Demonstration of Multi-vendor Protection Systems for Multiterminal VSC-HVDC Networks

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***Abstract*—This paper outlines the demonstration of partially selective and fully selective HVDC protection systems using a simulated industrial case study HVDC network, hardware HVDC protection IED prototypes, and simulated HVDC circuit breaker models. A summary of results are presented demonstrating the performance if the protection IEDs and indicating successful operation of the overall HVDC protection system according to system-level indicators. The presented results are intended to increase confidence that HVDC protection systems for multi-vendor HVDC networks are near ready for full-scale industrial implementation.**

I. Introduction

In order to integrate large amounts of renewable energy generation into the electricity transmission system, additional interconnection and reinforcement are expected. Although existing systems are predominantly point-to-point, the flexibility and possible cost savings of a multiterminal VSC-HVDC system has resulted in intense research and development and the first systems are now in operation [1].

Recent demonstration has shown that various topologies of HVDC Circuit Breaker (DCCB) can successfully isolate a fault under high power conditions, including devices in operation in several Chinese projects [1] as well as devices that have been laboratory tested: the ABB hybrid [2], Mitsubishi Electric current injection [3], and the SCiBreak VSC Assisted Resonant Circuit (VARC) DCCBs [4].

Considering the detection of DC faults and the discrimination of fault location, there are many algorithms that may be suitable for multiterminal HVDC networks [5], [6]. In a power system, these algorithms would be executed on a protection Intelligent Electronic Device (IED), sometimes known as a protection relay, which has the core requirement of receiving measurements from instrument transformers, executing algorithms to identify faults, and sending trip signals to circuit breakers. Selective protection algorithms will be required to operate an order of magnitude faster than a typical AC protection IED, and therefore this speed requirement is imposed on the IED executing the algorithm.

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When designing an HVDC protection system (combining DCCBs, protection algorithms on IEDs, and overall system design), fault clearance can be achieved by following several different philosophies; non-selective (for which the whole DC system is one protection zone), fully selective (for which each line or cable is a zone) or partially selective (for which the zone is a subset of the whole HVDC network) [6]. A range of in-depth analysis of protection system design has recently been performed in which the trade-offs of protection system design choices have been examined [7]. Additionally, although most existing systems are developed by a single vendor, future large scale systems are expected to be multi-vendor, bringing additional challenges regarding functional requirements, functional testing, and interoperability [8].

Even as the first multiterminal systems successfully transmit power, there are still remaining questions regarding the optimal design, protection and operation of future HVDC systems. Unlike in AC systems, there is not yet significant experience for multiterminal HVDC, and in the European context there is still a perceived lack of confidence in the maturity of technology for multiterminal VSC-HVDC systems.

Many of the components of the HVDC protection system have recently been developed and demonstrated individually: HVDC circuit breakers [2]–[4] and HVDC protection IEDs [9]. This paper brings the different components together, operating them simultaneously in a realistic system and demonstrating the overall system-level performance.

Although there are various examples of protection system testing using real-time systems, there is still only very limited information available when setting up a real-time demonstration with the very stringent model resolution required for accurate HVDC protection studies [10], [11]. Therefore it is expected that discussion of the real-time implementation provided in this paper will be of benefit to readers working on similar applications.

This paper will present an overview of results from the demonstration of partially selective and fully selective HVDC protection. First, the industrial case study and the components under test will be introduced, with details included on the real-time implementation and test procedures. The performance of the protection IEDs in single- and multi-vendor systems is shown. The overall protection system performance, including post-fault recovery, will then be demonstrated.

II. Demonstration of HVDC protection systems using industrial case studies

In order to demonstrate the performance of HVDC protection in as realistic an environment as possible, an industrial case study system is used. This allows the use of parameters and constraints from an HVDC system alongside DC-side protection; HVDC protection IEDs in hardware and DCCBs in a simulated environment.

Given that there is limited experience in DC-side protection and multi-vendor HVDC systems, the aim of this demonstration is to highlight the performance of an HVDC protection system in a realistic environment, and provide indication that multi-vendor DC-side protection might be possible in a future system.

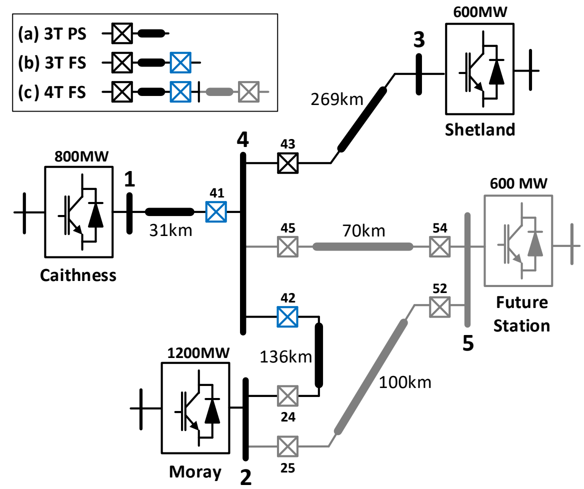

Fig. 1. Caithness-Moray-Shetland case study system; three terminal (3T) and hypothetical four terminal (4T). Hypothetical DC-side protection cases indicated; partially selective (PS) and fully selective (FS).

A. Caithness-Moray-Shetland case study system

The Caithness-Moray HVDC system is a operational point-to-point VSC-HVDC system in the north of Scotland, UK. Connection of a third terminal - Shetland - has recently been approved [12]. This three terminal radial system will be protected in a non-selective manner with AC-side circuit breakers. To enable effective commissioning and operational training, converter control and protection (C&P) replicas (with a simulated electrical system) for the three terminal system are present at The National HVDC Centre [13].

Although there are no plans to add DCCBs to the Caithness-Moray-Shetland (CMS) system, the simulated environment provides a real case study system to examine hypothetical possibilities for protection systems that could be applicable to this and other multiterminal systems.

In the long term power system planning there is a large amount of offshore wind power generation anticipated in the region, and therefore there may also be the possibility to connect more terminals to the CMS system in the future. With this in mind, and given the perceived challenges relating to protection of meshed HVDC systems, in this work we also examine the option of extending the CMS system with one additional converter station and two additional cables - resulting in a meshed HVDC system.

In order to demonstrate DC-side protection, several protection options are proposed, including both partially selective and fully selective strategies on the three terminal (radial) system and a fully selective strategy on the hypothetical four terminal (meshed) HVDC system. The different protection options under consideration are summarised in Figure 1, in which DCCB/IED locations are named according to the two buses on the cable they protect.

B. Protection IED hardware

Within the presented work, two HVDC protection IED prototypes have been examined; from Mitsubishi Electric and from KTH. The Mitsubishi Electric prototype executes primary and backup protection algorithms (based on [14] and [15]) on industrial hardware that could be used in a future HVDC system. The KTH prototype executes a variety of protection algorithms and is user configurable for use in education and research [16], and in the presented work dv/dt and travelling wave based algorithms are used for fault location discrimination. Each prototype contains multiple functional units, such that one physical device can execute multiple instances of algorithms and trip multiple DCCBs.

C. Protection system design

Inductor sizes and protection settings are chosen based on PSCAD simulation taking into account different DCCB operation times and converter responses. The additional inductor at each DCCB is sized so that the maximum DCCB current is not exceeded, and such that selective fault detection can be ensured. Converters are allowed to block and use an adaptive deblocking scheme in which they evaluate a deblocking criteria at a time depending on the fault location (detected locally). At the moment the criteria is evaluated, the converter either deblocks and resumes normal operation or remains blocked and the ACCB is tripped.

D. HVDC circuit breaker models

Models of three DCCB topologies have been developed in collaboration with manufacturers in the PROMOTioN project [17], [18]. Real-time models, used in the presented testing, have been validated against detailed PSCAD models.

E. Converter and system models

Manufacturer converter C&P replicas [13] are used for one of the studies. In the remaining studies, open-source converter models have been used [19], [20]. The open-source model adopted in this test setup includes typical high level and low-level control loops to provide a realistic system response [19], [20].

Although hardware protection IEDs are used to protect most of the cables, there are only a limited amount of IED functional units and in some system configurations it was not possible to use hardware IEDs in every location. Simulated IEDs are therefore applied to allow full system-level studies, although the performance of the simulated IED is not highlighted.

Cables are represented as frequency dependent phase domain models, with physical parameters from the CMS project. Pole rebalancing equipment using switched surge arresters is implemented to rebalance the charge on the network following pole-to-ground faults [21].

F. Real-time implementation

Given that the protection IEDs execute algorithms at a high sample rate, the real-time simulation is required to be executed at a small time step. In RTDS, the applied real-time simulator, the 'small time step' is used (executing at ~$3\,\mu$s) for all converters and DC-side electrical components, timings, inputs and outputs. The small time step environment was used for legacy reasons - some of the challenges detailed below may be resolved by the recently introduced 'sub-step' environment.

1) Hardware: The simulation models are executed on three NovaCor racks (each with 5 CPU cores licensed), six GTAO cards, two GTDI cards, one GTDO card, and five GTFPGAs running frequency dependent phase domain cable firmware (*gtfpga_707_TLFDP_0703*).

2) Model splitting: As with any real-time simulation environment, there are inherent processing limitations and larger models require parallelisation. The implemented model is split between small time step bridge-boxes and RTDS racks such that the required interfaces between CPUs are placed in positions where they have the least impact on the simulation result. IO cards are carefully arranged such that they are interfaced with the correct core and so that they can be updated at the small time step without additional delay.

3) Small time step interfaces: In the small time step environment, stub-line decoupling is required in cases for which components cannot be computed on the same processor/FPGA, or in case models need to be decoupled. Each stub line results in a half or one small time step delay. Each stub-line is constrained a fixed product of the required L and C for a particular time step according to $t = \sqrt{LC}$.

Cable-end interfaces (between bridge boxes, between racks, decoupling circuit breaker models) were specified according to the required additional inductance at the end of the cable.

Mid-cable interfaces were specified according to the impedance ratio of the modelled cable, resulting in the equivalent to $750\,\mathrm{m}$ of cable in each interface. The overall cable length was reduced by $750\,\mathrm{m}$ per interface such that the overall impedance of each cable was representative.

Surge arrester interfaces were chosen to provide a good trade-off between dynamic performance during pole imbalance and performance in pre-fault conditions (e.g., normal operation in which large capacitances can cause oscillations and result in other inaccuracies in dynamic performance). It is noted that the relatively large series inductance may not be suitable for other studies (e.g., involving very fast overvoltage transients due to lightning impulse).

TABLE I
CASE STUDIES TO DEMONSTRATE HVDC PROTECTION

Focus	Selectivity	Interoperability	Test	Section
IED + replica	Partially	i, ii	Primary	III-A
IED	Partially	i	Primary	III-B
IED	Fully	i, iii	Primary	III-C
IED	Fully	i, iii, iv	Backup	III-C
System	Fully	i, iii	Primary	IV-B
System	Fully	i, iii, iv	Backup	IV-C

G. Case studies presented in this paper

In order to demonstrate the successful operation of the HVDC protection IEDs and the overall protection system, several case studies have been selected, Table I. These case studies focus on either the IED performance or the system performance, and both primary and backup protection are demonstrated. Four types of interoperability are inherent in this work: (i) functional interoperability between IEDs and DCCBs, (ii) functional interoperability between C&P replicas and DC-side protection system, (iii) functional interoperability between IEDs, and (iv) communication interoperability between IEDs.

III. EVALUATION OF IED PERFORMANCE

This section focuses on the detailed performance of the protection IED in a realistic power system. It is valuable to assess the performance in this manner given that the power system is realistic and therefore the IED response would be expected to be representative. Both the IED operation time and the dependability have been assessed. Note that in each case, the IED operation time is that between the arrival of the fault at the IED location and the time at which a trip signal is issued. Note that, although there are no standardised functional requirements for HVDC IEDs, it is often considered that fault discrimination should occur in $1\,\mathrm{ms}$ to $2\,\mathrm{ms}$.

A. IEDs with converter control and protection replicas

In order to demonstrate the operation of the protection IEDs and DCCB models with the C&P replicas, the partially selective three terminal CMS system is examined, Figure 1a.

Combinations of C&P replicas (ABB), protection IED (Mitsubishi Electric, KTH) and DCCB (SCiBreak, ABB, Mitsubishi Electric) are evaluated to demonstrate particular cases of functional interoperability, Table II. All IEDs correctly detected the fault, all DCCBs operated to successfully isolate the faults, and remaining converters on healthy branches successfully ride through the fault and continue in normal operation. These results indicate that DC-side protection systems may, in some scenarios, be able to achieve functional interoperability with existing converter controls.

TABLE II
OUTCOMES OF STUDIES WITH IEDS, DCCBS AND C&P REPLICAS

C&P replica	IED	DCCB	Success?
ABB	Mitsubishi	SCiBreak	✓
ABB	Mitsubishi	ABB	✓
ABB	Mitsubishi	Mitsubishi	✓
ABB	KTH	SCiBreak	✓
ABB	KTH	ABB	✓
ABB	KTH	Mitsubishi	✓

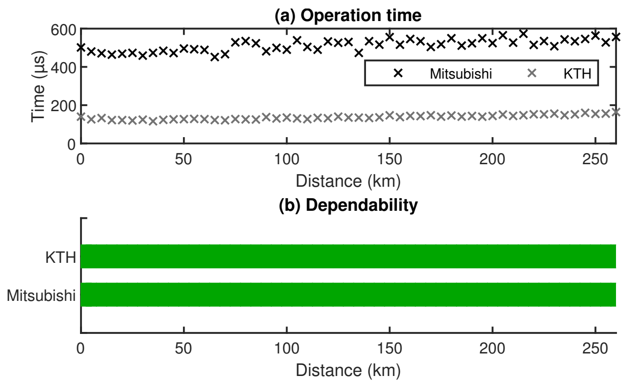

Fig. 2. Protection IED operation in 3T partially selective configuration with one Mitsubishi DCCB per pole; (a) mean operation time from 3 repeated faults at 5 km intervals along line 43 and (b) dependability for all faults, indicating that each IED successfully operated for each fault case.

B. Single-vendor IEDs with open converter controls

To assess the standalone performance of protection IEDs, the partially selective 3T radial case study is again used, Figure 1a. Selected results examining the operation time of the protection IEDs are shown in Figure 2. It is observed that there is some variation in operation time, $110\,\mu s$ to $170\,\mu s$ and $450\,\mu s$ to $570\,\mu s$ depending on the IED and fault location. This variation in operation time can be explained by the variability in the fault instance relative to the sampling instant of the IED. It can be seen that in each of the three repeated faults at each of the 53 fault locations, each IED is 100% dependable, Figure 2b. Further results are presented in reference [22].

C. Multi-vendor IEDs with open converter controls

In order to demonstrate the performance of IEDs in a multi-vendor protection system, the fully selective 3T radial network is examined, Figure 1b. In the case study selected for demonstration there are two protection IEDs under examination; the Mitsubishi Electric IED (acting as primary protection and able to detect the failure of a circuit breaker) and the KTH protection IED (which is able to receive a trip signal from an external device - controlling the backup DCCBs).

Two sets of results are presented. First the primary protection operation is evaluated using repetitive testing, in which it is observed that the primary protection operates in less than $600\,\mu s$, Figure 3a. The performance of the backup protection following a breaker failure is then shown to be in the region of $10.8\,ms$, Figure 3b, a time which consists of the primary

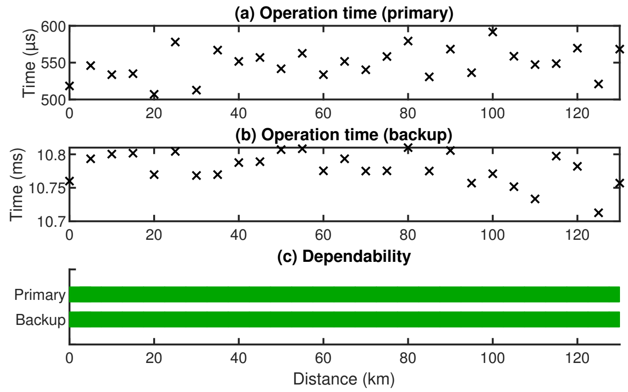

Fig. 3. Protection IED operation in 3T fully selective configuration; mean operation time from 3 repeated faults at 5 km intervals along line 42 (a) for primary protection and (b) for breaker failure backup protection, and (c) dependability for both cases, indicating that each IED successfully operated for each fault case.

TABLE III
IED AND DCCB CONFIGURATIONS FOR 4T SYSTEM STUDIES

Location	IED	DCCB	Additional L
24	KTH	Mitsubishi	110 mH
25	KTH	SCiBreak	25 mH
41	Mitsubishi or Simulated	ABB	20 mH
42	Mitsubishi	ABB	20 mH
43	Mitsubishi	ABB	15 mH
45	KTH	Mitsubishi	100 mH
52	Simulated	SCiBreak	20 mH
54	Simulated	Mitsubishi	95 mH

protection time (~$600\,\mu s$), a delay to allow for the breaker to open (in this case $10\,ms$) and the time to execute the backup protection algorithm (here observed to be ~$200\,\mu s$). In each case, the protection element is determined to be 100% dependable - that is, the primary protection IED always operated as expected, and when the DCCB was disabled, the backup protection IED always operated as expected, Figure 3c. IED failure protection has also been evaluated and further results can be found in reference [23].

IV. EVALUATION OF SYSTEM PERFORMANCE

In order to evaluate the performance of the overall (protection) system, the operation of the IEDs alongside the DCCBs and other protection equipment are evaluated. Assessment of the primary and backup protection operation is performed, and post-fault recovery is assessed.

To demonstrate the overall system performance, the four terminal meshed system is used, Figure 1c. A multi-vendor case study including protection IEDs and DCCBs is applied, and a protection system design exercise is performed (Section II-C) resulting in the required additional inductance at each DCCB, Table III. In this section the system-level performance will be examined for both primary and backup protection.

A. Methods for assessing protection system performance

In order to assess the system level performance in a consistent manner, several Key Performance Indicators (KPIs) have been proposed [24], and it is suggested that the KPIs and the methods to obtain them could be standardised such that performance of future protection systems could be consistently compared. In this paper two system level KPIs are evaluated: DC voltage restoration time and active power restoration time. However, the assessment of other KPIs, e.g., the fault detection margins, can be equally important. Note that in this paper these recovery KPIs are not presented for locations and faults for which no recovery is possible - e.g., on the radial part of the network (no recovery is expected at bus 3 for faults on the adjacent cable). Power restoration is measured at the AC-side of the converter stations and therefore is not calculated at bus 4 at which there is no converter. In the presented case studies converter 2 controls the DC voltage, therefore the power flow at converter 2 does not always recover to the pre-fault value - so power restoration is also not evaluated at this bus.

Pole-to-pole, positive and negative pole-to-ground faults are simulated at 5 km intervals along each cable on the network. In each case, the successful operation of each protection IED is verified. The KPIs are evaluated for each simulation case and the aggregated results are discussed in the following sections.

B. Primary protection

In this case study six hardware protection IED functional units are used. All DCCBs are enabled, therefore following any fault the DCCB(s) on the faulted cable would be expected to quickly isolate the fault from the rest of the network.

Example time domain results are presented for one fault case - a pole-to-pole fault on the cable between bus 4 and bus 3 - Figure 4. Following detection of the fault by the IED, it is observed that the DCCB isolates the fault quickly and the voltage on the remaining buses recovers quickly. Note that the DCCB implementation latches so the IED trip signal going low does not imply reclosing. After some time, power flow is resumed on the remaining cables.

Overall, 348 simulation runs are performed in order to characterise the performance over a range of fault cases. In general, it is observed that in each fault case, the IEDs operate selectively (as expected) and the voltage and power flow recover in the 100 ms time scale. It is observed that the mean voltage and power recovery times across all cases are less than 31 ms and 71 ms respectively.

C. Backup protection following DCCB failure

In order to examine the operation of the breaker failure detection algorithm in the IED and the backup protection operation, DCCBs are deliberately disabled to simulate a breaker failure. In this case study we use five physical protection IED functional units - IED 41 is simulated. In the presented work only the Mitsubishi Electric IED is configured to detect breaker failure. In the presented studies breaker failure is only studied at locations 42 and 43, and faults are only evaluated on these two cables, resulting in 237 fault cases.

Following a cable fault, the primary protection IED detects the fault and sends a trip signal to the local DCCB. After a delay to allow for DCCB operation, the bus voltage and the DCCB current are evaluated to determine if the DCCB has operated successfully. In case it is detected that the DCCB has not operated, a trip signal is sent to the DCCBs around the bus. Following a delay for operation of a high speed switch to isolate the faulted line, the adjacent DCCBs can reclose and power flow on the remaining network can resume.

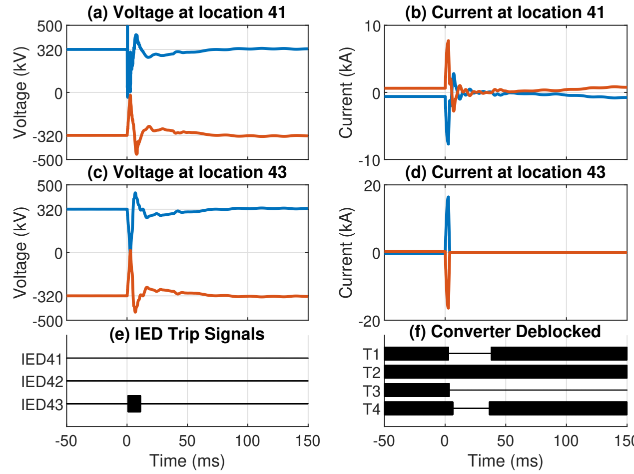

Fig. 4. Example time domain plots for operation of primary protection IED following a pole-to-pole fault on the cable between bus 3 and bus 4.

Example time domain data following a pole-to-ground fault the cable between buses 3 and 4 is presented in Figure 5. It is observed that the negative current rises quickly, however, it can be seen that the DCCB on the faulted line does not operate and there is a persistent current in the 20ms following the fault. IED 43 detects this breaker failure and orders the opening of the adjacent DCCBs, which can be observed in the current in adjacent DCCB 41 (~14 ms). Note that during this period, the pole rebalancing equipment is enabled and acts to rebalance the pole-to-pole charge. Following operation of the adjacent DCCBs and the high speed switch, it is observed that the adjacent cables are reconnected and power flow can resume. In this case, the voltage is rebalanced in about 100 ms and the power flow is resumed in about 150 ms.

Overall, 237 simulation cases are evaluated (faults every 5 km on the two indicated cables) to gain a understanding of the performance of the system over the full range of fault conditions. In general, it is observed that in all fault cases the breaker failure detection algorithm successfully detects the failure, and the backup protection and post-fault recovery are successfully carried out. In every case, power flow recovery is achieved in less than 250 ms, which may even be acceptable for weak AC systems [25]. The mean voltage and power restoration times are less than 70 ms and 190 ms respectively.

V. Future work

The work presented in this paper leads to many open questions for future research. Although a protection design methodology has been followed, it would be of interest to develop an optimisation of the protection system and a more robust methodology for proper consideration of protection

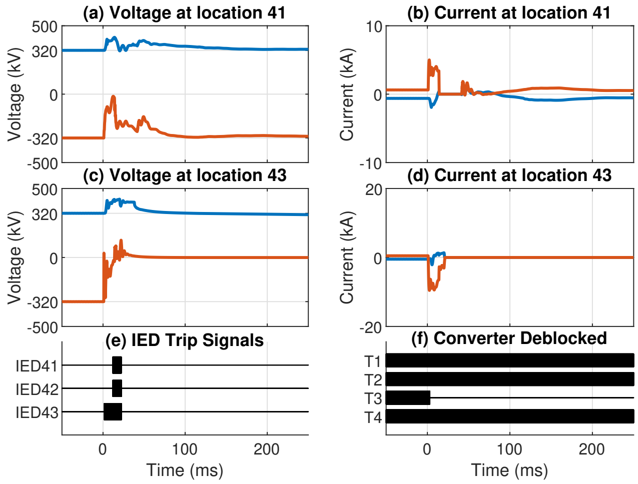

Fig. 5. Example time domain plots for operation of backup protection IED following a pole-to-ground fault on the cable between bus 3 and bus 4.

margins. The presented IEDs use hardwired communication, but in the future a suitable industrial protocol should be developed for inter-IED communications. The presented work provides a minimal proof of concept demonstration of interoperability between DC-side protection and manufacturer C&P replicas, however, it should be noted that most of the presented studies were not performed with the C&P replicas. There are a wide range of potential challenges in a future full system implementation; full coordination between the converters and DC-side protection, what interfaces should be imposed in future standards, how to robustly test the overall system including replicas, and how best to design and integrate protection and control if there is no access to vendor models.

VI. Conclusion

The presented work has used prototype HVDC protection IEDs integrated into a real-time simulation of an industrial HVDC case study network. The HVDC protection IEDs are the first standalone prototypes for grid protection tested in independent laboratories and the work presented in this paper is the first system-level testing of these devices. In addition to extensive details about the case study system and the real-time implementation, results are presented demonstrating successful operation of the HVDC protection IEDs and the overall protection system. Several single-vendor and multi-vendor protection scenarios have been demonstrated, including one using converter C&P replicas. In all presented cases it is demonstrated that the HVDC protection system is effective and results in a operational protection system.

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