Replica Hosting at The National HVDC Centre

Replica Options

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1 Introduction

The National HVDC Centre ("HVDC Centre" or "Centre") – www.hvdccentre.com – is owned and operated by Scottish and Southern Electricity Networks Transmission (SSEN-T), which is a trading name of Scottish Hydro Electric Transmission plc. It works in partnership with National Grid Electricity Transmission (NGET), Scottish Power Transmission (SPT), and the National Energy System Operator (NESO), and collaborates with a wide range of industry stakeholders. The Centre hosts state-of-the-art real-time simulators that can be used in conjunction with HVDC and other replica control and protection systems to provide a realistic and flexible test environment to support and de-risk project delivery.

The Centre provides a unique bridge between manufacturers, developers, Transmission Owners and NESO, enabling de-risking of the deployment and operation of HVDC and other new technologies by providing a simulation environment where multiple parties can participate in a practical manner. The HVDC Centre is uniquely placed to host proprietary equipment and models from various organisations and facilitate the required studies while ensuring the protection of confidential data and intellectual property. As the only place in GB hosting replicas of transmission-connected equipment, the HVDC Centre was created to provide a secure environment for testing that can, subject to agreement, include equipment from multiple owners in one simulation, providing a means of assessing interaction risks and exploring overall system behaviour more thoroughly.

The HVDC Centre supports real-time simulations using RTDS®/RSCAD® and OPAL-RT®/HYPERSIM®, and off-line analysis using PSCAD®, Power Factory® and PSS/E®. It is at the global cutting edge of new developments in modelling and simulation of future power systems, having worked with various partners to develop and test new approaches like "software in loop" and hybrid modelling. The Centre is also a leader in training and knowledge dissemination on HVDC, related technologies, and advanced modelling, simulation and analysis.

1.1 This Document

This document is intended to inform stakeholders about the different types of HVDC control and protection replicas and what function and features they bring. It can be shared freely with all parties interested in the HVDC Centre replica hosting services. For further information, please contact the Centre.

2 The Benefits of Replicas and Real-Time Simulation

High Voltage Direct Current (HVDC) converters and similar technologies used in modern power grids rely upon highly complex control and protection systems that are typically implemented on specialist hardware running proprietary software code. Replicas are copies of the actual hardware and software systems that have been deployed on site and can be used in conjunction with a real-time simulator for hardware-in-loop (HiL) or software-in-loop (SiL) simulation and analysis, supporting a wide range of performance studies, testing and training.

Replicas, used within a real-time simulation (RTS) environment, provide a very accurate representation of the system, including latencies and hardware effects, without the modelling simplifications often necessary in other simulation tools. This enables the performance of the system to be tested across a range of conditions where the replicas give a true representation of real-world behaviour.

Replicas provide an ability to validate and benchmark commissioned designs, above and beyond the Factory Acceptance Test (FAT) stage. HVDC, wind farm and other systems can evolve as control systems are tuned based on in-service experience, and the amended tuning may not be included in any manufacturer offline models. Replicas can be updated with the same software/firmware as implemented on site, providing a true representation without modelling compromises or delays. HVDC replica systems deliver value across different project stages as summarised below.

Pre-commissioning:

- De-risking HVDC projects by identifying potential control and integration issues before they impact commissioning or operational performance.
- Ensure that the design meets grid codes, interoperability requirements, and performance standards without risking real assets.
- Verify wide-area controls for accurate fault response and supervisory control behaviour.
- Demonstrate interoperability with the rest of the system or identify and resolve adverse control interactions early (e.g., with generators or other HVDC links).
- Enhance asset owner’s technical understanding and confidence in HVDC technology.

Commissioning Stage:

- Rehearse commissioning procedures to reduce delays and improve coordination with system operators.
- Validate firmware, control logic, and protection settings prior to site deployment.
- Assess performance of the HVDC scheme under various network conditions and contingencies.
- Verify protection and wide-area controls for accurate fault response and supervisory control behaviour.
- Detect and correct network integration and compliance issues before they cause costly delays.

Operational Stage:

- Maintain system reliability and minimise downtime through fault diagnosis and solution validation.

- Replicate site events for incident investigation and operational risk assessment.
- Validate control system upgrades and assess evolving network interactions for compliance.
- Facilitate rapid return-to-service timelines and pre-emptive fault mitigation.

Training & Maintenance:

- Provide a safe environment for operator training using identical HMI screens as on-site systems.
- Support alarm analysis and procedural rehearsal for maintenance activities.
- Validate control software updates and optimise maintenance schedules for cost-efficiency.
- Practice maintenance of the HVDC control and protection, reducing dependence on vendors and improving operational responsiveness.

Cybersecurity & Risk Management:

- Explore cyber vulnerabilities and test mitigation strategies in a controlled environment.
- Allow updates to software and operating systems to be tested in a safe environment, before deployment to the real system.

Long-Term:

- Maintain an accurate representation of the HVDC system for ongoing performance validation.
- Support planning studies and network risk management through accurate model exchanges.
- Assist in strategic planning and integration with transmission owners and system operators.
- Enable continuous improvement of system performance under evolving network conditions.

2.1 Complementary Roles of Offline and Real-Time Simulation

Most power system modelling, simulation and analysis is performed with offline tools rather than in real-time simulation, using purely software models rather than any hardware replicas or code running on dedicated real-time hardware. Offline tools with appropriate models are essential to the efficient design, development, delivery and long-term support of HVDC and similar technologies [1]. However, offline analysis should not be regarded as an alternative to real-time simulation with replicas. Rather, the different methods deliver distinct but complementary functions.

Offline simulation provides a flexible environment for design, development, evaluation, and scenario analysis without the constraints of real-time execution. With sufficient computing power it can be parallelised and automated to explore a wide range of operating conditions and perform detailed sensitivity studies. However, the models of HVDC control and protection will be just that, i.e. models that aim to represent behaviour, often with compromises made due to computational limitations. In contrast, real-time simulation enables the use of real code with realistic timing constraints. This approach captures latencies, hardware characteristics, and system-level dynamic interactions that cannot be fully reproduced in offline studies. Used together, the combination of offline and real-time simulation provides the most comprehensive way of analysing and de-risking a HVDC project.

3 Replica Types

CIGRE Technical Brochure 864 [2] provides general guidelines on the use of HVDC replicas in real-time simulation and the development of associated models to support analysis of HVDC performance and complex system behaviours. TB864 is a valuable resource for detailed information on replicas and real-time simulation. However, terminology varies between vendors and there is ongoing development in the types of replica solution available. Here, we identify three main types of HVDC converter replica. The descriptions are generic and it should be noted that detailed designs will vary by HVDC project and vendor.

While most HVDC projects continue to be point-to-point designs with two converter stations, the different replica types are all applicable to multi-terminal designs.

3.1 FULL REPLICA (Redundant)

This is a physical replica of all the control and protection hardware to be implemented at site, including redundant systems for failover where applicable. This means that the replica can match the full range of functions and behaviour during failover and account for ancillary system availability in a real-time simulation environment. Maintenance of the protection and control equipment can be demonstrated or practiced on this type of replica in low-risk conditions. This is most like what TB864 describes as a MAINTENANCE replica.

A full replica will have a larger footprint, higher installation and operating costs, and require more complex support than other options.

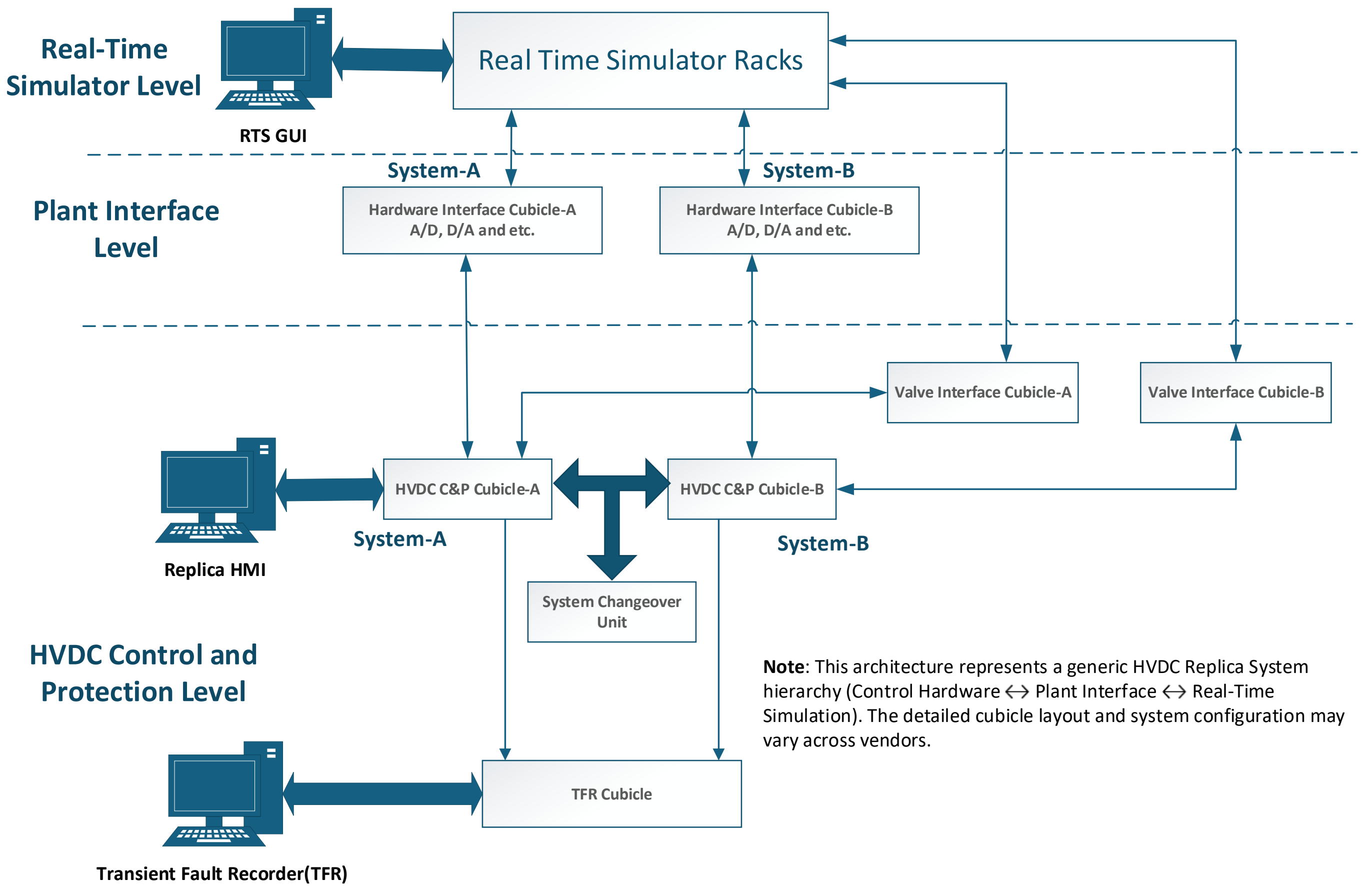

Figure 1: Full Replica Generic Architecture (ancillary systems not shown)

3.2 PARTIAL REPLICA (Non-Redundant)

This is a physical replica of control and protection functions within an amalgamated or minimised hardware design. This gives a near exact copy of the main control and protection of the converter and shows accurate results of real-time simulation from a power system perspective. Auxiliary protection or control functions that do not affect the power system performance are simplified. This is most like what TB864 describes as a STUDY replica.

A partial replica offers a compromise between functionality and cost/complexity. It provides full capability in terms of power system performance and operator interaction with the control systems while taking up much less space than a full replica.

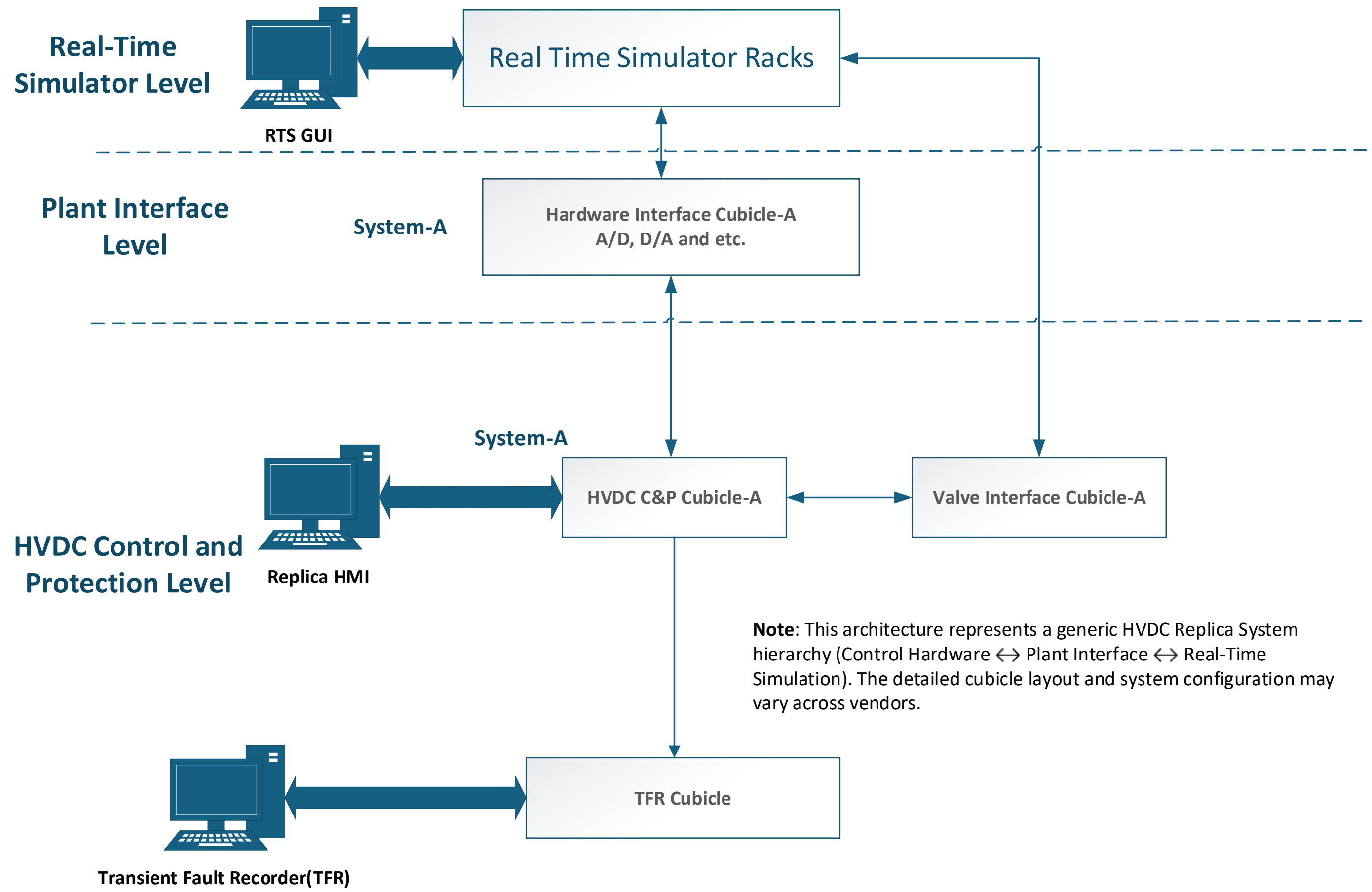

Figure 2: Partial Replica Generic Architecture

3.3 SOFTWARE REPLICA

This replica type involves running the actual code for control and protection functions on generic hardware. This hardware must be able to operate within the real-time simulation environment but is designed to be configurable with different code. Examples include the GTSOC platform from RTDS or the Interval Zero platform. This approach provides a functional environment for modelling and analysing system performance while minimising hardware dependency. Hardware-specific behaviours are not fully represented. This is most like what TB864 describes as a C&P SOFTWARE MODELLING replica.

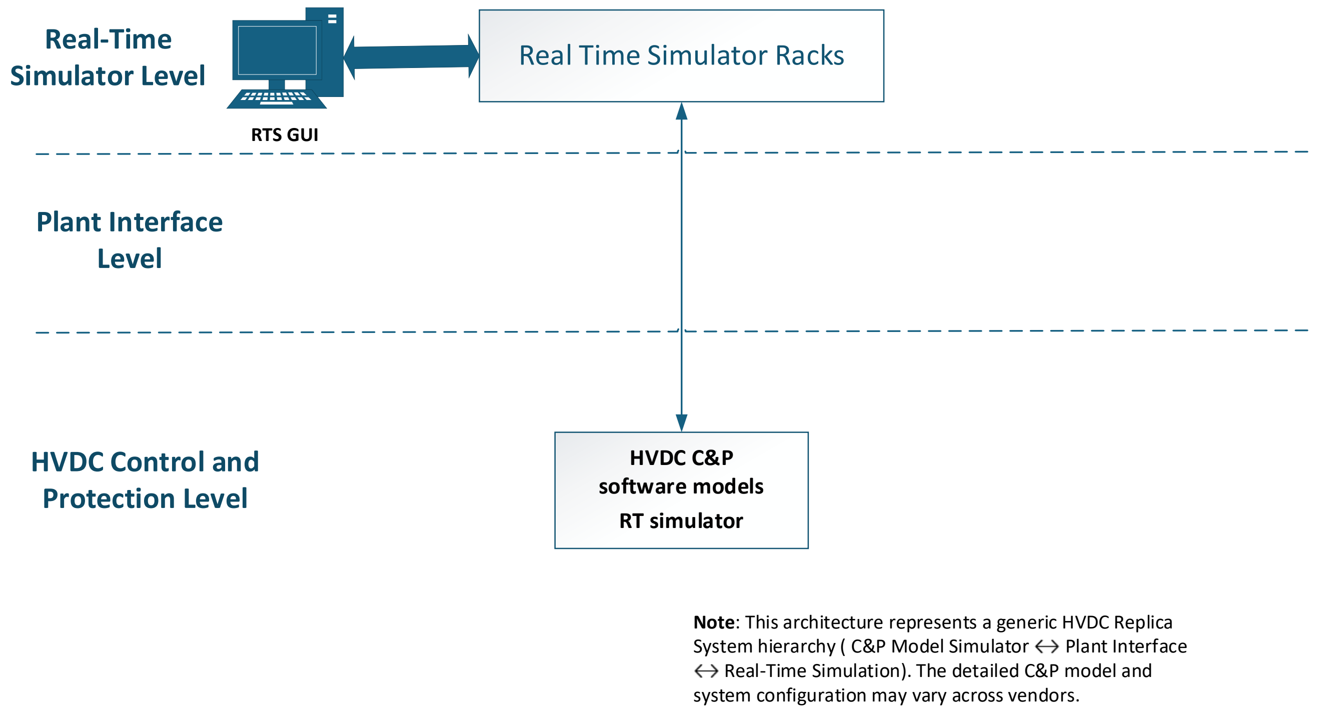

Figure 3: Software Replica Generic Architecture

A clear advantage of a software replica is that it runs on generic hardware and so should be cheaper and quicker to produce than hardware replicas, the production of which is likely to be aligned to the production of the hardware going to site. The vendor can be contracted to provide early versions of the HVDC control and protection code that can be implemented as software replicas and used for preliminary testing. This enables early analysis of performance and interaction risks, supporting project delivery. As the vendor design matures, code updates can be provided and re-tested. The software replica may eventually be replaced by a hardware replica when it is available.

Software replicas might be used in combination with a hardware replica for secondary systems and controllers that are not the focus but influence overall performance. For example, an HVDC link connecting an offshore wind farm might have a hardware replica for the HVDC system and use a software replica for the offshore wind farm.

3.4 Comparison of Replica Types

The features and functionality of each type of replica is summarised in Table 1. Note that this list is not comprehensive in terms of the features and functionality available with replicas and describes only what is considered typical for the three types; each vendor and each project may offer variations on these types.

Table 1: The Main Features of Different Replica Types

Feature / Functionality	Full (Maintenance) Replica	Partial (Study) Replica	Software Replica
Control and protection systems are full duplicates of those on site	Y	N	N
All control and protection functions are included	Y	Y	Y
Key control and protection functions are represented	Y	Y	Y
Replica control and protection hardware is the same as on site	Y	Y	N
Replica control and protection software is the same as used on site	Y	Y	Y
Operator Workstation (OWS) interfaces match the control screens and functionality used on site	Y	Y	N
Transient Fault Recorders	Y	Y	N
Communication link terminal equipment for operations requiring inter-station communication	Y	Y	N
A gateway computer for testing remote control interfaces, e.g. SCADA	Y	Optional	N
Redundancy such that automatic changeover functionality can be tested and the performance demonstrated	Y	N	N
Simplified valve switching “average models” within the real-time simulator	Y	Y	Y
Test proposed changes to control and protection concepts	Y	Y	Y
Test proposed changes to control and protection hardware	Y	Y	N
Test proposed changes to control and protection software	Y	Y	Y
Analyse/diagnose faults and events that occur during commissioning tests and/or during operation	Y	Y	Y
Test solutions or improvements for faults and/or events which occur during commissioning and/or operation	Y	Y	Y
Analyse and test refinements to the control settings	Y	Y	Y
Demonstrate and diagnose alarms on the high-level control system	Y	Y	N
Simulate AC and DC faults and their consequences for protection and control systems in real time	Y	Y	Y
Simulate dynamic events in real-time and understand the dynamic behaviours exhibited by the real control and protection system	Y	Y	Y
Identify, study, and test solutions for potential adverse control interactions with other active elements such as generators and adjacent HVDC converters on the same AC network	Y	Y	Y
Establish and rehearse commissioning tests	Y	Y	Y
Optimise the scope and frequency of maintenance activities	Y	N	N
Train those involved at all stages of the project, including Operators and Maintenance personnel	Y	Y	N
Test cyber security risks and solutions	Y	Y	Y*

(* The effects of all physical hardware, such as network switches, may not be modelled unless requested, but suitable representation in the software replica architecture can facilitate cyber security testing.)

It may be possible for a replica to have different types of representation for each HVDC converter station. For example, one terminal might be represented by a Partial replica and others by a Software replica. The replica design may allow for reconfiguration to change which terminal is represented with hardware and which uses software only. If multi-terminal HVDC systems are being developed in stages, or involve different parties and potentially different vendors, it may be necessary to combine different replica types, possibly including Software replicas with generic controllers for parts of the system to be developed in future. The options can be explored with the vendor(s) and any other parties involved.

If multiple HVDC systems are being supplied by the same vendor, it may also be possible for the vendor to supply a single set of replica hardware that can be configured to represent different HVDC systems. This is not the same as a Software replica because it would have the same hardware as used on site. This would significantly reduce the amount of replica hardware that needs to be built and maintained but would mean having hardware that can only represent one HVDC system at a time. If other HVDC systems need to be represented in the simulation this could be done with Software replicas. However, this approach faces various challenges, including hardware upgrade cycles that mean projects delivered even a relatively short time apart may require different replica hardware.

The replicas currently hosted at the HVDC Centre are of the partial (study) type, with some software replicas being used in research and development activities.

4 Other Aspects

As well as selecting the type of replica, there are various aspects of the design and specification to be considered .The replica owner should give careful thought about what features of the main project they want to be made available with the replica, and what equipment or features the vendor might not provide with their replica equipment by default. This section details some other aspects that the replica owner should consider. These aspects should be discussed with the replica vendor; the HVDC Centre can support such discussions.

4.1 Number of Cubicles and Space Requirement

The choice of replica type and the detailed design done by the vendor will determine the number of cubicles and the associated requirements on installation space, power supplies, and environmental controls. Table 2 shows indicative values for the number of cubicles and workstations and typical space requirements based on past projects. Actual requirements will vary depending on the vendor, system architecture, and project specific scope. Ideally replicas should consist of the least number of cubicles for the required functionality. More cubicles mean a larger footprint and higher lifetime costs for hosting the replica.

Table 2: Estimated Hardware and Space Requirements for a HVDC Two-Terminal Monopole Replica Facility

Replica Type	Cubicles per Converter Station	Workstations	Space Required
Full (Maintenance) Replica	Approx 10 to 30, or potentially many more	1 for running real-time simulation 1-2 per converter station for the operator and engineering Interfaces	Approx 50 to 200 m^2
Partial (Study) Replica	Approx 5 to 15	1 for running real-time simulation 1-2 per converter station for the operator and engineering Interfaces	Approx 25 to 100 m^2
Software Replica	Typically, less than 1	1 for running real-time simulation Possibly 1 for control of the generic hardware	Approx 5 to 10 m^2

4.2 Real-Time Simulator

Replicas are designed to be operated within a real-time simulation (RTS) environment. The most common for HVDC replica applications are the RTDS or OPAL-RT platforms but others are available. The choice of RTS platform should be determined by the replica owner possibly with input from the intended replica hosting facility (like the HVDC Centre) but should also be discussed with the vendor to ensure the best solution is delivered. It is possible for replicas to be designed to allow interchangeability between RTS platforms. It is useful for replica owners to understand the dependencies of the replica on the RTS platform and the implications of any potential change in future.

If simulations are to be run with two or more replicas connected within a common simulation on a single RTS platform then compatibility issues may arise, e.g. simulation time step. If a replica is expected to be used in such studies – which is increasingly likely as HVDC becomes more common and interaction risks need to be explored – then compatibility of the replica for these studies should be included in the requirements specification or discussed with the vendor. However, it may also be possible to configure a co-simulation environment between different RTS platforms or to overcome compatibility issues.

4.3 HVDC System Models

When specifying HVDC system models for replicas, it is important to understand the available options and their implications. CIGRE TB864 [2] identifies four main types of HVDC valve model, each offering different levels of fidelity and computational requirements. These models are widely referenced in industry practice and supported by example implementation strategies [3]:

- **Processor-Based Valve Model**: Represents individual submodules (SMs) and their switching behaviour using surrogate networks. Suitable for detailed studies and HIL testing but limited by processor capacity (typically 40–50 SMs per valve). Requires fibre-optic communication for real-time control integration.
  Pros: Accurate representation of SM-level dynamics and faults.
  Cons: High I/O complexity and limited scalability for large valves.

- **Simplified Processor-Based / Average Model**: Uses aggregated capacitor voltage and block/deblock signals rather than individual SM control. Ideal for system-level performance studies where internal balancing is less critical.
  Pros: Lightweight computation, supports large-scale studies.
  Cons: Cannot represent internal faults or detailed SM behaviour.

- **FPGA-Based Model**: Implements detailed SM-level modelling (typically up to 512 SMs per valve) using parallel computation on FPGA hardware. Supports internal fault simulation and high-fidelity real-time performance.
  Pros: Enables full valve representation with realistic timing and fault scenarios.
  Cons: Requires specialized hardware and firmware development.

- **Surrogate Network Model**: Represents valves using equivalent branches for blocked, deblocked, and bypassed SMs. Reduces computational burden while preserving essential dynamic behaviour. Often combined with FPGA or processor-based approaches.
  Pros: Efficient and accurate for real-time simulation.
  Cons: Requires careful parameterization and validation.

The choice of valve model should be discussed and agreed with the vendor, considering project objectives, available hardware, and the level of detail required for studies.

Simulation of main circuit breakers is done in RTS. However, simulation of disconnectors and earthing switches are usually not performed in RTS models to limit the number of I/O signals. The state of these switches is usually simulated in an external software or directly modified in the code of the controller used in the replicas.

4.4 AC System Models

The representation of the connected AC system is critical for accurate performance evaluation. Two primary approaches are commonly used:

Simplified Static Voltage Source Model

Represents the AC system as an infinite bus behind a short-circuit impedance. It focuses on steady-state conditions without modelling dynamic behaviours such as generator electromechanical transients.

Pros:

- Simple and computationally efficient.
- Easy to adjust system parameters (e.g., short-circuit ratio, frequency).
- Suitable for functional performance tests and basic control verification.

Cons:

- Does not capture AC system dynamics (e.g., oscillations, stability).
- Limited for studies involving AC/DC interactions or harmonic resonance.

Dynamic Equivalent Model

A reduced representation of the AC network that preserves key dynamic characteristics such as generator inertia, excitation systems, and frequency-dependent impedance.

Pros:

- Captures electromechanical dynamics and system stability.
- Suitable for interaction studies (HVDC-AC, HVDC-FACTS, multi-infeed HVDC).
- Enables accurate assessment of harmonic impedance and fault recovery behaviour.

Cons:

- Requires more computational resources.
- Complex to develop and validate.
- Needs detailed system data (generator models, network parameters).

4.5 Interfaces to Other Systems

Hardware replicas typically include hardware-user interface equipment like that installed on the main project site. This would typically include several Human Machine Interface (HMI) computers to operate the replica and examine event information, or to carry out engineering and maintenance tasks. Replica owners may also want hardware at the hosting facility to include interfaces to other systems (e.g. SCADA systems). For example, it may be useful to replicate the remote operator interface (e.g. a Network Management System like GE PowerOn) as an operator training facility, especially if the remote operator interface differs significantly from the user interfaces available on replica HMIs.

4.6 Remote Access to Hardware Replicas

The replica owner should carefully consider if remote access to replica hardware is required. Remote access to hardware replicas enables engineers at a remote location to download test results from the replica or diagnose and fix faults on the replica hardware or carry out maintenance tasks. If the vendor is required to provide rapid (e.g. 24hr) response in supporting the replica, they are likely to need remote access to the replica hardware to achieve this.

Providing remote access to hardware requires a suitable internet connection to be provided at the hosting location. Remote connections inevitably introduce additional cyber security risks that need to be understood and managed.

4.7 Lifetime Support

The replica owner should establish support agreements with the HVDC vendor. It is beneficial to agree support for the replica at the same time as agreeing support for the main project hardware, to ensure both systems are covered and kept consistent with one another. It is recommended that lifetime support agreements cover the following:

- Hardware warranties and procedures for repairing or replacing faulty hardware on the replica
- Management of hardware spares (possibly combined across the main project and replica)
- Procedures for software and firmware updates on the replica to maintain alignment with the main project, including appropriate version control arrangements
- Response times and service levels for any issues arising on the replica (this is likely to be much less urgent than for the main project)
- Regular maintenance checks of the replica by the vendor service team
- Provision of additional vendor support and services if needed

5 Conclusion

While the cost of replicas is a small fraction of the total cost of delivering an HVDC project, it is still a significant investment and decisions made early on in design and procurement will have impacts through the lifetime of the asset. This document presents the main types of replicas available and other aspects to be considered when a project team decides on a replica specification. The technologies and approaches taken by vendors to replicas and real-time simulation continue to evolve and any decision should be made in close consultation with the equipment suppliers as well as the future users of a replica. Please contact The National HVDC Centre if you would like further information or additional support with your project design and replica specification.

6 References

[1] IEEE, “IEEE Recommended Practice for Hardware-in-the-Loop (HIL) Simulation-Based Testing of Electric Power Apparatus and Controls”, IEEE Standard 2004-2025, February 2025.
[2] CIGRE, “TB 864 - Guide to Develop Real-Time Simulation Models for HVDC Operational Studies”, February 2022.
[3] T. Maguire, B. Warkentin, Y. Chen, J. Hasler, “Efficient Techniques for Real-Time Simulation of MMC Systems,” International Conference on Power Systems Transients (IPST), Canada, July 2013.