PROMOTioN
PROGRESS ON MESHED HVDC OFFSHORE TRANSMISSION NETWORKS

D12.a
Meshed HVDC Transmission Network Technology Readiness Level Review

PROMOTioN – Progress on Meshed HVDC Offshore Transmission Networks
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EXECUTIVE SUMMARY

The PROMOTioN project (Progress on Meshed HVDC Offshore Transmission Networks), is a European Union funded research and demonstration program that has advanced the HVDC technology required to build, control and protect meshed HVDC transmission offshore grids. In this last phase of PROMOTioN, it is significant to evaluate how much the HVDC technology has been advanced by PROMOTioN. Technology Readiness Level (TRL) is a methodology to systematically assess the maturity level of a specific technology at this project phase. By assessing the TRLs of the HVDC technologies at each development stage, from respective Work Packages, the progress made on advancing these technolgies as well as the current status of the technologies has been independently assessed. The main objective of this document is to report on the TRLs of the HVDC technologies investigated and demonstrated in PROMOTioN, with highlighting the development progress. To achieve a better overview of the status of HVDC technologies, the TRL advancements made by previous studies and the international experience in China is referred as well.

For assessing TRLs of technologies in PROMOTioN, the H2020 TRL scale had been applied with accordingly adapted definitions for the T&D industry – the objective having been consistency and coherence, while dealing with primary and secondary equipment technologies. With the adapted TRL scale, five HVDC technologies are assessed: HVDC circuit breaker, HVDC transmission and grid control, HVDC grid protection, HVDC gas insulated system (GIS), and interoperability within DC grid.

The TRL assessment results clearly indicate that all the HVDC technologies have undergone a development progress in PROMOTioN. While previous projects have made the maturity level of HVDC circuit breaker technology to medium level, PROMOTioN advanced it to high level of TRL 7 by full-scale demonstrations. Different aspects of control in DC meshed grids have been demonstrated, which all could reach to TRL 6. Different fault clearing strategies for DC grid protection, which were demonstrated, have progressed to medium-high level as TRL 6. HVDC GIS system, which already had medium mature level, was advanced to high level of TRL 8. The interoperability between different converter technologies was assessed to reach TRL 6.

The TRL assessment results is an input to the WP 12 for the deployment plan. Meanwhile, some other aspects associated to interoperability will be futher investigated in a next step.

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1 INTRODUCTION

1.1 PURPOSE

The purpose of this document is to present the assessment results of Technology Readiness Level (TRL) of the HVDC technologies developed and demonstrated in PROMOTioN, which are necessary to realize offshore meshed HVDC grids. The TRL assessment for each technology serves as the indicator of the maturity level of the technology towards eventual commercial readiness. The aim of the TRL assessment is to show the progress made in PROMOTioN for developing the HVDC technologies, as well as the future steps needed for industrialization and commercialization of the technologies. The results delivered in this report are input to WP12.

1.2 DOCUMENT STRUCTURE

In chapter 2, the concept of TRL scale is first introduced. Then, the original TRL scale proposed to be used in EU policy – TRL H2020 – is presented together with its definitions. For assessing the technologies in PROMOTioN, the definition of each TRL level of the original TRL scale was adapted to reflect technology development for primary and secondary HVDC transmission equipment. Finally, the approach that was applied in assessing the TRL of technologies in PROMOTioN is explained.

In chapter 3, the TRL assessment results of the HVDC technologies developed in PROMOTioN are presented and explained.

In chapter 4, the progress in the HVDC technologies made by PROMOTioN are summarized and presented. Moreover, the TRL status and the progress of the HVDC technologies are compared with the results from other EU projects as well as the experience from China.

In chapter 5, the conclusions are made based on the TRL assessment results, again with reference to other EU and international projects.

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2 TRL DEFINITION AND APPROACH

2.1 TRL SCALE

Technology Readiness Level (TRL) is an indicator of the maturity level of a technology towards eventual commercialization. The TRL scale was originally developed at NASA for the space program. In European Union, the universal usage of TRL scale in EU policy was proposed and consequently implemented in the subsequent EU Horizon 2020 framework program (H2020). Assessment by means of TRL is tool for risk reduction in infrastructure planning and investment decision making. For example, generally technology is not considered ready for real (pilot or trial) operation at TRLs below 7.

2.2 TRL DEFINITIONS APPLIED IN PROMOTION

The TRL scale H2020 is adopted to assess the readiness levels of technologies in PROMOTioN. However, the TRL scale H2020 is generic: no sound definition of individual levels has yet been fully explained and exemplified for the electricity T&D sector. In order to adopt the original TRL scale for a specific organisation or program, the TRL scale needs to be adapted and customised accordingly, which is subsequently illustrated.

2.2.1 TRL SCALE H2020

The TRLs defined in H2020 are given as follows [1]:

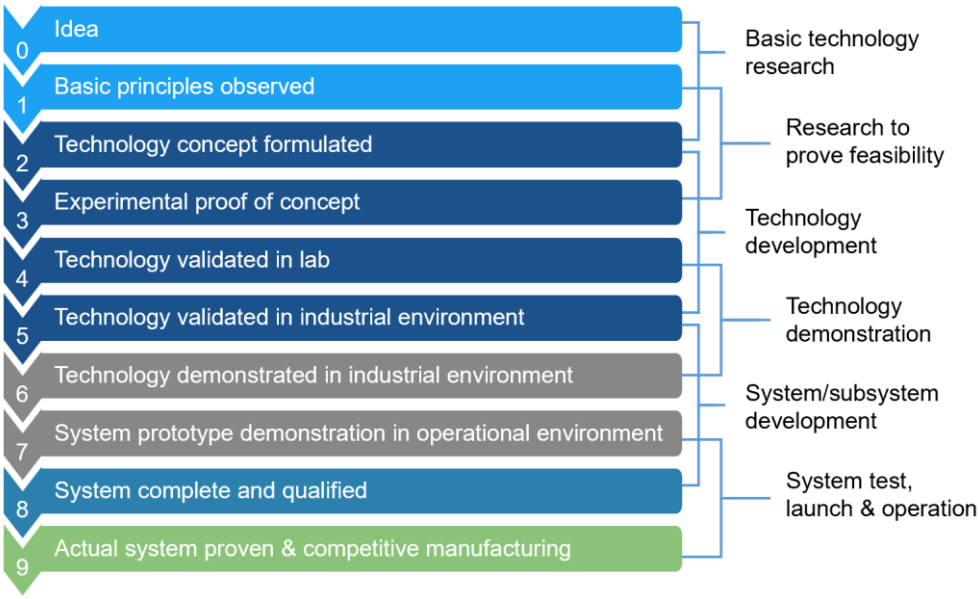

Figure 2-1 TRL scale as defined in H2020.

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2.2.2 TRL ADAPTION IN PROMOTION

The adapted H2020 TRL scale for assessing the readiness levels of technologies investigated in PROMOTioN is about product-oriented technologies [2], including hardware-based and algorithm-based technologies. Hardware-based technologies are primary equipment e.g. DC circuit breakers, starting from dielectric materials to components to a complete system. Algorithm-based technologies are secondary equipment, e.g. starting from Bode-plots analysis of control systems to software algorithms for stable grid operation to programming into dedicated hardware platforms. Thus, non-technological aspects such as the readiness of regulation and the cost benefit to go to market are not incorporated.

The definitions of TRLs customized for the T&D industry and applied in PROMOTioN are described in the following:

TRL 1 – basic principles observed

Initial scientific research has been conducted. Basic principles are observed. Focus is on analytical studies on fundamental understanding of the principle.

TRL 2 – technology concept formulated

Technology concept is formulated based on the analytical studies. Practical applications of the technology are identified or predicted.

TRL 3 – experimental proof of concept

Technology concept / analytical prediction of the technology is validated by initial laboratory-scale measurements. Modelling / simulation validation in software are also considered as experimental proof of the technology concept.

TRL 4 – technology validated in lab

Individual components and their functionalities are tested to work in lab-scale, as in theoretical modelling / simulation.

TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)

Individual technology components and their functionalities are tested to work as in theory, in an industrial environment. Independent labs, real-time simulator, and National HVDC centre, for example, are regarded as industrial environment.

TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)

Individual technology components are tested together as a semi-integrated system. The semi-integrated system with its functionalities is tested and confirmed to work as expected in an industrial environment using real system inputs.

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TRL 7 – system prototype demonstration in operational environment

The prototype of full-scale integrated system with its functionalities are tested and confirmed to work as expected in an operational environment (on-site environment outside of manufacturers laboratory) using the real system input.

TRL 8 – system complete and qualified

Integrated system with its functionalities is proven to work as expected against industrial norms and standards. The manufacturing process is considered as preliminary.

TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies)

Actual developed system operating as a technology with its full functionalities is proven to work under full range of operating conditions. The developed technology is ready for commercial production and delivery. The manufacturing process is optimised.

In the adapted TRL scale for PROMOTioN, at lower levels of TRL 1-3, only technology concepts are investigated with analytical studies or preliminary lab-scale measurements. No physical realization has yet been started. The initiation of algorithm development also starts at these stages. When referring a technology to a level from TRL 4 to TRL 9, physical realizations are implemented: either algorithms are implemented and functionally stressed, or equipment hardware is implemented and physically stressed. At TRL 4 and TRL 5, technology is limited to individual components. When moving to TRL 6, technology refers to a semi-integrated system with individual components working together interactively. At higher levels of TRL 7-9, technology refers to the completely integrated system with full functionality. At TRL 7, technology being considered is still a system prototype, whose manufacturing process is operational. When technology is assessed as TRL 8-9, the actual system is considered, and the manufacturing process is fully established and optimized. Such scales and development stages of technology defined in adapted TRL H2020 are summarized in Table 2-1. More detailed development progresses of algorithm- and hardware-based technologies along the TRL scale are described in Figure 2-2. Two examples of the development process of algorithm- and hardware-based technologies are given in the next section.

2.2.3 TECHNOLOGY DEFINITION

Based on the adapted TRL scale definition for T&D industry, a technology is defined in the scope of PROMOTioN, as a concept, equipment hardware, or a software algorithm, with a unique functionality, which can be either physically or functionally stressed and validated in independent lab, demonstrated in industrial environment and qualified against industrial norms and standards (if present), for eventual commercial deployment.

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Table 2-1 Summary of scale and development of TRL H2020 adapted to technology in T&D industry.

TRL	Technology scales	Development stages
1	Analytical research	Principle
2		Concept
3	Lab measurement	Concept
4	Technology components and/or breadboard	Algorithms implemented and functionally stressed Or Equipment hardware implemented and physically stressed
5		
6	Low-fidelity, semi-integrated system of technology components	
7	System prototype, high-fidelity, integrated system of technology components with full functionality. Manufacturing process is operational.	
8	Integrated system of technology components with full functionality. Manufacturing process is established and optimized.	
9		

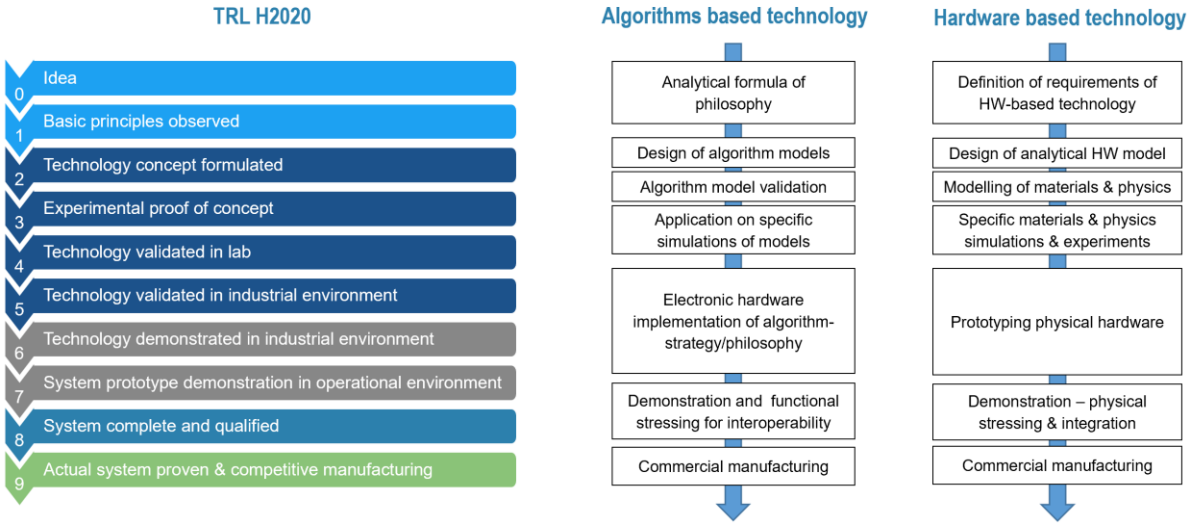

Figure 2-2 Development progress of algorithm- and hardware-based technologies along the TRL scale.

2.3 TRL ASSESSMENT APPROACH

As one of the specific objectives of PROMOTioN, full-scale demonstrations of cost-effective HVDC grid technologies, which will enable the realization of the meshed HVDC grids, are to be carried out. The maturity levels of those HVDC technologies, especially the progress made by PROMOTioN, are to be assessed and indicated by applying the adapted TRL scale H2020. Specifically, these HVDC technologies are:

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- HVDC grid control
- HVDC grid protection
- HVDC circuit breaker
- HVDC GIS system

In the scope of PROMOTioN, each technology has been investigated, stepwise developed and eventually demonstrated. Different PROMOTioN WPs have made contributions to the development steps of a certain technology, which enable the final demonstration. The relevant PROMOTioN WPs are marked in the red frame in Figure 2-3.

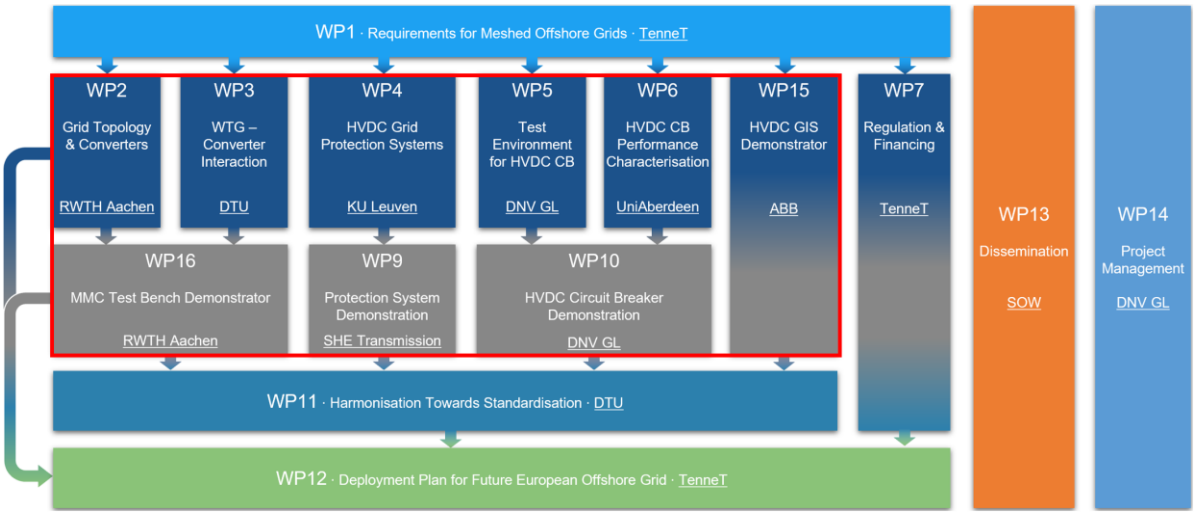

Figure 2-3 Overview of all WPs and the WPs focusing on HVDC technologies in PROMOTioN.

During the TRL assessment, the deliverables of relevant WPs were firstly reviewed. The development steps contributed by different WPs which enable the final demonstration of each technology were summarized. The adapted TRL scale H2020 was then applied, consistently and coherently, to assess each development step as well as the final status of the technology after being demonstrated. The TRL assessment results are presented in the perspective of individual technology along the development steps. The TRL of a system is considered to be as high as the highest TRL of one of its subcomponents. By this way, the readiness level increase of a certain technology finally achieved in the scope of PROMOTioN is clarified. Moreover, it is also clear which level steps still need to be taken before the technology can be considered ready for commercial and industrial deployment.

As discussed in section 2.2.2, the technologies being assessed in PROMOTioN can be classed as either algorithm-based or hardware-based technologies. Based on the development progresses described in Figure 2-2, the HVDC control technology and HVDC circuit breaker, representing algorithm-based and hardware based technologies respectively, are given as examples in Figure 2-4 with their development progresses.

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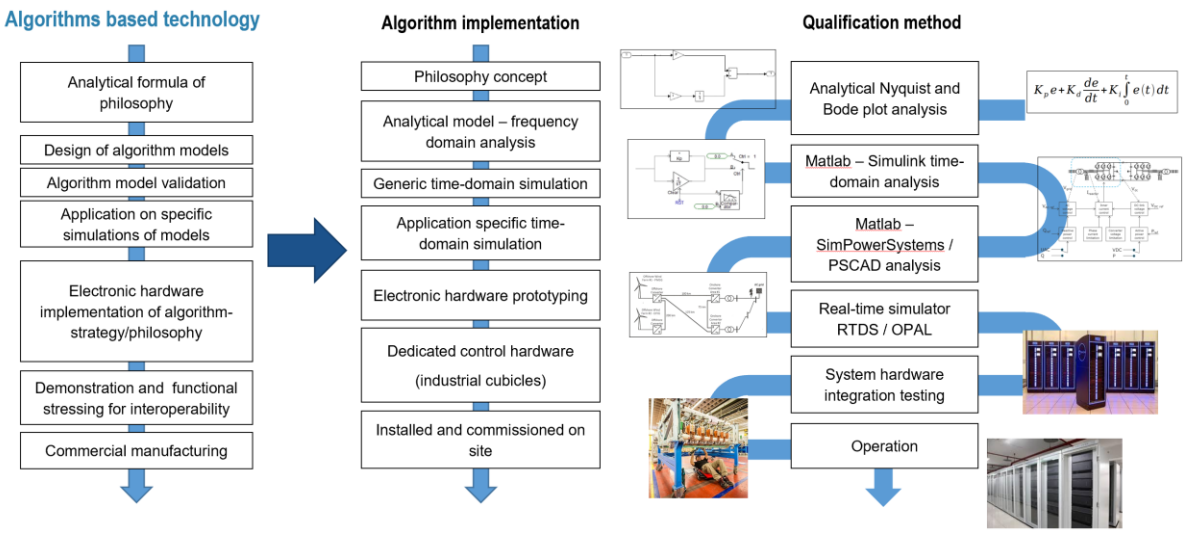
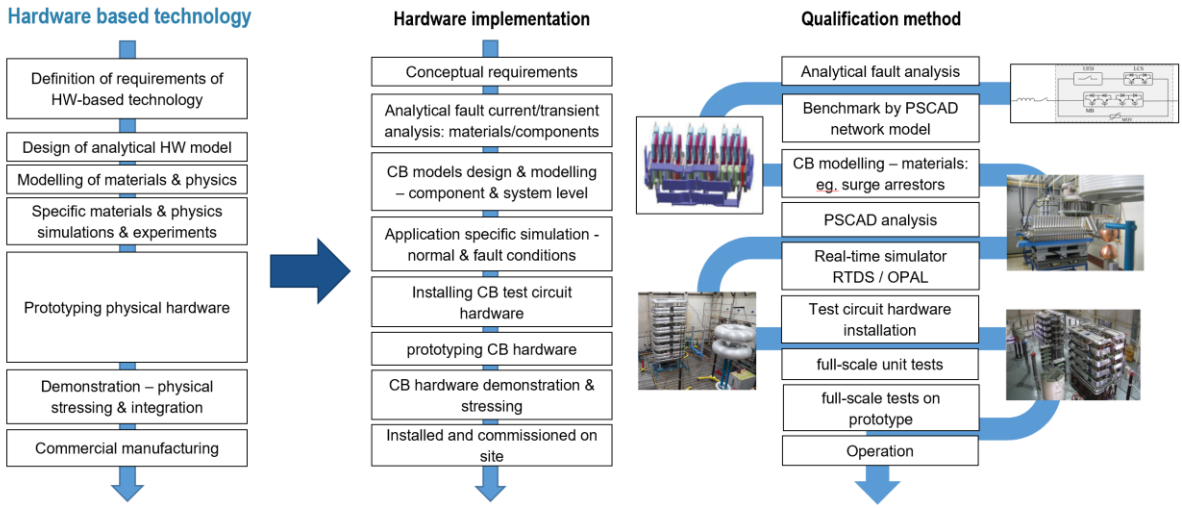


a. Example for algorith-based technology: HVDC controls.



b. Example for hardware-based technology: HVDC circuit breaker.

Figure 2-4 Examples of development progress of algorithm- and hardware-based technologies along the TRL scale.

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3 TRL ASSESSMENT OF TECHNOLOGIES IN PROMOTION

3.1 HVDC CIRCUIT BREAKER

PROMOTioN sets out to model, analyse and demonstrate the HVDC circuit breaker (CB) technologies. The relevant WPs which have contributed to the development include WP 2, WP 4, WP 5, WP 6, WP 9 and WP 10. The final demonstrations focus on the full power DC short-circuit current interruption testing of three different types of DC circuit breakers from three suppliers. The three types of circuit breakers and their demonstration status are given follows:

- **ABB hybrid HVDC circuit breaker**
  A 350 kV 20 kA hybrid circuit breaker from ABB has been successfully demonstrated in KEMA laboratory in 2020.
- **SCiBreak Voltage Source Assisted Resonance Current (VARC) HVDC circuit breaker**
  A single module 26.7 kV 10 kA prototype of the VARC circuit breaker from SCiBreak has been demonstrated 2018. The triple module 80 kV prototype has been demonstrated in August 2020.
- **Mitsubishi Electric mechanical HVDC circuit breaker with active current injection**
  A single module 80 kV 16 kA prototype circuit breaker from Mitsubishi has been demonstrated in 2017. A double module 160/200 kV 16/20 kA active current injection circuit breaker has been partially (70-80%) demonstrated in 2019 and fully demonstrated in September 2020.

a) ABB hybrid 350 kV CB. b) SciBreak VARC 80 kV CB. c) Mitsubishi 320 kV mechanical HVDC CB with active current injection.

Figure 3-1 Three types of HVDC circuit breakers and their demonstration status.

In the next, the TRL assessment of the three DC circuit breakers will be presented and explained.

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3.1.1 HYBRID HVDC CIRCUIT BREAKER

Different WPs in PROMOTioN contributed to the modelling, analysis and demonstration of hybrid DC circuit breakers (CB) and the TRL assessment results of each development step are shown in Figure 3-2.

PROMOTioN started the work on the hybrid DC CB from TRL 1 with analysing the models in WP5 and WP 6.

New DC CB concept and control strategies were formulated in WP 6 in order to improve its performance in the DC transmission grid. The performance of the DC CB with different fault clearing strategies was investigated in WP 4, upon which, the requirements of DC CB were formulated. In WP2, the integration of HVDC circuit breakers in HVDC grids was studied by analysing interactions between HVDC circuit breakers and converter and system control. Detailed component level models for hybrid, mechanical and VARC DC CB were then developed in WP 6, which also led to possible new designs with beneficial dimensions, weight and cost models. In these steps, concepts in several aspects of DC CB have been formulated analytically, which justifies progress up to TRL 2.

Small-scale (kW-size) hardware demonstrators of hybrid and mechanical DC CBs were designed and implemented in the lab in WP 6, which has been proven to work through experiments. This is viewed as TRL 3.

In the next immediate step, the failure modes and DC CB control strategies were tested by using the kW-size hardware demonstrator in the lab, which is assessed as TRL 4.

RTD simulator models of the DCCBs were developed for testing under different fault scenarios as part of WP9 in the national HVDC centre, which is considered as an industrial environment. Hereby, this step is viewed to reach TRL 5. In parallel, ABB and Mitsubishi performed unit tests on full-scale subcomponents in their own lab, which is assessed as TRL 5. However, ABB's unit tests are beyond the scope of PROMOTioN. In spite presenting it in the TRL assessment result, this step is shown in red colour for notice.

In PROMOTioN, the test environment for testing DC CB, including the test requirements, test procedures and test circuits, were developed in WP 5. However, this is considered as an enabler to the development of the DC CB, instead of an actual development step. Therefore, an arrow is used to present the development of the test environment in the TRL assessment result, rather than the achievement of an actual TRL advance.

The unit tests on full-scale subcomponents were demonstrated again in KEMA lab, which is considered as an industrial environment. This makes this step to reach TRL 6.

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In the next step, the short circuit tests were performed on full-scale single module system in ABB lab and on fully rated prototype system in KEMA lab respectively, which lead to a TRL 7 for both steps.

In the last step, the DC short-circuit current breaking capability of a fully rated and fully integrated prototype of a 350 kV hybrid HVDC circuit breaker from ABB was demonstrated successfully at a system level, which justifies an advance to TRL 7. The test object was manufactured using regular production processes and implemented using an existing fully qualified valve support structure design. According to ABB, full-scale operational, dielectric and endurance tests were done internally. Due to the lack of standards and qualification process, the demonstrated hybrid DC circuit breaker is not going to be qualified against norms or standards.

ABB	**Hybrid HVDC circuit breaker**	
Description	Rated voltage	350 kV
	Rated current	3 kA, uni-directional, no reclosing
	Maximum continuous current	3,3 kA
	Breaker operation time	3 ms
	Transient interruption voltage	480 kV
	Short-circuit breaking current	20 kA
	Rated energy absorption	10 MJ
	Nr. of modules	9

Scale & functionality	• Full-scale subcomponents rated for HVDC applications.
	• Sufficient number of modules, current rating and energy absorption rating to meet realistic HVDC project requirements.
	• Fully integrated system (all primary equipment and control) with the exception of:
	  ○ series current limiting reactor
	  ○ residual current breaker
	  ○ mechanical support structure
	  ○ load commutation switch cooling system	

System integration	• System level model developed in WP6 was used to study performance in protection systems and interaction with converter control systems in power system simulation studies in WP2 and WP4. • RTDS model developed in WP6 was used demonstrate integration with hardware protection IED and converter control & protection replicas in real time simulation test environment in WP9.	
Qualification	• Full-power DC short-circuit current breaking tests were carried out in WP10. ABB provided evidence of operational testing, dielectric and endurance testing during development. • Dielectric performance of support structure is same used for VSC	

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	valves and well-proven.
Manufacturing	• Production prototype using same well-proven manufacturing process as for VSC valves. Final commercial design may incorporate smaller support structure which would require new qualification.

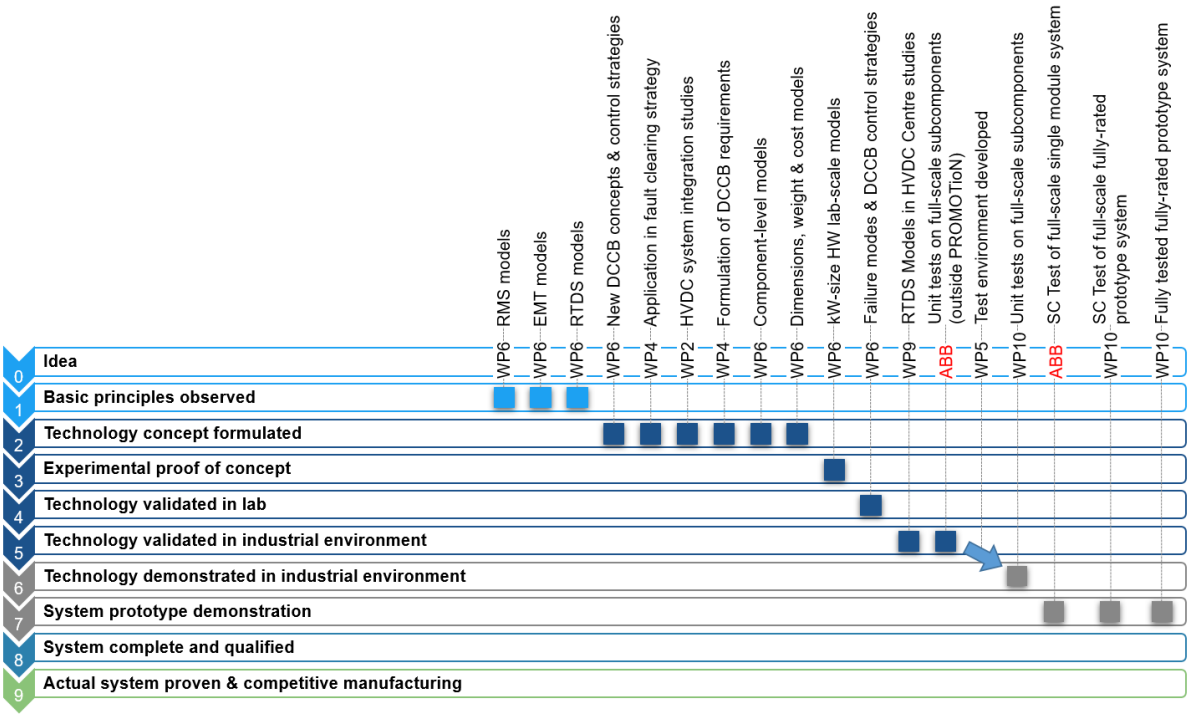

Figure 3-2 TRL assessment result of hybrid DC circuit breaker.

3.1.2 VARC HVDC CIRCUIT BREAKER

The development of VARC DC CB from SciBreak and the corresponding TRL assessment results are given in Figure 3-3.

Similar to the hybrid DC CB, PROMOTioN started the analysis of the VARC DC CB from TRL 1 with developing the models in WP 6. For the last step of demonstration, the single module of the VARC HVDC circuit breaker prototype has been demonstrated successfully in 2018. The triple module has been demonstrated in August 2020 (postponed due to COVID-19). This means that the basic functionality of the circuit breaker concept is validated at engineering scale ratings. No operational, dielectric or endurance tests have been done, and the test object is an experimental prototype build in a laboratory, rather than as a part of a production process. Hence, the readiness level is justfied to TRL 6, as shown in Figure 3-3.

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SCiBreak	**Voltage Assisted Resonance Converter HVDC circuit breaker**	
Description	Rated voltage	80 kV
	Rated current	2 kA, bi-directional, no reclosing
	Maximum continuous current	2,5 kA
	Breaker operation time	2 ms
	Transient interruption voltage	120 kV
	Short-circuit breaking current	15 kA
	Rated energy absorption	3 MJ
	Nr. of modules	3

Scale & functionality	• Full-scale subcomponents rated for HVDC applications.
	• Insufficient number of modules and energy absorption rating to meet realistic HVDC project requirements.
	• Fully integrated system (all primary equipment and control) with the exception of:
	  ○ series current limiting reactor
	  ○ residual current breaker
	  ○ mechanical support structure
	  ○ isolated power supply for HVDC line rating	

System integration	• Performance in protection systems and interaction with converter control systems was not studied in WP2 and WP4. • RTDS model developed in WP6 was used to demonstrate integration with hardware protection IED and converter control & protection replicas in real time simulation test environment in WP9.	
Qualification	• Full-scale DC short-circuit current breaking tests were carried out in WP10 on a DC circuit breaker with three modules. • No evidence delivered of operational, dielectric and endurance testing during development	
Manufacturing	• Experimental prototype. No manufacturing process or facilities in place	

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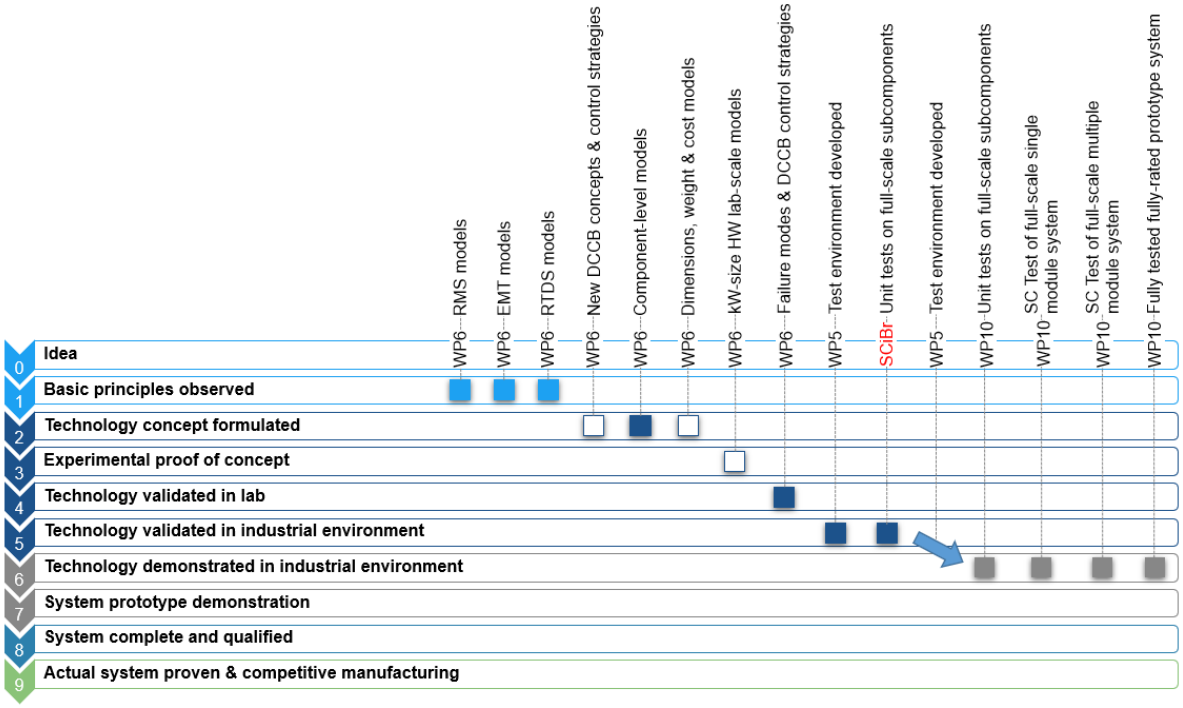

Figure 3-3 TRL assessment result of VARC DC circuit breaker.

3.1.3 ACTIVE CURRENT INJECTION CIRCUIT BREAKER

The development of the active current injection DC CB from Mitsubishi electric and the corresponding TRL assessment results are given in Figure 3-4.

For the active current injection circuit breaker, the 80 kV single module type has been demonstrated in 2017. The 160/200 kV double module type has been partly demonstrated in 2019 (70-80%) and fully demonstrated in September 2020 (postponed due to COVID-19). The tests validated the basic functionality of the circuit breaker technology at engineering scale. However, the supplied test object is an experimental prototype and not a final production prototype. Even though engineering scale ratings were used, the system was not complete, since it did not for example include a charging circuit. Moreover, no final dielectric design has been made, nor is the tested system complete (for example no injection capacitor charging circuit was included). Hence, the readiness level of the active current injection DC CB reaches up to a maximum of TRL 6 as shown in Figure 3-4.

Mitsubishi Electric	**Mechanical HVDC circuit breaker with active current injection**	
Description	Rated voltage	160 (200) kV
	Rated current	2 kA, bi-directional, no reclosing
	Maximum continuous current	2.5 kA
	Breaker operation time	7 ms
	Transient interruption voltage	240 kV
	Short-circuit breaking current	16 kA

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	Rated energy absorption 4 MJ Nr. of modules 2

Scale & functionality	• Full-scale subcomponents rated for HVDC applications.
	• Insufficient number of modules and energy absorption rating to meet realistic HVDC project requirements.
	• Fully integrated system (all primary equipment and control) with the exception of:
	  ○ series current limiting reactor
	  ○ residual current breaker
	  ○ mechanical support structure
	  ○ injection capacitor charging circuit & isolated power supply
	  ○ line voltage insulated instrumentation and communication

System integration	• System level model developed in WP6 was used to study performance in protection systems and interaction with converter control systems in power system simulation studies in WP2 and WP4. • RTDS model developed in WP6 was used demonstrate integration with hardware protection IED and converter control & protection replicas in real time simulation test environment in WP9.
Qualification	• Full-power DC short-circuit current breaking tests were carried out in WP10. • No evidence provided of operational testing, dielectric and endurance testing during development. • Dielectric performance of support structure is same used for VSC valves and well-proven.
Manufacturing	• Development prototype without support structure. Implementation on support structure requires further qualification not only through dielectric testing, but also DC short-circuit current breaking testing due to different arrangement compared to tested prototype. Manufacturing process and facilities are in place

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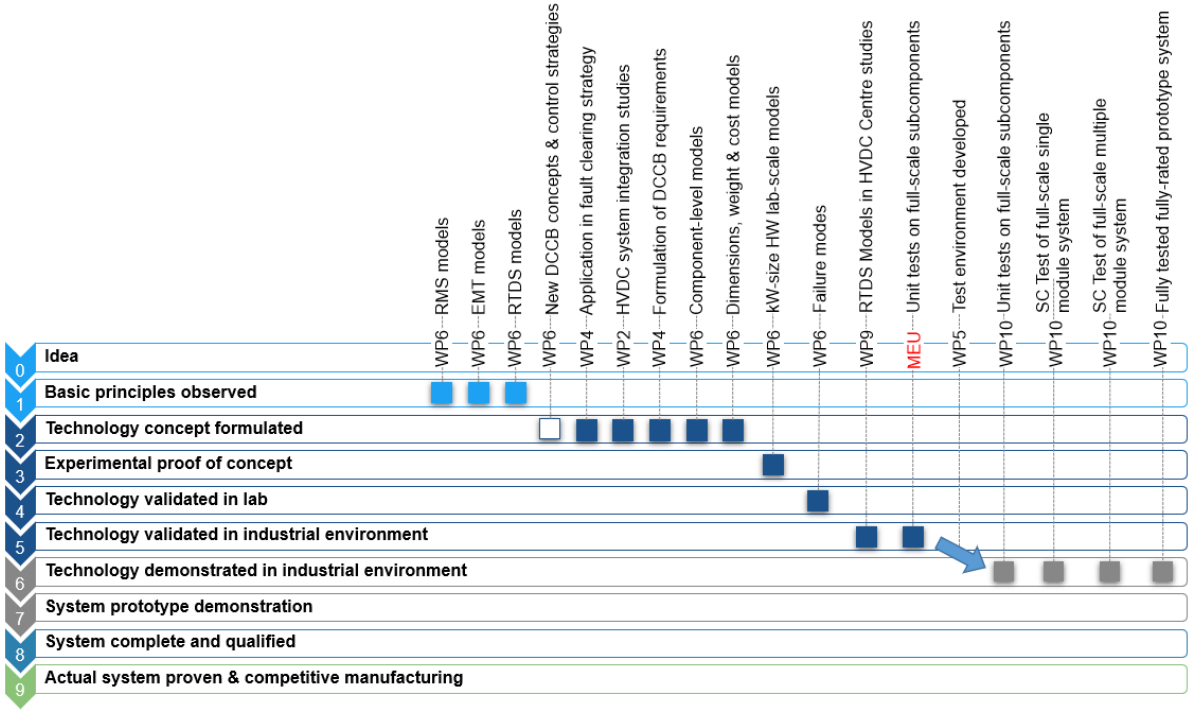

Figure 3-4 TRL assessment result of active current injection DC circuit breaker.

3.2 HVDC TRANSMISSION AND GRID CONTROL

A meshed DC system must be controllable. Specifically, the meshed DC system should be capable to return to a (new) equilibrium after physical disturbance and to control its active power injection up to its maximum power in each direction within dynamic limit. The offshore wind farms, the converters and their controllers, and the HVDC system itself should be capable to withstand the fault-conditions and to remain connected to support the grid.

In PROMOTioN, several aspects related to grid control have been investigated and demonstrated:

- Control in a meshed DC grid
- Grid forming cluster control
- Converter control during fault clearing in meshed DC grids

The WPs which are relevant and have contributed to the development include WP 2, WP 3, WP4, WP 16.

3.2.1 CONTROL IN A MESHED DC GRID

The development of control in a meshed DC grid and the corresponding TRL assessment results are given in Figure 3-5.

Before PROMOTioN project, considerable research on the control in a meshed DC grid was done, achieving a TRL 2-3. PROMOTioN work on this subject started at TRL 1, by studying the grid

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topology, model and specifying the required functionality and scenarios. The control concepts were formulated and proven by simulations, in both software and RTDS. The software tools and models (for example PSS/e, NETOMAC, PowerFactory etc.), and/or RTDS are sufficiently accurate to validate controllability of interconnected AC grids. The same applies to meshed DC grids. This promotes the control to TRL 6. The laboratory MMC test bench for meshed DC grid integration had been put into operation, which is considered as a signifier to enable the qualification of controllers to higher TRLs. Moreover, within the European context, a system prototype, or full-scale demonstration of a meshed DC grid is not foreseen due to the significant CAPEX required, hence the simulated DC grid and test bench set-up, along with a well-defined and extensive set of analysed scenarios, are considered credible enablers towards TRL 6.

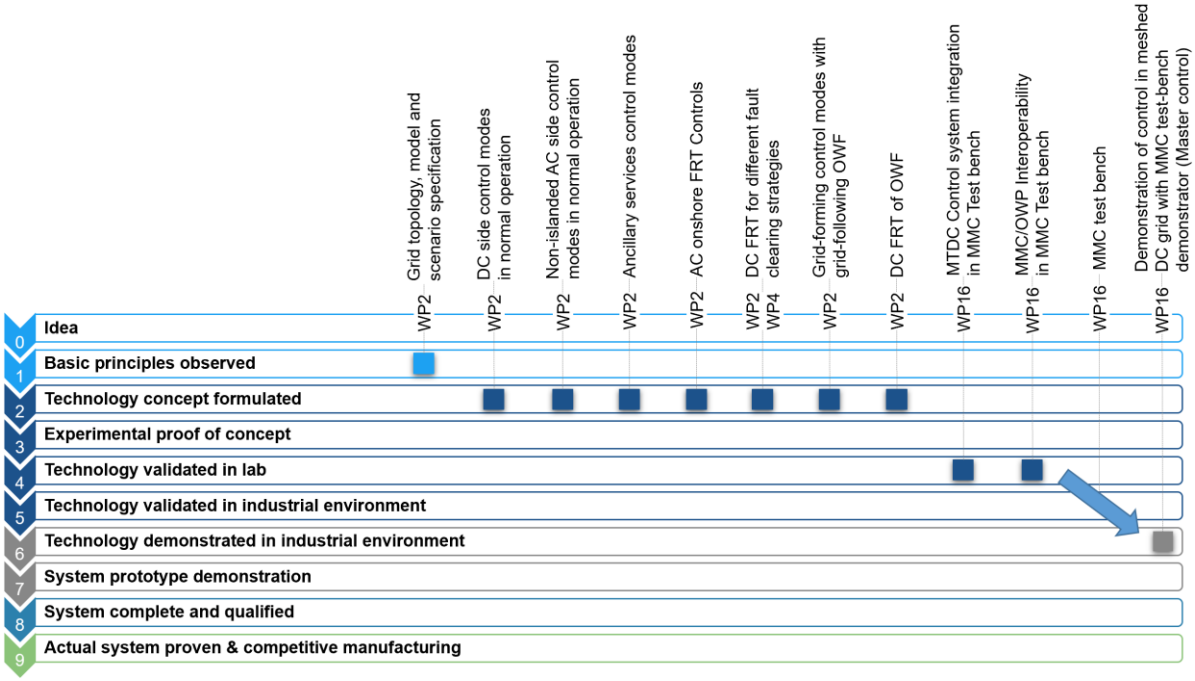

Figure 3-5 TRL assessment result of control in a meshed DC grid.

3.2.2 GRID FORMING CLUSTER CONTROL

The Diode rectifier units (DRUs) is one of the key technologies that PROMOTioN sets out to develop and demonstrate towards a meshed DC offshore grid. DRU connected systems and wind turbine converters need to be able to actively control their voltage and frequency, active power flow through the DRU and the umbilical cable, so that they could support the complete system during faults. In this sense, the wind turbine controls are not only grid following but also grid forming.

The development of grid forming cluster control and the corresponding TRL assessment results are given in Figure 3-6.

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PROMOTioN started the subject with specifying the requirements for DRU connected offshore wind farms and the grid forming strategies, at TRL 1. The control strategies were further investigated in the aspect of normal condition, fault handling, ancillary service as well as black start of HVAC/HVDC connected offshore wind farms. In the last step, the grid forming cluster control capability, including the frequency support and power oscillation damping performance, were demonstrated via control hardware-in-loop in Valencia and power hardware-in-loop in KEMA Laboratory, which made the technology achieve TRL 6.

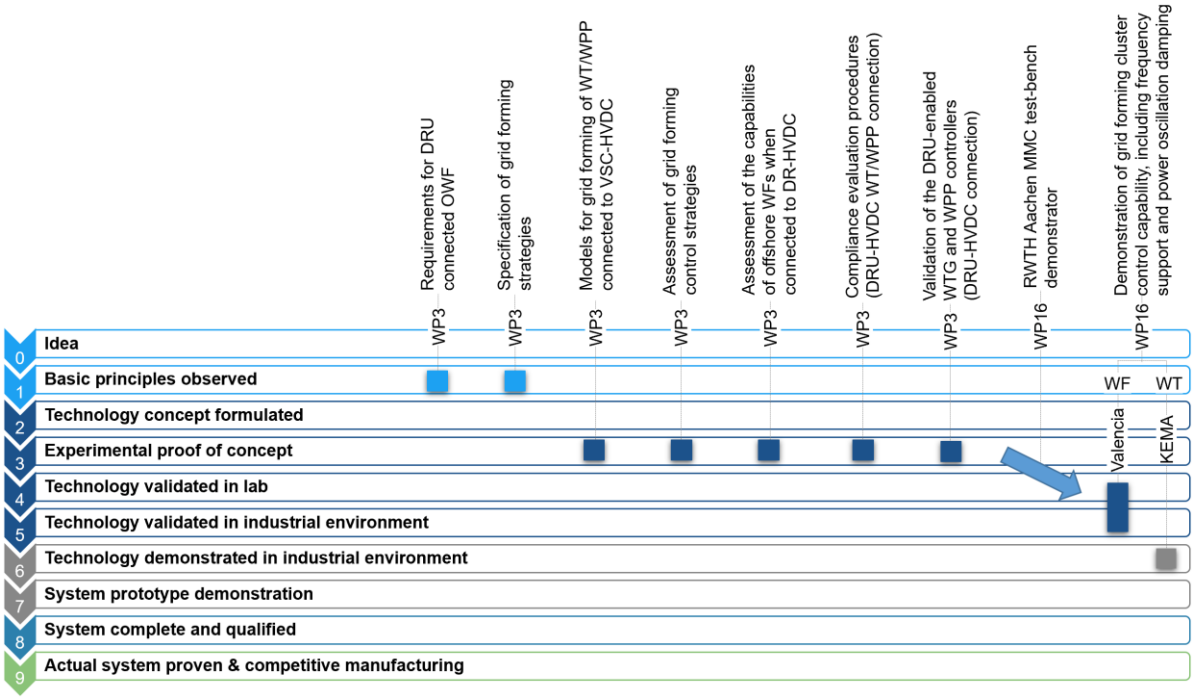

Figure 3-6 TRL assessment result of grid forming cluster control.

3.2.3 CONVERTER CONTROL DURING FAULT CLEARING IN MESHED DC GRIDS

The development of converter control during fault clearing in meshed DC grids and the corresponding TRL assessment results are given in Figure 3-7.

PROMOTioN started the investigation at TRL 2 with specifying the models of meshed offshore HVDC grids. Software modelling of meshed offshore HVDC grids, simulation of the control of MMC converters and DRUs during normal operation and faults, as well as the analysis of fault clearing strategies brought the readiness level to TRL 3. The test bench developed in RWTH Aachen serves as an enabler to promote development in the converter control. In the last step, the converter control operation was demonstrated on a RTD simulator under circuit breaker based and full bridge based fault clearing strategies, collectively lead to a TRL 6. Here, RTD simulator is considered to be able to reflect an industrial environment providing complete and realistic system inputs. In industry, prior to being shipped to site for commissioning, controls are equally factory tested on RTD simulator.

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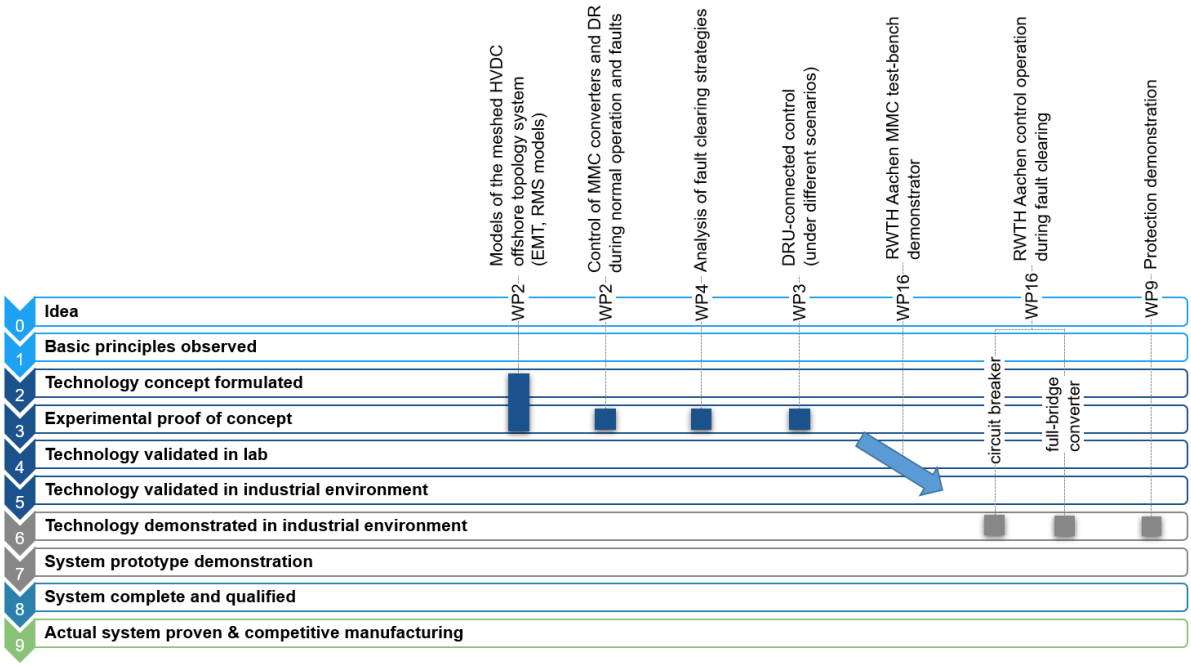

Figure 3-7 TRL assessment result of converter control during fault clearing in meshed DC grids.

3.3 HVDC GRID PROTECTION

HVDC grid protection system, seen as a barrier towards a meshed HVDC offshore grid, is another objective set in PROMOTioN to be investigated and demonstrated. A plurality of protection strategies was analysed and further developed:

- Selective fault clearing strategy
- Non-selective fault clearing strategy
    - Converter-breaker strategy
    - Full-bridge based converter strategy

Selective fault clearing strategies, reflect an offshore HVDC grid with circuit breakers strategically placed for higher selectivity in fault clearing. Alternatively, non-selective fault clearing strategies, reflect an offshore HVDC grid with fewer circuit breakers and the HVDC grid is de-energised to disconnect and isolate.

The related WPs for grid protection system includes WP 2, WP 4, WP 6, WP 9 and WP 16.

3.3.1 SELECTIVE FAULT CLEARING

The development of selective fault clearing and the corresponding TRL assessment results are given in Figure 3-8.

PROMOTioN started the investigation at TRL 1. By integrating the DC CB modelling from WP 6, the DC protection development and IED from WP 4, the IED from Mitsubishi, and the converter control &

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protection replicas from the Caithness-Moray-Shetland HVDC scheme, the system prototype demonstration in WP 9 advanced the TRL assessment to level TRL 6.

The interoperability between different vendors and technologies of DC grid protection system was also addressed in the scope of the demonstration and will be discussed in the section of Interoperability.

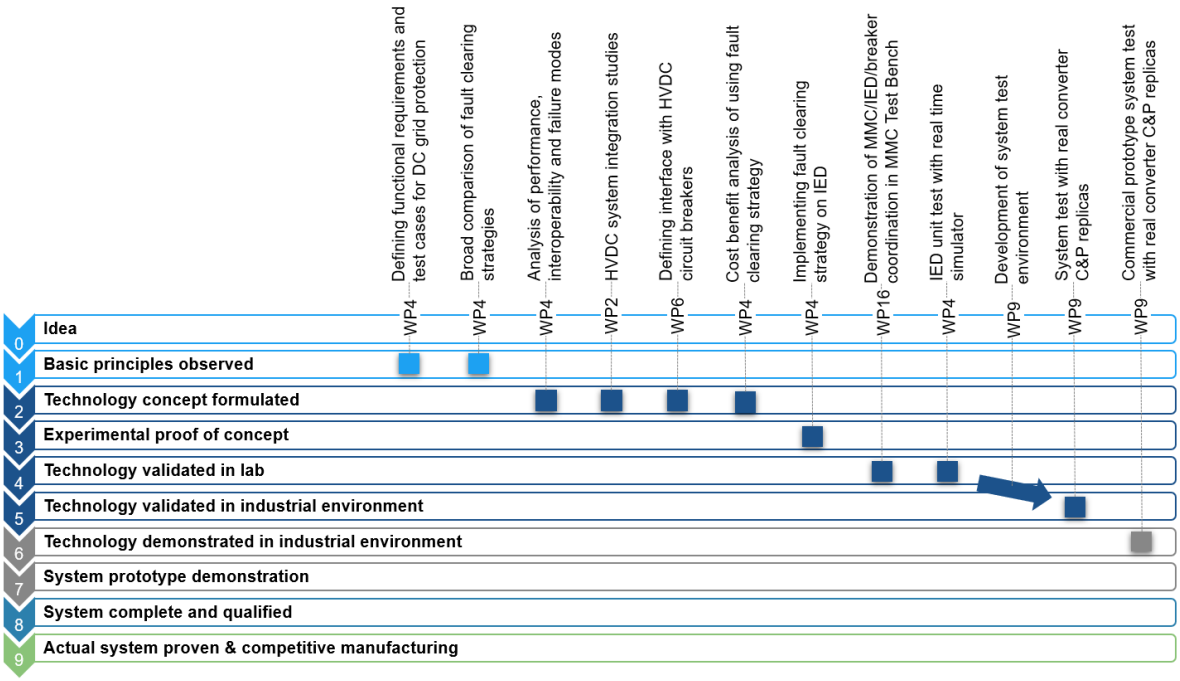

Figure 3-8 TRL assessment result of selective fault clearing.

3.3.2 NON-SELECTIVE FULL-BRIDGE BASED FAULT CLEARING

The development of non-selective full-bridge converter based fault clearing and the corresponding TRL assessment results are given in Figure 3-9.

Similarly, PROMOTioN started the investigation at TRL 1. Instead of demonstrating the technology in a real system, the hardware-in-loop demonstration of the non-selective full-bridge based fault clearing was performed on small-scale physical multi terminal DC system, which enables a TRL 6.

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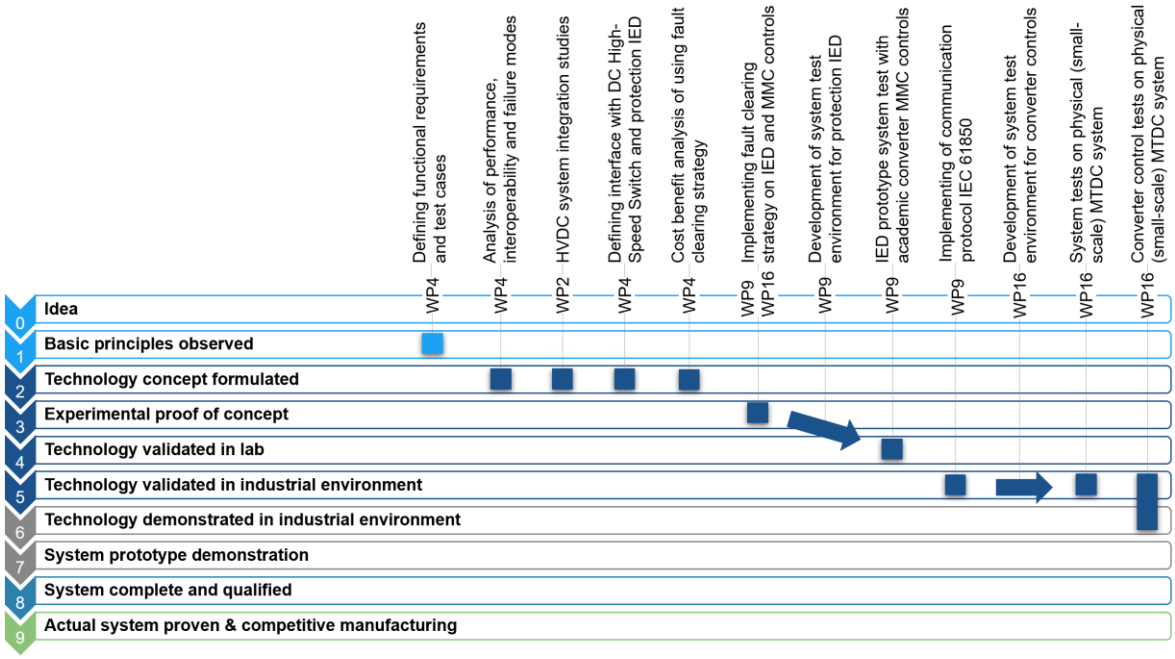

Figure 3-9 TRL assessment result of non-selective full-bridge converter based fault clearing.

3.3.3 NON-SELECTIVE CONVERTER BREAKER FAULT CLEARING

The development of non-selective converter breaker based fault clearing and the corresponding TRL assessment results are givin in Figure 3-10.

PROMOTioN started the investigation at TRL 1. In WP 9, the implemention of DC grid supervision with IEC protocol brought the readiness level to TRL 5.

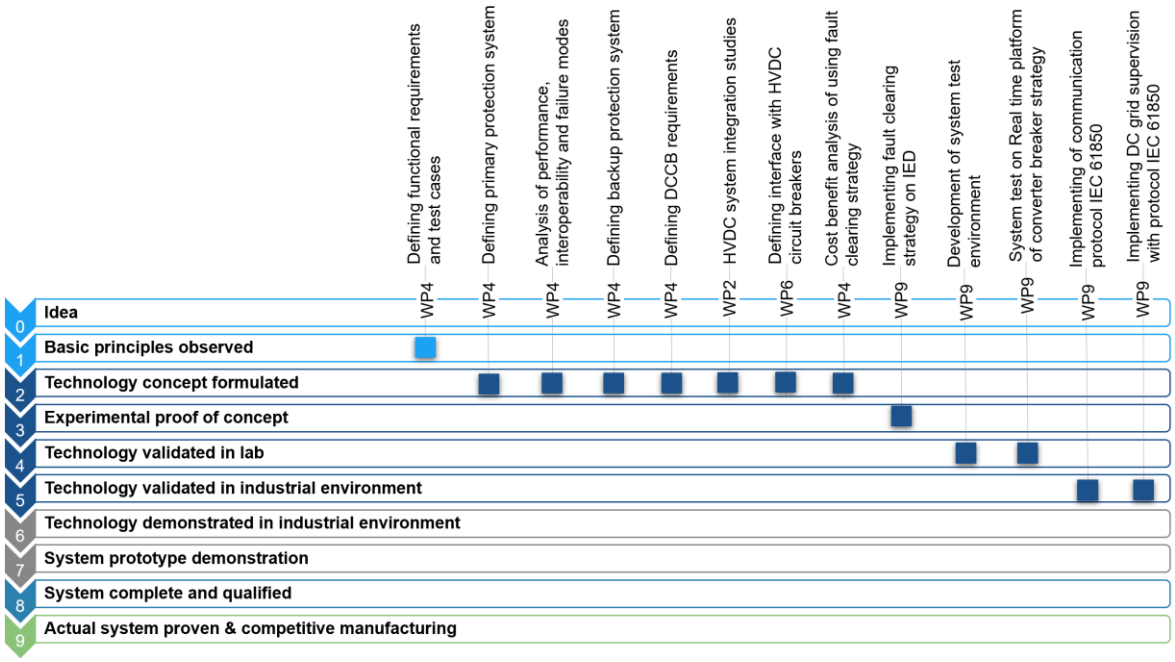

Figure 3-10 TRL assessment result of non-selective converter breaker based fault clearing.

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3.4 HVDC GIS SYSTEM

HVDC gas insulated switchgear (GIS) for use in HVDC transmission has been under development by several manufacturers for several years. Thus, the maturity level of HVDC GIS is relatively high when PROMOTioN started the investigation. However, there is no international standard for the specification requirements and test procedure for HVDC GIS. The investigation of HVDC GIS in WP 15 in PROMOTioN provides specification and long-term test requirements, and also promoted the HVDC GIS to an advanced status. The aspects investigated in PROMOTioN include:

- HVDC GIS system with SF_6
- HVDC GIS system with SF_6 alternative
- New PD monitoring and diagnostic system

3.4.1 HVDC GIS SYSTEM WITH SF_6

The development of HVDC GIS system with SF6 and the corresponding TRL assessment results are given in Figure 3-11.

Before PROMOTioN started, the HVDC GIS system and its monitoring and diagnostic system have already achieved TRL 6. In PROMOTioN, the monitoring and diagnostic system has been promoted to TRL 9. The long-term demonstration of prototype system advanced the readiness level to TRL 8.

ABB	**Gas insulated system – SF6**	
Description	Rated voltage	350 kV
	Rated normal current	4000 A
	Rated lightning impulse withstand voltage	1050 kV
	Rated switching impulse withstand voltage	950 kV
	Rated short-time withstand current	64 kA
	Rated duration of short-circuit	1 s
	Rated peak withstand current	160 kA
	Ambient temperature range	-30..+40 º
Scale & functionality	• Primary components: gas-air bushings, busbars, corner pieces, disconnectors, ultra-fast earthing switch, surge arrestor, RC divider, current sensor, (current transformers for heating the conductor) • Secondary components: bay controller, monitoring equipment for gas quality and partial discharge • Support structure • Full-scale subcomponents rated for HVDC applications • Fully integrated system (all primary equipment and control) with the exception of:	

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	○ Cable sealing end ○ Transformer bushing ○ High-speed switch ○ Pre-insertion resistor
System integration	• Guide for specification of gas insulated systems was developed as part of WP15
Qualification	• Long term prototype installation test requrements and program developed and agreed with users, and used for demonstration • Enclosure is same as well-proven design for AC GIS. All non-HVDC specific test requirements applicable to AC (internal arc, pressure tests, etc.) have been fully qualified and proven through field experience
Manufacturing	• Production prototype, from same assembly line as AC GIS. Manufacturing process and facilities present and mature

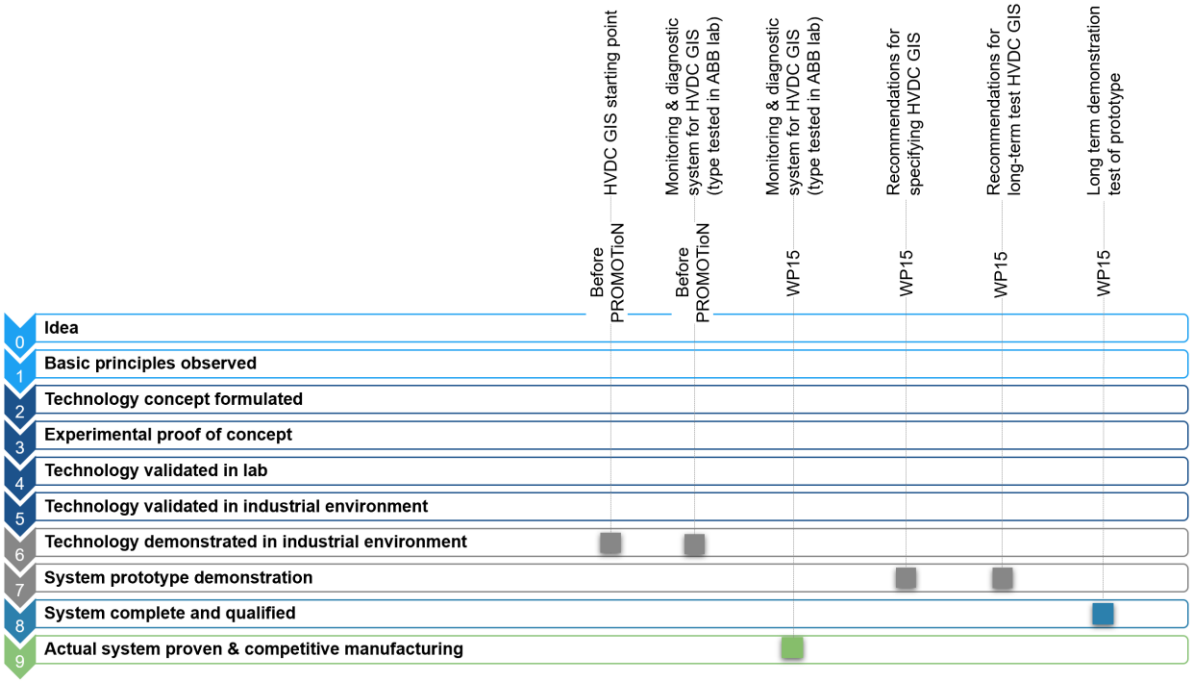

Figure 3-11 TRL assessment result of HVDC GIS system with SF6.

3.4.2 HVDC GIS SYSTEM WITH SF_6 ALTERNATIVE

The development of HVDC GIS system with SF_6 alternative and the corresponding TRL assessment results are given in Figure 3-12.

The full HVDC GIS verification in the lab with SF_6 alternative enables the readiness level to TRL 5.

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	Gas insulated system – SF6 alternative
Description	Behaviour of defects in different insulating gases studied for representative dielectric stresses in representative experimental GIS enclosure.
Scale & functionality	Same insulating gases as in realistic application. No basic GIS components such as coatings, sealing rings, bushings, cable sealing ends, switchgear, surge arrestors, instrumentation, etc.
System integration	None
Qualification	Gases subjected to realistic dielectric stresses
Manufacturing	Gas production facilities mature

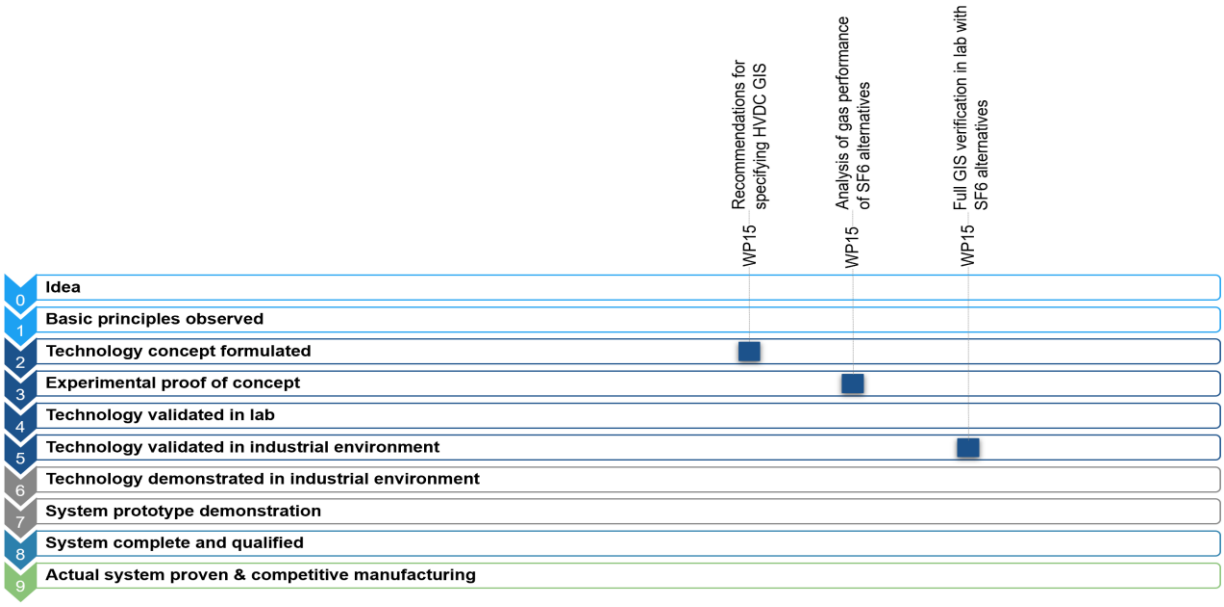

Figure 3-12 TRL assessment result of HVDC GIS system with SF_6 alternative.

3.4.3 NEW PD MONITORING AND DIAGNOSTIC SYSTEM FOR HVDC GIS SYSTEM

The partial discharge monitoring and diagnostic system was also investigated in PROMOTioN. The development of new partial discharge monitoring and diagnostic system and the corresponding TRL assessment results are given in Figure 3-13. Has been validated in the KEMA lab, the readiness level is assessed as TRL 5.

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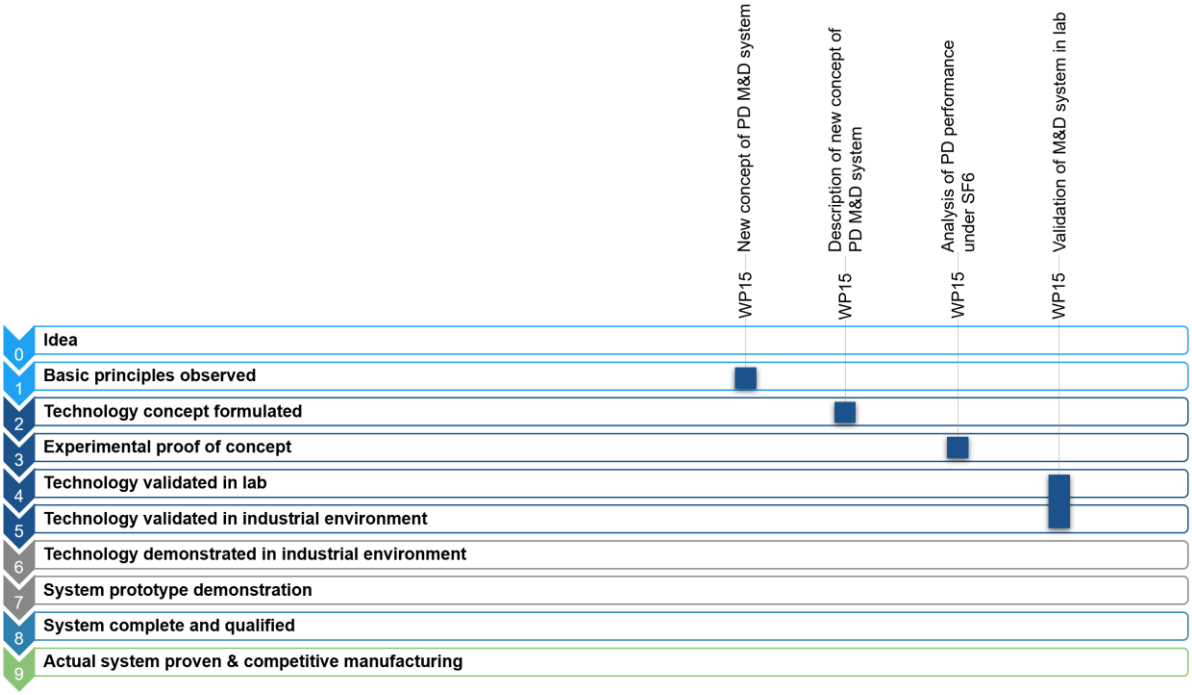

Figure 3-13 TRL assessment result of partial discharge monitoring and diagnostic system for HVDC GIS.

3.5 INTEROPERABILITY

The interoperability is the possibility to at any point in a grid's lifecycle, integrate different types of technologies from different vendors into the meshed offshore grid without compromising the optimal behaviour of the system. Interoperability is to be achieved, for example between:

- Different converter technologies
- Converters from different vendors
- Converter control and protection system in DC grids
- Protection system elements or different protection philosophies
- Converter (system) control and offshore wind turbine generator (farm) control
- Interaction with connected AC grid(s) within above scenario.

So far, the interoperability between different converter technologies at protection and control level has been demonstrated. In this document, the TRL of the interoperability between different converter technologies is assessed and presented, as shown in Figure 3-14. Further development and subsequent assessment are to be performed for the interoperability, including power transfer.

PROMOTioN started this subject at TRL 1 by specifying the grid topology, models and scenarios. Interoperability at controller level has been validated in laboratory environment for half-bridge converter, full-bridge converter and Diode Rectifier Unit technologies. Granted, controllers had not been connected to actual converter bridges or DRU, hence falling short of physical power transfer. Viewed differently, both type converter bridges, and the DRU, are industrially proven devices. By

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sound engineering reasoning, connecting the validated controllers to its respective power devices, is a matter of wiring, as was demonstrated by comparing CHiL and PHiL results in WP16. Hence, with interoperability at controller level having been validated, no major technological constraints are foreseen, and TRL 6 is accorded.

Moving ahead to system prototype, or full-scale demonstration, would require vendor participation, which lies beyond PROMOTioN influential reach, for obvious industrial reasons like proprietary or confidential information, intellectual property or patent protection.

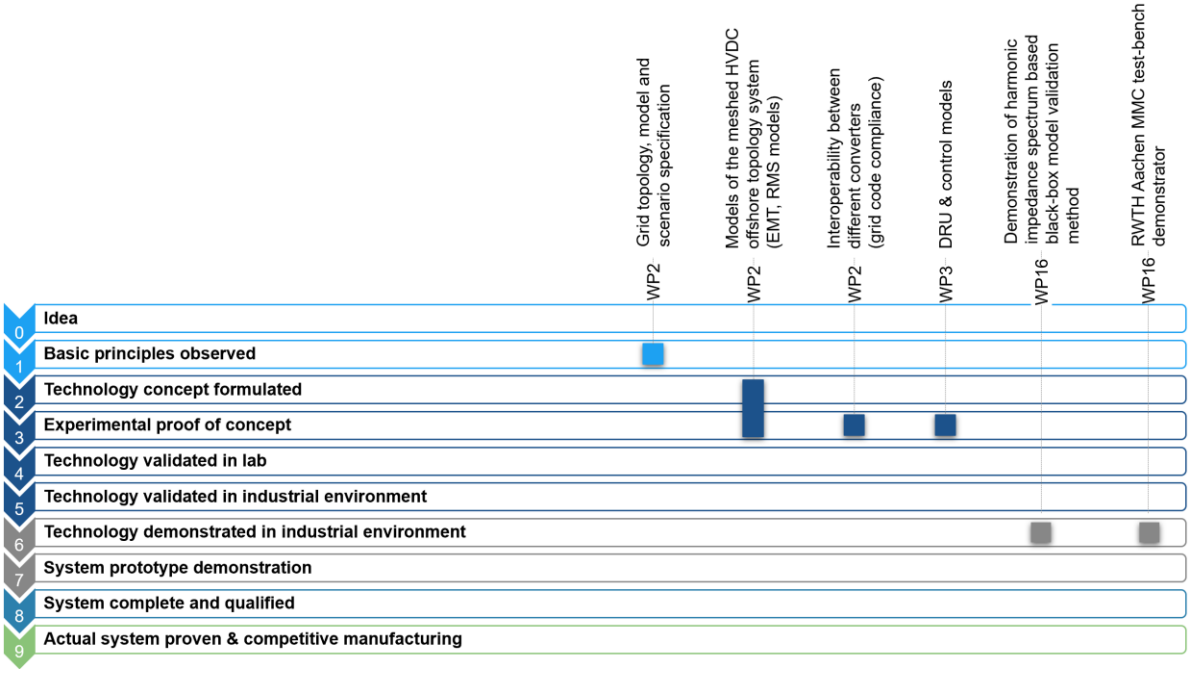

Figure 3-14 TRL assessment result of interoperability between different converter technologies.

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4 MATURITY OF TECHNOLOGIES FOR HVDC MESHED GRID

The HVDC technologies have been investigated by various projects in EU and worldwide, for example, in China. It is helpful to have an overview of the maturity levels of the HVDC technologies from a wider scope. Hence, a review of the HVDC technologies that have been investigated and commercialized in different EU projects and China projects has been carried out, as shown in Figure 4-1.

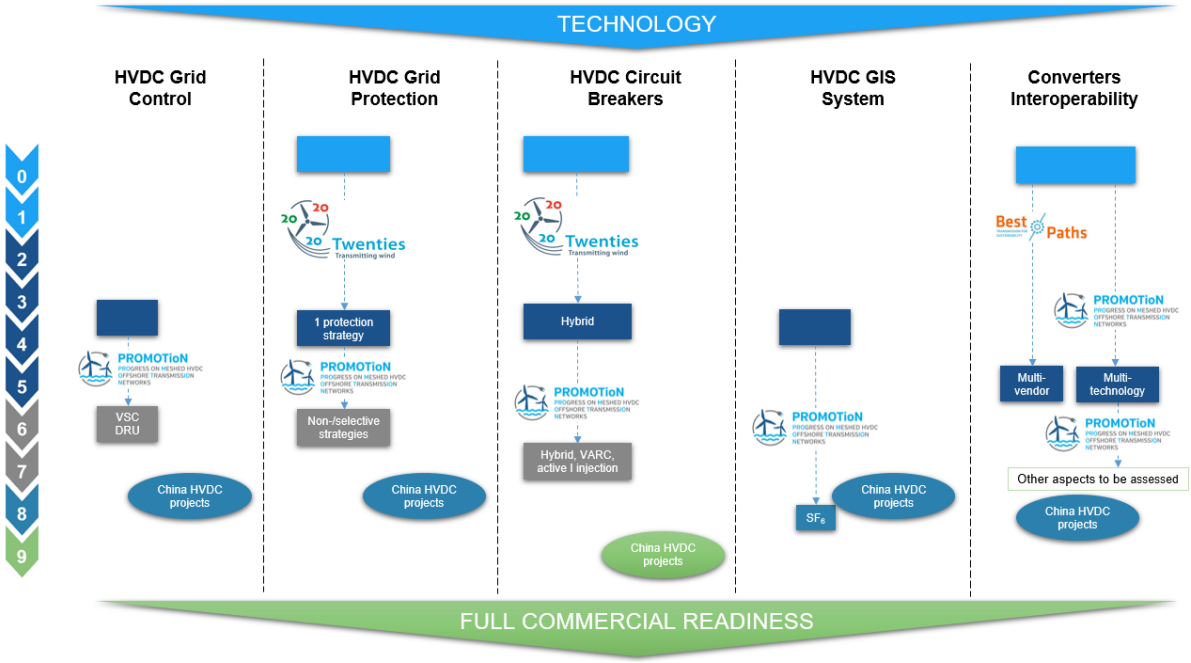

Figure 4-1 Overview of TRL of HVDC technologies in PROMOTioN, in other EU projects and in China projects.

4.1 PROGRESS IN TECHNOLOGY READINESS MADE IN PROMOTION

As discussed in Chapter 3, PROMOTioN has contributed to advance the maturity levels of several HVDC technologies, specifically for meshed offshore DC grid. The current status of the readiness levels of the four key HVDC technologies are viewed as high.

4.2 PROGRESS IN TECHNOLOGOY READINESS MADE BY PREVIOUSLY PERFORMED STUDIES

There are several previous EU studies having addressed the development of offshore meshed HVDC grids. Deliverable 1.3 [3] from PROMOTioN gives a comprehensive overview of the previous EU studies. Deliverable 12.2 [4] from PROMOTioN compare the non-/technical scopes of previous

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studies. In the scope of technical issues, PROMOTioN has covered technologies related to converter technologies, control system, grid protection, HVDC circuit breaker, interoperability etc. Each of those previous studies focused on one or more of the aforementioned technologies. Among them, Twenties and Best Paths are remarkable with demonstrations of the critical technologies. A short overview and TRL status of these two studies in as follow:

TWENTIES

DC circuit breaker technology has been demonstrated in Twenties. The hybrid DC circuit breaker, provided by Alstom Grid, was demonstrated in an industrial representative environment HV laboratory. The fault current breaking capability was tested in small cell and full scale. Other functionalities such as the capability to withstand DC line voltage, recovery voltage and transient interruption voltage, the energy absorption capability as well as the losses were not tested. Moreover, the topology of the DC circuit breaker studied in Twenties has been determined in PROMOTioN as not viable for commercialization at HV rating. The readiness level of the DC circuit breaker developed by Twenties is assessed as TRL 5 in perspective of fault current breaking capability. Grid protection has been demonstrated in Twenties as well. Only one type of grid protection strategy was considered and simulated via electromagnetic transient tools. The algorithm was demonstrated using a five-terminal DC grid with physically installed 15 km cable and five converters, two of which were simulative models and the rest were down-scaled physical converters. The readiness level of the grid protection demonstrated in Twenties is assessed as TRL 5.

BEST PATHS

The interoperability between converter controllers in a multi-vendor VSC system was investigated in Best paths. Aspects such as common starting/shutdown sequences for all converters, use of a common Master Control to coordinate converters operation, assessment of dynamic performance of converter controls, common signal list were precisely defined in the demonstration, implemented and tested for the first time in a realistic environment involving various manufacturers. VSC converter models and controllers provided by manufacturers were adapted according to the functional specifications, tested by offline simulations first individually in single-vendor point-to-point configurations and, then in multi-vendor configurations, and finally by real time simulation based on converters control replicas. The demonstration results show that, those aspects are valid and relevant from a practical standpoint. For the identified interoperability issues, a generic approach to fix them was successfully tested and demonstrated in a public live demo at the end of the project [5]. The readiness level of the interoperability in multi-vendor VSC system demonstrated in Twenties is assessed as TRL 4.

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4.3 READINESS LEVEL OF TECHNOLOGY FOR HVDC MESHED GRID IN CHINA

4.3.1 HVDC CIRCUIT BREAKER

In the world's first HVDC grid - Zhangbei HVDC project, hybrid HVDC circuit breakers from different suppliers have been installed in the four converter stations in the transmission ring. In two stations, the HVDC circuit breakers have been partially commissioned. In the other two stations, the commissioning just began. Before installation, all the DC circuit breakers have been fully type tested in either independent laboratories, or at manufacturers' laboratories where the witness testing by a third party is required. The DC circuit breakers being successfully type tested are then accepted by the customers. In such sense, the readiness level of the DC circuit breakers is viewed as mature and manufacturing competitive, being assessed as TRL 9.

4.3.2 CONTROL IN DC GRIDS

For the control in meshed DC grids and the grid forming cluster control, the experience in China indicates the readiness level having achieved TRL 8.

For the converter control during fault clearing in DC grid, the converter control and the DC circuit breakers were tested together in the same system, which advanced the readiness level to TRL 8.

4.3.3 HVDC GRID PROTECTION

In several HVDC projects in China, for example Nanao MTDC project and Zhangbei MTDC project, DC devices from multiple vendors have been integrated in the same HVDC system, with compatibility to interface protocols realized by specific developed software. So far, the protection systems work well as expected. In this condition, the readiness level of the DC grid protection is assessed as TRL 8.

4.3.4 HVDC GIS SYTEM

The 320 kV DC GIS from Siemens has been procured for an offshore HVDC converter platform. The 550 kV DC GIS has been qualified according to the pre-standardization recommended within CIGRE. The readiness level of the considered DC GIS components is assessed as TRL 9. However, the absence of testing requirements for HVDC GIS cable sealing ends means that this specific, but crucial, component cannot advance beyond TRL 7, reducing the TRL of the total HVDC GIS system to 7.

4.3.5 INTEROPERABILITY

In China, several multi-terminal HVDC projects have been commissioned and are in operation now. For example, the first MTDC project – Nanao ± 160 kV three-terminal symmetrical monopole HVDC network, where the DC circuit breakers and the MMV-VSC terminals from different manufacturers

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have been used. Zhoushan ± 200 kV five-terminal symmetrical monopole HVDC network, which has the most terminals worldwide, applied half-bridge MMC technologies and HVDC circuit breakers. In Zhangbei ± 500 kV four-terminal HVDC grid, which has been mentioned before, half-bridge MMC and HVDC circuit breakers have been used. In these HVDC projects, devices are communicatively connected working together by adapting the data models according to IEC protocol 61850.

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5 CONCLUSIONS

This document aims to assess the TRL levels of technologies and their respective progress made by PROMOTioN. For this purpose, the H2020 TRL scale was applied, whose definitions were further evolved and adapted to T&D industry for utilization in PROMOTioN. Five technologies that are critical in enabling the offshore meshed DC grid were assessed.

HVDC circuit breakers with their fault current breaking capabilities were investigated in PROMOTioN. Prior to PROMOTioN, one type of hybrid DC circuit breaker has been demonstrated in project Twenties, which made the TRL level to 5. In PROMOTioN, three types of DC circuit breaker prototype systems were considered: the hybrid one from ABB, the VARC one from SCiBreak and the active current injection one from Mitsubishi electric. PROMOTioN started the investigation of all three types from observing the principle. Among the three types, the ABB hybrid DC circuit breaker prototype has been successfully demonstrated in full rate, which advanced the TRL to 7. The VARC and the active current injection DC circuit breaker prototypes have been demonstrated in later 2020, which advanced the TRL to 6. By viewing the international experience, DC circuit breakers from multiple vendors have been installed in the HVDC grid in China and commissioned partially, which is viewed as mature and manufactured competitively, being assessed as TRL 9.

HVDC transmission and grid control was demonstrated in three aspects. PROMOTION started the investigation on the control in a meshed DC grid from observing the principle, while the previous studies have already made the technology to TRL 2. By demonstration, the TRL was advanced to 6 by PROMOTioN. Similar progress is made on the grid forming cluster control technology. For converter control during fault clearing in meshed DC grid, PROMOTioN started the investigation at TRL 2 with specifying the models of meshed offshore HVDC grid and advanced it to TRL 6. All the three control technologies implemented in the HVDC projects in China have reached TRL 8.

Regarding DC grid protection system, Twenties has demonstrated one protection strategy to advance the TRL to 5. In PROMOTioN, selective and non-selective fault clearing strategies were investigated from observing the principle and demonstrated in PROMOTION. For selective fault clearing, with the commercial prototype system being demonstrated with real converter replicas, the TRL is advanced to level 6. The tests on non-selective full-bridge based fault clearing and converter breaker fault clearing promote the TRL to 6 and 5 respectively. In China, the protection systems are viewed as TRL8.

HVDC GIS system with SF_6 has a semi-mature level at TRL 6 prior PROMOTION. During PROMOTioN, the TRL was advanced to 8 through long-term test. HVDC GIS system with SF_6 alternative was investigated in PROMOTioN from formulating the concept as TRL 2 and ended up at being validated as TRL 5. The monitoring and diagnostic (M&D) system for HVDC GIS system was

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type tested in ABB lab prior PROMOTioN which has reached to TRL 9. While in PROMOTioN, a new PD M&D system was developed and validated as TRL 5. The HVDC GIS systems installed in the offshore platform in China are assessed as TRL 8-9.

Several aspects need to be considered for interoperability. Interoperability between different converter technologies at protection and control level has been demonstrated. The interoperability between multiple vendors of converters has been investigated and demonstrated in Best Paths, with the result showing the validity. The interoperability between different converter technologies has been demonstrated in PROMOTioN with the readiness level being assessed as TRL 6. The interoperability between converter control and protection system in DC system with physical power transfer, protection system elements or different protection systems, or converter (system) control and offshore wind turbine generator (farm) control will be further investigated in a next step.

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