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Assessment of interoperability in multi-vendor VSC-HVDC systems: interim results of the BEST PATHS DEMO #2

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SUMMARY

This paper describes the methodology and interim results from the ongoing European project Best Paths DEMO #2, which is the first attempt to undertake systematic investigation on interoperability in multi-vendor VSC-HVDC systems. The study is based on state-of-the-art technologies provided by three world-class HVDC vendors and involves TSOs and academics for investigations covering various HVDC layouts, from point-to-point to radial and meshed multi-terminal structures.

The paper describes the methodology used to assess and maximize interoperability, which comprises two stages: the first one relies on electromagnetic transient (EMT) simulation tools, while the second and ongoing one relies on real-time simulation with actual control cubicles provided by HVDC vendors.
The paper mainly reports on the different tasks which were carried out during the first stage (EMT simulations) and exhibits the results observed. The main tasks and results are listed as follows:

- Commonly agreed definition of interoperability
- Definition of common converter specifications for all involved HVDC vendors, based on the ENTSO-E Network Code for realism and replicability
- Definition of 5 different DC systems (including DC grids) on which interoperability should be assessed
- Provision of detailed vendor-specific EMT converter models, and their individual validation
- Assessment of interoperability on more than 1.000 realistic scenarios, from which 15% are representative of actual interoperability issues between the vendors
- First set of recommendations to maximize interoperability

Finally, the paper provides insights on the second and ongoing stage of the project based on real-time simulation using actual vendor control cubicles for deeper investigations.

KEYWORDS

HVDC – VSC – Interoperability - Multi-vendor - DC grid – EMT – Real-time - Hardware in the loop.

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1. MOTIVATION

Existing HVDC projects (such as FAB [1], Caithness Moray HVDC Link (CMS) [2], Cobra Cable or Ultranet) are under preparation in which the option of a multi-vendor system is considered. Such links highlight the urgent need for interoperability in VSC-based converters provided by various suppliers; of course, this requirement is also expected at a later stage for future DC grids (DCG), which are unlikely to be delivered by a single manufacturer.

In this context, the Best Paths R&D project[1] [3] (which purpose is to help to overcome the challenges of integrating massive renewable energies into Europe's energy mix) explores interoperability in a dedicated demonstration project called "DEMO #2". Three world-class HVDC vendors, three TSOs and two academics partners agreed to joint their effort in this 4-year project, which is the first attempt to undertake systematic investigation on interoperability in multi-vendor VSC-HVDC systems. This variety among partners ensures that the ongoing studies comply with actual needs and requirements as expressed by TSOs, that realistic results are delivered thanks to state-of-the-art HVDC technologies provided by the vendors, and finally that results are challenged and various techniques can be considered to improve interoperability thanks to academia.

The purpose of this project is twofold: (i) to provide an assessment of interoperability in multi-vendor VSC-HVDC systems based on readily available technology as supplied by major manufacturers; (ii) to provide public recommendations for standardization bodies and TSOs in order to maximize interoperability in future VSC systems.

Recently, China provided the first multi-terminal and multi-vendor HVDC arrangements based on VSC technology in the world: the Nan'Ao [4] and Zhoushan [5] projects. Without minimizing this major achievement, it should be highlighted that the approach considered in Best Paths DEMO #2 is significantly different. Indeed, in both Chinese projects, the control and protection were designed by one single stakeholder for the whole system, while others provided the valves and associated valve-based controls. Undoubtedly, those projects should be regarded as an important step forward with respect to interoperability, but this organization would not be applicable in a competitive framework or for the step-by-step erection of a complete DCG, as expected in Europe for instance.

2. METHODOLOGY AND ORGANIZATION OF BEST PATHS DEMO #2

The activities undertaken in Best Paths DEMO #2 decompose in two distinct stages which spread throughout the whole project duration (4 years).

2.1. First stage: EMT offline simulation with vendor-specific converter models

The first stage is dedicated to preliminary investigations using offline simulation based on EMT software; the converter models used in this stage are detailed and realistic ones, which individually capture the specific characteristics of each HVDC vendor involved in the project, thus ensuring realistic results compared to generic models generally used in the literature.

The successive tasks performed at this stage are as follows:

a. All partners agreed on common specifications for a single converter as well as AC configurations for their connection; in addition, various topologies for the DC system were defined. This is detailed in sections 3 and 4.
b. Based on previous common specifications, the three vendors involved in Best Paths DEMO #2 designed specific converters which fulfil these requirements based on their respective state-of-the art technologies; as a result, each of them delivered a detailed EMT model of their converter, which was individually tested to validate its compliance to the specifications. This is detailed in section 5.

[1] This project is co-funded by the European Union's Seventh Framework Programme for Research, Technological Development and Demonstration under the grant agreement no. 612748. Best Paths started in October 2014 and will end in September 2018.

c. TSOs and academics designed a wide variety of scenarios and tests with varying parameters, from which interoperability was tested with the vendors' converter models, as exposed in section 6. Finally, the learnings from these offline simulations made it possible to provide guidance in order to improve interoperability (section 7) and initiate the second stage (section 8).

2.2. Second stage: offline simulation with real-time Hardware-In-the-Loop

The second stage consists in rather similar steps, but using real hardware converter controls (aka control cubicles or replicas) connected to real-time simulation environment, so as to be in even more realistic conditions.

Thanks to the experience gained with EMT studies during the first stage, improved specifications were provided to vendors for the delivery of vendor-specific control cubicles. Then, the next steps are similar to previous ones: implementation of the control cubicles for a single converter; validation of each individual cubicle with respect to the common specifications; interoperability tests using real-time simulation; and at last, provision of final recommendations to maximize interoperability.
Currently, Best Paths DEMO #2 activities are fully committed to this stage (section 8). Yet, as will be exposed, some adaptations had to be considered in the course of the project.

2.3. General comments on the Best Paths DEMO #2 approach

The two stages approach is similar to existing practice in real-world HVDC project (such as the INELFE project [6]), where preliminary studies were performed with offline simulation tool (including EMT software) before final validation with real-time control replicas of the actual converters. This stepwise approach is intended to fix most issues in a quite flexible framework (offline simulation), before switching to a more advanced stage (real-time simulation).

In addition to confidentiality aspects, the contribution of three competitors required treating each of them with equity while in the project. In particular, some technical assumptions were made based on readily available technology for each of them. For example, DC protection could be handled with fault-blocking converters (such as Full-Bridge or Alternating Arm topologies) or DC Circuit Breakers (DCCB), but it was agreed to use commercially available technology only for the three suppliers; hence, specifications were elaborated so that Half-Bridge MMC converters would comply.

Finally, model validation, control cubicle validation and interoperability tests were performed by TSOs and academic partners only, for obvious "neutrality" reasons. Yet, the results were presented to the relevant vendors in order to have a common agreement on validation issues or interoperability problems.

3. SELECTION OF DC TOPOLOGIES AND COMMON CONVERTER SPECIFICATIONS

First, all DEMO #2 partners agreed on five different HVDC topologies on which to perform interoperability studies. They range from the standard point-to-point link (Topology 1, T1) to a five-terminal DCG, comprising tree-like and meshed structures as depicted in Figure 1. All topologies are monopolar symmetric schemes.

The main reasons for selecting different topologies on which interoperability is evaluated are the following: first, this study is driven by the perspective of future DCGs which are expected to be built gradually, thus involving several vendors. Yet, the most likely layout for those grids is still unknown, hence the need to explore the widest possible range of them. The five topologies above are considered as elementary building blocks, from which future DCGs will be created. It is therefore assumed that thorough investigations on those topologies will dramatically reduce the risk of a new interoperability issues appearing in any specific multi-vendor HVDC system.

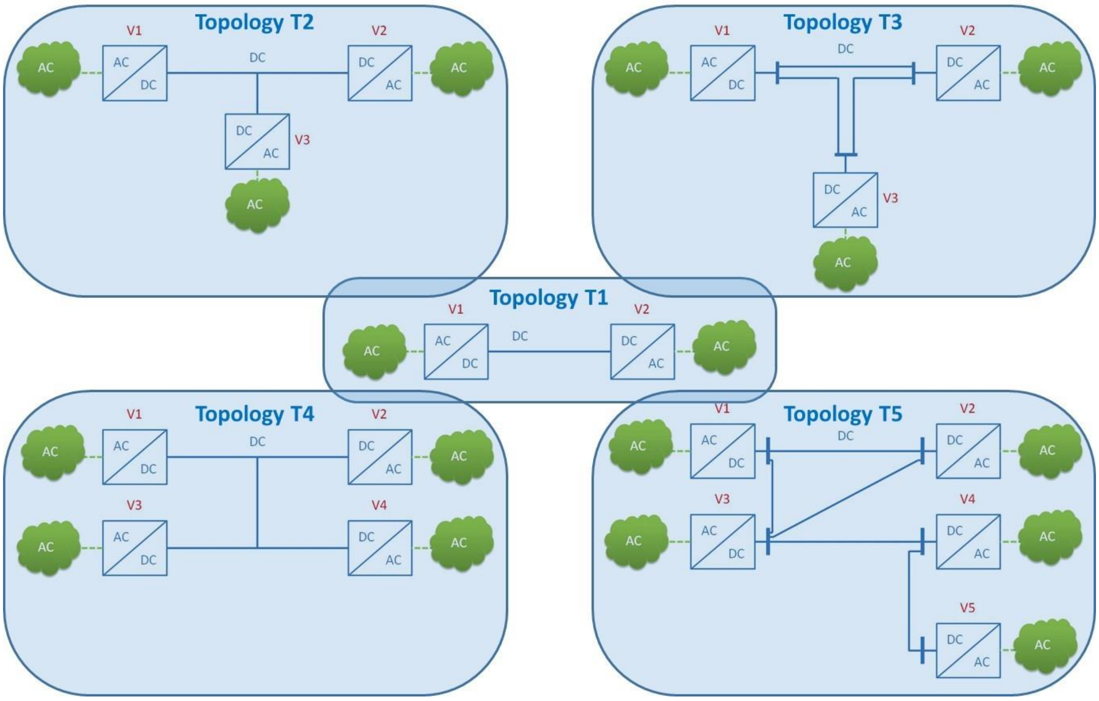


Figure 1: DC topologies investigated in DEMO #2.

The second driver for exploring various topologies is that no actual interoperability issue was reported prior to this project for VSC. In the absence of any knowledge on the possible circumstances leading to such problems, it was decided in DEMO #2 to explore as many configurations as possible, with a priority set to the most likely ones.

4. COMMON CONVERTER SPECIFICATIONS

In order to maximize compliance between converters, identical specifications were provided to the three vendors, which set requirements all partners agreed upon. Careful attention was given on the European grid codes (especially the one related to DCGs [7]) so that DEMO #2 specifications, which comply with the code requirements, are similar to any real HVDC project specification and can easily be replicated for new ones.

Yet, it should be emphasized that the common specifications provided by DEMO #2 cover a wider scope than standard ones, since the latter are provided for a complete HVDC link or system (so that they mostly focus on the expectations at the AC Point of Common Coupling): on contrary, DEMO #2 specifications cover the requirements for a single converter. As a consequence, they are specifications for both the AC-side and DC-side connection of the converter, which is certainly new practice.

Another novelty of those specifications is the fact that they include specific requirements for converter models to be delivered by the vendors, as well as the detailed validation tests and their acceptance criteria.

Finally, a key element to ensure consistency is the definition of a first standard interface relevant for all vendors, to exchange signals and measurements between their converter stations and a Master Control (MC), which coordinates the orders sent to them (control modes and references), and the AC/DC Protection System (PS). The usage of an independent third-party MC to operate all converters in a DC system complies with recommendations from CENELEC [8], while ensuring similar roles to all converters (rather than having one vendor’s converter conducting the others, for instance).

5. IMPLEMENTATION AND VALIDATION OF EMT VENDOR-SPECIFIC CONVERTER MODELS

5.1. Provision of a common generic converter model

A generic converter model was designed, which implements exactly the standard interface defined in the common specifications, for exchanging signals between the vendors' converter stations and the MC. The purpose of this generic model is twofold:

- To make sure that the inputs and outputs of the vendors' models perfectly match the specifications, as manufacturers had to implement their own models with identical interface as the generic one (as described in section 5.3).
- To facilitate the smooth development of DCGs and associated MCs and scenarios for future interoperability tests (as described in section 6).

This step was needed to guarantee homogeneous development between various contributors of the project (vendors on one hand; academia and TSOs on the other hand) which completed different tasks in Best Paths DEMO #2.

5.2. Provision of validation tests and associated Master Controls

Each validation test (already defined in the common specifications) and associated Master Control was provided by the simulating partners (TSOs and academia) in EMTP-RV environment to the vendors, so that the latter could perform in-house tuning and validation of their own converter model. At this stage the MCs were oversimplified, as they were mainly used to coordinate the start-up sequences of converters, define the initial conditions and run predefined validation scenarios.

5.3. Provision of vendor-specific converter models

Based on the above-mentioned common specifications and generic model, the three vendors implemented independently their own state-of-the-art commercial designs and converter models. The latter are truly realistic and detailed EMT converter models aiming at fulfilling all specification requirements.

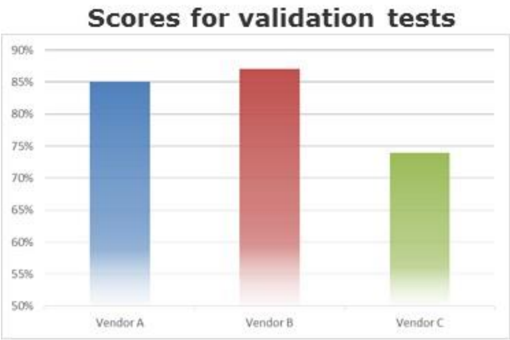
The specifications were very stringent ones, and given for a wide variety of situations (for instance: offshore wind connection, weak or strong AC networks), which had to be fulfilled by each model. For this reason, various iterations were needed between TSOs and vendors (individually) to ensure that the final models would merely match with all requirements.

Finally, all three vendors delivered black-boxes EMTP-RV models, available for TSOs and academia partners only, for obvious confidentiality reasons.

5.4. Individual validation of vendor-specific converter models

Thanks to the validation tests and associated acceptance criteria initially defined in the common converter specifications, the vendors' models were individually validated by "simulating partners" (TSOs and academia). 39 validation tests were performed, which is certainly not enough to cover the large number of requirements in the specifications, but still made it possible to validate the behaviour of each converter model in all different control modes, with various DC conductors and types of AC connection, and distinct ramp rates.

As depicted in the left figure (Figure 2, left), no vendor could completely comply with all requirements (results spread between 74% and 87% success in validation tests). The main reason for this is that strong requirements were requested for very different AC and DC configurations for each individual model. Such a wide range of expectations are quite unlikely in a single real-world project, but were needed in Best Paths DEMO #2 so as to enable interoperability tests on very diverse situations. The existence of different sweet spots for each vendor model (depicted by the red lines on Figure 2, right) had a consequence regarding interoperability tests, as they had to be restricted on the set of requirements common to the three vendors only (which is slightly reduced with respect to initial specifications).



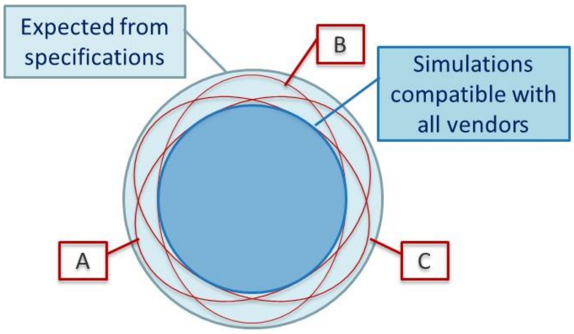


Figure 2: Validation tests results (left) and resulting reduction in common operation (right).

In addition to the confirmation of their overall compliance to the specifications (and consequently, that all converter models would behave alike), this validation was necessary to provide good confidence of all the involved partners in the quality and level of detail of the models, as well as good practice and understanding to simulating partners of each independent system before mixing them in interoperability simulations.

6. IMPLEMENTATION OF TEST SCENARIOS AND INTEROPERABILITY RESULTS BASED ON OFFLINE SIMULATION

6.1. Interoperability tests

Prior to the beginning of Best Paths DEMO #2, no interoperability issue was reported with VSC converters. Hence, in the absence of any practical experience, the objective in the project was to explore as many different situations as possible, as depicted in Figure 3.

First, for each of the five topologies, various parameters were changed (converter control modes, strength and coupling of the AC networks, type and length of the DC conductors, position of each vendor). As an example, this resulted in more than 200 different *situations* for the simplest topology (point-to-point topology, also referred to as T1); likewise, hundreds of other *situations* (reported in the five tables in Figure 3) were elaborated for each other topology.

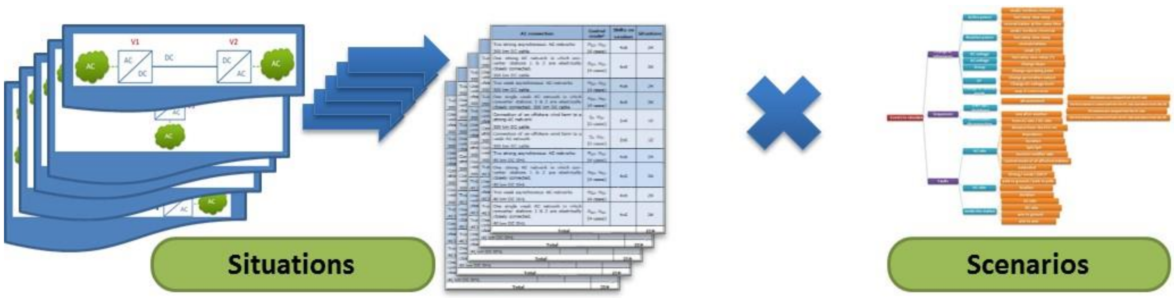


Figure 3: From DC topologies to situations and scenarios

Then, each individual *situation* could be used for different types of *scenarios*: start-up and shutdown sequences, changes of setpoints with various ramp rates, voltage dips, AC faults (symmetric and asymmetric ones), DC faults, etc. Finally, the application of one *scenario* to a specific *situation* defines a unique *simulation*.

Finally, among all possible simulations, only the more realistic simulations were considered due to time limitations (but still ensuring a wide variety of them). In practice, the most stable and simple configurations were tested first, then gradually shifting to more unstable and challenging ones.

6.2. Definition and example of interoperability issue

For offline tests using EMT simulation, all involved partners agreed on the following definition for an interoperability issue:

A simulation test reveals an interoperability issue if and only if the following two conditions are met:

- *The same scenario can be simulated successfully when using converter models from one vendor at a time; a simulation is considered as successful when it ends up normally (no simulation crash) and the behaviour of the overall AC/DC system is as expected (which implies that the converter model complies to the common specifications).*
- *The overall AC/DC system performance is deteriorated when using the converters from different vendors, compared to the same test performed with one single vendor model at a time.*

As an illustration of an interoperability issue, some oscillatory behaviour is reproduced in Figure 4 in a point-to-point topology with two vendors. In this simulation, both converters are rated for 1 GW and connected to different strong AC systems (30 GVA); the DC conductor is a 300 km underground cable. MMC1 is in active power control (reference power is in red, and the blue curve represents the ramped setpoint considering 1 GW/s ramp rate) while MMC2 is in constant DC voltage control (active power for MMC2 in green).

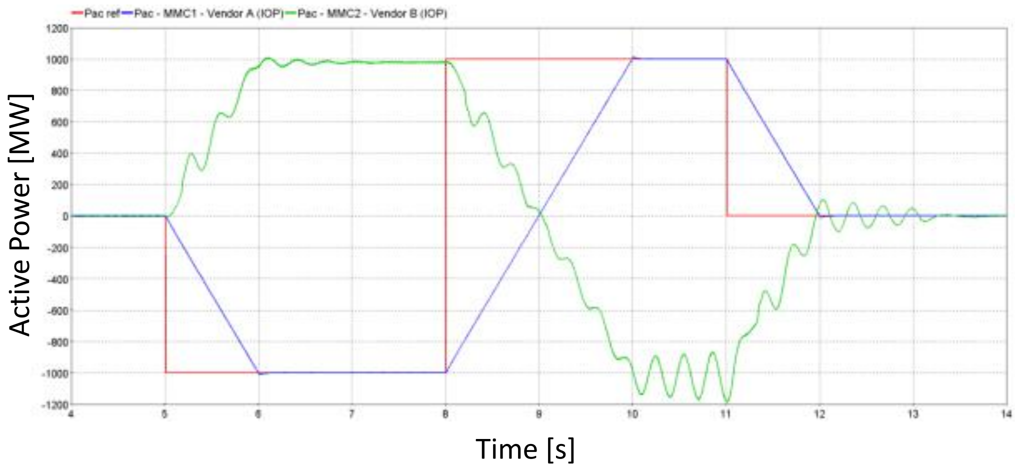


Figure 4: Interoperability issue example (multi-vendor point-to-point connection)

6.3. Offline simulation results

About 400 different situations and 1100 simulations were performed and deeply analysed by simulating partners to test interoperability. The majority of them did not result in major problem, but all DEMO #2 partners agreed to consider that 15 % of all simulations were actual illustrations of interoperability issues. For the first time, the existence of interoperability issues in multi-vendor VSC-HVDC schemes could be assessed.

Finally, the observed interoperability issues were categorized in different types: oscillatory behaviour, difference in converter ratings, difference in converter dynamics, abnormal converter blocking, abnormal converter tripping, abnormal protection actions, simulation uncompleted, accuracy and filtering of measures and biased control.

7. INTERIM LEARNINGS

From the offline simulation stage, it appeared that a majority of simulation did not result in interoperability issues. Surprisingly, some complex scenarios running on large DCGs (AC fault on 4-terminal topology connecting offshore wind farms, or 5-terminal topology with meshing) were successful, while very some very stable and simple ones highlighted issues when connecting some specific combination of vendors' converters. Also in connection with DC topologies, it was witnessed that for a 3-terminal topology, a tree-like arrangement is slightly more stable than the meshed equivalent one.

Furthermore, some points were identified which limit interoperability, such as the implementation of smart controls which behave seamlessly in a single-vendor configuration (as those controls are implemented in all converter stations), but result in unexpected situations as soon as they are used in combination with another vendor's converter.

Although they are not highlighted in this paper, investigations on interoperability using state-of-the-art technology provided by competitors impose some strict legal framework to protect their interest. But in addition to that, it appeared that some technical features offered by VSC technology could not be tested because of patents owned by vendors. In a real-world project, such situation could cause issues as some patented techniques could impose specific alternative solutions to another, which would not be compatible with the initial one.

Another aspect of confidentiality constraints is that, for obvious reasons, no communication could be made on one vendor's detailed data to another vendor without prior consent. In case of interoperability issues where collaboration from all involved vendors was needed to fix them, this situation resulted in interlocked situations, and finally, few interoperability issue could be solved so far.

Despite this situation, it should be highlighted that the conditions and observations made during interoperability tests made it possible for the involved TSOs and academic partners to guess probable root causes for some interoperability issues. Hence, noticeable improvements could be performed in the specifications for the second stage of the project [9], such as the definition of an IEC 61850 interface model based on the IEC61850-90-14 to establish communication with a MC or the provision of new validation tests, or requirements for new controls and parameters.

Finally, interim recommendations to improve interoperability were delivered in the first public deliverable [10].

8. ONGOING ACTIVITIES USING REAL-TIME SIMULATION

At the end of EMT simulations, a new stage started based on real-time simulation using the three vendors' control cubicles in a similar fashion to previous studies. However, only one of them delivered a control replica for Hardware-In-the-Loop simulation, and the two others withdrew from the project.

Fortunately, multi-vendor conditions could be reproduced by using existing industrial MMC replicas used for a real-world application, which specifications are very close to the ones used in Best Paths DEMO #2. Hence, instead of having a multivendor multi-terminal HVDC system created from scratch, the new configuration corresponds to an existing HVDC link (with one single supplier for the converters, which cubicles are sketched in grey in Figure 5), which is extended to a 3-terminal system by adding a new station provided by a different vendor (red cubicles in Figure 5). Consequently, multi-vendor interoperability tests will be performed despite the participation of one single vendor in the remaining of the project. Furthermore, the main benefit of this new configuration is that it is more realistic (with regards to real-world projects in Europe such as FAB, Cobra Cable, Ultranet or Caithness Moray HVDC Link) compared to the initial scope (three-terminal three-vendor topology), and will consequently provide more value for this EU-funded project.

Additionally, as supplementary task, the remaining vendor has provided control hardware for DC Circuit Breakers (DCCB) including protection relays, to control DCCBs models implemented in the real-time simulator, to evaluate the possible adverse interaction of the DCCBs in a multi-vendor DCG in case of DC faults.

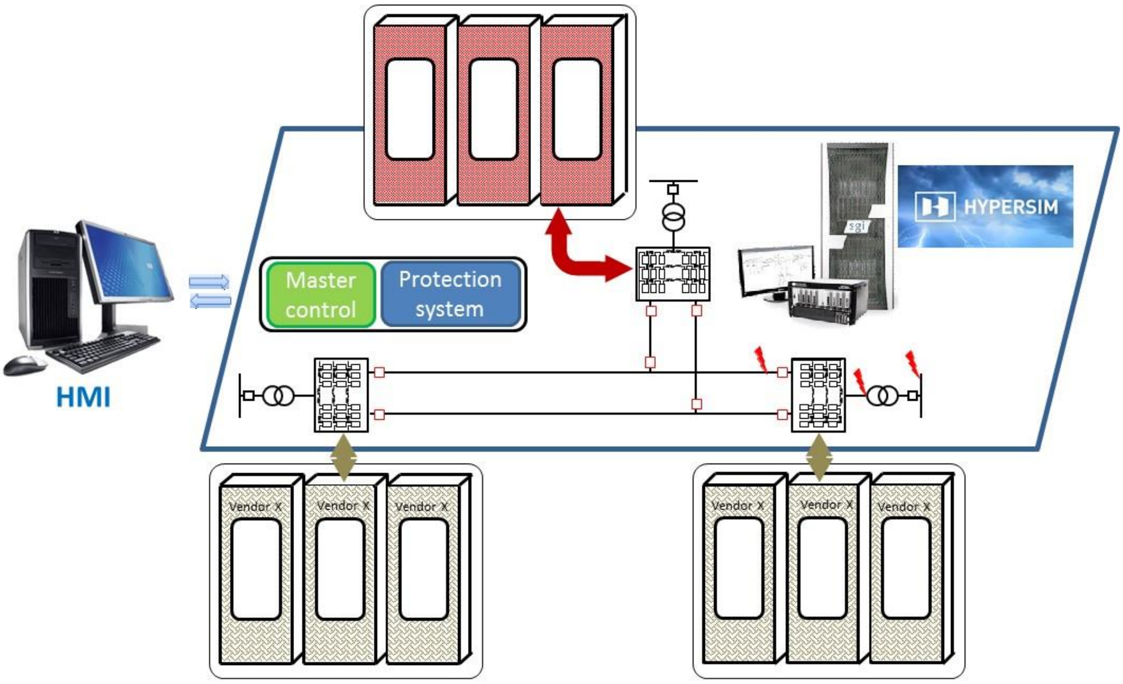


Figure 5: Real-time arrangement for interoperability tests (tapping into an existing HVDC link)

9. CONCLUSIONS

To our knowledge, Best Paths DEMO #2 is the first project to undertake a systematic investigation of interoperability issues in multi-vendor VSC-HVDC systems. From the EMT studies, interim but outstanding results were highlighted, among which the most remarkable is the assessment of interoperability issues, based on detailed models provided by three leading HVDC vendors: 85% of the simulations were deemed satisfactory, while 15% revealed actual interoperability issues.

Due to unforeseen circumstances resulting in reduced number of partners, ongoing studies using real-time simulation had to be re-arranged. However, the resulting configuration makes it possible to explore more realistic configurations (similar to 4 major HVDC projects in Europe) and even extend the scope of work to investigate adverse interaction with DCCBs. Consequently, ongoing studies using real-time simulation and vendors control cubicles are truly expected to bring value for the future expansion of HVDC systems.

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