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Protection Testing for Multiterminal High-Voltage dc Grid

Procedures and Assessment

ZHOU LIU, SEYED SATTAR MIRHOSSEINI, MARJAN POPOV, YASH AUDICHYA, DANIELE COLANGELO, SADEGH JAMALI, PETER PALENSKY, WEIHAO HU, and ZHE CHEN

The application of multiterminal (MT), high-voltage dc (HVdc) (MTdc) grid technology requires test procedures for the operation and implementation of the protection solutions. The test procedures are usually derived from experience and from extensive measurement data, which, at present, are still not widely available. Based on a hardware-in-the-loop (HIL) method, advanced dc protection testing strategies, utilizing existing experience for ac grids and requirements for MTdc grids, may overcome this gap.

This article proposes procedures and guidelines for testing system-level dc protection based on the functionality of MTdc grids for both primary and backup dc protection. Specific performance criteria have been defined, based on multivariate testing and statistical analysis, with the considerations of related critical testing parameters for each functional requirement of the dc protection. Accordingly, procedures for a dc protection testing environment and various fault scenarios are defined. The proposed algorithm test procedures will contribute to the standardization of dc protection system design and testing.

Background

Renewable energy sources (RESs) have many advantages for the environment and sustainable energy development. The replacement of traditional fossil fuels by RESs is an energy development trend and energy policy requirement for future power systems [1]. In northern Europe,
in particular, the installation of offshore wind power is ever increasing; hence, the development of HVdc systems to support wind power integration is becoming more urgent. The evolution of HVdc systems from point-to-point connections and radial HVdc grids to meshed MTdc grids by making use of voltage source converter (VSC) technology, especially modular multilevel converter (MMC)-based schemes, is also a significant subject for the European power utilities and governments [2]. Worldwide, there are already many relevant projects commissioned or being developed, such as the Québec–New England three-terminal HVdc system [3], Nan’ao four-terminal HVdc system [4], and Zhoushan five-terminal grids [5].

One of the main challenges of the implementation of HVdc power grids is the unavailability of standardized approaches for grid protection, which is a significant barrier for the secure operations of new HVdc grids [5]. DC fault currents in MTdc networks increase rapidly in amplitude, and outages can be easily cascaded from one converter station to another. Thus, protection against these faults is very important to provide safety for the HVdc grid operation and to pave the way for the integration of bulk offshore wind power to the ac grid [6], [7].

Existing HVdc protection concepts are derived from the well-known HVac protection concepts, as illustrated in Figure 1 [8]. Three kinds of protection philosophies are adopted in MTdc protection, i.e., fully selective, nonselective, and partially selective. In the fully selective philosophy, each line is protected using HVdc circuit breakers (dc CBs) at both ends, so power flow remains uninterrupted in the rest of the grid. In the nonselective philosophy, the whole HVdc grid is protected as one zone by converters with fault-blocking capability or by using ac-side CBs (ac CBs). The partially selective philosophy is a compromise between the two former ones, in which the grid is divided into several protection zones based on the placement of dc CBs, the converters with fault-blocking capability, and ac CBs [9].

Three kinds of protection philosophies are adopted in MTdc protection, i.e., fully selective, nonselective, and partially selective.

A simple illustration can be seen in Figure 2. When fault F1 occurs in the middle of lines 2 and 3 in the three-terminal HVdc grid, this faulty line will be only disconnected by the dc CB4 and dc CB5 at both line ends in the fully selective philosophy. In the partially selective philosophy, with an insufficient installation of dc CBs, subgrid2 will be disconnected due to F1 only if dc CB4 and dc CB6 are installed. The red elements [ac CBs, full-bridge (FB) converters, or dc CBs behind converter terminals] will be used to clear F1 in the nonselective philosophy, in which the whole dc grid will be isolated.

There have been many different HVdc grid protection algorithms proposed by academia and industry so far, which can be categorized as unit protection and nonunit protection. Unit protection algorithms are based on double-ended detection, which makes use of closed protection zones; nonunit protection algorithms are realized with single-ended detection and open zones. The nonunit protection algorithms are mainly used for the primary protection functions, which can be current/current derivative-[10], [11], voltage/voltage derivative-[12], [13], and traveling wave-based approaches [14]–[16]; different combinations of these approaches [17], [18]; and frequency or time-domain approaches [19]–[21].

The unit protection algorithms mainly include the current differential [22] and traveling wave differential [23]. Since communication is required for unit protection, it is used for the primary protection functions of the bus bar or for the protection of short lines and as a backup protection function of longer dc lines [24]. Possible protection failures (including breaker failure and relay failure) need to be considered in backup protection functions of an MTdc grid protection system [25].

There are no consensus and standards, so far, about how the dc protection algorithms perform and how they could be used for practical

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**FIGURE 1** – The categories of the protection philosophies and examples of algorithms: (a) ac grid protection and (b) MTdc grid protection.
For VSC HVdc, the MMC, as the most promising option to develop an MTdc grid, can adopt either a half-bridge or FB structure for each submodule.

implementation [8]. Considering that today’s dc CBs can operate in several milliseconds, fault detection realized by the protection algorithms should also be within the same timescale, which also depends on the speed of fault current development and the withstand capability of system components [26].

In HVdc systems, the current source converter (CSC)-based HVdc, which is known as classic HVdc, can control the dc current during a dc fault. However, the CSC HVdc is, currently, mainly limited to the applications of point-to-point connections, since the reversal of the power flow direction requires a change of voltage polarity on all terminals, and there are other bottlenecks associated with the control systems. The application of dc CBs in CSC HVdc systems is limited, and the maximum ratings are 250 kV, 8 kA or 500 kV, 4 kA, which are not more than 1.6 times the rated nominal current. An interruption time on the order of 35 ms is sufficiently fast for CSC HVdc systems, where large inductors serve to limit the rate of rise of the fault current. These dc CBs are very large and more expensive than the ac CBs for comparable current and voltage ratings. Therefore, for point-to-point CSC HVdc connections, the controlled converter stations or installed ac CBs at the ac side of CSCs are applied to disconnect the HVdc from the ac side [27].

Regarding the fault current characteristics, VSC HVdc systems are mainly distinguished from the CSC

<table>
<thead>
<tr>
<th>HVdc Grid Protection Philosophy</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fully Selective</td>
<td>Protection zones defined to individually protect each dc line and bus. Only the fault element has to be disconnected with sufficient dc CBs installed at each end of protected elements, e.g., the faulted line 2–3 is disconnected by dc CB4 and dc CB5 located at two ends of the line.</td>
</tr>
<tr>
<td>Partially Selective</td>
<td>DC grid divided into several protection zones or subgrid. The grid has been split into two subgrid with an insufficient installation of dc CBs, e.g., the Subgrid2 is disconnected with only dc CB4 and dc CB6 installed in the grid, when F1 occurs.</td>
</tr>
<tr>
<td>Nonselective</td>
<td>No protection zones or entire dc grid as one zone. The fault will be cleared by ac CBs or full-bridge converters or dc CB behind converter terminals; e.g., only red elements in the grid can be used to clear the dc fault F1.</td>
</tr>
</tbody>
</table>

FIGURE 2 – The different MTdc grid protection philosophies.
HVdc systems by the higher rates of rise and large magnitudes of the fault currents as well as the lower current withstand capability of VSC power electronics [27]. These differences necessitate higher fault current-breaking capabilities within shorter interruption times of the dc CBs in VSC-based HVdc grids.

For VSC HVdc, the MMC, as the most promising option to develop an MTdc grid, can adopt either a half-bridge (HB) or FB structure for each submodule. The HB MMC with freewheeling diodes is unable to stop ac grid contribution to the dc fault currents, and the excessive current stresses may damage the freewheeling diodes. Therefore, the requirement for fast dc CBs becomes inevitable. Moreover, to realize a fully selective protection philosophy and provide power supplying continuity for the healthy part of HVdc grids, more dc CBs are required to be installed to protect each line and bus in the grid, even though the FB MMC can block current flow in the converter during dc faults.

The objective of the protection testing is to determine whether the performance of an intelligent electronic device (IED) can meet the industry requirements before it can be commissioned in practical applications [28]. Since the converter self-protection scheme is vendor dependent, the scope of the future MTdc grid protection for MTdc grids, here, excludes converter protection. For ac protection testing, well-established designs and methods can be adopted according to IEEE and International Electrotechnical Commission (IEC) standards [29], [30]. In these ac protection standards, the performance test (or type testing) is normally conducted by IED vendors to verify, describe, and certify the performance of protection IEDs used in a specific application, which is normally tested by a simple power system model.

The application tests are normally driven by the users to determine the suitability of an IED for a specific protection system design application. The tests are based on a detailed model of the power system in question and include performance testing against a wide variety of possible fault conditions. The goal of application tests is to ensure that a specific protection IED can perform adequately for a specific application or location before actual installation. These general concepts and classifications of protection testing will be continuously applied in MTdc grids, even though the challenges and requirements are different for dc protection testing [31].

In this article, MTdc grids are the target test power systems, and the application tests are mainly focused from users’ viewpoints to provide reasonable test procedures for dc protection testing. Although the fault dynamics and the related protection algorithms of MTdc grids have been investigated and designed by many researchers [10]–[25], no certified HVdc protection IED has been commissioned so far. Moreover, the relatively new testing considerations and methods of MTdc grid protection have rarely been discussed, and many published articles are mainly focused on one specific protection algorithm [32]–[37].

A fault detection and location scheme using the rate of change of voltage measured for an HVdc grid is proposed and tested in [32], where the different fault types and locations have been mainly considered in testing, and a systematic procedure for calibrating the protection threshold values is designed. A transient measured impedance-based protection scheme for HVdc line faults is proposed in [33], where numerous simulations on the power systems CAD/electromagnetic transients including dc (PSCAD/EMTDC) platform and field fault recording data-based tests have been utilized with the consideration of fault types, fault locations, and sampling frequency. A similar PSCAD/EMTDC-based test has been used in [34] for a generalized protection strategy of HB MMC-based MTdc grids with a fault current limiter branch and hybrid dc CBs, where the different fault resistances, line inductors, and types of dc CBs are considered during the testing.

The types of dc lines and prefault operation points of MTdc grids were used to test a proposed new protection method in [35]. A real-time OPAL-RT-based HIL testing platform was developed in [36] to demonstrate and validate an integrated control and protection scheme for HV ac/dc grids, where the fault types, locations, and combinations are mainly considered. In [37], HIL-based testing was regarded as an ideal choice to simulate the transients of MMC stations and to test the dynamic performance of a complete control and protection system for the Nan’ao VSC-MTdc grid (i.e., application test).

The aforementioned testing methods are normally introduced together with the new dc protection algorithms, which only consider several important factors or requirements about the specific protection algorithms simulated in the simulation software or hardware environment. They are not appropriate or efficient for industrial testing on multifunctional protection IEDs. In this article, one user-oriented application testing approach for industrial applications of HVdc grid protection is developed based on three steps:

- a systematic investigation and summary of new requirements along with testing considerations for HVdc grid protection in both the component and system levels
- new systematic test procedures for protection IEDs in HVdc grids, based on the statistical analysis of dc fault cases and performance criterion checking
- a new systematic assessment method for possible protection algorithms implemented in multifunction protection IEDs.
The main contribution of this article is to develop dc protection testing methods for systematic testing and assessment of the newly proposed MTdc grid protection algorithms.

Thus, the main contribution of this article is to develop dc protection testing methods for systematic testing and assessment of the newly proposed MTdc grid protection algorithms. In this way, it can be determined whether the proposed algorithms can meet the operation requirements of the MTdc grids [38].

New Challenges and Requirements

General Considerations

The choice of a specific MTdc grid protection philosophy, i.e., fully selective, partially selective, and nonselective, fundamentally determines the size of the grid part that will be isolated from the rest of the grid during a fault at a particular location. Moreover, since the protection of MTdc grids deals with complex fault scenarios and fast operational performance and takes into account the performance of the dc CBs, the system-level protection of MTdc grids is regarded as one of the most difficult remaining technical challenges in the power system. Some related considerations for future dc applications can be listed as follows [8]:

- multivendor solutions with a proper consideration of interoperability
- the much quicker response of MTdc grid protection for dc faults without current zero crossings
- the development and implementation of dc protection testing methods for the newly available dc protection algorithms.

In addition to the general differences from ac protection shown in Figure 1, the fault-clearing times of both the primary and backup protections in MTdc 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 the protection IED processing time and several milliseconds for the dc CB operation time [31]. A related comparison of the time sequences of ac and dc protections can be observed in Figure 3 [8]. As there are only a few practical dc CB prototypes applicable for HVdc grids and there is not much experience in this

![FIGURE 3 – The typical times for primary and backup protection in ac and dc systems.](image-url)
The stability of the control system in the MTdc grid: The control system responsible for the control of the voltage and the power flow to ensure stability of the MTdc grid imposes a limit on system-level protection. The related criteria and the stability limits have been discussed in CIGRE technical brochure 657 [9].

The stability of ac systems: 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. Furthermore, dc faults should be cleared in a timely manner to avoid instability issues in the ac grid.

When local dc protection is considered, the requirements can be listed as follows:

- Functional requirements, as described in Table 1
- Requirements on protection system components.

The requirements for the components, such as measuring, detecting, and acting components, can be determined according to how long the system can sustain a particular disturbance. The MTdc grid protection philosophy is fundamentally determined by the selectivity of the protection devices and the way of dc fault current interruption development. To effectively implement dc protection algorithms and meet the speed requirement, nonconventional instrument transformers with a bandwidth of a few megahertz, e.g., fiber-optic current/voltage sensors [39], need to be adopted.

The main technologies and the bandwidth of today’s instrument transformers are summarized in Table 2. As an example, the Rogowski coil has attracted much attention in the electric power industry, as it can meet the requirements of dc protection for frequency bandwidth and dynamic accuracy due to its superior performance, inherent linearity, outstanding dynamic response, wide bandwidth, and without magnetic saturation. These features can support accurate and reliable data measurement to trace the faulty dynamics in the dc system for those protection applications when the Rogowski coil is combined with the shunt capacitor [8].

The digital interface of instrument transformers for both ac and dc applications is specified by IEC 61869-9 [40]. To perform general measurement and protective data processing, the typical sampling rates for ac and dc measurements are 4.8 kilo samples (ksa)/s and 96 ksa/s, respectively. The fault current interruption capability of the dc protection system is determined not only by the capability of dc CBs but also by the

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**Table 1 – The Functional Requirements for DC Protection [24].**

<table>
<thead>
<tr>
<th>PROTECTION FUNCTIONAL REQUIREMENT</th>
<th>DEFINITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>Detection of every dc fault, including high-impedance faults</td>
</tr>
<tr>
<td>Selectivity</td>
<td>Operating only after fault occurrence and only if the fault is in a related protection zone</td>
</tr>
<tr>
<td>Speed</td>
<td>To be fast enough to interrupt faults before they may damage grid equipment</td>
</tr>
<tr>
<td>Reliability</td>
<td>To perform a required function under given conditions for a given time interval, i.e., security and dependability</td>
</tr>
<tr>
<td>Robustness</td>
<td>Having the ability to detect dc faults in normal operation mode as in degraded operation mode and to discriminate faults from any other operation occurrence (set point changes and so on)</td>
</tr>
<tr>
<td>Seamlessness</td>
<td>After the fault clearance, the ability to keep the remaining part of the system operating in a secure steady state</td>
</tr>
</tbody>
</table>

**Table 2 – The Technologies and Bandwidths of the Instrument Transformers [8].**

<table>
<thead>
<tr>
<th>TYPE</th>
<th>TECHNOLOGY</th>
<th>BANDWIDTH</th>
<th>APPLICATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT</td>
<td>Electromagnetic (iron core)</td>
<td>A few kilohertz</td>
<td>ac</td>
</tr>
<tr>
<td></td>
<td>Hybrid electro-optical (combined shunt and Rogowski coil)</td>
<td>A few megahertz</td>
<td>ac/dc</td>
</tr>
<tr>
<td></td>
<td>Fiber-optic current sensor (magneto-optic effect)</td>
<td>A few megahertz</td>
<td>ac/dc</td>
</tr>
<tr>
<td></td>
<td>Zero flux (dc CT)</td>
<td>A few hundred kHz</td>
<td>dc</td>
</tr>
<tr>
<td></td>
<td>DC zero flux (Hall effect CT)</td>
<td>A few hundred kHz</td>
<td>dc</td>
</tr>
<tr>
<td>VT</td>
<td>Inductive VT</td>
<td>few kHz</td>
<td>ac</td>
</tr>
<tr>
<td></td>
<td>Capacitor VT</td>
<td>few kHz</td>
<td>ac</td>
</tr>
<tr>
<td></td>
<td>Compensated resistive–capacitive divider</td>
<td>few MHz</td>
<td>ac/dc</td>
</tr>
<tr>
<td></td>
<td>Fiber-optic voltage sensor (magneto-optic effect)</td>
<td>few MHz</td>
<td>ac/dc</td>
</tr>
<tr>
<td>CT: current transformer; VT: voltage transformer.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
system design of the converter and the current limiter. The speed requirement and the interaction between the dc CB and dc protection can be briefly observed in Figure 3. If more details and testing of dc protection are considered, the specific hardware, software, and communication protocols should be investigated [9], [29]:

- **hardware platform**: e.g., an HIL testing platform based on the real-time digital simulator (RTDS), protection IEDs, physical interfaces, and connections
- **software platform**: i.e., power system and control function models, reasonable test cases, protective function algorithms, and dc CB models
- **communication**: a hardware- or software-defined data transmission network for the links between any combinations of the hardware platforms and software platforms.

An example of a real-time cyber-physical testing platform can be seen in Figure 4(a). The test MTdc grid is first developed in RSCAD software and then simulated in real time using RTDS [41]. To simulate detailed models of HB MMC converters, dc CBs [26], [42] in small time-steps, and new dc protection algorithms, new generations of processors in RTDS are preferred. Furthermore, the IEC 61850-9-2LE sample value communication [43] has been developed based on one GTFPGA unit and one GTNETx2 card, together with the related software interface configuration within the RTDS racks.

The sample values of the critical measurement points in the MTdc grids are provided by GTFPGA-based merging unit functions to the local Ethernet network, while the GTNETx2 card is configured to obtain the sample values from the local network for the protection functions modeled in RTDS. The related message flows can be monitored and analyzed based on the manageable Ethernet switch and Wireshark network analyzer [44]. If the protection IEDs under test for ac/dc systems are available with the required communication interfaces, then the application performances of IED under test can be easily testified based on this simulation platform, shown in Figure 4(a).

There are many different schemes using real-time simulation for the testing and commissioning of protection, control, and communication systems, which can be mainly categorized into two groups, i.e., software in the loop (SIL) and HIL. A simple illustration can be seen in Figure 4(b). In an SIL scheme, both the controller and the physical test system are simulated by RTDS, when it is difficult to access IEDs. In an HIL scheme, the IED under test is accessed and connected to the real-time simulator through specific interface converters, e.g., amplifiers and sensors [45]. The test platform shown in Figure 4(a) can be regarded as SIL with additional communication links for IEC 61850-9-2LE, when the object under test is the simulated relay model in RTDS. When the object under test is the protection IEDs, then the related testing schemes based on the test platform in Figure 4(a) belong to HIL schemes.

In an RTDS-based simulation platform, the network solution technique is performed by nodal analysis. This is different from the OPAL-RT-based simulation, which is realized by a state–space nodal method to perform network calculations [46]. For every real-time simulator, the online simulation is discrete time based. With a large number of data points computed within a given power system cycle, the online simulation approximates the continuous time power system appropriately [47].

![Figure 4](image.png)

**FIGURE 4** – The real-time simulation platforms. (a) One example based on RTDS and IEC 61850-based ICT infrastructure. (b) The general groups of real-time simulation: SIL and HIL. ICT: information and communications technology. HMI: human–machine interface. (Source: RTDS.)
**Test Procedures for MTdc Grid Protection**

**The Structure of Test Procedures for dc Protection**

The script of protection performance testing is depicted in Figure 5. The blocks with black arrows represent the normal progress of fault development and protection performance, while the blocks with red arrows represent the evaluation and testing progress.

The general testing steps for the dc protection can be described as follows:

- **step 1**: fault scenarios: simulation-based fault studies
- **step 2**: statistical analysis of system-level performance
- **step 3**: threshold setting adjustment
- **step 4**: criteria checking
- **step 5**: report and troubleshooting.

The details of these five steps are different when the dc protection function is different, e.g., primary protection testing and backup protection testing are conducted with different fault scenarios, which will be introduced later.

**Test Circuit and Fault Scenarios**

Figure 6 shows an example of a simulated dc fault current in the four-terminal meshed HVdc grid based on the testing platform in Figure 4(a). This MTdc grid is built on an HB MMC and cable lines, and each cable is terminated by mechanical dc CBs [6] and series inductors. The related specification of the MTdc grids is included in Table 3, and more data on the system and controllers can be found in CIGRE technical brochure 604 [48]. It should be noted that, in Figure 6, the MTdc test system, fault scenarios, and the current waveforms are simulated and produced based on the RTDS simulation platform, which aims to testify the system-level performances of studied protection IEDs. The main time-step in RTDS is set as 50 µs, while VSCs and dc CBs make use of a small time-step of 3.124 µs.

When a fault occurs at the end of the line between converters A1 and C1 at time $t_0 = 0.1$ s, the related traveling wave reaches the terminal A1 at $t_1 = 0.1056$ s. Then, the dc fault current quickly increases, and its rate of rise is limited by the series inductors.

**TABLE 3 – THE AC GRIDS AND MMC PARAMETERS.**

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>MMCs 1, 2, AND 4</th>
<th>MMC 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC voltage</td>
<td>± 200 kV</td>
<td>± 200 kV</td>
</tr>
<tr>
<td>Converter ac voltage</td>
<td>220 kV</td>
<td>220 kV</td>
</tr>
<tr>
<td>Rated power</td>
<td>800 MW</td>
<td>1,200 MW</td>
</tr>
<tr>
<td>Number of sub-modules per arm</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>Arm resistance $R_{arm}$</td>
<td>0.54 Ω</td>
<td>0.36 Ω</td>
</tr>
<tr>
<td>Arm reactor $L_{arm}$</td>
<td>29 µH</td>
<td>19 µH</td>
</tr>
<tr>
<td>Arm capacitance $C_{arm}$</td>
<td>25 µF</td>
<td>37.5 µF</td>
</tr>
<tr>
<td>Transformer leakage reactance</td>
<td>0.18 per unit</td>
<td>0.18 per unit</td>
</tr>
<tr>
<td>AC grids</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-ac grid and 2-ac grid</td>
<td>380 kV</td>
<td></td>
</tr>
<tr>
<td>3-ac grid and 4-ac grid</td>
<td>145 kV</td>
<td></td>
</tr>
</tbody>
</table>
In the first millisecond, successive reflections (e.g., at $t_2$) occur, caused by waves traveling along the line between the fault location and the protection system location. Furthermore, other terminals start to feed into the fault current. At $t_3$, converter A1 blocks its insulated-gate bipolar transistors (IGBTs), and the dc fault current is fed by the ac side. All converters in the system are blocked around $t_3$. At $t_4$, the mechanical dc CB located at A1 opens to interrupt the fault current increment. Eventually, after $t_5$, the fault is completely cleared by dc CBs installed in the faulty line between A1 and C1. A detailed overview of the phenomena, which occur during the fault, is given in Figure 7.

It should be noted that the dc grid protection considered in this article excludes the converter protection that is normally designed by different converter vendors. However, in the real or simulated cases, these two protection systems are incorporated with each other. In the simulation example in Figures 6 and 7, the recommended parameters from [48] are directly adopted for the converter protection, e.g., the valve current threshold of 6 kA and dc bus voltage threshold of 0.9 per unit are considered. The fault current withstand capability of the freewheeling diode is set based on their own design parameters, e.g., the thermal capability limits.

To deal with a possible current imbalance in the combination of diodes for the MMC, the thermal capability limit could be calculated based on the minimum current thermal limit of each diode, which could resort to a related reliability test. Moreover, when a hybrid dc CB is applied instead of a mechanical dc CB, the break time can be improved from approximately 8 to 2 ms [8], which can release the thermal stress on the remaining components in the fault current loop.

Based on the progress and mechanism analysis during the dc fault development and interruption, the critical parameters influencing the dc fault current and the related dc protection system can include the type of transmission lines, fault resistance, dc-side inductance, dc-side capacitance, converter blocking instant, ac system strength, earthing system, and converter topology [24]. The impact of these parameters is briefly explained in Table 4. In addition, the sampling frequency is critical for the signal processing and the operation speed of dc protection; a sampling frequency of 96 ksa/s is assumed here, considering the IEC 61869 standards [40].

**Test Procedures**

For the testing of a specific protection IED, the specifications of the protection functions should be provided by the IED vendor first. The critical ratings and the performance limitations of the basic protection functions, e.g., input, output, detection, directional determination, measurement...
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Step 2: Statistical Analysis of System-Level Performance
The basic accuracy checking of protection characteristics and the operation time based on the performance analysis will be mainly conducted in this step. The statistical analysis of IED system-level performance is important to find a fault type-based probability distribution, which is the precondition to obtaining and checking the related criteria. The classical transient overreach analysis used in IEC 60255-121 [49] is adopted here for the accuracy testing.

An example of the testing procedures can be seen in Figure 9(a). With the chosen testing parameters in Figure 8(a), multicase testing can be easily conducted. The repeating sequence of five times is a common practice in IED testing in terms of reliability checking.

Based on the recorded test performances, the operation times can be determined in a statistical form. For example, the test data at the three fault positions (0%, 50%, and 80%) and with $L = 100 \mu H$ for the line inductor are considered. This results in a total of 1,800 (600 operation times for the cable line tests, 600 operation times for the overhead line (OHL) tests, and 600 operation times for the hybrid line tests) obtained operation times. This

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The basic accuracy checking of protection characteristics and the operation time based on the performance analysis will be mainly conducted in this step. The statistical analysis of IED system-level performance is important to find a fault type-based probability distribution, which is the precondition to obtaining and checking the related criteria. The classical transient overreach analysis used in IEC 60255-121 [49] is adopted here for the accuracy testing.

An example of the testing procedures can be seen in Figure 9(a). With the chosen testing parameters in Figure 8(a), multicase testing can be easily conducted. The repeating sequence of five times is a common practice in IED testing in terms of reliability checking.

Based on the recorded test performances, the operation times can be determined in a statistical form. For example, the test data at the three fault positions (0%, 50%, and 80%) and with $L = 100 \mu H$ for the line inductor are considered. This results in a total of 1,800 (600 operation times for the cable line tests, 600 operation times for the overhead line (OHL) tests, and 600 operation times for the hybrid line tests) obtained operation times. This

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is equal to 450 operation times for each fault type. 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 [50].
1) The test results for PTP1 are weighted by a factor of four.
2) The test results for the fault types PTP2, PTG1, and PTG2 are weighted by a factor of two.
3) The test results for other faults are weighted by a factor of one. These factors are defined according to the fault occurrence probability and its impact on the system.

The weighting is done by simply repeating the available results. Figure 9(b) shows the fault statistics of the typical operation time. In total, 4,500 operation times are available for the statistics.

These tests are aimed at determining the accuracy of the operation times of primary functions. They are based on monitoring the time difference between the arriving instant of the first fault traveling wave to the line end and the operation output signals of the IED. The time range and the associated classes based on the operation time could be defined based on the collected data set. For example, the minimum and maximum operation times in the data set are min_T = 1,512 μs, max_T = 4,167 μs. Thus, the range of operation times could be defined as 1,500–4,200 μs, similar to that reported in [30]. The classes of the performances of the IED under testing can be defined by making average groups with an interval of 300 μs, as can be seen in Table 6. Here, it is necessary to point out that, under an IED class, a particular operation time range is chosen.

---

**FIGURE 9** – The general procedures for system-level performance analysis: (a) the system-level accuracy testing and (b) the statistics for the typical operation times.
The number of operation times belonging to each class ($N$), with 300-µs 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 6. These procedures are related generally for all IEDs, and the table refers to the IED that will be tested.

**Step 3: Threshold Setting Adjustment**

The setting rules, variation range, and accuracy of the thresholds are introduced and analyzed in the type testing of protection IED specifications. However, for system-level testing, more influencing factors will be involved, and the corresponding thresholds can be optimally adjusted to achieve better system-level performance. Thus, the test settings of the thresholds can be expressed as percentages of the available range, with 0% being the minimum available setting, and 100% representing the maximum available setting. Similarly, 50% would indicate the midpoint of the available setting range. The actual setting to be used can be calculated using the following formula:

$$S_{AV} = (S_{MAX} - S_{MIN})X + S_{MIN}, \quad (1)$$

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, and $X$ is the test point percentage value expressed in the test methodology. For example, assuming the available setting range is 0.1–5 A and the 40% test point percentage, the actual operating current settings are 2.06 A.

To tune the threshold setting, the testing procedures 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 precalculated threshold setting is 63.5%, the threshold setting values change from 62 to 65% by 0.5%; then, the related testing procedures can be seen in Figure 10. The statistics data analysis can be conducted using the weighting factors of step 2 to obtain the best threshold settings corresponding to the highest probability of correct operation.

**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

---

**TABLE 6 – THE CRITICAL TESTING PARAMETERS FOR PERFORMANCE TESTING.**

<table>
<thead>
<tr>
<th>CLASS</th>
<th>FROM $t \geq [\mu s]$</th>
<th>TO $t \leq [\mu s]$</th>
<th>$N$</th>
<th>% $N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 1 (min = 1,500 µs)</td>
<td>min</td>
<td>min + 300</td>
<td>The number of operation times belonging to each class ($n$)</td>
<td>The probability of $N$ for each class ($n$)</td>
</tr>
<tr>
<td>Class 2</td>
<td>min + 300</td>
<td>min + 600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class 3</td>
<td>min + 600</td>
<td>min + 900</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class 4</td>
<td>min + 900</td>
<td>min + 1,200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class $n$</td>
<td>min + $(n - 1) \times 300$</td>
<td>min + $n \times 300$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class $M$ (max = 4,200 µs)</td>
<td>min + $(M - 1) \times 300$</td>
<td>max</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

max: maximum; min: minimum.

---

**FIGURE 10 – The testing procedures for threshold setting adjustment.**
The robustness of the MTdc grid protection refers to the detection of faults in the normal or degraded mode and the discrimination from other operational events in the grid.

tested when the objectives of protection system performance are met. The critical criteria are speed, sensitivity, selectivity, reliability, seamlessness, and robustness, which were mentioned in the “New Challenges and Requirements” section. To develop these criteria, the performance of the dc protection is divided into three different operations.

- **Correct operations**: The protection system operates for faults in its protection zone within the required time.
- **Failed operations**: The protection system does not operate for faults in its protection zone within the required time.
- **Incorrect operations**: The protection system operates for faults out of its protection zone.

Then, the related qualification criteria can be expressed as follows:

where \( P_{\text{classes.speed}} \), \( P_{\text{classes.sensitivity}} \), \( P_{\text{classes.selectivity}} \), \( P_{\text{classes.security}} \), \( P_{\text{classes.dependability}} \), \( P_{\text{classes.reliability}} \), \( P_{\text{classes.seamless}} \), and \( P_{\text{classes.robustness}} \) represent the probabilities of related operations for the checking of speed, sensitivity, selectivity, security, dependability, reliability, seamlessness, and robustness on the protectionIED under the test, respectively.

For the checking of each criterion, the critical testing parameters are revised according to specific requirements, which can be compared and observed from Figure 11. The testing procedures on speed, sensitivity, selectivity, and security can be seen from Figure 11(a), (b), (c), and (d), respectively. Thus, the meanings of (2)–(5) are different with different testing parameters, even though they are in the same form.

Since the speed of the primary protection is related to the time when the current reaches the dc CB interruption capability, a fast breaker could allow more complex and time-consuming algorithms to be applied. Thus, the different dc CB types are considered in the test procedures of speed checking, as shown in Figure 11(a). For the sensitivity checking in Figure 11(b), those testing parameters, which have big impacts on the operation quantities to give the possible minimum faulty condition, will be considered more, e.g., high fault impedances, different line inductors, converter blocking instants, and fault locations.

PTG faults are mainly considered in the sensitivity checking. For the selectivity checking, the fault resistance, fault location, fault type, and line inductor are chosen as critical testing parameters, with a greater focus on the borders of protection zones. The related changes on the related parameters can be found in Figure 11(c).

For the security checking, the unnecessary protection operations could result from the loss of selectivity and sensitivity due to wrong thresholds or the operation condition changing, e.g., dc line outage (dcL), energization/deenergization of a converter, and so on. Thus, in addition to the testing parameters considered for selectivity and sensitivity, the operation condition changes due to dcL and energization/deenergization of a converter must be considered in security-related testing. Neighboring dcL1 and deenergization of a local converter [converter event 1 (COEI)] are added in the fault type block in Figure 11(d).

After these multicase tests conducted by the corresponding testing procedures, the fault data statistics analysis is derived based on the user-defined ranges of testing parameters, which have been described in the former steps. Then, the related probabilities can be calculated based on (2)–(5). For the latter, the four criteria checks are related to (6)–(9), and the testing procedures or work flowcharts are similar to the first four criteria checks, but with a different focus. [See (2)–(9) at the bottom of the page.] The dependability is highly related to the sensitivity and the speed. Thus, in the related testing, similar testing parameters and critical time ranges based on dc CB types can be chosen as critical testing parameters. For the reliability, the total number of tests is the sum of the tests performed for the criteria of dependability and security.

\[
P_{\text{classes.speed}} = \frac{\text{number of correct operations}}{\text{total number of tests}} \quad (2)
\]

\[
P_{\text{classes.sensitivity}} = \frac{\text{number of correct operations}}{\text{total number of tests}} \quad (3)
\]

\[
P_{\text{classes.selectivity}} = \frac{\text{number of correct operations}}{\text{total number of tests}} \quad (4)
\]

\[
P_{\text{classes.security}} = \frac{\text{number of correct operations}}{\text{total number of tests}} \quad (5)
\]

\[
P_{\text{classes.dependability}} = \frac{\text{number of correct operations}}{\text{total number of correct and failed operations}} \quad (6)
\]

\[
P_{\text{classes.reliability}} = \frac{\text{number of correct operations}}{\text{total number of tests}} \quad (7)
\]

\[
P_{\text{classes.seamless}} = \frac{\text{number of effective operations}}{\text{total number of tests}} \quad (8)
\]

\[
P_{\text{classes.robustness}} = \frac{\text{number of necessary operations}}{\text{total number of tests}} \quad (9)
\]
The seamlessness of the MTdc grid protection refers to the ability to hold the remaining part of the grid to continue operating in a secure state after the fault clearance [51]. This is related to the continuous adaptability of the MTdc grid protection when the system transfers from a normal operation condition to \(N-1\) or \(N-k\) conditions due to a fault clearance. In this case, the effective operations in (8) mean the correct operations of the protection with predefined settings (for specific operation conditions) in a postfault stage, such as the \(N-1\) or \(N-k\) stages.

The robustness of the MTdc grid protection refers to the detection of faults in the normal or degraded mode and the discrimination from other operational events in the grid [50]. The difference with respect to seamlessness is that the adaptability to both normal and degraded operational modes is required, but continuous operation transition is not. Moreover, the discrimination from any other operational events causes the robustness to become a kind of reliability as well. Accordingly, in this case, the necessary operations in (9) mean the correct operation of the protection with different predefined settings for different stages, those being adaptive and available for several operation conditions.

**Step 5: Report and Troubleshooting**

In this step, the summary of the data analysis should be given based on the previous work steps, and the limitations and related troubleshooting should be registered, as illustrated in Figure 8, so that this can be improved for all work steps in future work. For backup protection testing from the viewpoint of the IED under test, the different actions of the backup protection should be mapped to the backup fault-clearing options given for fault interruption and based on the categories in Figure 2 [52].

Due to rigorous requirements on the time of fault clearance and communication delays, only local backup will be considered here for the dc protection system. The general testing progress of the backup protection performance is depicted in Figure 12. The testing considerations and steps are similar to those in the primary protection testing, but the failure detection is a critical function of backup protection. Here, two kinds of failures have been considered, i.e., the failure

![FIGURE 11](image-url)
of primary protection and the failure of dc CB operations.

Moreover, the test cases for backup protection testing need to be processed based on previous cases in primary protection testing. The cases used in the testing of dependability checking can be adopted directly here, since some nondependable operations (e.g., nontripping signals) in the required time interval are regarded as the failure of primary protection. Inversely, the failures of dc CB operations will be tested with those dependable cases, which are mainly induced by the dc CB’s own capabilities and features. Thus, when the failure of primary protection and the failure of dc CB operation are identified, the backup protection functions will be initiated to choose one of the backup options of fault interruption to execute suitably. These two types of failures and their derived rules can be seen in Figure 13. Based on the obtained cases, similar performance analysis of related backup protection functions can be undertaken accordingly.

Suggestions on Technical Guidelines for dc Protection Testing

Definitions of the Test Environment and Scenarios

The critical requirements and testing parameters of the test environment and fault scenarios vary as the target MTdc grid under study and applied protection algorithms are changed. In case a reduction of the number of test scenarios is needed from several tens of thousands of scenarios [Figure 9(b)]

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![Flowchart showing test scenario choices](image-url)
to a reasonable number, it is proposed that test scenarios could be defined considering the limitations of the protection algorithms. For example, when an algorithm is intrinsically limited with respect to the fault resistance, the fault scenarios are determined with more focus on this parameter.

If more practical parameters are considered in the test environment, some standard or proposed models can be improved and adapted to the actual grid under study, with consideration of:

- the types of transmission lines, including cable, overhead, and hybrid lines
- the length, parameters (resistance, inductance, and capacitance), and structure of transmission lines
- more fault types and resistances (e.g., a self-clearing fault in the case of OHLs and faults involving metallic return wire in bipolar HVdc grids with metallic return)
- more MMC converter station structures, including monopolar and bipolar
- the converter station earthing, including earthed (earth return or metallic return) and ungrounded systems, and earthing methods
- more converter topology, including two-level and MMC (FB, HB, and so on)
- the dc-side capacitance
- the control methods and control modes of the converters (PV, PQ, and so on)
- more types of dc CBs and other switchgears
- HVdc grid ratings such as voltage, current, and transferred power
- different ac-side equivalent systems.

With respect to fault scenarios, in addition to those parameters mentioned in the “Test Procedures for MTdc Grid Protection” section (i.e., fault resistance, fault location, dc-side inductance, and converter blocking instant), the measurement accuracy, sampling rate, and noise level on the voltage and current can be considered as well.

**System-Level Assessment of dc Protection**

After a test of different protection algorithms is carried out, the performance of the algorithms can be analyzed. The algorithms show different performances in terms of different requirements. Therefore, it is necessary to classify the performance of the protection algorithms by considering each requirement or criterion. Here, the performance obtained by performed tests in the “Test Procedures for MTdc Grid Protection” section can be classified into low, medium, and high performance classes for all protection algorithms based on the

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![Diagram](image-url)  
**FIGURE 12** – The testing progress of backup protection performance testing.

![Diagram](image-url)  
**FIGURE 13** – The evolution from primary protection to backup protection testing.
values of the corresponding qualification criteria.

To determine the range of qualification criteria values for each class, the computed qualification criteria values for each requirement for all protection algorithms are sorted in decreasing order. Then, these qualification criteria (of a particular requirement) and their corresponding algorithms are divided into three groups with equal (in the case of an odd number of algorithms) or almost equal (in the case of an even number of algorithms) members: groups 1, 2, and 3. An example with the consideration of nine algorithms and speed criteria is given in Table 7.

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 \( \geq \) average of group 1
- average of group 2 \( \leq \) medium performance \( < \) average of group 1
- low performance \( < \) average of the group 2.

It is also possible to use the minimum and maximum values of the groups instead of the average values:
- high performance \( \geq \) minimum of group 1
- minimum of group 2 \( \leq \) medium performance \( < \) minimum of group 1
- low performance \( < \) minimum of the group 2.

This classification method can be applied to all of the requirements in Table 1. Then, 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 other requirements and may also differ for different IEDs. Because the test procedures and assessment methods are designed in a systematic way, the efficiency for the full performance assessment of IEDs is higher and more difficult to quantify than the simple testing methods used in [32]–[37] for only single protection algorithms. By comparing them to single protection algorithm testing with lesser performance requirements, the computation efforts of the proposed testing method will be made to systematically consider all of the requirement criteria, i.e., speed, sensitivity, selectivity, security, dependability, seamless, and robustness, which are necessary for the industrial application and the certification of protection IEDs.

Compared to IEEE and IEC standards for ac protection testing, the proposed methods are more advanced and applicable for dc protection IEDs. The extra system-level assessment method proposed in the article can help evaluate the different kinds of dc protection algorithms implemented in the protection IEDs. It should be noted that the efficiency of the proposed method can be quantified by comparing the test results and practical results recorded in practical MT HVdc grids. However, performing such a study needs a reasonable amount of practical information about the performance of IEDs and the protection algorithms, which implies longer time exploitation and operation of MT HVdc grids. At this moment, such information is not available because there are a few newly commissioned practical MT HVdc grids and even fewer protection IEDs equipped with different protection algorithms.

**Conclusion**

This article first identifies challenges for system-level testing of MTdc grid protection, and it exploits the already available standard procedures for ac protection system testing to develop MTdc grid protection testing procedures. It also applies the knowledge of dc protection testing and makes recommendations based on the developed procedures and guidelines for both primary and backup dc protection functions. The specific performance criteria are designed, based on multcase testing and statistical analysis, with consideration of the related critical testing parameters for the functional requirements of dc protection. Suggestions for the dc protection testing environment and fault scenarios and the assessment methods of the algorithms’ performances are provided, which will be important for the future standardization of MTdc grid development and related protection testing.

**Acknowledgments**

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