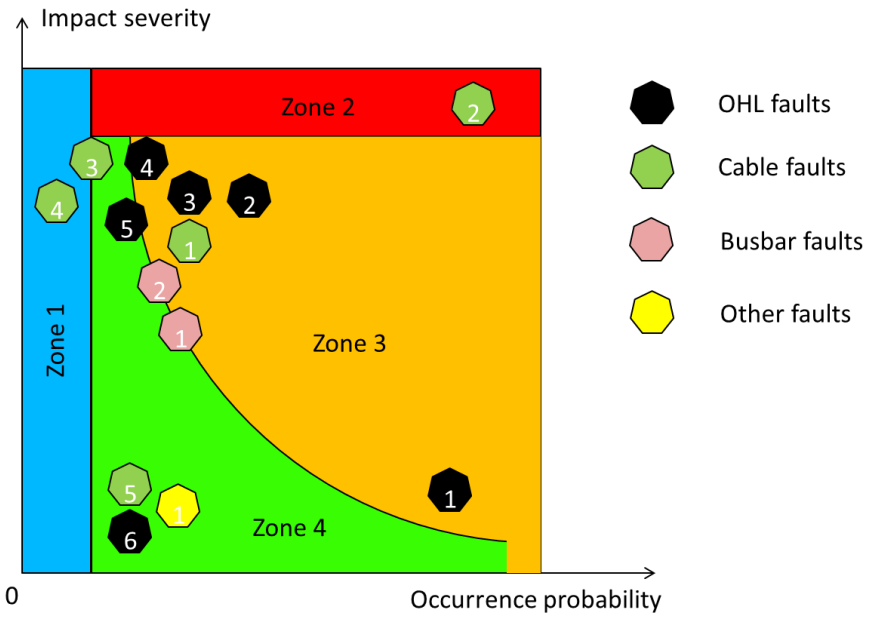

Fig. 9 A categorization of the critical DC fault types

In the testing of DC protection in next sections, the protection algorithms will be run with the critical fault cases in Zone 2 and Zone 3, which are listed as:

- Pole-to-ground OHL fault (self clearing)
- Pole-to-ground OHL fault (permanent)
- Pole-to-pole OHL fault (self clearing)

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- Pole-to-pole OHL fault (permanent)
- Pole-to-ground cable fault (self clearing)
- Pole-to-ground cable fault (permanent)

Other faults, which are very rare normally, should be covered by detection, identification, backup or restoration functions for the suitable performance of whole protection system, i.e.:

- Pole-to-pole cable fault
- Pole-to-pole busbar fault
- Pole-to-ground busbar fault
- Loss of grounding
- Metallic return to ground fault of cable section
- Metallic return to ground fault of OHL section

3.3 TEST PROCEDURES

With the considerations of the complex fault dynamics on DC grid, the following critical factors may be considered mainly:

- Reliable testing case, feasible operational modes, across variety of network requirements
- Multiple DC fault scenarios on a range of operation topologies and scenarios
- Converter-protection interactions
- The real-time testing will involve analysis of a sequence of events under given performance criteria
- DC protection IED/algorithms will be tested for accuracy, speed of response, and fulfilment of protection criteria
- The critical objectives (as explained in Section 3.1) from component and system levels can be reached or not.

The script of protection performance testing is depicted in Fig. 10. The black workflows represent the normal progress of fault development and protection performance, whilst the red workflows represent the evaluation and testing progress.

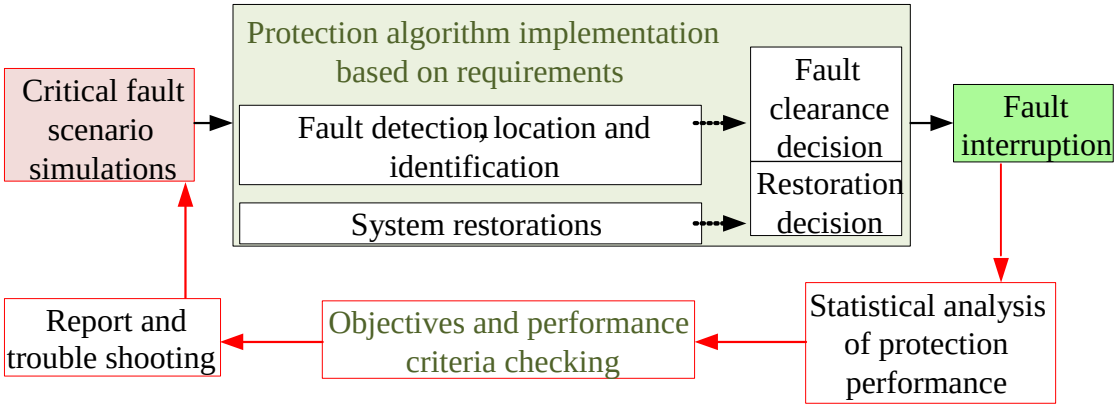

Fig. 10 The general script of protection performance testing

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3.3.1 DC GRID PROTECTION ALGORITHMS

A DC grid protection system should at least include primary and backup protection and may include power flow restoration. The corresponding test procedures for these three parts will be considered in this subsection.

Normally, based on the selective or nonselective fault clearing philosophy, different protection algorithms will be chosen as studied and reported in [18]. Due to high speed communication requirements for meshed DC grid protection, the non-unit communication-less protection algorithms in the scope of fully selective fault clearing philosophy will be firstly considered before including the options of communication-based algorithms. Non-unit protection algorithms only utilize local measurements at one location, while the communication-based or unit protection algorithms make use of communication for the utilization of information from several locations.

As reported in Chapter 2, the differences between AC and DC protections can be found from the essential aspects, e.g. operation speed, measurement, communication, circuit breaker, protection algorithms, etc. The “brain” of the protection system, the protection algorithms play the most important role to ensure the timely detection of the faulty condition and thus guarantee the timely disconnection of faulty lines, in order to minimize the negative consequences associated with the fault [25].

The protection algorithms currently considered for DC power systems have been listed and categorized in Table 16 [7] and [26]-[35].

Table 16 The critical fault types, related information and categories

Protection algorithms	**Categories**		
Travelling wave based [26]	Primary/backup	Non unit	Selective
Voltage/voltage derivative [27] [28]	Primary/backup	Non unit	
Current/current derivative [29] [30]	Primary/backup	Non unit	
Different combinations of above approaches [31] [32]	Primary/backup	Non unit	
Travelling wave differential [33]	Primary/backup	Unit	
Current differential [34]	Primary/backup	Unit	
Failure of breaker and relay [35]	Backup protection	Non unit/Unit	
Open grid method [7]	Primary/backup	Non unit/Unit	Non selective

It should be noted that the time delay of differential algorithms can influence the protection performance; less influence can be achieved based on the travelling wave differential protection algorithm. Thus, the differential protection algorithms which use a longer time frame before a decision is taken could be applied more in primary protection functions of busbar/short lines protection, as well as in backup protection functions of longer DC lines. Protection algorithms not requiring communication can be applied for fast primary protection, albeit that they might face limits for protection of long DC lines. Additionally, the distance protection algorithm as used in AC systems is not readily applicable in DC system, since the fundamental frequency component and the steady state reactance cannot be determined.

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3.3.2 THE TESTING PROCEDURES FOR DC GRID PROTECTION

The faults in the DC system under consideration have been discussed in the former sections. Besides, the test systems should be introduced and modelled normally before the protection system is developed and the faulty test cases are simulated. In this section, the possible variations (configuration and grounding principles) will not be discussed.

In addition to the configuration of HVDC system, the fault clearing strategy will influence the protection system implementation and testing as well. The fully selective fault clearing strategy will in this document be considered for protection system implementation and related IED testing. Thus, the DCCBs and series inductors are located at the end of each line. For fully selective strategy, each line is one protection zone, whilst for partially selective strategy, each zone includes some part of the network. The procedures can also be applied for partially selective strategy by replacing each line in fully selective strategy by each protection zone applied in the partially selective strategy.

3.3.2.1 GENERAL CONSIDERATIONS ON PROTECTION SPECIFICATION

For the testing of specific protection IED, the specifications of protection functions need to be provided by the IED vendor. Normally, the basic protection functions with its inputs, outputs, measuring element, time delay characteristics and functional logic is shown in Figure 11 [36]. Normally, the manufacturer shall provide the functional block diagram of the specific implementation, and the related explanation of each function which can be seen in Table 17. This table is based on the up to date knowledge of AC protection which is summarized in [36].

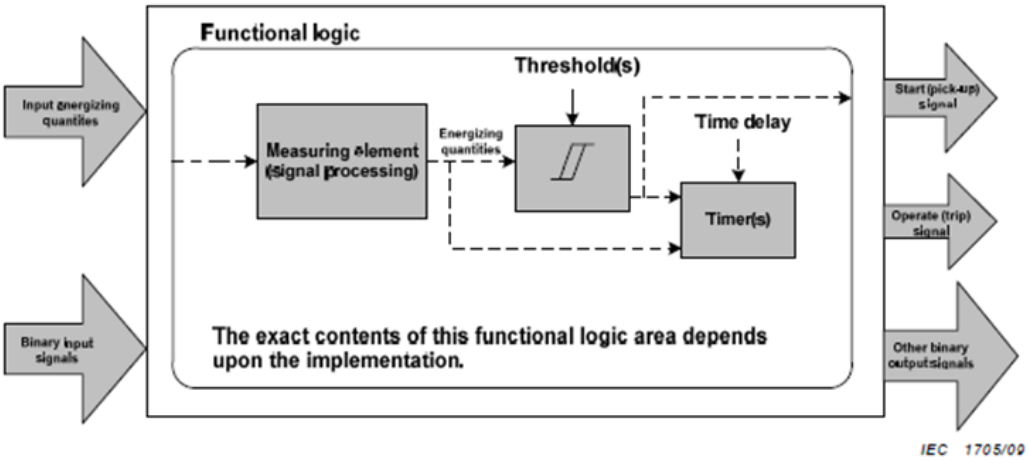

Figure 11 Simplified protection function block diagram [36]

Table 17 The normal specification of protection functions (adapted from [36])

Input energizing quantities/ energizing quantities	The input energizing quantities are specific measuring signals, e.g. currents and voltages. Input energizing quantities can come with wires from current and voltage transformers or as a data packet over a communication port using an appropriate communication protocol (such as IEC 61850-9-2). Manufacturer shall declare rated values of ratings for a.c. or d.c. The type of measurement of the energizing quantity shall be stated.
Binary input signals	If any binary input signals (externally or internally driven) are used, their influence on the protection function shall be clearly described on the functional logic diagram, e.g. the state signals of converters and DCCBs for backup and restoration functions. The manufacturer shall declare the ratings.

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Binary output signals	**Pick up signal**	The output of measuring and threshold elements, without any intentional time delay. In DC system, it can be directly used as a trip signal for main protection functions.	The manufacturer shall declare the ratings.
	Trip signal	The output of measuring and threshold elements, after completion of any intentional operating time delay. In the case of instantaneous elements, this signal may occur at the same time as the start signal (if provided).	
	Others	If any binary output signals are available for use, their method of operation shall be clearly shown on the functional logic diagram, e.g. some signals used in cooperation with converter protective control and other protection functions.	
Functional logic	**Operating characteristics**	• Starting/fault detection • Directional determination • Calculation of characteristic quantities • Protection characteristic settings (zone reach) • Operation logic	The manufacturer shall declare any performance limitation of the protection function when used in conjunction with programmable logic if used. And the effective and operating ranges should be declared by the manufacturer.
	Reset characteristics	To allow users to determine the behaviour of the relay in the event of repetitive intermittent faults or for faults which may occur in rapid succession, relay reset characteristics shall be defined by the manufacturer or a coordination logic with pick up signals and breaker states could be applied to block the unnecessary relay operations.	
	Restoration characteristics	The restoration functions could be an independent part to detect fault clearance, breaker reclosing, voltage and power flow recovery. The restoration functions could be integrated with backup protection functions to detect breaker failure and do system recovering (to be considered as a future algorithm).	

The evaluation of the protection system, i.e. protection testing, will be based on the specification of the protection functions and protection performances. The first consideration of the specification of protection performance is the accuracy of protection system, which should be evaluated in the IED type testing [3]. The accuracy issues will include:

- Intrinsic accuracy- the accuracy under reference conditions
  - Accuracy relating to the characteristic quantity
  - Accuracy specification of time delayed elements
  - Accuracy specification of instantaneous elements

- Operating accuracy

The accuracy includes the intrinsic accuracy and variations due to influence quantities (line inductor). The determination of variation due to changing any influencing quantity or factor between the limits of its nominal range shall be made under the test reference conditions.

- Overall system accuracy

System accuracy includes operating accuracy; variation due to network configurations and variations due to sensors accuracy.

According to IEC 60255-1[3], the type (unit) testing is used to verify the new hardware/software designs against the product specification and standards. Once a product has been type tested, it shall not be necessary to repeat the testing unless the design changes. If a design change takes place, then a risk assessment needs to be performed and documented to determine, which type of tests are still valid and which tests need to be repeated.

The verification procedure, especially in the level of overall system in this report, should ensure that the equipment is in accordance with its specification and that its functions perform correctly during the initial measurement at the beginning of the test sequence and maintains its design characteristics throughout all the tests where this has been specified.

Hence, in this report, the testing of protection performance is focused on the system level. Other detailed type testing items will be given in WP4.

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3.3.2.2 THE TESTING STEPS FOR PRIMARY PROTECTION

With the consideration of the fully selective fault clearing strategy, the primary protection algorithms should be implemented together with the operational times of the DCCBs. The operation time can be simulated directly from the RTDS models of DCCBs as reported in 6.9.

In order to evaluate the failure rate of primary protection, the effectively required operations and the operation times shall be the important indicators to check if the required actions can be done in the required time range for DC protection.

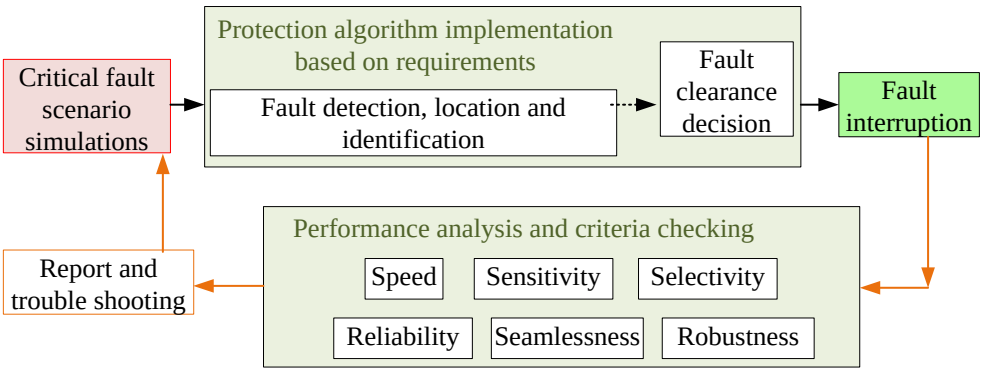

Figure 12 The general process of primary protection performance testing

Different test scenarios will be required for different systems configuration. It is assumed here that the testing system has been developed with symmetric monopole half-bridge HVDC grid, fully selective fault clearing strategy and related DCCBs. The intrinsic accuracy, available testing range and points need to have basic considerations in the type testing [3]. The general testing progress of the primary protection system level performance is depicted in Figure 12. The procedures of related testing steps are listed as follows:

Step 1: Fault scenarios-simulation based fault studies

The critical testing parameters listed in Table 18 could be different according to the different testing systems and testing objectives. These critical testing parameters can be changed in order to do multicase testing and record the responses of the objective protection systems or protection IEDs. The fault resistance and the series inductor parameters between 0-400 ohm and 0-200 mH respectively were proposed. However, the choice of these parameters are system dependent and are generally decided by the user/vendor through knowledge of system studies and operation.

Table 18 The critical testing parameters for performance testing

Relatd testing parameter	**Typical value**
Fault resistance	0-400 Ohm Variation: 0, 0.01, 0.1, 0.5, 1, 5, 10, 25, 50, 100, 200, 300, 400 Ohm
Fault type	PTP1: pole-to-pole permanent fault PTP2: pole-to-pole self clearing fault PTG1: pole-to-ground permanent fault PTG2: pole-to-ground self clearing fault
Fault location	0%-100% of the line with reasonable interval, $0\%_{L-}$, $0\%_{L+}$, 20%, 40%, 60%, 80%, $100\%_{L+}$, $100\%_{L-}$, 110% 'L+': the fault is applied at the end of the line before the series inductor.

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	'L-': the fault is applied after the series inductor close to the bus.
Series line inductor	0-200 mH with reasonable interval, 0, 50, 100, 200 mH

Step 2: Statistical analysis of system level performance

a. Accuracy of protection characteristics, e.g. settings of thresholds.

Since the concepts of protection zones have been implemented with the fully selective clearing strategy, the transient overreach related analysis used in IEC 60255-121 [37] could be adopted for accuracy testing. An example of detailed testing procedures on these diagrams can be seen in Figure 13. We need to point out that the testing scenarios are repeated 5 times, just as it is normally done in AC testing. The reason for this is because of the possible deterministic property of the IED with the associated software. It is a common practice in terms of reliability check.

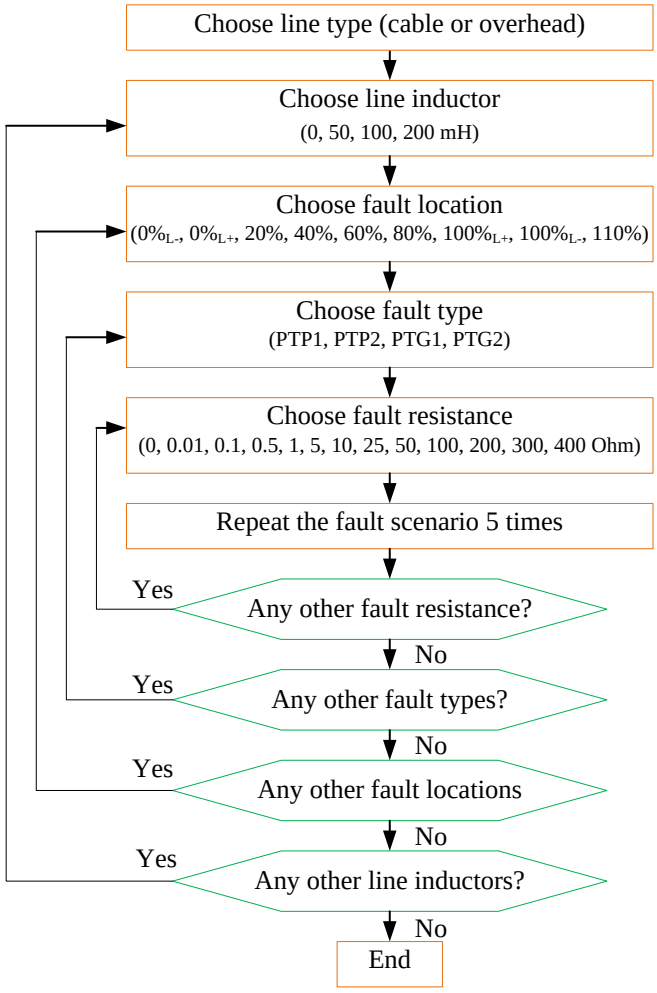

Figure 13 The general procedures for system level accuracy testing

b. Operation time

Based on tests performed according to Figure 13, the operation times can be determined in a statistical form. In order to evaluate the operation time, a subset of the operation time data collected during the tests will be considered. For example, the test data at fault positions 0

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$\%_{L+}$, 50 % and 80 % of the protection setting reach and for L = 100 mH for the line inductor will be considered.

This will result in a total of 1560 (780 operation times for the cable line tests and 780 operation times for overhead line tests) obtained operation times. This is equal to 240 operation times for each fault type. In order to create a fault-type distribution in the operation time statistics, the following weights are given to the available data according to the fault categories defined in Section 3.2:

Test results for faults in Zone 2, i.e. PTP1, will be weighted by a factor 4.
Test results for faults in Zone 3, i.e. PTP2, PTG1, PTG2, will be weighted by a factor 2.
Test results for other faults will be weighted by a factor 1.

The weighting is done by simply repeating the available results. Figure 14 shows the fault statistics of the typical operation time. Totally, 3900 operation times are available for the statistics.

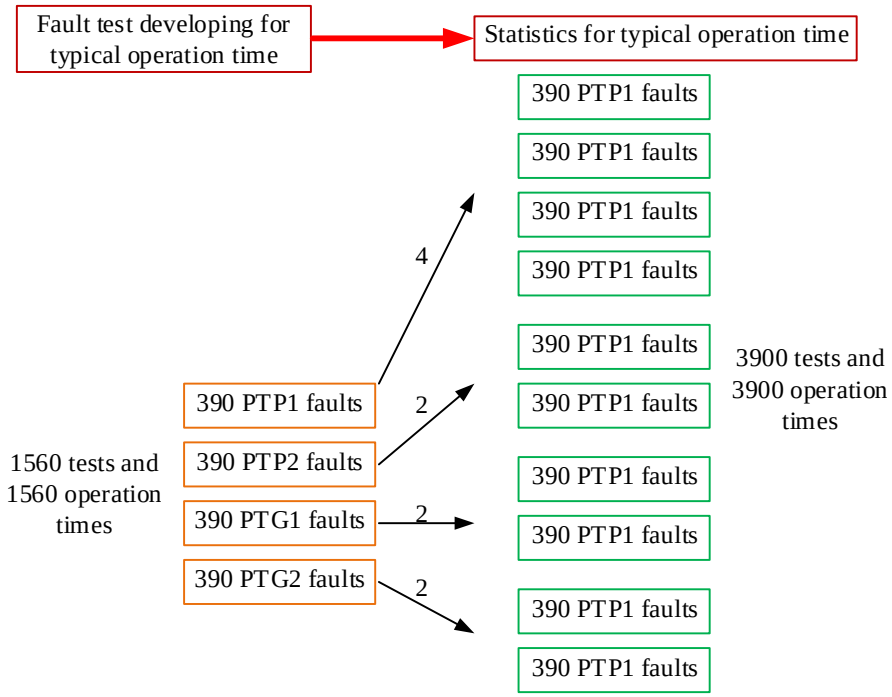

Figure 14 The fault statistics for typical operation time

These tests are aimed at determining the accuracy of the operation times for protection zones of primary functions. They are based on monitoring the time difference between the fault occurrence and operation output signals of the relay.

The time range and associated classes based on the operation time could be defined based on the collected data set. For an example, the minimum and maximum operation times in the data set are detected: min_T=1512 us, max_T=4167 us. Thus, a range of operation time could be defined as [1500, 4200] us similar like it was done in [18]. The classes of the performances of the IED under testing can be defined by making average groups with an interval of 300 us, which can be seen in Table 19. We need to point out that under relay class we consider a particular operation time range.

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Table 19 Classes of target IED performances based on operation time

Class	From t ≥ [us]	To t ≤ [us]	N	% N
Class 1 (min=1500 us)	min	min + 300	The number of operation times belonging to each class (n)	The probability of N for each class (n)
Class 2	min + 300	min + 600		
Class 3	min + 600	min + 900		
Class 4	min + 900	min + 1200		
…				
Class n	min + (n-1)×300	min + n×300		
…				
Class M (max=4200 us)	min + (M-1)×300	max		

The number of operation times belonging to each class (N), with 300 us resolution, is counted to show the probability distribution of the operation times. The probability of N for each class is calculated and the values can be filled in Table 19. These procedures are related generally for all relays, and the table refers for the relay that will be tested.

Step 3: Threshold setting adjustment

The setting rules, variation range and accuracy of thresholds will be introduced and analysed in the type testing of relay IED specifications. However, for the system level testing, more influencing factors will be involved and the corresponding thresholds could be optimally adjusted to achieve better system level performance.

The test settings of the thresholds to be used are expressed in percentage of the available range with 0 % representing the minimum available setting and 100 % representing the maximum available setting. Similarly, 50 % would represent the mid-point of the available setting range. The actual setting to be used can be calculated using the following formula:

$$S_{AV} = (S_{MAX} - S_{MIN})X + S_{MIN}$$

where S_{AV} is the actual setting value to be used in the test; S_{MAX} is the maximum available setting value; S_{MIN} is the minimum available setting value; X is the test point percentage value expressed in the test methodology. For example, assuming the available setting range is 0.1 to 5 A and 40 % test point percentage, the actual operating current settings will be 2.06.
For the threshold setting optimization, testing procedure can be performed with the consideration of variable threshold setting values that will result in the determination of the most accurate threshold setting. For example, if the pre-calculated threshold setting is 63.5%, threshold setting values change from 62 % to 65 % by 0.5 %, then the related testing procedures can be seen in Figure 15. The statistics data analysis can be conducted using weighting factors of step 2 to obtain the best threshold settings with highest probability of correct operation. It should be noted that the minimum changing step for the threshold setting (0.5% in this example) can not be smaller than the IED data resolution.

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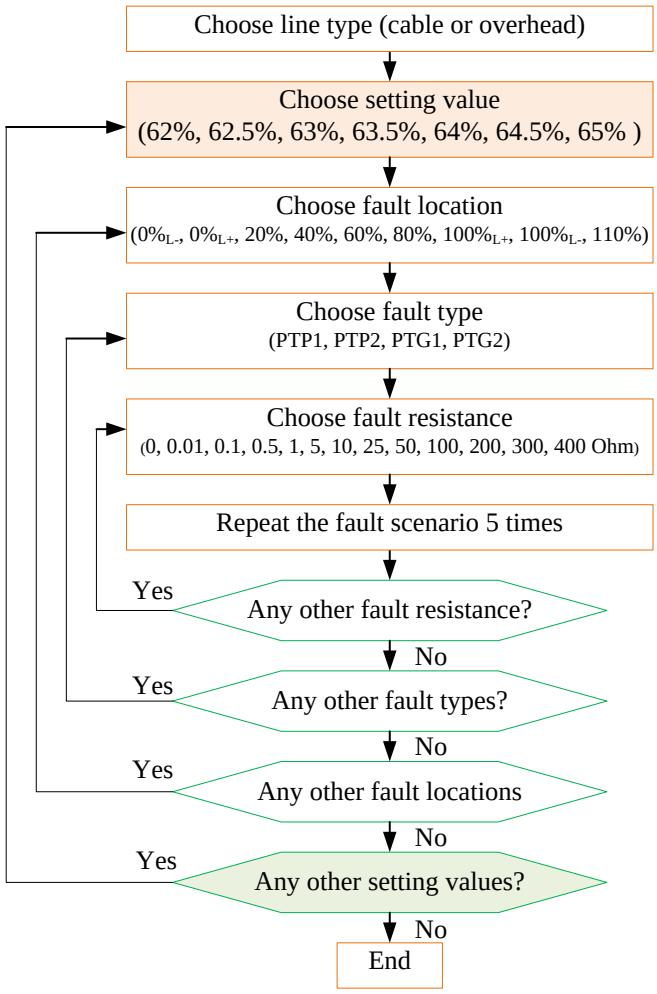

Figure 15 The testing procedures for threshold setting adjustment

Step 4: Criteria checking

After the verification of the accuracy and the threshold settings for the specific system operation conditions, the primary protection functions need to be tested if the objectives of protection system performance are met. The critical criteria are speed, sensitivity, selectivity, reliability, seamlessness and robustness, which have been introduced in the former chapters. In order to evaluate these criteria, tests are divided in three different operations:
Correct operations: protection system operates for faults in its protection zone
Failed operations: protection system does not operate for faults in its protection zone
Incorrect operations: protection system operates for faults out of its protection zone

Firstly, the objective of the speed of the primary protection is understood in a way that the protection must act fast to avoid damage to the equipment, limit the fault current within the maximum interruptible current time and limit the impact of the disturbance on the network. The time for the current to reach this limit gives the maximum acceptable time for protection and breaker operations. In some cases, the maximum allowed current can be reached in less than 10 ms [13] [20]. If some components have a fast response others can be slower. For example, a fast breaker could allow more complex and time consuming algorithms to be applied. Based on the designs of DCCBs in WP6, the typical allowed time ranges from fault occurrence, detection to trip signal output of protection IED has been provided in the following

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Table 20. All the values are typical values which could be varied with different series line inductors and breaker interruption capabilities.

Table 20 The typical time range for DC protection system operation

Breakers	**Operation time (Typical value) [13,20]**	**Time range for protection IED (Typical value)**
Hybrid DCCB	1.5-3 ms	depending on the vendor IED
Mechanical DCCB	5-10 ms	depending on the vendor IED
Other types		

The testing parameters may consider the DCCB types used in the test system, as shown in Figure 16. Accordingly, the fault data statistics analysis will be revised based on required operation time range. However, in [18], the total time 20 ms is regarded as a typical value of the first time frame of DC grid protection (including the protection functions and breaker operations).
Then a qualification criterion can be expressed as follow:

Speed criterion: Pclasses.speed = $\frac{Number\ of\ correct\ operations}{Total\ number\ of\ tests}$

where Pclasses.speed represents the probability of related classes in the required time range for speed checking on protection IED. We should point out that speed as a requirement just as other requirements are defined in 2.2.2.2.

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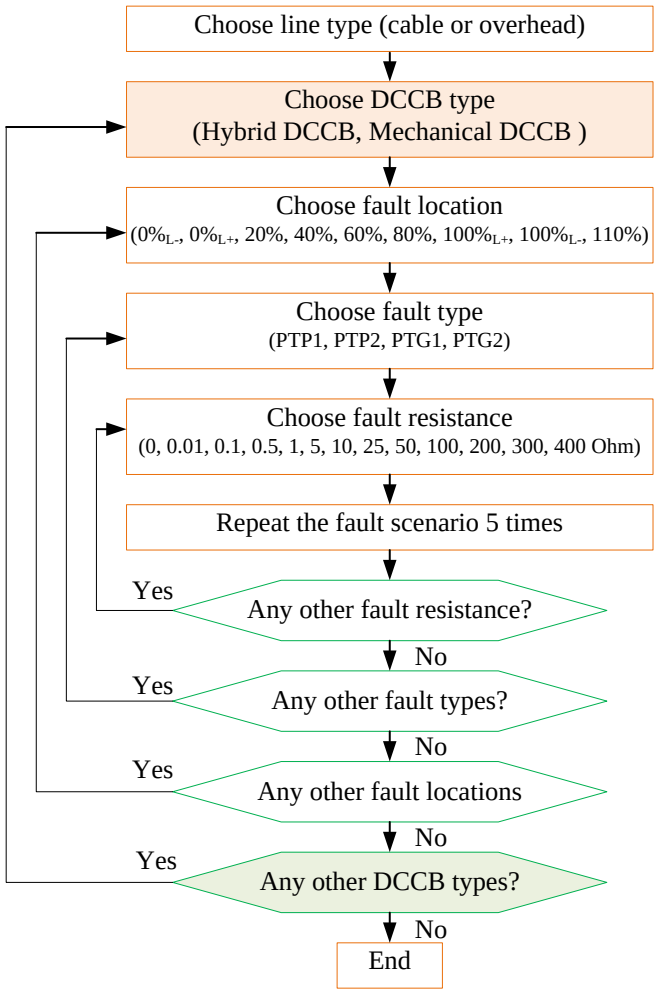

Figure 16 The testing procedures for speed checking

Secondly, the objective of the sensitivity of DC primary protection refers to the minimum operating quantities required for the system to detect a fault. Certain problems, such as detecting high-impedance ground faults (if applicable)and different line inductors, still affect the sensitivity of the protection IEDs and should be considered when the protection systems are tested in real-time simulation environment. Thus, in the related testing, the fault resistance and line inductance will be chosen as the critical testing parameters with the focus to consider more on the minimum faulty conditions, as shown in Table 21. And the revised testing procedures can be seen in Figure 17 accordingly.

Table 21 The typical critical testing parameter for DC protection sensitivity

Related testing parameter	**Typical value**
Fault resistance	0-400 Ohm 0, 0.01, 0.1, 0.5, 1, 5, 10, 25, 50, 100, 200, 300, 400 Ohm
Line inductor	0-200 mH 0, 50, 100, 200 mH
Fault type	PTG2: pole-to-ground self clearing fault
Fault location	0%-100% of the line with reasonable interval $0\%_{L-}$, $0\%_{L+}$, 20%, 60%, 80%, 90%, $100\%_{L+}$, $100\%_{L-}$ 'L+': the fault is applied at the end of the line before the series inductor. 'L-': the fault is applied after the series inductor close to the bus.

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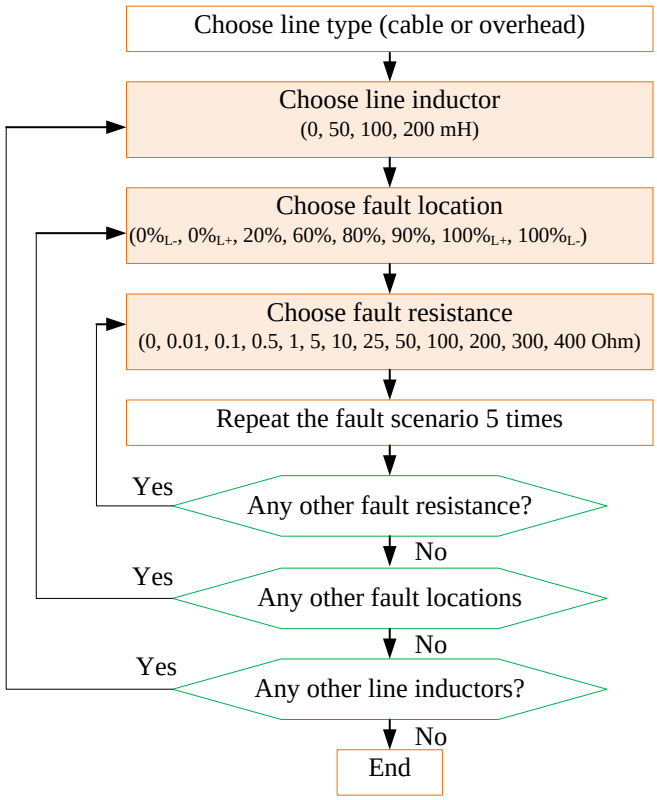

Figure 17 The testing procedures for sensitivity checking

Accordingly, the fault data statistics analysis will be revised based on the focused operation range, e.g. [100, 200] mH of line inductor, [200, 400] Ohm of fault resistance, [90%, 100%$_{L+}$, 100%$_{L-}$] of line as fault locations. The suggested line inductors and fault resistances are typical values as used in the analysis related to DCCB and protection in WP6 and WP4 respectively[17], [18].

Then a qualification criterion can be expressed for instance:

Sensitivity criterion: $P_{classes.sensitivity} = \frac{Number\ of\ correct\ operations}{Total\ number\ of\ tests}$

where $P_{classes.sensitivity}$ represents the probability of correct operations in the required operation range for sensitivity checking on protection IED.

Thirdly, the objective of the selectivity of DC primary protection refers to the ability to identify the faulty section and/or faulty pole(s) of a HVDC power system. The selectivity is tightly related to protection zones, fault types and fault locations. The line inductance and the fault resistance are also the key parameters, which influence the voltage and current transients from a faulty line to neighbouring lines. Thus, in the related testing, the fault resistance, fault location, the fault type and line inductance will be chosen as the critical testing parameters with the focus to consider more on the borders of protection zones. The typical values of these parameters can be seen in Table 22, and the revised testing procedures can be seen in Figure 18 accordingly.

Table 22 The typical critical testing parameter for DC protection selectivity

Related testing parameter	**Typical value**
Fault resistance	0-400 Ohm 0, 0.01, 0.1, 0.5, 1, 5, 10, 25, 50, 100, 200, 300, 400 Ohm

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Line inductor	0-200 mH 0, 50, 100, 200 mH
Fault type	PTP1: pole-to-pole permanent fault PTP2: pole-to-pole self clearing fault PTG11: positive pole-to-ground permanent fault PTG12: negative pole-to-ground permanent fault PTG21: positive pole-to-ground self clearing fault PTG22: negative pole-to-ground self clearing fault
Fault location	0%-100% of the line with reasonable interval, and neighbouring areas. $0\%_{L-}$, $0\%_{L+}$, 20%, 80%, 90%, $100\%_{L+}$, $100\%_{L-}$, 105%, 110%

Accordingly, the fault data statistics analysis will be derived based on the selected fault locations and fault types, e.g. [90%, $100\%_{L+}$, $100\%_{L-}$, 105%, 110%] of line. The number of required correct operations will be recorded for this criterion. Then a qualification criterion can be expressed as:

Selectivity criterion: $P_{classes.selectvitiy} = \frac{Number\ of\ correct\ operations}{Total\ number\ of\ tests}$

where $P_{classes.selectivity}$ represents the probability of required correct operations from the number of performed tests to check selectivity of the protection IED.

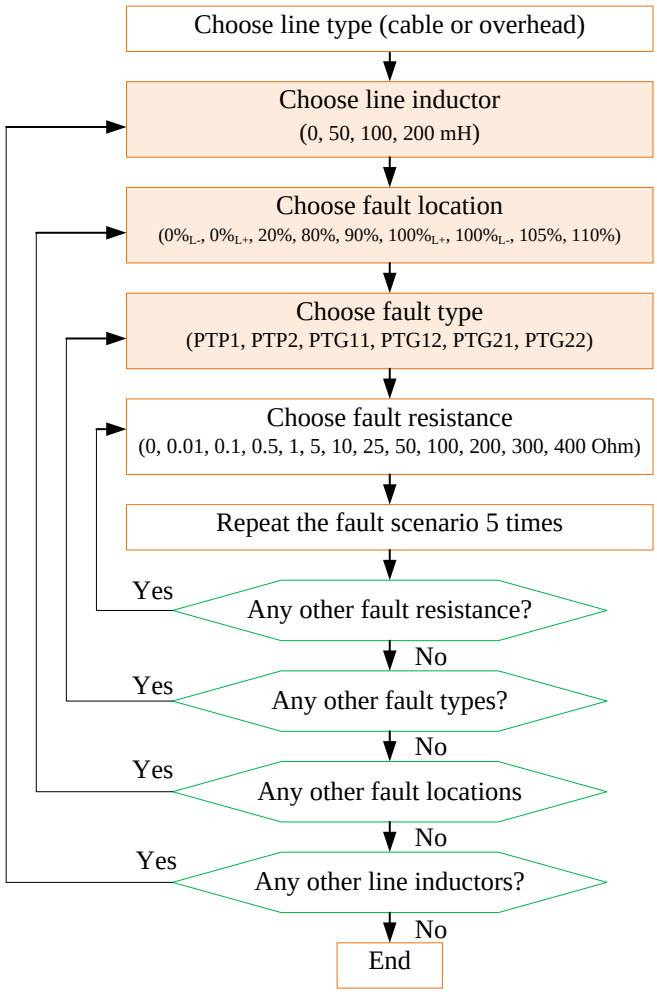

Figure 18 The testing procedures for selectivity checking

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Fourthly, the objective of the reliability of DC primary protection refers to the ability to perform a required function under given conditions for a given time interval. The required function for protection is to operate when required to do so. In this respect, two more definitions are given, i.e. security and dependability.

The security of protection system is the ability of a system to refrain from unnecessary operations [17]. In HVDC grids, the unnecessary protection operations could result from the loss of selectivity and sensitivity due to wrong thresholds or operation condition changing, e.g. DC line outage, energization/de-energization of a converter, etc. Thus, in an addition to the testing parameters considered for selectivity and sensitivity, the operation condition changes due to DC line outage and energization/dis-energization of a converter needs to be considered in the security related testing.

The values of these parameters can be seen in Table 23, and the derived testing procedures are shown in Figure 19 accordingly.

Table 23 The typical critical testing parameter for DC protection security

Related testing parameter	**Typical value**
Fault resistance	0-400 Ohm 0, 0.01, 0.1, 0.5, 1, 5, 10, 25, 50, 100, 200, 300, 400 Ohm
Line inductor	0-200 mH 0, 50, 100, 200 mH
Fault type and related emergency event	PTP1: pole-to-pole permanent fault PTP2: pole-to-pole self clearing fault PTG1: pole-to-ground permanent fault PTG2: pole-to-ground self clearing fault DCL1: neighbouring DC line outage COE1: dis-energization of a local converter
Fault location	0%-100% of the line with reasonable interval, and neighbouring areas. $0\%_{L-}$, $0\%_{L+}$, 20%, 80%, 90%, $100\%_{L+}$, $100\%_{L-}$, 105%, 110%

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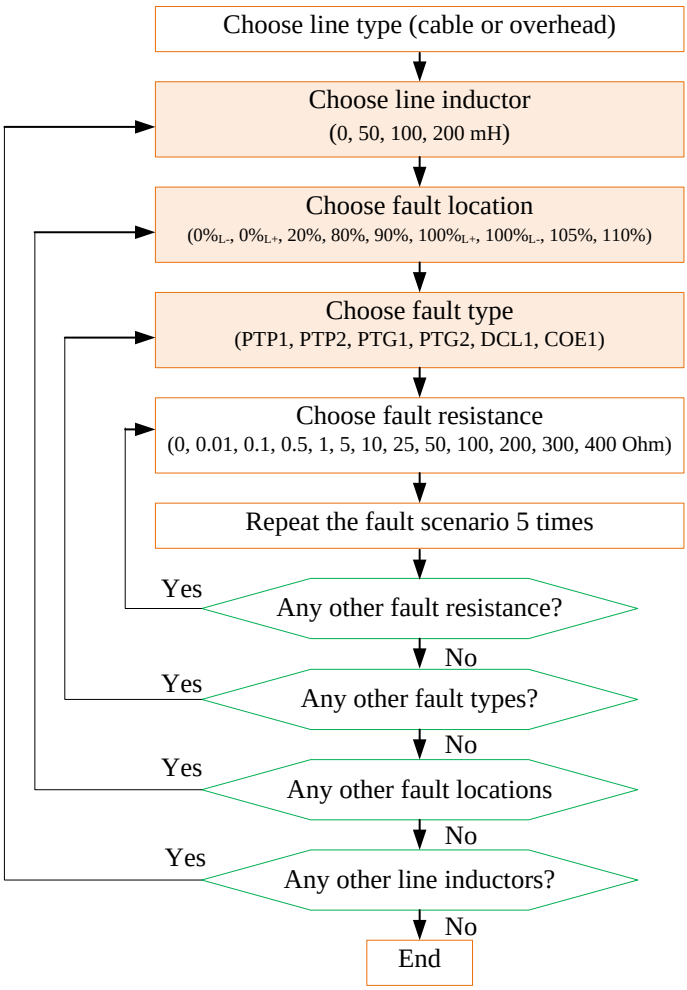

Figure 19 The testing procedures for security checking

Accordingly, the fault data statistics analysis will be derived based on the selected ranges of testing parameters, e.g. [100, 200] mH of line inductor, [200, 400] Ohm of fault resistance, [90%, 100%$_{L+}$, 100%$_{L-}$, 105%, 110%] of line as fault locations. The number of necessary operations, i.e. required correct operations, will be processed for the criterion. Then a qualification criterion can be expressed for instance:

Security criterion: $P_{classes.security} = \frac{Number\ of\ correct\ operations}{Total\ number\ of\ correct\ and\ incorrect\ operations}$

where $P_{classes.security}$ represents the probability of necessary operations based on the total number of tests.

The dependability of the DC grid protection system refers to not failing to operate in case of fault situations. Normally, it can be represented by the probability of the protection to have expected correct operations under given faulty conditions for a given time interval. The dependability is regarded to be proportional to sensitivity and speed. Thus, in the related testing, the similar testing parameters and critical time ranges based on DCCB types will be chosen as critical testing parameters. The typical values of these parameters can be seen in Table 24.

Table 24 The typical critical testing parameter for DC protection dependability

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Related testing parameter	Typical value
Fault resistance	0-400 Ohm 0, 0.01, 0.1, 0.5, 1, 5, 10, 25, 50, 100, 200, 300, 400 Ohm
Line inductor	0-200 mH 0, 50, 100, 200 mH
Fault type and related emergency event	PTP1: pole-to-pole permanent fault PTP2: pole-to-pole self clearing fault PTG1: pole-to-ground permanent fault PTG2: pole-to-ground self clearing fault DCL1: neighbouring DC line outage COE1: dis-energization of a local converter
Fault location	0%-100% of the line with reasonable interval, and neighbouring areas. $0\%_{L-}$, $0\%_{L+}$, 20%, 80%, 90%, $100\%_{L+}$, $100\%_{L-}$, 105%, 110%
DCCB type	Hybrid DCCB Mechanical DCCB

Accordingly, the fault data statistics analyse will be revised based on the focused ranges of testing parameters, e.g. time ranges based DCCB types, [100, 200] mH of line inductor, [200, 400] Ohm of fault resistance, [90%, $100\%_{L+}$, $100\%_{L-}$, 105%, 110%] of line as fault locations. The number of correct operations and total expected operations in the related ranges will be processed for the criterion. Then a qualification criterion can be expressed for instance:

Dependability criterion: $P_{classes.dependability} = \frac{Number\ of\ correct\ operations}{Total\ number\ of\ correct\ and\ failed\ operations}$

where $P_{classes.dependability}$ represents the probability of correct operations in the focused factor ranges for dependability checking on protection IED.

The reliability criterion can be computed by:

Reliability criterion: $P_{classes.reliability} = \frac{Number\ of\ correct\ operations}{Total\ number\ of\ tests}$

where *Total number of tests* is the number of tests that have been performed for this criterion. This total number of tests is the sum of the tests performed for the criteria of Dependability and Security.

The seamlessness of the DC grid protection refers to the ability of holding the remaining part of the DC grid to continue operating in a secure steady state after the fault clearance. This is related to the continuous adaptability of DC grid protection when a DC system transfers from a normal operation condition to ‘N-1’ conditions due to a fault clearance. Thus, the possible post fault ‘N-1’ or even ‘N-k’ operation transitions need to be simulated to test the objective of protection schemes, when the test DC grid system has been defined in the related specifications.

Moreover, the seamlessness of DC grid protection can be regarded as a kind of reliability in the post fault stage. Then in addition to possible post fault ‘N-1’ or ‘N-k’ operation transitions, the related critical testing parameters in security and dependability needs to be considered as well, with the aim to evaluate the seamlessness.

Accordingly, the related testing procedures and fault data statistics analysis will be revised by focusing on the ranges of testing parameters. The number of correct operations and total number of tests in the post fault ‘N-1’ or ‘N-k’ stages, will be processed for the criterion. Then a qualification criterion can be expressed:

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Seamlessness criterion: Pclasses.seamless = $\frac{Number\ of\ effective\ operations}{Total\ number\ of\ tests}$

where Pclasses.seamless represents the probability of effective operations on the focused factor ranges for seamlessness checking on protection IED. In this case, under *effective operations* we understand correct operations of protection with predefined settings (for specific operation conditions) in post fault stage like N-1 or N-k stages.

Last but not least, the robustness of the DC grid protection refers to the detection of faults in normal or degraded mode and the discrimination from other operational events in the DC grid. The difference with respect to seamlessness is that the adaptability to both normal and degraded operational modes is required but not continuous operation transition. Moreover, the discrimination from any other operational events makes the robustness become a kind of reliability as well.

Here the possible degraded modes, e.g. changes of power grid topology need to be considered to test the objective protection schemes, which are not caused by faults or are not in the post fault stages. Thus, besides the possible diverse operation conditions, the related critical testing parameters for the security and dependability could be considered here to evaluate the robustness.

Accordingly, the related testing procedures and fault data statistics analysis will be derived based on the selected ranges of testing parameters as well. Similarly, the number of correct operations and the total number of tests in this regard will be recorded for the criterion. Then a qualification criterion can be expressed for instance:

Robustness criterion: Pclasses.robustness = $\frac{Number\ of\ neccessary\ operations}{Total\ number\ of\ tests}$

where Pclasses.robustness represents the probability of effective operations within the focused factor ranges for robustness checking on protection IED. In this case, under *necessary operations* we understand correct operations of protection with different predefined settings for different stages; being adaptive and available for several operation conditions.

Step 5: Report and trouble shooting

The summary of the data analysis should be given based on the work steps above, the limitations and related trouble shooting should be registered as illustrated in Figure 12 so that this could be improved in the work steps in Figure 12 in the future work.

3.3.2.3 THE TESTING STEPS FOR BACKUP PROTECTION

In order to evaluate the backup protection in DC protection, the required detection operations and operation times of backup protection shall be the important indicators.

Based on the discussions of breaker failure or relay failure, the different actions of backup protections should be mapped with the backup fault clearing options [18]. And due to rigorous requirements on the time of fault clearance and communication delays, only local backup will be considered here for DC protection system.

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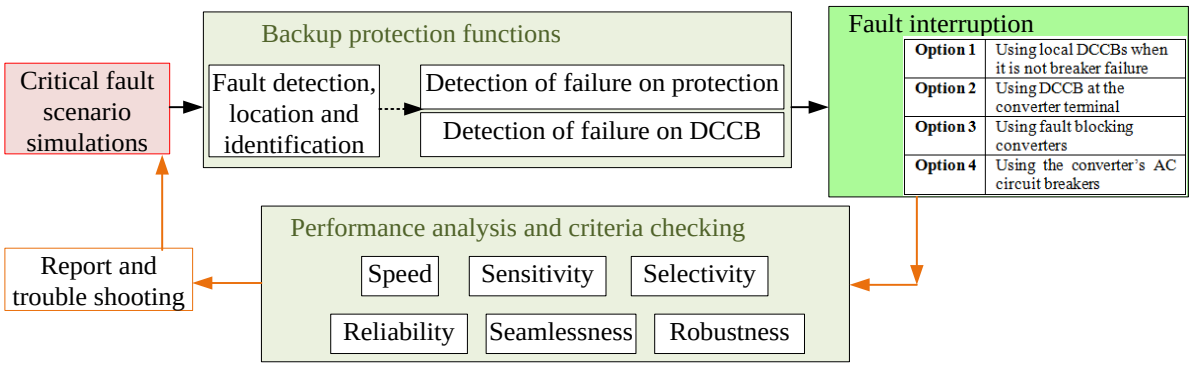

Figure 20 The testing progress of backup protection performance testing

The testing of the backup protection for real-time testing of IED and related operational conditions will be kept same as for the testing of the primary protection. The general testing progress of the backup protection performance is depicted in Figure 20. Besides the basic functions on detection, location and identification, the failure detection is a critical function for backup protection. Here, two kinds of failures have been considered, one is the failure of primary protection functions and the other is the failure of DCCB operations. The procedures of related testing steps are listed as follows:

Step 1: Fault scenarios simulation based fault studies

This step can be conducted in a similar way as what has been done in the primary protection testing. The cases used in the testing of dependability checking can be adopted directly here, the nondependable operations, i.e. non tripping operations in the required time interval, can be regarded as failures of primary protection. And the failures of DCCB will be tested with dependable cases with correct operations, so these failures will be mainly induced by DCCB' own capabilities and features. These two types of failures and their derived rules can be seen in Figure 21.

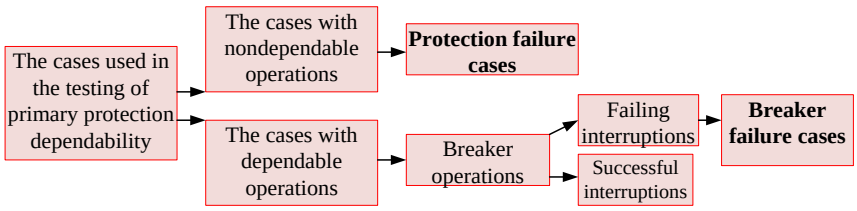

Figure 21 The evolution from primary protection testing to backup protection testing

Step 2: Statistics analysis of system level performance

a. Accuracy of protection characteristics, e.g. settings of thresholds.

For the backup protection, the failure detection will be mainly based on the operational characteristics and related operation time thresholds for primary protection, voltage or current during the fault period. Then the test procedures can be derived from Figure 13 with testing parameters considered in primary protection dependability and more considerations on DCCB scales and types. Then the associated classification of cases can be easily obtained based on the deducing rules in Figure 21 to find the failure cases for backup protection testing.

Based on the responses of backup protections under these failure cases, the accuracy of backup protection characteristics can be checked with the probability distribution on operation time of backup protection subsequently.

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b. Operation time

Based on those testing cases performed for backup protections, the operation times of backup protection can be determined in a statistical way used similarly in Figure 14 and Table 19. Then the probability distribution of the operation times of backup protection can be obtained, which is the basis for later evaluations.

Step 3: Threshold setting adjustment

In order to achieve better and reliable performances of backup protection before we check them, the related threshold settings need to be optimally adjusted, based on the data analysis developed in Step 2. Similar methods and testing procedures in the Step 3 of primary protection testing can be adopted as well.

Step 4: Criteria checking

The criteria checking of backup protection will take the concepts and methods used in Step4 in the testing of primary protection as references. The related critical criteria will still be on speed, sensitivity, selectivity, reliability, seamlessness and robustness.

The speed of backup protection for DC grids is expected to have the same requirements as main protection or even more stringent in order to clear the DC faults as soon as possible. Accordingly, the fault data statistical analysis will be revised based on required operation time range of backup protection. Then a qualification criterion can be expressed for instance:

Speed criterion: $P_{classes.speed.b}$

where $P_{classes.speed.b}$ represents the probability of related classes in the required time range for speed checking on backup protection.

For other criterion checking of backup protection on sensitivity, selectivity, reliability, seamlessness and robustness, the concepts , testing procedures and criteria in the testing of primary protection can be adopted similarly, expect the total number of tests are from failure cases defined in Figure 21.

Step 5: Report and trouble shooting

The summary of the data analysis of backup protection test cases should be given based on the work steps above, the limitations and related trouble shooting should be described in order to let readers to improve the work steps on backup protection in the future work.

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4 SUGGESTIONS ON TECHNICAL GUIDELINES FOR DC PROTECTION TESTING

4.1 INTRODUCTION

This chapter deals with proposing suggestions on technical guidelines for system level assessment of DC protection. The suggestions in this chapter are intended to assist technical testing procedures and to help the planning of real-time hardware-in-loop test scenarios.

4.2 DEFINITION OF TESTING ENVIRONMENT AND SCENARIOS

This section is intended to determine a reasonable test environment and to make fault scenarios more suitable for testing the protection algorithm(s) implemented on an IED. At this stage, the test environment is determined by the actual HVDC grid under study and the fault scenarios are selected depending on the limitation of applied protection algorithm(s) and their operation principles. In case a reduction of the number of test scenarios is needed from several tens of thousands (see chapter 3, Table 18) to a reasonable number, it is proposed to define test scenarios considering limitation of the protection algorithms [18]. For example, if an algorithm is limited with respect to the fault resistance, the fault scenarios are determined with more focus on this parameter.

Regarding the test environment, some standard models can be improved and adapted to the actual grid under study with the consideration of:

- Type of transmission lines including cable and overhead lines
- Length and parameters (material and geometry) of transmission lines
- Fault types and resistances, e.g. permanent fault in case of overhead lines, and faults involving metallic return wire in bipolar HVDC grids with metallic return
- Converter station structure including monopolar and bipolar
- Converter station earthing including earthed (earth return or metallic return) and unearthed systems, and earthing method
- Converter topology (full bridge, half-bridge etc.)
- DC side capacitance
- Control methods and control modes (PV, PQ etc.) of the converters
- Type of DC CBs and other switchgears
- HVDC grid ratings such as voltage, current and transferred power
- AC side equivalent system

With respect to the fault scenarios, following parameters can be considered:

- Fault resistance
- Fault location
- DC side inductance
- Voltage and current measurement accuracy, sampling rate and noise level

4.3 SYSTEM LEVEL ASSESSMENT OF DC PROTECTIONS

As elaborated in Chapter 3, the following requirements are used to assess the DC protection:

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- accuracy of protection characteristics
- operation time
- functional requirements:
    - Speed
    - Selectivity
    - Sensitivity
    - Security
    - Dependability
    - Reliability
    - Seamlessness
    - Robustness

After a test of different protection algorithms is carried out, the performance of the algorithms can be compared. The algorithms will show different performance in terms ofdifferent requirements. For example, a certain algorithm may be more selective than another algorithm while it is less sensitive than that algorithm. Therefore, it is necessary to classify the performance of the protection algorithms considering each requirement. It is proposed to classify the requirements obtained by performed tests in Sections 3.3.2.2 and 3.2.2.3 in Chapter 3 into low, medium and high performance classes for all protection algorithms based on the value of corresponding qualification criteria. In order to determine the range of qualification criterion value of these classes for each requirement, the computed qualification criteria of each requirement for all protection algorithms are sorted in a decreasing order. Then, these qualification criteria (of a particular requirement) and their corresponding algorithms are divided into three groups with equal (in case of odd number of algorithms) or almost equal (in case of even number of algorithms) members; group 1, 2 and 3.
For example: Table 25 contains the qualification criterion "Pclasses.speed". Protection algorithms 1-9 are sorted according to their performance starting with the highest performance. We allocated three performance classes ranged as high, medium and low.
Group 1 (which is a set of algorithms) denotes the algorithms that belong to performance with a high class, whilst groups 2 and 3 belong to performance classes medium and low respectively.
The range of each performance class is defined by taking into account an average value of these three groups in the following way:

- High Performance ≥ average of group 1
- average of group 2 ≤ Medium Performance < average of group 1
- Low Performance < average of the group 2

It is also possible to use minimum and maximum values of the groups instead of average values:

- High Performance ≥ minimum of group 1
- minimum of group 2 ≤ Medium Performance < minimum of group 1
- Low Performance < minimum of the group 2

An example is shown in Table 25, considering 9 algorithms and speed as the protection requirement.

Table 25 Example for determination range of performance classes for speed

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Groups	Protection algorithm	Pclasses.speed (%)	Performance class	Range (%) (Average method)	Range (%) (Min & Max method)
Group 1	Alg. 5	99	High	≥ 97.66	≥ 96
	Alg. 3	98			
	Alg. 4	96			
Group 2	Alg. 1	94	Medium	91.66 - 97.66	89 - 96
	Alg. 6	92			
	Alg. 8	89			
Group 3	Alg. 2	85	Low	91.66 <	89 <
	Alg. 9	83			
	Alg. 7	80			

Table 25 can be applied for all requirements as listed in the beginning of this section. In this way, the performances of the algorithms can be compared considering each requirement. It should be noted that the range of classes of each requirement may be different from the other requirements, and may also differ for different IEDs.
To give an overall assessment for each protection algorithm, performance assessment results can be summarized in Table 26.

Table 26 Assessment of a specific protection algorithm

Test item	Sub item	Performance Class of the requirement		
		Low	Medium	High
Accuracy of protection characteristics	-			
Operation time	-			
Functional requirements	Speed			
	Selectivity			
	Sensitivity			
	Security			
	Dependability			
	Reliability			
	Seamlessness			
	Robustness			

The performances of different protection algorithms can be compared using the matrix shown in Table 27. The empty spaces in Table 27 will be filled out by low, medium or high performance based on the determined range of each requirement.

Table 27 Comparison of different protection algorithms performance

Test item	Sub item	protection algorithm

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		Alg. 1	Alg. 2	Alg. 3	Alg. 4	Alg. 5	Alg. 6	Alg. 7	Alg. 8	Alg. 9
Accuracy of protection characteristics	-									
Operation time	-									
Functional requirements	Speed									
	Selectivity									
	Sensitivity									
	Security									
	Dependability									
	Reliability									
	Seamlessness									
	Robustness									

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5 CONCLUSION

This report provides test procedures and guidelines for testing protection of multi-terminal HVDC grids. The developed procedures are for testing system level protection based on the functionality of MTDC, existing similarities between the operation of DC and AC grids, and the requirements for DC protection.
Hence, general and functional requirements of DC protection systems are described as well as its component requirements (DC CBs, converters and other equipment).

The requirements that DC protection needs to satisfy are the accuracy of protection characteristics, the operation time and the functional requirements. Functional requirements comprise Sensitivity, Selectivity, Speed, Security, Dependability, Reliability, Seamlessness and Robustness criteria. Fault scenarios are selected by changing critical testing parameters i.e. fault resistance, fault type, fault location, series line inductor, line length and parameters. All tests performed by using these scenarios for the aforementioned requirements of DC protection system are recorded and evaluated by making use of statistical analysis.
For the determination of the accuracy of the operation times of the protection system, the time difference between the fault occurrence and operation output signals of the relay is needed. Besides, the report applies weights that are given to the available data according to the zones of probability of fault occurrence in order to create a fault-type distribution in the operation time statistics. Then, these results are used to define operation time classes of the IED.
In this report, the testing steps of primary and backup protection are elaborated for the aforementioned functional requirements and general procedures for system level testing have been presented by using fault scenarios. For all functional requirements, algorithms defining testing procedures have also been defined in a similar way and are presented in a flow chart. The probability of each performance criteria from all functional requirements is evaluated by making use of predefined expression related to the number of correct operations, incorrect operations, failed operations and total number of tests, where necessary.
Threshold setting optimization is carried out by performing a test procedure considering variable threshold setting values around their pre-calculated values in the design phase of the protection, and the determination of the most accurate threshold setting. In other words, the pre-calculated threshold settings are modified and the setting with the highest probability of correct operation is adopted. Furthermore, suggestions related to the assessment of algorithm performance according to predefined requirements have been made. The performances can be assessed based on different methods, e.g., the average, minimum or maximum performance over all the tests. Based on these methods, it is proposed to classify the algorithm's performances in three classes; high, medium and low performance.
According to the proposed procedures and the number of cases that should be considered, to test a particular criterion from the functional requirements, maybe several tens of thousands of tests should be performed. The experience shows that with the existing RTDS infrastructure and knowledge, it is possible to do this by making use of a C-code builder in an RTDS environment. However, in case some criteria seem to be well satisfied, the number of tests can be reduced by reducing some of the parameters defined in the flow chart.

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6 Bibliography

[1] M. Wang, D. Van Hertem, et al. "A Review on AC and DC Protection Equipment and Technologies: Towards Multivendor Solution", *Cigre Winnipeg 2017 Colloquium*, 2017.

[2] D. Jovcic, D. Van Hertem, et al. "Feasibility of DC Transmission Networks", *IEEE PES Innovative Smart Grid Technologies Conference*, Europe, 2011.

[3] IEC 60255-1, Generic requirements for measuring relays and protection equipment, 2009.

[4] Communication networks and systems for power utility automation - Part 9-2: *Specific communication service mapping (SCSM) - Sampled values over ISO/IEC 8802-3*, IEC Standard 61850-9-2, 2011

[5] Y. Matsui, K. Nagatake, M. Takeshita, K. Katsumata, a. Sano, H. Ichikawa, H. Saitohu, and M. Sakaki, "Development and Technology of High Voltage VCBs; Breaf History and State of Art," 2006, 4 pages.

[6] A. Mokhberdoran, A. Carvalho, H. Leite, and N. Silva, "A review on HVDC circuit breakers," in *3rd Renew. Power Gener. Conf. (RPG 2014)*, Naples, Italy, 24-25 Sept. 2014, 6 pages.

[7] B. Geebelen, W. Leterme, and D. Van Hertem, "Analysis of DC breaker requirements for di_erent HVDC grid protection schemes," *in Proc. IET ACDC 2015. Birmingham, UK: Institution of Engineering and Technology*, 10–12, Feb. 2015, 7 pages.

[8] S. Liu, M. Popov, "Development of HVDC System-level Mechanical Circuit Breaker Model" *International Journal of Electrical Power & Energy Systems* Volume 103, December 2018, Pages 159-167

[9] D. Jovcic, A. Jamshidifar, M. Popov, and S. Liu, : Modelling and Comparison of Common Functionalities of HVDC Circuit Breakers, presented at the *PES General Meeting* 2018, paper number 1371.

[10] Promotion Deliverable 6.9 "*Standard DC CB model verification plan and RTDS models*" December 2017.

[11] I. P. &. E. Society, IEEE Std C37.06 for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis- Preferred Ratings and Related Required Capabilities for Voltages Above 1000 V, Std., 2009, 60 pages.

[12] WP4 Promotion, D4.1 – Definition of test cases and functional requirements for DC grid protection methodologies , 2017

[13] Technical Brochure, Protection and local control of DC grids, WG B4/B5. 59 TB-739, www.e-cigre.org

[14] R. Li, J.E. Fletcher, L. Xu, D. Holiday and B.W.Williams: A Hybrid Modular Multilevel Converter with Novel Three-Level Cells for DC Fault Blocking Capability, *IEEE Transactions on Power Delivery*, Vol. 30, No. 4, August 2015, pp. 2017-2026.

[15] Technical Brochure 657 (2016) Guidelines for the preparation of "connection agreements" or "grid codes" for multi-terminal DC schemes and DC grids, WG B4.56, www.e-cigre.org

[16] W. Leterme, D. Van Hertem, "DC fault phenomena and dc grid protection" in HVDC grids for offshore and supergrid of the future, Eds. Hoboken, NJ:J. Wiley & Sons, 2016, ch 17.

[17] WP6 Promotion, D6.2 – Develop system level model for mechanical DCCB , 2017.

[18] WP4 Promotion, D4.2 – Broad comparison of fault clearing strategies for DC grids , 2017

[19] W. Leterme, P. Tielens, S. De Boeck, D. Van Hertem, "Overview of Grounding and Configuration Options for Meshed HVDC Grids", *IEEE Transactions on Power Delivery*, Vol. 29, No. 6, 2014

[20] Technical Brochure 683 (2017) Technical Requirements and specifications of state-of-the-art HVDC switching equipement, JWG A3/B4.34, www.e-cigre.org

[21] Technical Brochure 604 (2014) Guide for the Development of Models for HVDC Converters in a HVDC Grid, WG B4.57, www.e-cigre.org

[22] M. K. Bucher and C. M. Franck, "Analysis of Transient Fault Currents in Multi-Terminal HVDC Networks during Pole-to-Ground Faults," *International Conference on Power Systems Transients (IPST2013)*, Vancouver, Canada, 2013.

[23] L. Liu, M. Popov, M. A. M. M. van der Meijden, V. Terzija, "Optimized Control of LCL-VSC Converter with Refined s-Parameter," *IEEE Trans. on Power Delivery*, vol. 32, no. 4, pp. 2101-2110, Aug. 2017.

[24] RTE, "Power System Reliability Memento," 2005.

[25] *Power System Protection*, P. M. Anderson, IEEE Press and Wiley Interscience A John Wiley & Sons, Inc. 1998.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691714.

[26] N. Johannesson, S. Norrga and C. Wikstrom, "Selective Wave-Front Based Protection Algorithm for MTDC Systems," in *Proc. IET DPSP*, Edinburgh, UK, 2016.
[27] D. Naidoo and N. M. Ijumba, "HVDC line protection for the proposed future HVDC systems," in *IEEE PowerCon 2004*, 2004.
[28] J. Descloux, B. Raison and J.-B. Curis, "Protection algorithm based on differential voltage measurement for MTDC grids," in *Proc. IET DPSP 2014*, 2014.
[29] S. Pirooz Azad and D. Van Hertem, "A Fast Local Bus Current-Based Primary Relaying Algorithm for HVDC Grids," *IEEE Transactions on Power Delivery*, vol. 32, no. 1, pp. 193-202, 2016.
[30] I. Dallas and C. Booth, "Fault Discrimination in Multi-Terminal DC Supergrids," in *Proc. CIGRE Brussels*, Brussels, Belgium, 2014.
[31] J. Wang, B. Berggren, K. Linden, J. Pan and R. Nuqui, "Multi-Terminal DC System line Protection Requirement and High Speed Protection Solutions," in *Proc. CIGRE Lund*, Lund, Sweden, 2015.
[32] K. De Kerf, K. Srivastava, M. Reza, D. Bekaert, S. Cole, D. Van Hertem and R. Belmans, "Wavelet-based protection strategy for DC faults in multi-terminal VSC HVDC systems," *IET Gener. Transm. Distrib.*, vol. 5, pp. 496-503, Apr. 2011.
[33] N. Johannesson and S. Norrga, "Longitudinal differential protection based on the Universal Line Model," in *Proc. IEEE IECON*, Yokohama, Japan, 2015.
[34] I. Dallas and C. Booth, "Teleprotection in Multi-Terminal HVDC Supergrids," in *Proc. IET DPSP*, Copenhagen, Denmark, 2014.
[35] W. Leterme, S. Pirooz Azad and D. Van Hertem, "A local backup protection algorithm for HVDC grids," *IEEE Transactions on Power Delivery*, vol. 31, no. 4, pp. 1767-1775, 2016.
[36] IEC 60255-151, Measuring relays and protection equipment, -Functional requirements for over/under current protection, 2009.
[37] IEC 60255-121, Measuring relays and protection equipment, -Functional requirements for distance protection, 2014.

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