Lessons Learnt from the BEST PATHS Project for the Integration of Offshore Wind Power Plants using Multi-Terminal HVDC Grids

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5th June 2019

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For power system expertise

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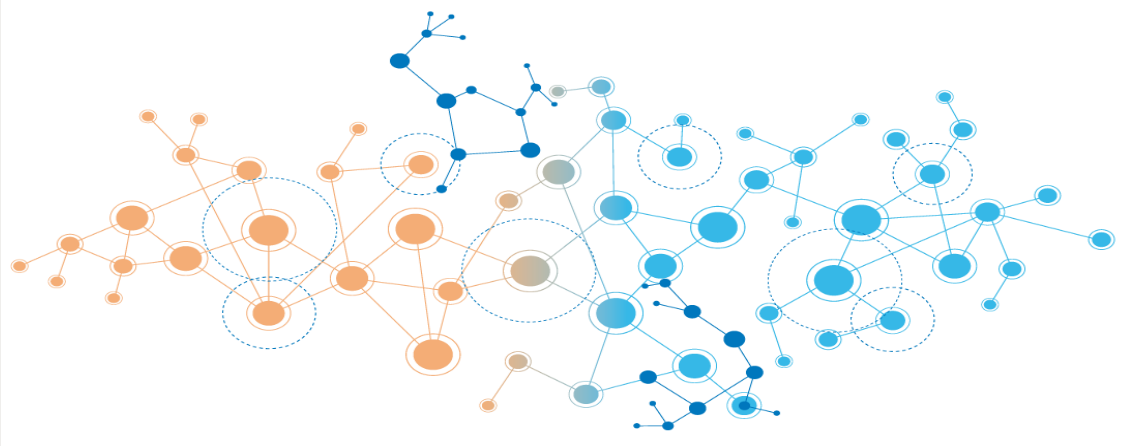
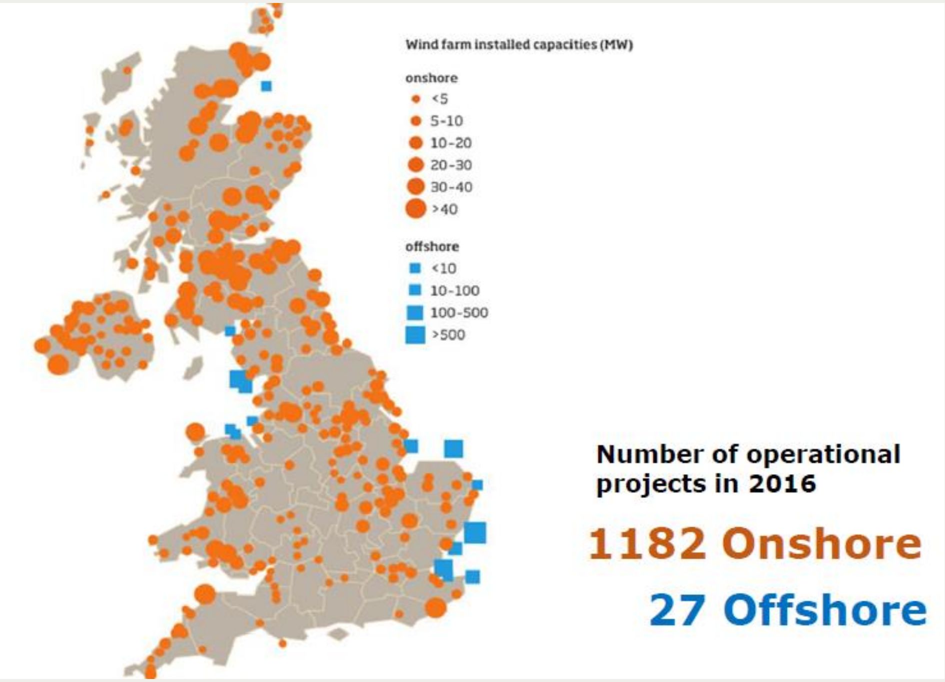
Outline of the Presentation

1. Introduction
2. The BEST PATHS Project
3. BEST PATHS Demo 1:
    a) Network Topologies
    b) Key Performance Indicators
    c) The ‘Open Access’ Toolbox
4. Simulation Results
5. Real-Time Demonstrator
6. Experimental Results
7. Further Work
8. Conclusions



Introduction

- **Wind energy** will be the most widely adopted renewable energy source (RES) by 2050 to contribute towards the **abatement of green house gas emissions.**
- **Europe's installed wind capacity** is **189 GW*** (18.8% of EU's total installed power generation capacity). In the **UK**:
  - **Operational in June 2019:**
    - **Onshore: 13.04 GW** (2017 projects, 7853 turbines);
    - **Offshore**: **8.48 GW** (37 projects, 2016 turbines).
    - **Total: 21.521 GW****

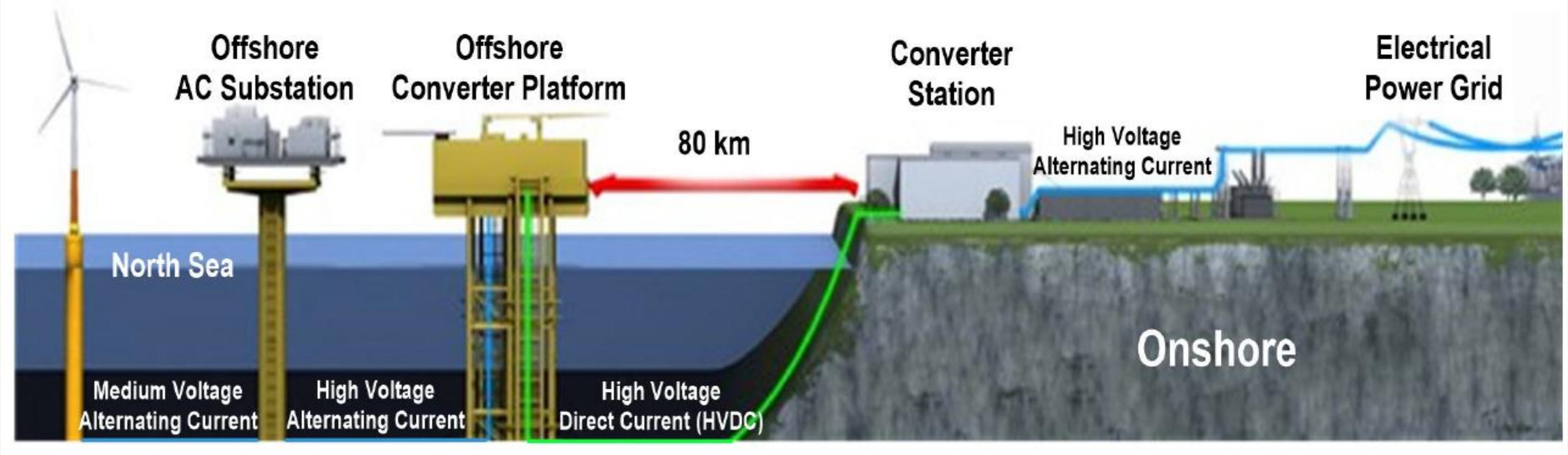


* https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Statistics-2018.pdf
** https://www.renewableuk.com/page/UKWEDhome

Introduction (2)

- **HVAC technology** is mature and suitable for subsea transmission at typical voltages up to 150 kV and distances up to 100 km.
- **HVDC** has better control capabilities, lower power losses and occupies less space compared with HVAC.
- A **'Business as Usual'** approach to improve infrastructure will not be sufficient to meet policy objectives at reasonable cost.
- **Operators and manufacturers** are now considering **HVDC solutions** over HVAC for **offshore power transmission systems**:
  - A **higher quality and more reliable** wind resource with higher average wind speeds is farther away from shore.
  - **Long distances** to shore.
  - **Above** 150 kV **and beyond** 100 km **HVAC is not practical** due to capacitance and hence charging current of submarine cable.

Introduction (3)

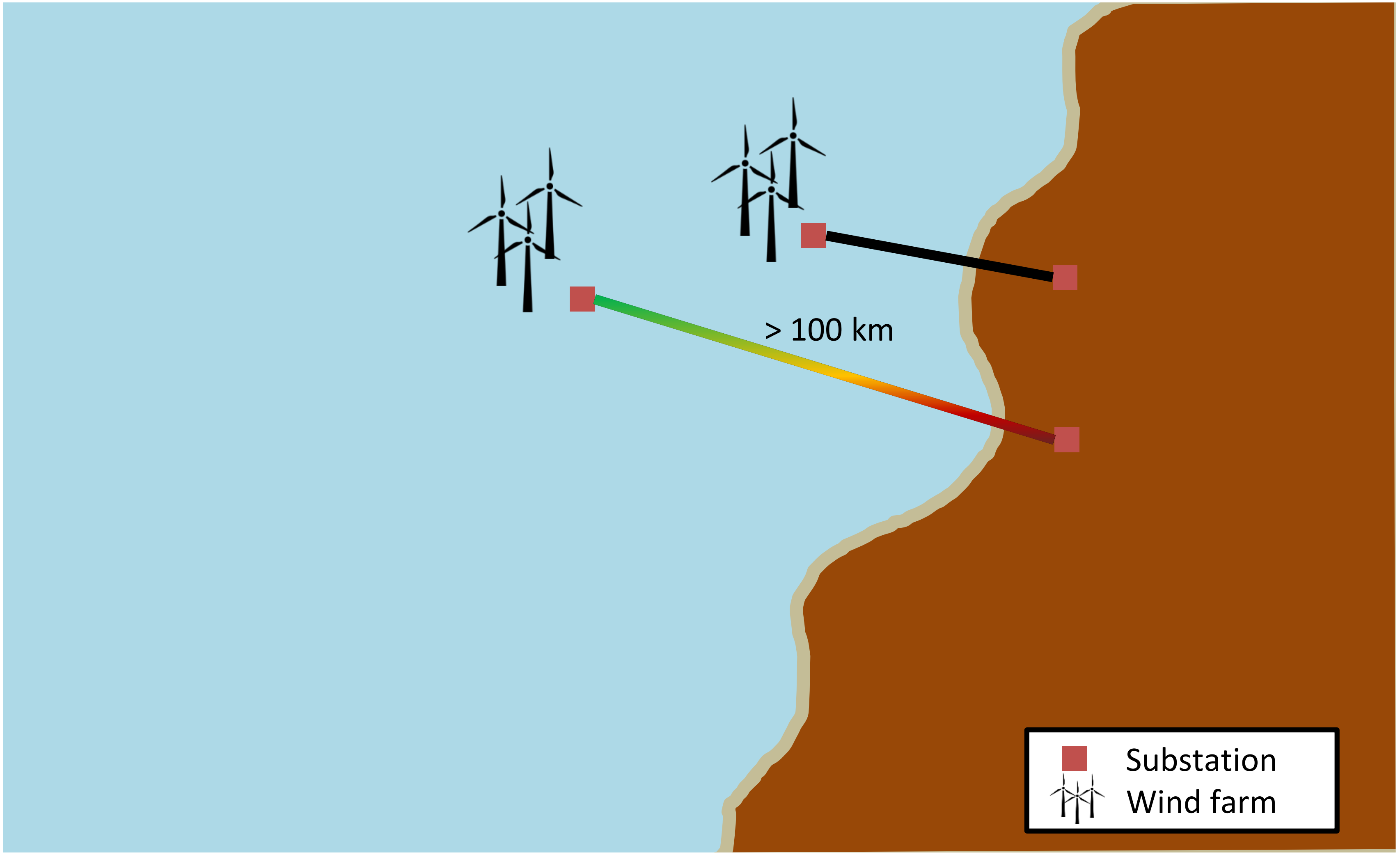


- **Voltage source converter (VSC)** based schemes are becoming the preferred option over **line commutated converter (LCC)** alternatives due to their decoupled power flow control, black-start capability and control flexibility.

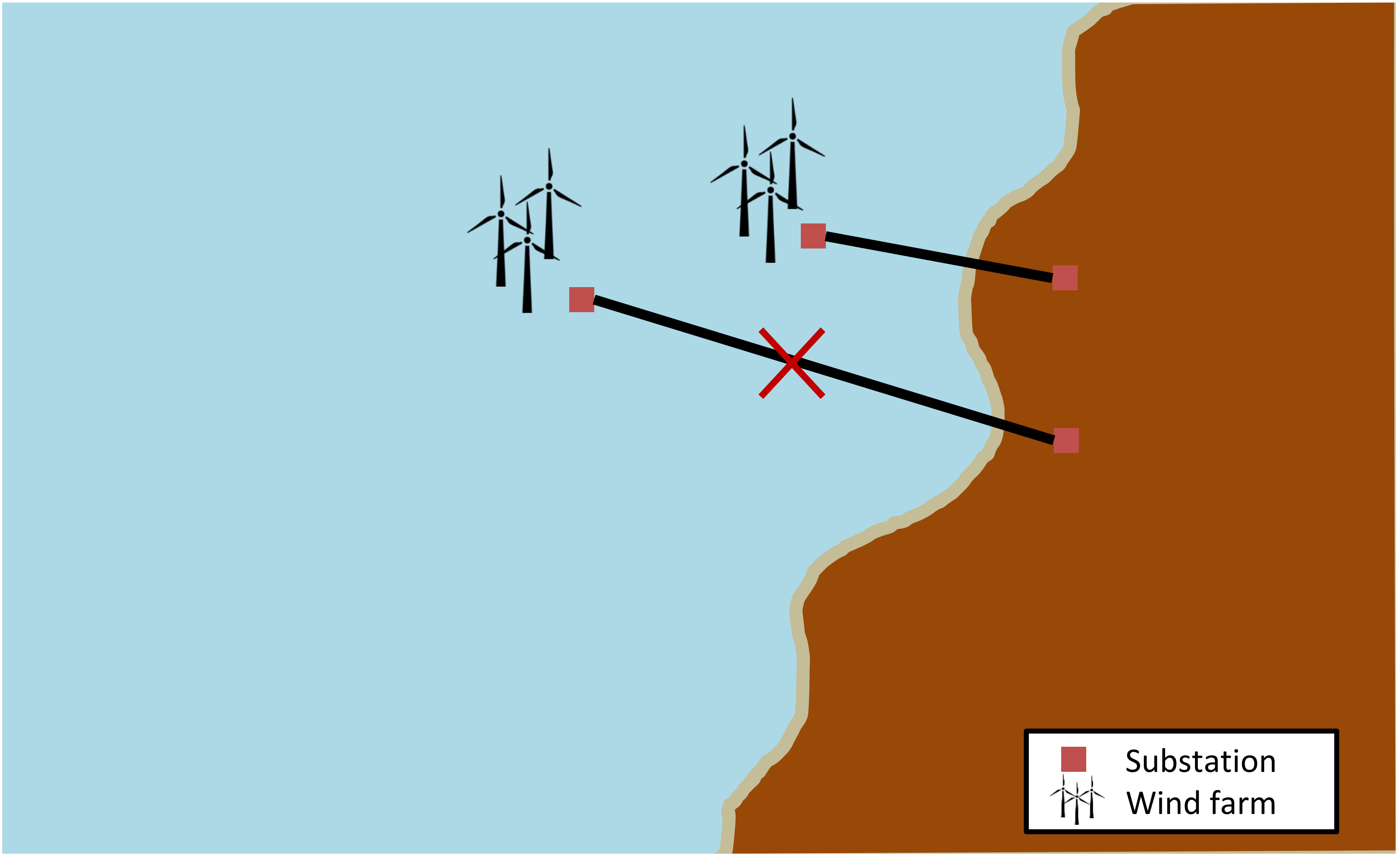
- **MTDC grids** will facilitate a cross-border energy exchange between different countries and will enable reliable power transfer from **offshore wind farms (OWFs)**.

- The **interactions between wind turbine (WT) converters and different VSC types** in a meshed topology need further investigation.

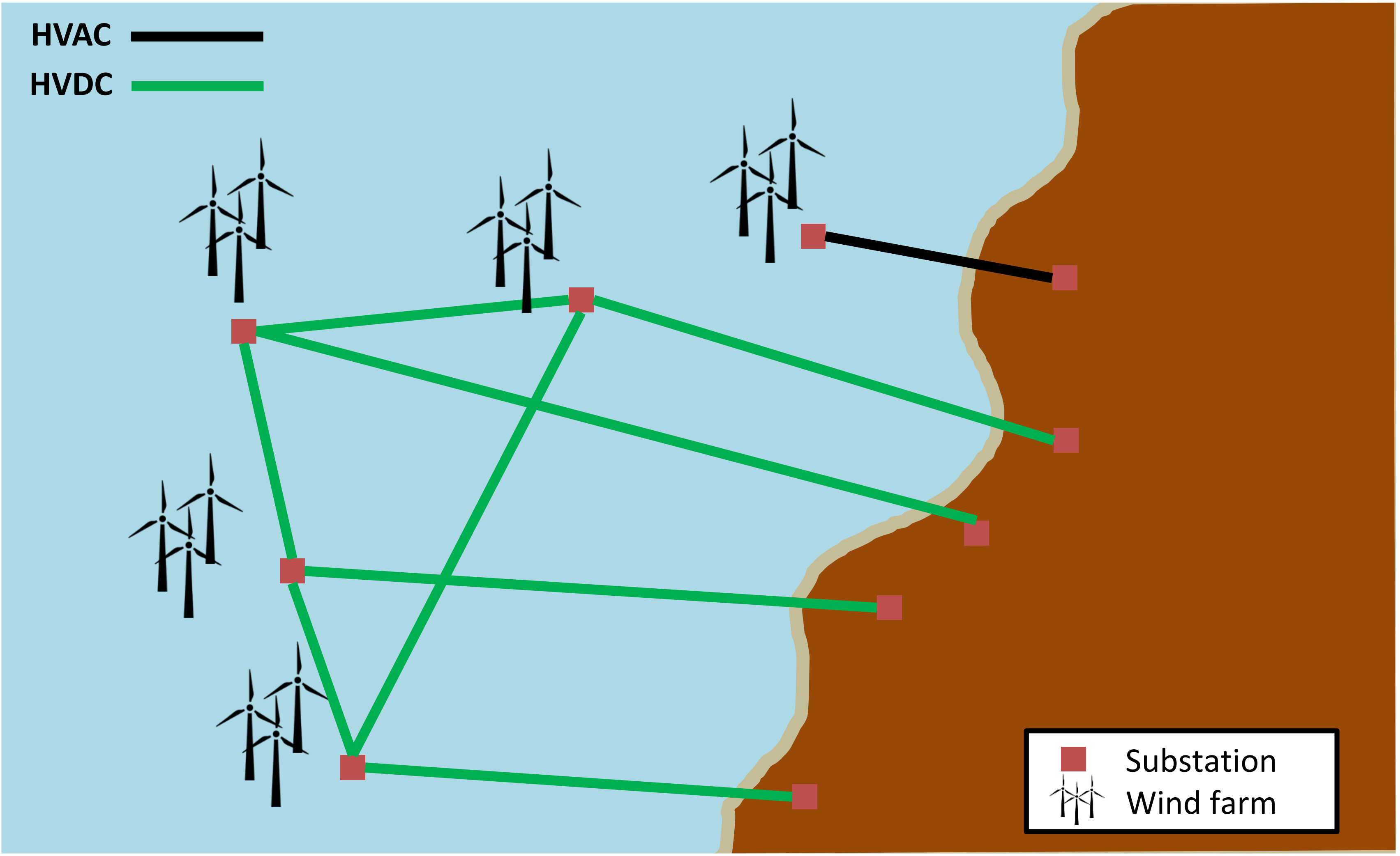
Introduction (4)



Introduction (5)



Introduction (6)



The BEST PATHS Project

BEyond State-of-the-art Technologies for re-Powering Ac corridors & multi-Terminal Hvdc Systems

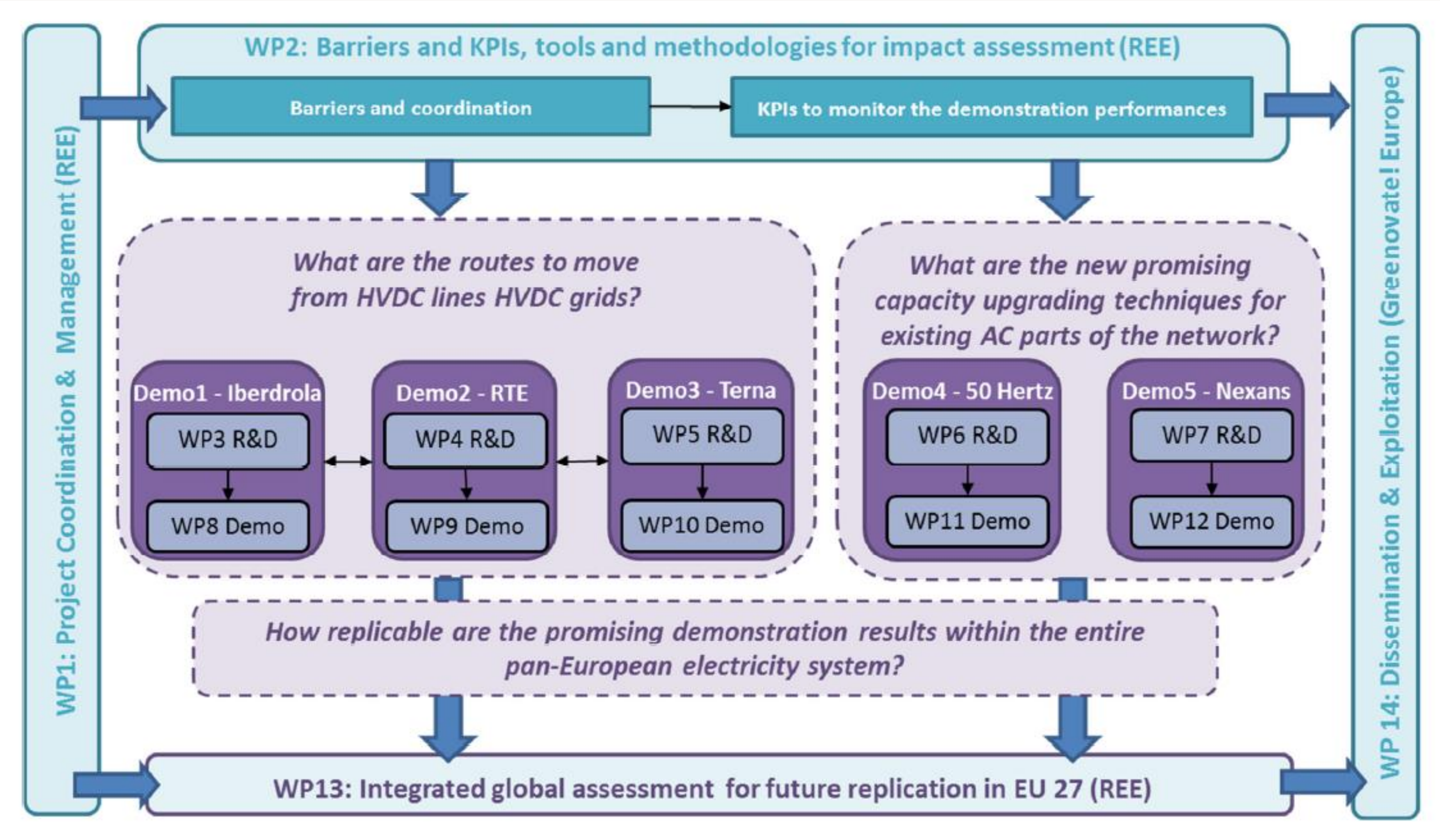
Key Figures

- **Budget** of **€62.8M,** 56% co-funded by the **European Commission** under the **7th Framework Programme for Research, Technological Development and Demonstration (EU FP7 Energy).**
- **Duration**: 01/10/2014 – 30/09/2018 (**4 years**).
- **Composition**: **5 large-scale demonstrations**, **2 replication projects**, **1 dissemination project**.

Key Aims

- Through the contribution of **40** leading **research institutions**, **industry**, **utilities**, and **transmission systems operators (8)**, the project aims to ***develop novel network technologies to increase the pan-European transmission network capacity and electricity system flexibility***.

The BEST PATHS Project (2)



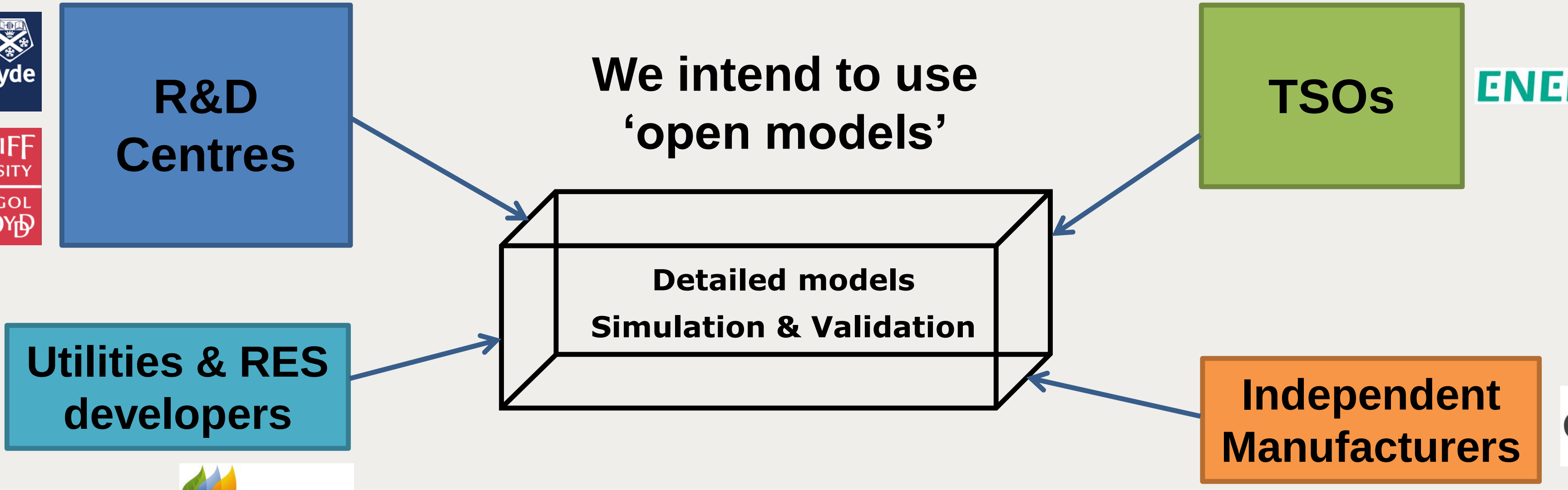
BEST PATHS Demo #1

- **Objectives:**

  1. To **investigate** the **electrical interactions** between **HVDC converters and wind turbine (WT) converters in OWFs**.
  2. To **de-risk multivendor and multi-terminal HVDC (MTDC) schemes**.
  3. To **demonstrate** the **results in a laboratory environment** using **scaled models.**
  4. To **use** the validated models to **simulate** a **real grid with OWFs connected in HVDC**.

BEST PATHS Demo #1 (2)

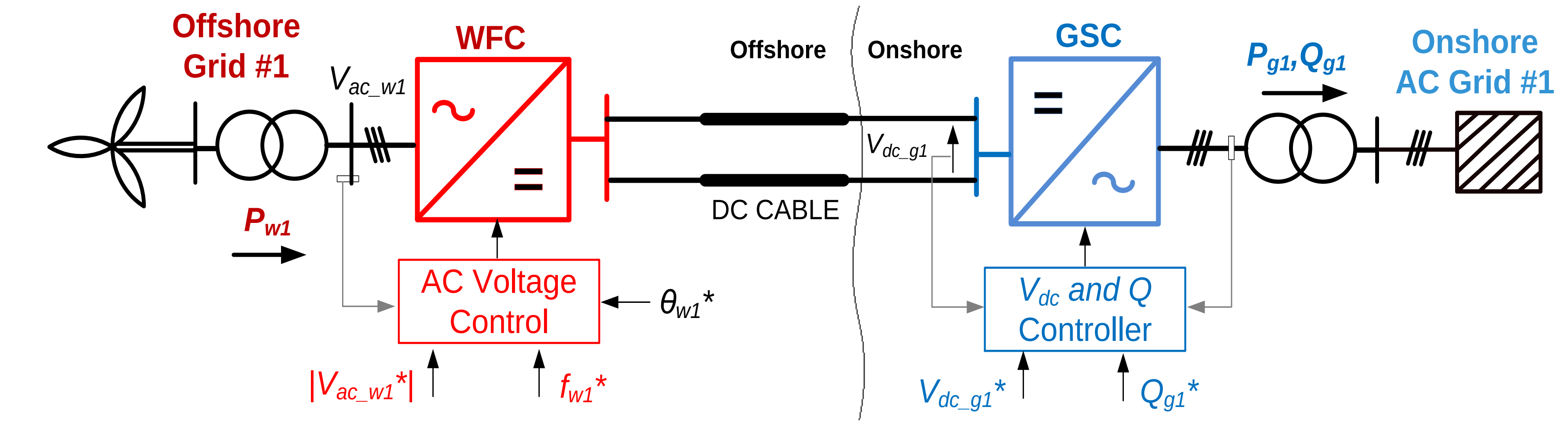
HVDC equipment manufacturers provide 'black boxes'



Network Topologies

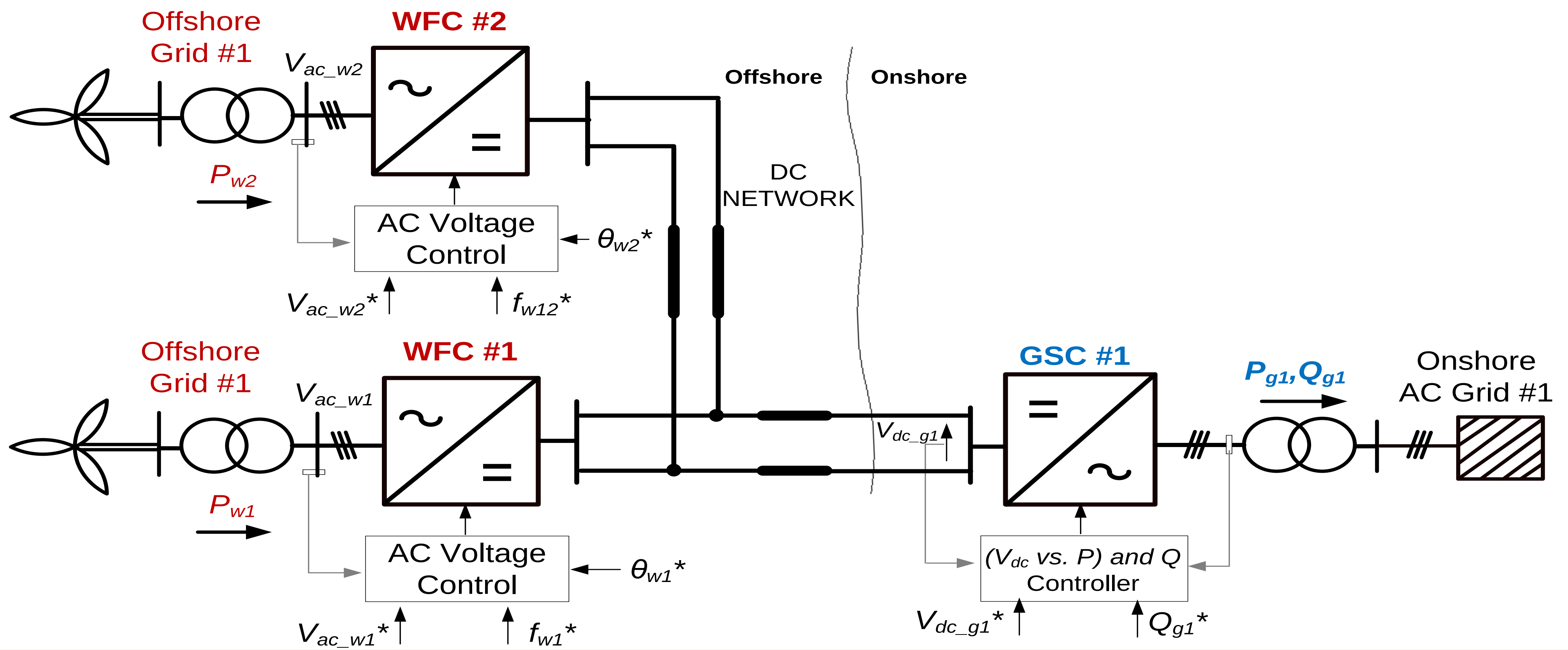
- **System configurations have been implemented in Simulink**
  - A number of ***topologies*** has been **modelled, simulated and analysed**.
  - The topologies considered constitute ***likely scenarios*** to be adopted for the transmission of offshore wind energy in future years.
  - Full details available in **Deliverable D3.1 of the BEST PATHS project**.

- **Point-to-Point HVDC Link (Topology A)**



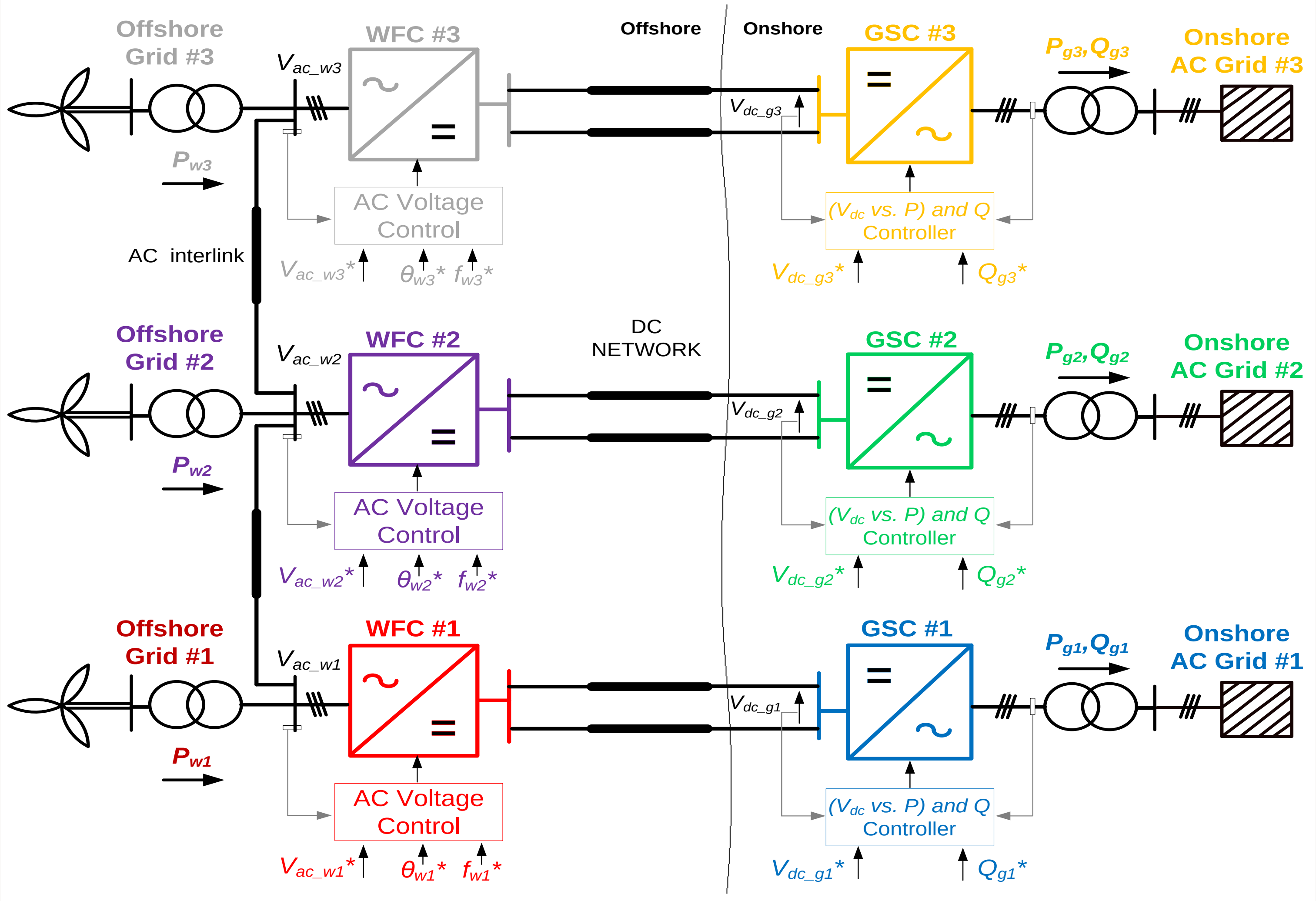
Network Topologies (2)

➢ **Three Terminal HVDC System**



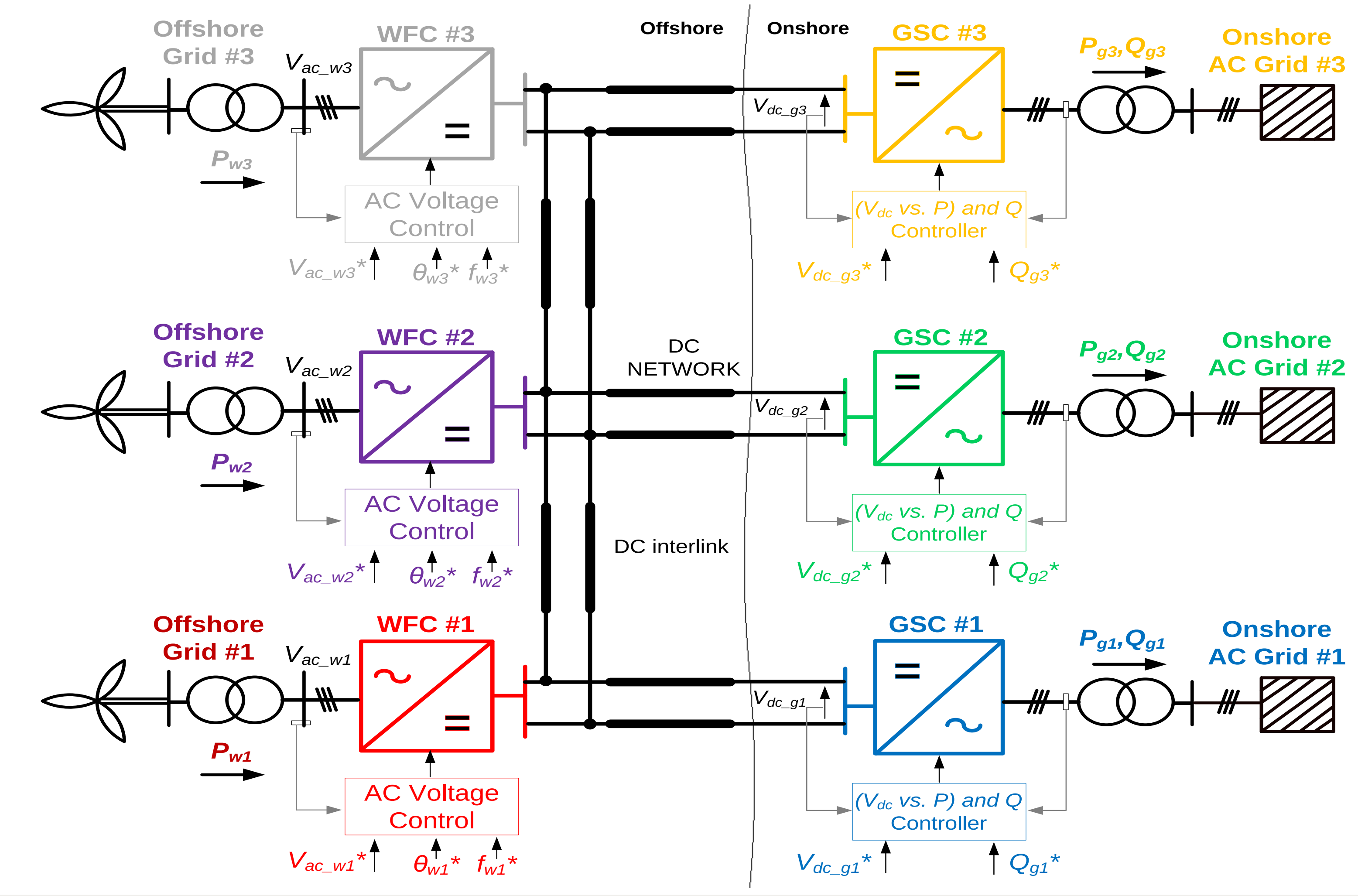
Network Topologies (3)

➢ **Six-Terminal HVDC System with Offshore AC Links (Topology B)**



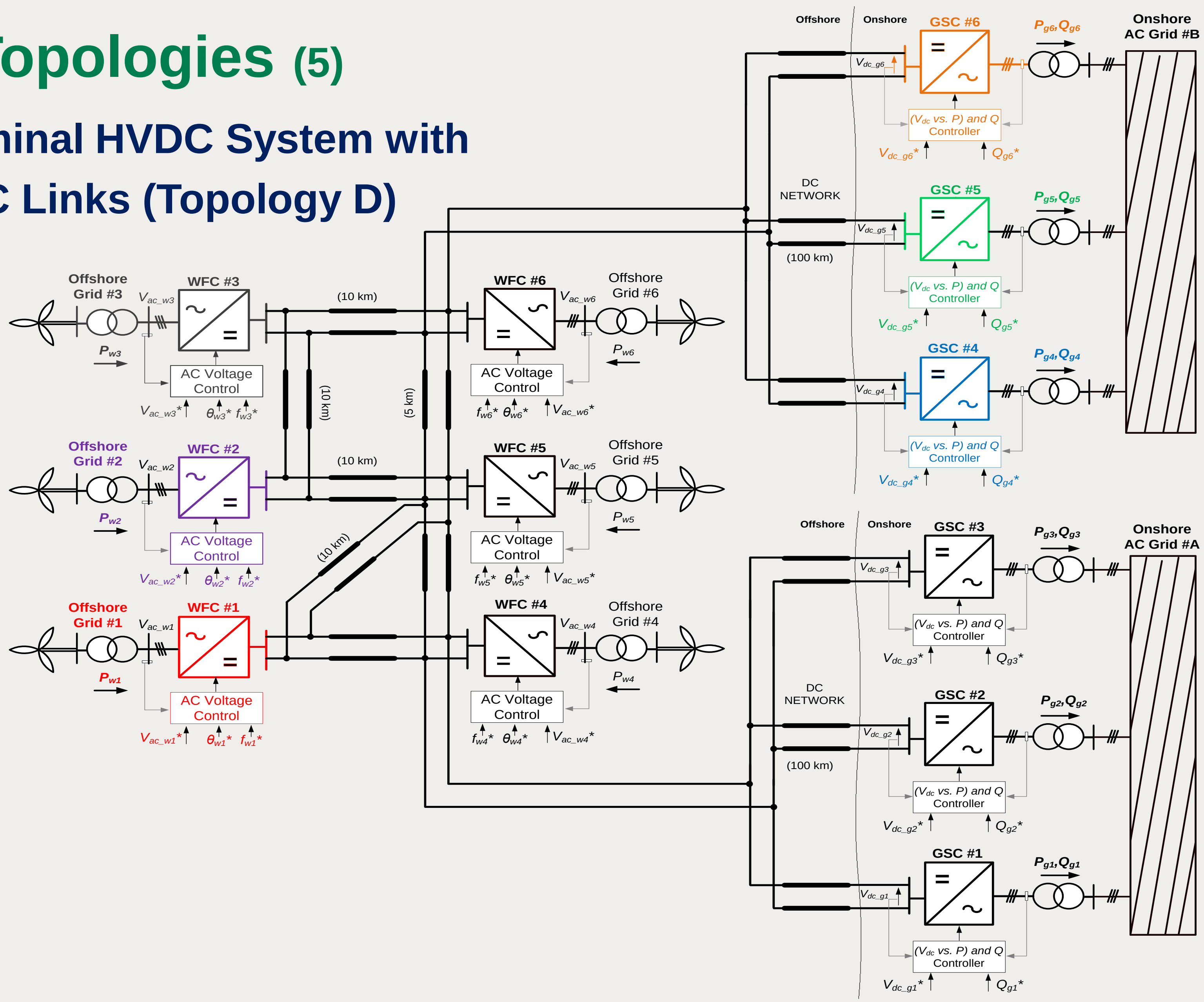
Network Topologies (4)

➢ **Six-Terminal HVDC System with Offshore DC Links (Topology C)**



Network Topologies (5)

➢ **Twelve-Terminal HVDC System with Offshore DC Links (Topology D)**



Key Performance Indicators

➢ **System configurations have been implemented in Simulink**

- To assess the **suitability of the models and proposed HVDC network topologies**, converter configurations and control algorithms, a ***set of KPIs*** have been defined.
- Full details available in **Deliverable D2.1 of the BEST PATHS project**.

KPI.D1.1 – AC/DC interactions: power and harmonics		
Steady state	Power quality	WT ramp rates

KPI.D1.2 – AC/DC Interactions – Transients & Voltage Margins	
Normal operation	Extreme operation

KPI.D1.3 – DC Protection Performance / Protection & Faults	
Protection selectivity	Peak current and clearance time

KPI.D1.4 – DC Inter-array Design		
Inter-array topology	Power unbalance	Fault tolerance

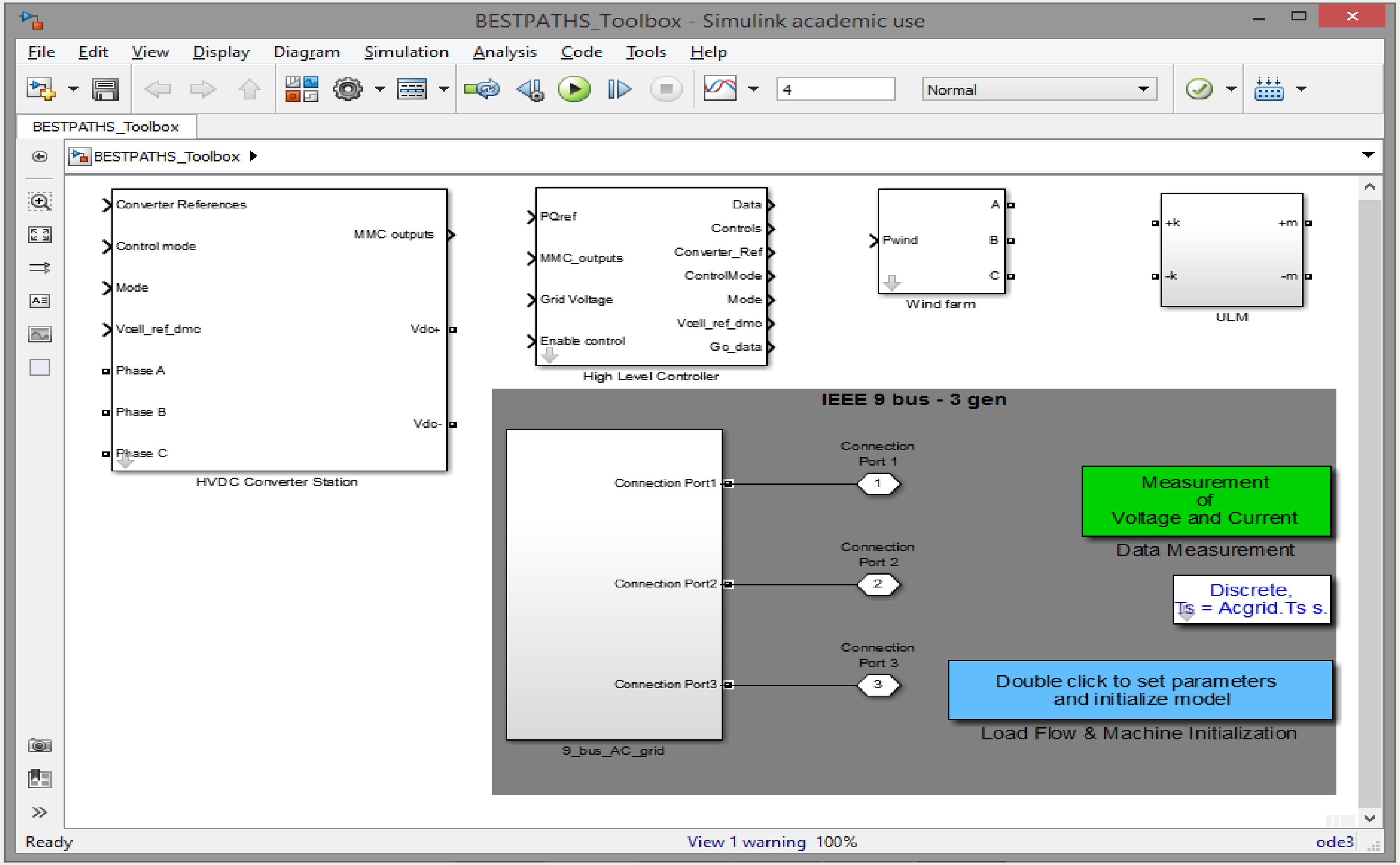
KPI.D1.5 – Resonances	
AC systems oscillation	Internal DC resonance

KPI.D1.6 – Grid Code Compliance	
Active and reactive power	Fault ride-through

The ‘Open Access’ Toolbox

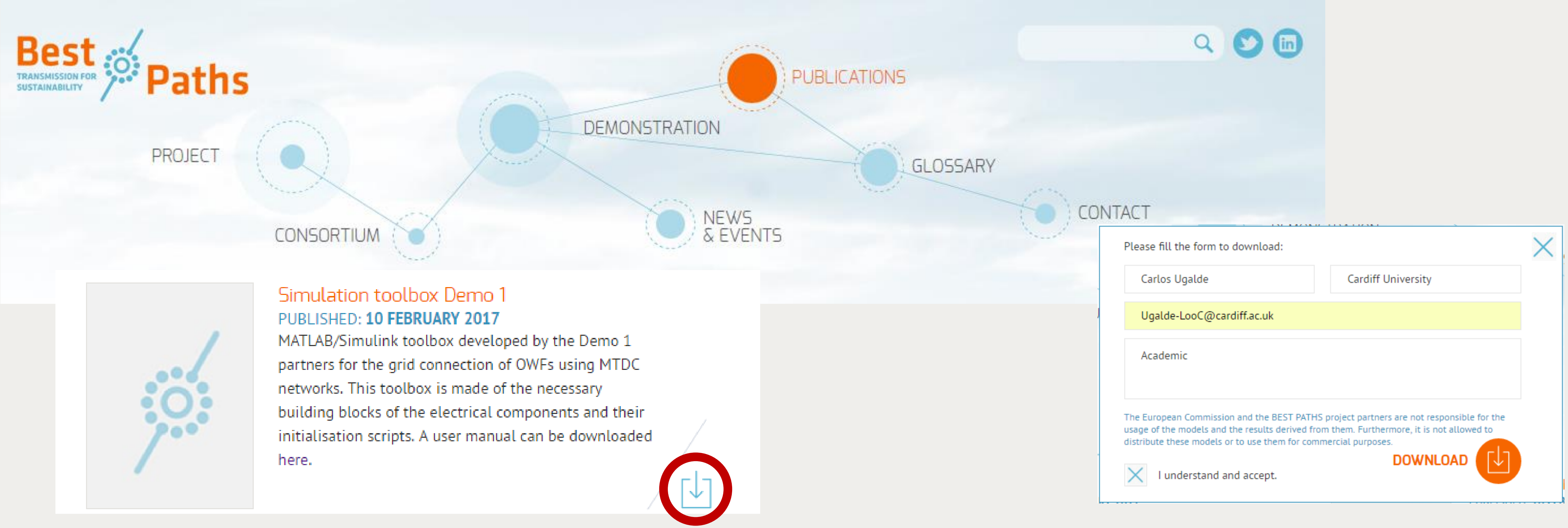
- A **set of models and control algorithms** has been **developed, simulated and assessed.**

- Their portability as ***basic building blocks*** will enable researchers and designers to study and simulate any system configuration of choice.



The ‘Open Access’ Toolbox (2)

- The models and control algorithms have been published in the BEST PATHS website as a **MATLAB ‘*Open Access’ Toolbox:* http://www.bestpaths-project.eu/**.



- The toolbox was originally presented last year in the ***13th IET Conference on AC and DC Power Transmission (ACDC2017):***
  - CE Ugalde-Loo, *et al.*, *“Open Access Simulation Toolbox for the Grid Connection of Offshore Wind Farms using Multi-Terminal HVDC Networks”, 13th IET ACDC17, Manchester, UK, 2017.*

The ‘Open Access’ Toolbox (3)

- A **user manual** is also provided, together with the published models and **accompanying examples.**

Best Paths PROJECT

BEST PATHS Demo #1

MATLAB Simulation Toolbox

(for the grid connection of offshore wind farms using multi-terminal HVDC networks)

User Manual

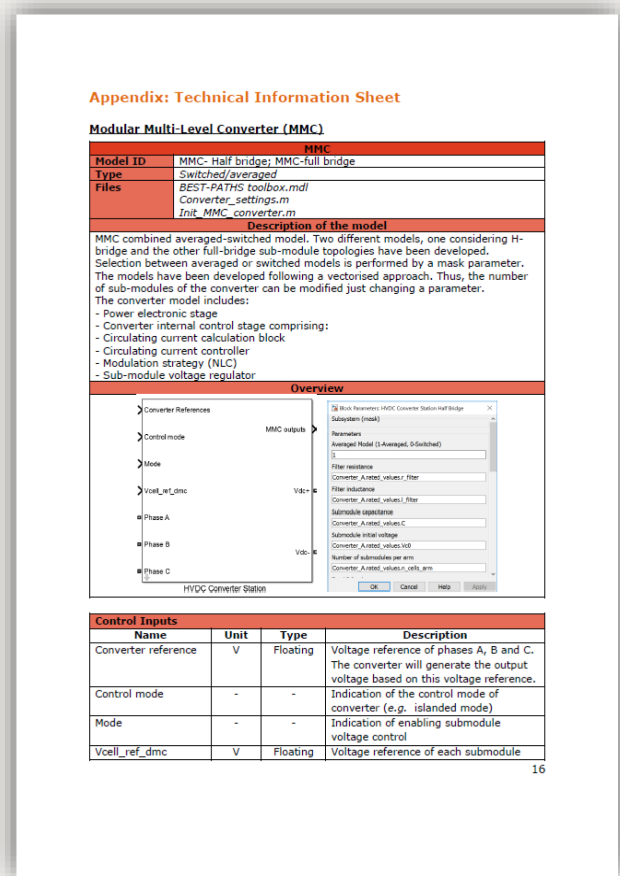
February 11th, 2017

S Wang (SW), OD Adeuyi (DA) and CE Ugalde-Loo (CUL), Cardiff University

Revision	Date	Modifications	Authors
V 1.0	11/02/2017	First version	SW, DA and CUL

SEVENTH FRAMEWORK PROGRAMME

European Commission



Appendix: Technical Information Sheet

Modular Multi-Level Converter (MMC)

MMC	
Model ID	MMC- Half bridge; MMC-full bridge
Type	*Switched/averaged*
Files	*BEST-PATHS toolbox.mdl* *Converter_settings.m* *Init_MMC_converter.m*
Description of the model	
MMC combined averaged-switched model. Two different models, one considering H-bridge and the other full-bridge sub-module topologies have been developed. Selection between averaged or switched models is performed by a mask parameter. The models have been developed following a vectorised approach. Thus, the number of sub-modules of the converter can be modified just changing a parameter. The converter model includes: - Power electronic stage - Converter internal control stage comprising: - Circulating current calculation block - Circulating current controller - Modulation strategy (NLC) - Sub-module voltage regulator	
Overview	

Control Inputs			
Name	**Unit**	**Type**	**Description**
Converter reference	V	Floating	Voltage reference of phases A, B and C. The converter will generate the output voltage based on this voltage reference.
Control mode	-	-	Indication of the control mode of converter (*e.g.* islanded mode)
Mode	-	-	Indication of enabling submodule voltage control
Vcell_ref_dmc	V	Floating	Voltage reference of each submodule

16

- Full details of the models available in **Deliverable D3.1 of the BEST PATHS project**.

The ‘Open Access’ Toolbox (4)

➢ Converter Stations

- **Averaged** and **switched** models for an **MMC.**
- The combined **averaged-switched** model consists of two blocks:
  - ***Power electronics block***,
  - ***Low level controller block*:** circulating current reference generation, circulating current controller, nearest level control modulation strategy & sub-module voltage regulator.

➢ AC Grid

- AC network adapted from the classical ***nine-bus power system***.

➢ DC Cable

- The **DC cable section** has been modelled as a one-phase, frequency-dependent, **travelling wave model**.
- It is based on the ***universal line model*** **(ULM)**, which takes into account the frequency dependence of parameters.

The ‘Open Access’ Toolbox (5)

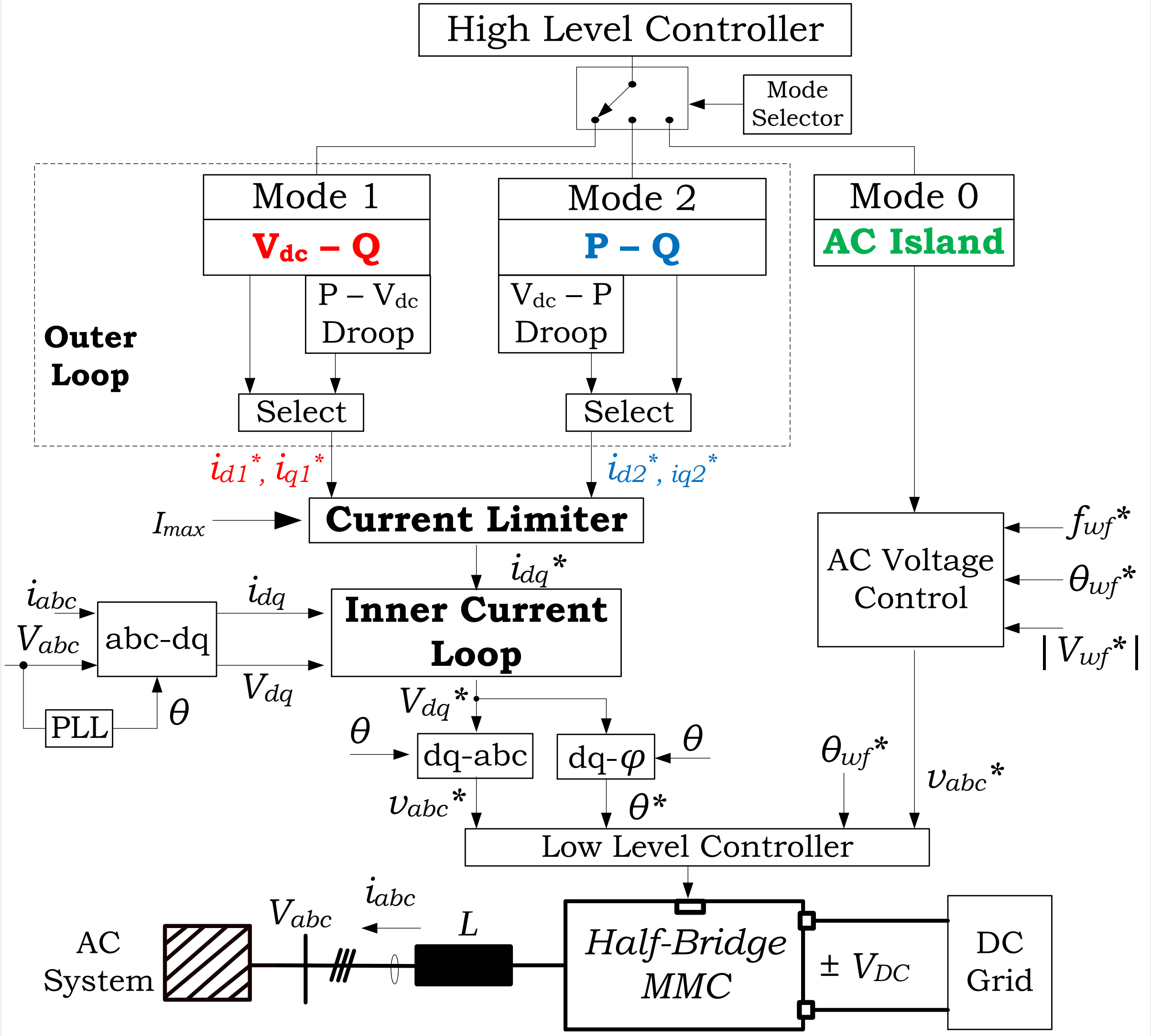
➢ Wind Farm

- It accurately represents the behaviour of an **aggregated OWF**.
- To avoid large simulation times and undesirable computer burden, simplifications have been carried out in the electrical system:
  - The converter of the a **wind turbine generator (WTG)** is modelled with ***averaged-model based voltage sources***.
  - A ***current source*** represents the remaining WTGs of the OWF. The **current injection** of the first WTG is properly **scaled** to complete the rated power of the whole OWF.
- The detailed WTG contains:
  - A ***permanent magnet synchronous generator*** model;
  - Averaged models: ***machine- and grid-side converters***, including filters and ***DC link***;
  - An LV/MV ***transformer*** and ***internal control algorithms***.

The 'Open Access' Toolbox (6)

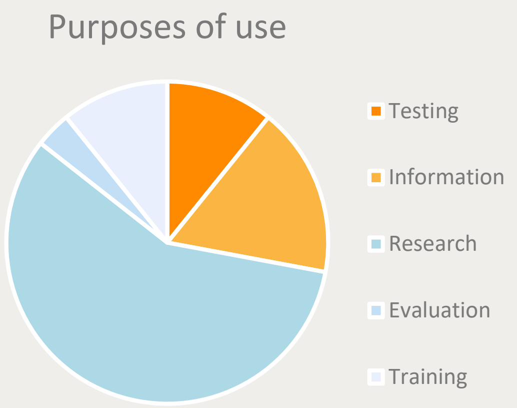
➢ High-Level Controller

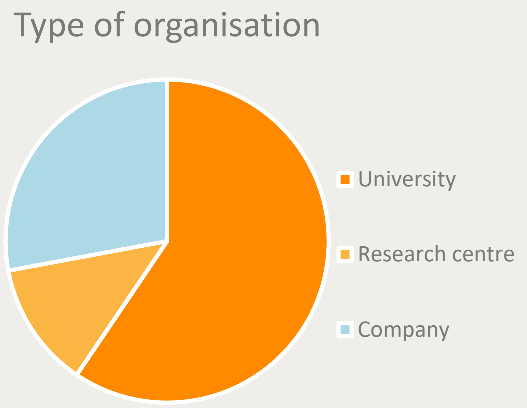
- It considers converter operation in ***three control modes.***
- The aim is to cover the main control needs for different system configurations.
  - **Mode 0:** V_{ac} voltage control;
  - **Mode 1:** $V_{dc} - Q$ control scheme with a $P - V_{dc}$ droop;
  - **Mode 2:** $P - Q$ control scheme with a $V_{dc} - P$ droop.



The 'Open Access' Toolbox (7)

- Toolbox and user manual uploaded on BEST PATHS website on 14th February 2017.
- Presentation at ***13th IET ACDC2017***; advertisement via social media and on project website.
- >**5,100 new users** were been recorded on the website since the toolbox was uploaded.
- The toolbox has been downloaded by >**115 different users** (until May 2019).





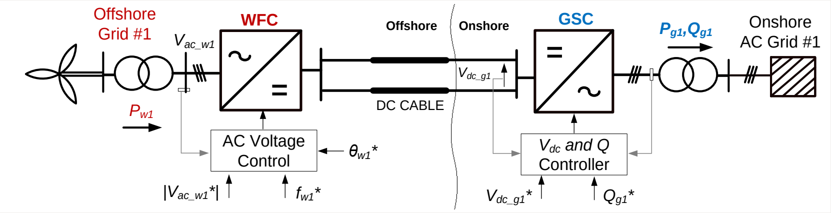
  - **Universities** include Aalborg University, KU Leuven, Fukui University of Technology, Imperial College London, Technical University of Denmark, University College of Dublin, Ensam, Technical University of Darmstadt, Technical University of Eindhoven, University College London, Pontifical Comillas University, King Fahd University of Petroleum and Minerals, Shanghai Jiao Tong University, Huazhong university, Florida State University, and Technical University Kaiserslautern.
  - **Research centres** include KTH Royal Institute of Technology, the SuperGrid Institute, GridLab, IREC (Institut de Recerca en Energia de Catalunya) and L2EP (Laboratoire d'Electrotechnique et Electronique de Puissance, Lille).
  - **Companies** include Siemens, Tractebel, Sarawak Energy, DNV GL, IBM Research, SP Energy Networks, TenneT Offshore, Nissin, Enstore, SCiBreak, and General Electric.

Simulation Results

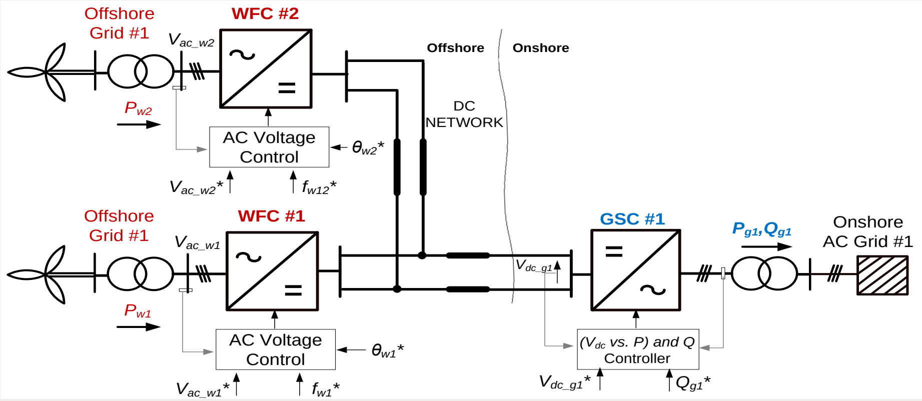
➢ EXAMPLE: KPI Assessment

- Simulation results for **three topologies** are presented.
- A **subset of the KPIs** is shown.

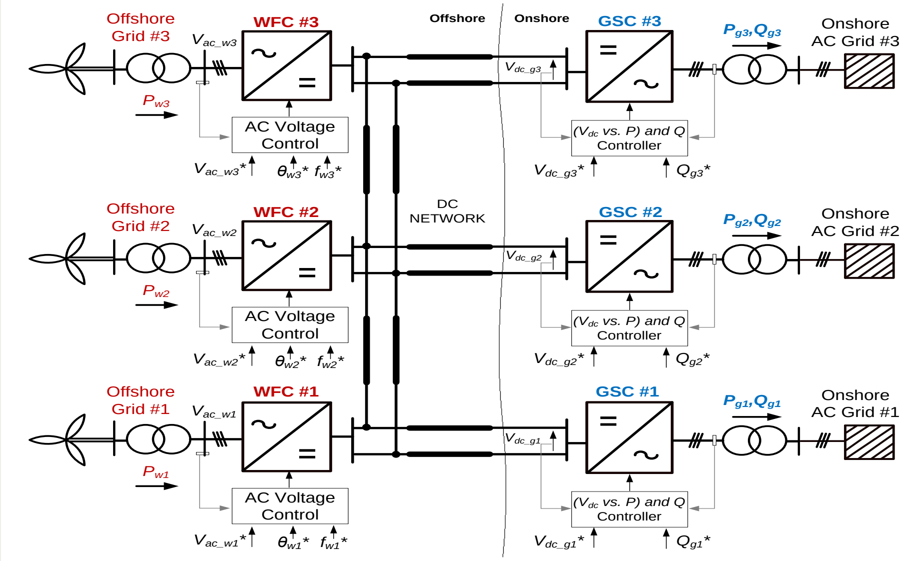
Topology 1



Topology 2



Topology 3



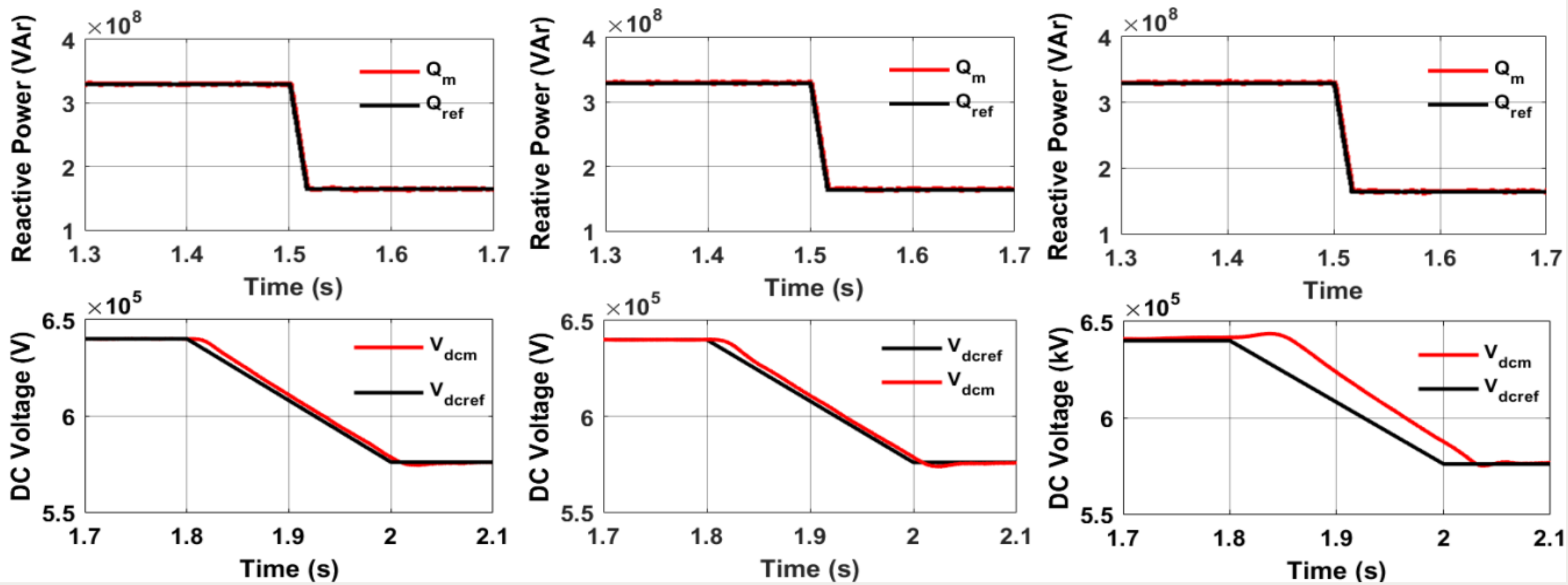
- Full details of KPI assessment for all defined topologies available in **Deliverable D3.2 of the BEST PATHS project**.

Simulation Results (2)

➢ Assessment of KPI.D1.1 – Steady state error (SSE)

- The converter control performance is assessed when references for ***DC voltage and reactive power*** are changed to ***onshore converter*** GSC in Topologies 1 and 2 and GSC2 in topology 3.
  - Reactive power changed from 330 MVAr to 165 MVAr at 1.5 s;
  - DC voltage changed from 640 kV to 576 kV at 1.8 s.

Topology 1 Topology 2 Topology 3

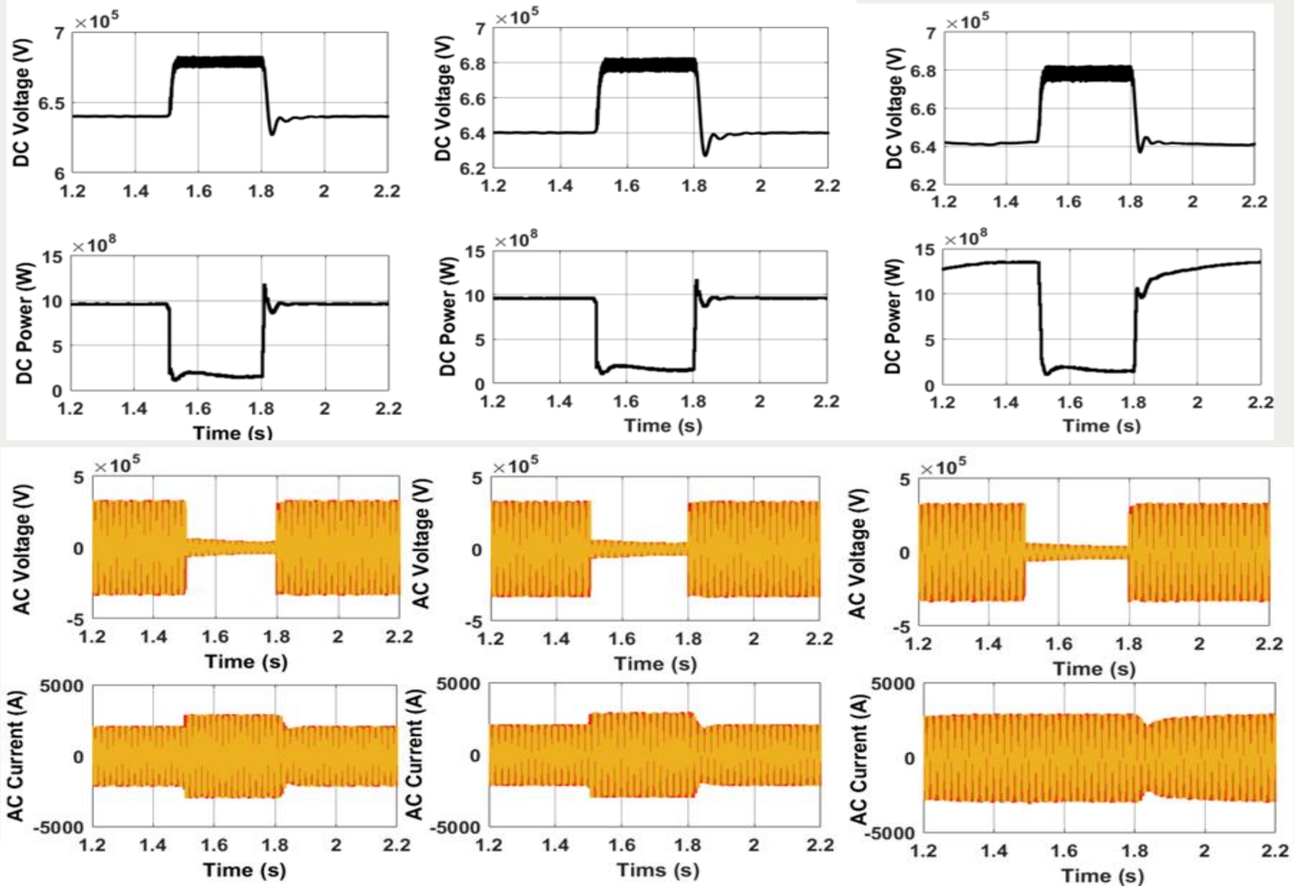


Simulation Results (3)

➢ Assessment of KPI.D1.6 – Grid Code compliance

- The ***AC fault ride-through capability*** of the systems is evaluated.
  - A voltage dip at an onshore grid converter is applied at 1.5 s during 300 ms, reducing the AC voltage from 1 p.u. to 0.15 p.u.

Topology 1 **Topology 2** **Topology 3**

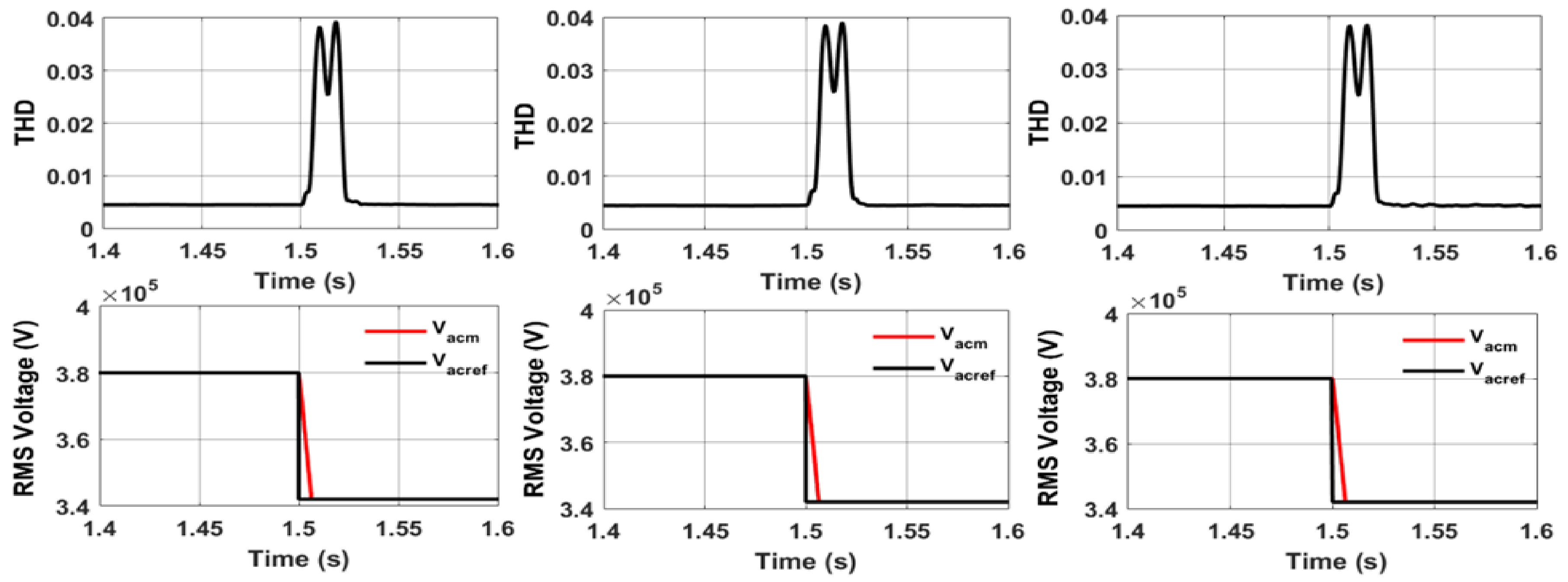


Simulation Results (4)

➢ Assessment of KPI.D1.1 – Harmonics and SSE

- The THD of the AC voltage and the converter performance are evaluated during ***AC voltage regulation (offshore converter).***
  - The offshore AC voltage (rms) is changed from 1 p.u. (380 kV) to 0.9 p.u. (342 kV) at 1.5 s.

Topology 1 **Topology 2** **Topology 3**



Simulation Results (5)

➢ KPI Assessment Summary

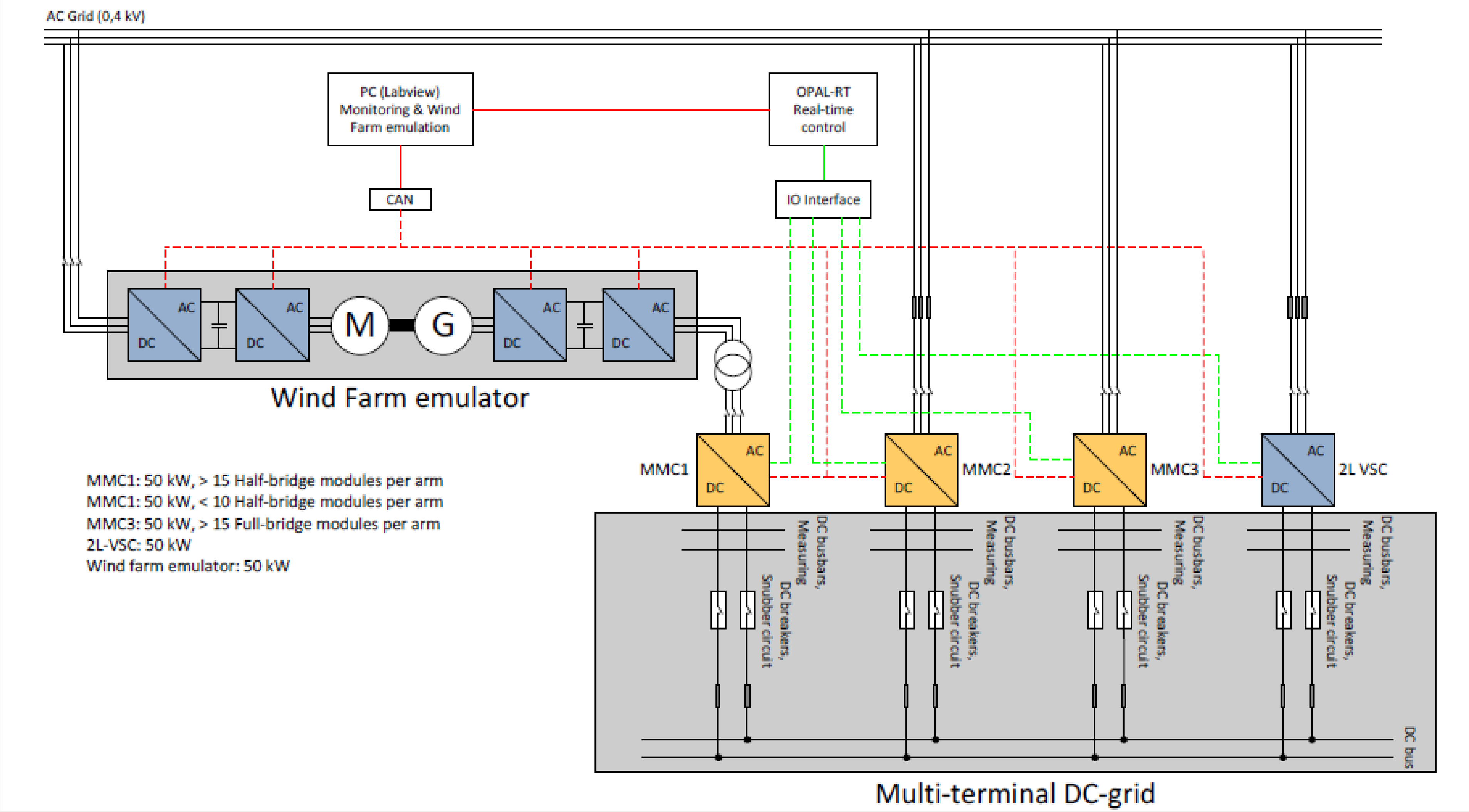
KPI	Description	Status	
1.1	Steady State AC/DC Interactions	✓ Fully Met	
1.2	Transient AC/DC Interactions	○ Partially met	Due to converter overloading and DC overvoltage during extreme conditions (e.g. AC faults). Overloading sustained for a very short time <300ms and braking resistor prevents overvoltage.
1.3	Protection Performance	✓ Fully Met	
1.4	DC Inter-array Design	✓ Fully Met	
1.5	Resonances	✓ Fully Met	
1.6	Grid Code Compliance	○ Partially met	Due to steady-state error between actual and reference active power during frequency oscillations on the AC grid of Topology A & B.

- Full details available in **Deliverable D3.2 of the BEST PATHS project.**

Real-Time Demonstrator

- **Built in the premises of SINTEF (Trondheim, Norway), it aims to:**
  - **Provide experimental validation** to the results obtained from simulations:
    - Establish a correspondence between simulation and experimental setup on single components and at system level;
    - Identify relevant scenarios to test in the laboratory;
    - Perform experiments.
  - **Reduce** risks of HVDC link connecting OWFs.
  - **Validate** meshed HVDC grids with different VSC technologies.
  - **Foster** new suppliers and sub-suppliers of HVDC technology.
- **Facilities include:**
  - a **four-terminal 50 kW HVDC grid** with 3 VSC-based MMCs and 1 two-level VSC;
  - a 20 kW **synchronous generator**;
  - **DC circuit breakers**;
  - a **wind emulator**;
  - a **real-time simulator system** and **control unit** (OPAL-RT).

Real-Time Demonstrator (2)



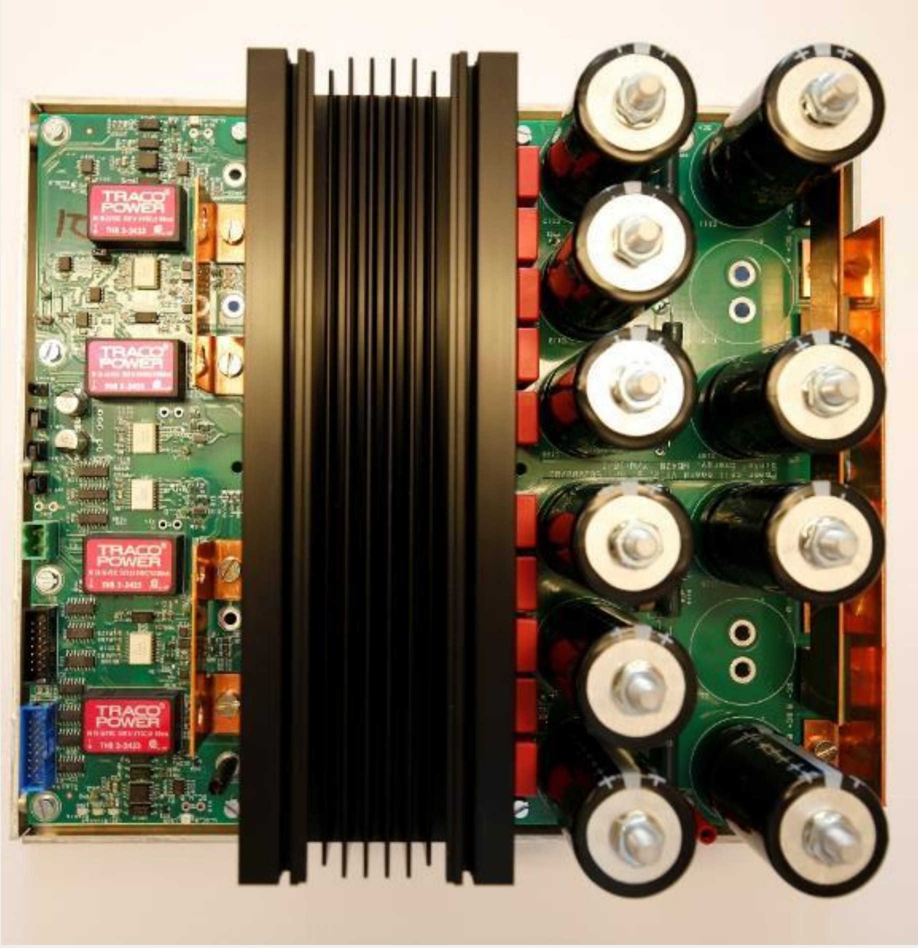
- Further details on the demonstrator available in **Deliverable D8.1 of the BEST PATHS project**.

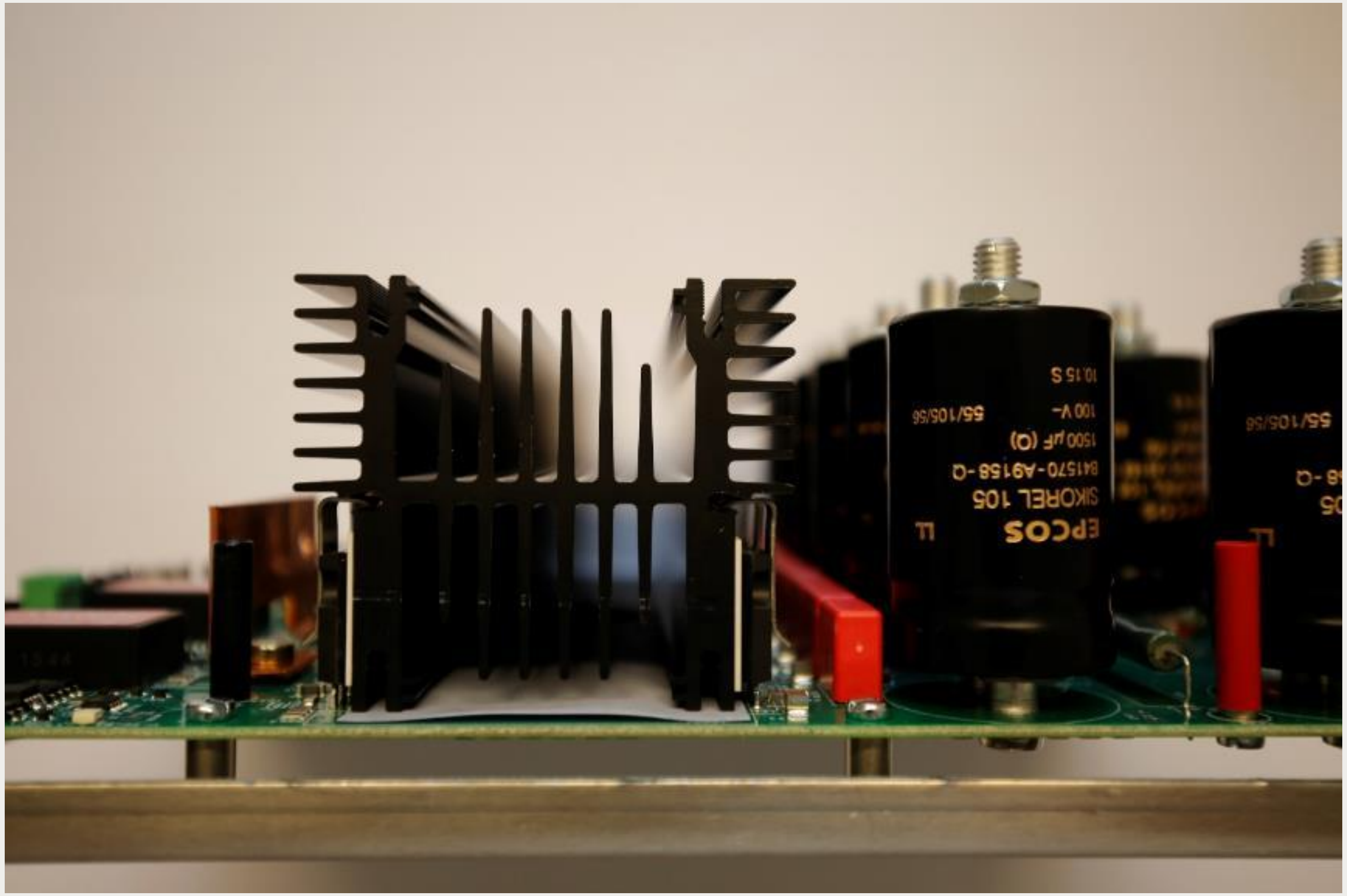
Real-Time Demonstrator (3)

➢ **National SmartGrid Laboratory (SINTEF)**

Real-Time Demonstrator (4)

➢ **MMC Power Cells Boards**





Real-Time Demonstrator (5)

- **MMC Assembling Stages**

Real-Time Demonstrator (6)

➤ **MMC Assembling Stages (2)**

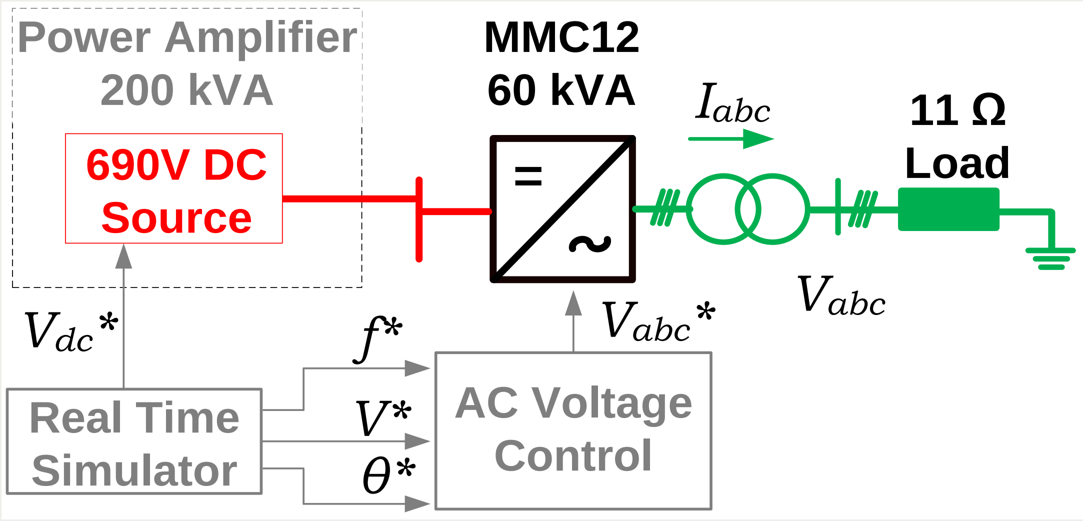
Experimental Results

➢ **Matching converter parameters of demonstrator with those of simulation models**

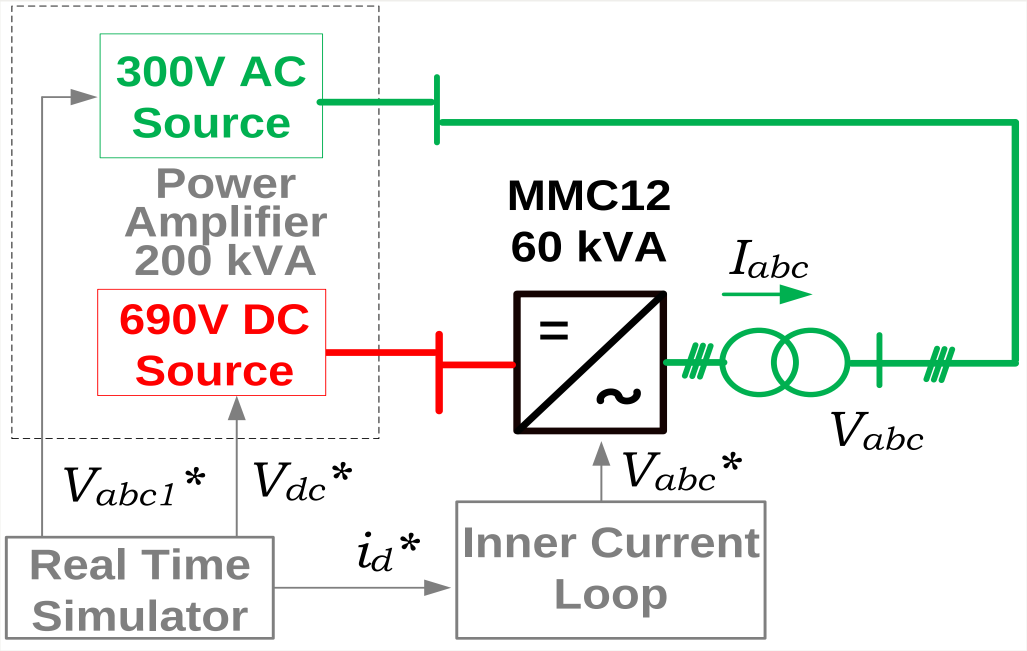
- The **matching process** was based on **experimental results** from the demonstrator running in **open loop connected to a resistive load**.
- This way, the **MMC arm current** and **submodule voltages** would depend only on **converter parameters** and **not on the control action**.
- MMC parameters were iteratively matched, including **arm inductance**, **arm resistance**, and **submodule capacitance**.
- With component parameters matched, the **delay** between measurements of **arm current and submodule voltage** could be determined from experimental results.
- The main aim of this iterative exercise was to:
  - **Increase** the **accuracy** of the simulation models.
  - **Obtain** a highly **reliable** representation to perform offline tests.
  - Help **ensure** adequate **performance** of test configurations.
  - **Identify adverse** operating conditions via software.

Experimental Results (2)

➢ **Matching converter parameters of demonstrator with those of simulation models** (continued…)



- **MMC** with **AC voltage control** connected to a **load resistance**.
    - The control schemes creates an AC voltage with a reference amplitude of 330 V and 50 Hz.

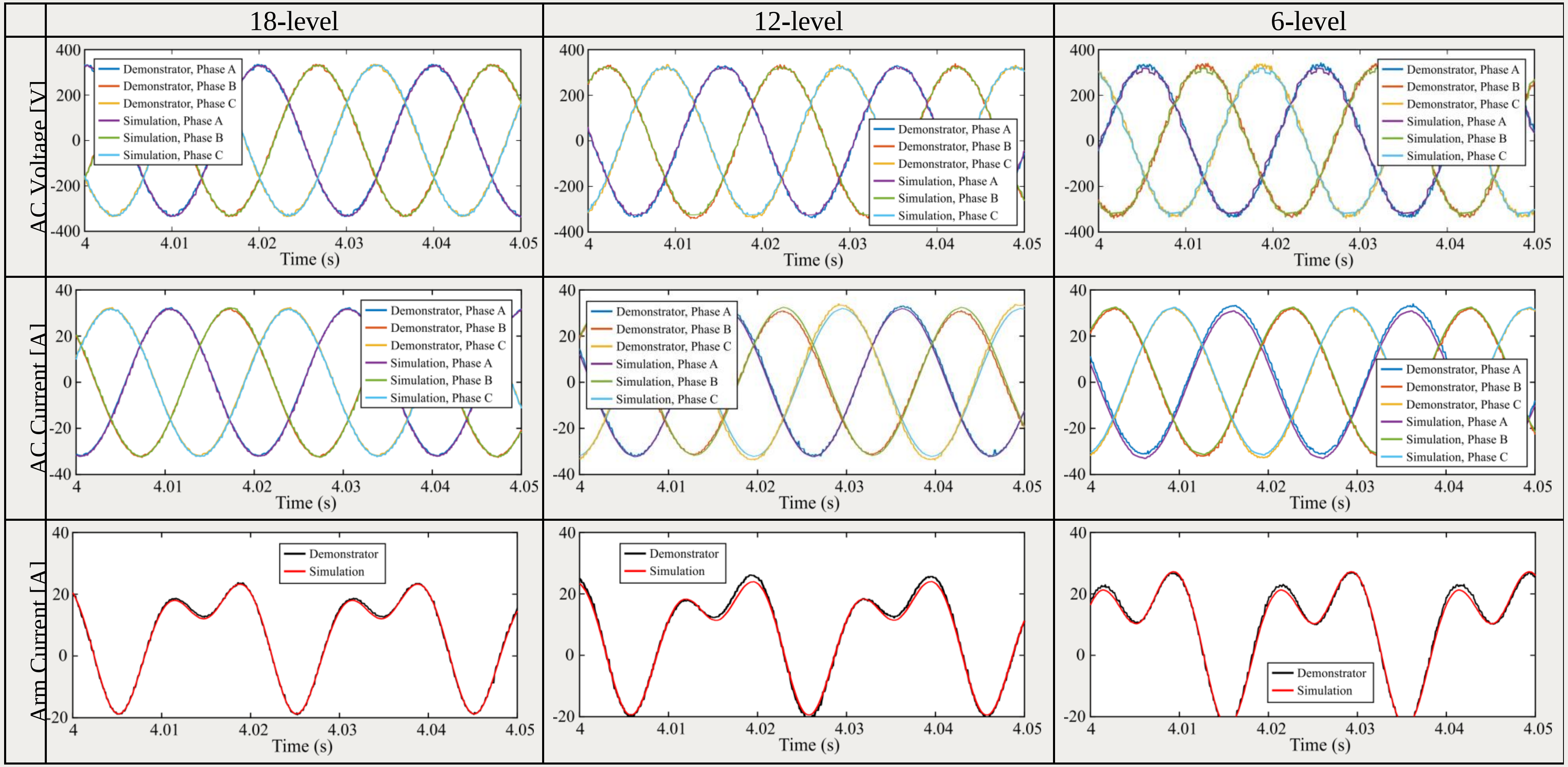


- **MMC** with **inner current control** connected to an **islanded AC grid**.

Experimental Results (3)

- **Matching converter parameters of demonstrator with those of simulation models (continued…)**

MMC with AC voltage control connected to load resistance

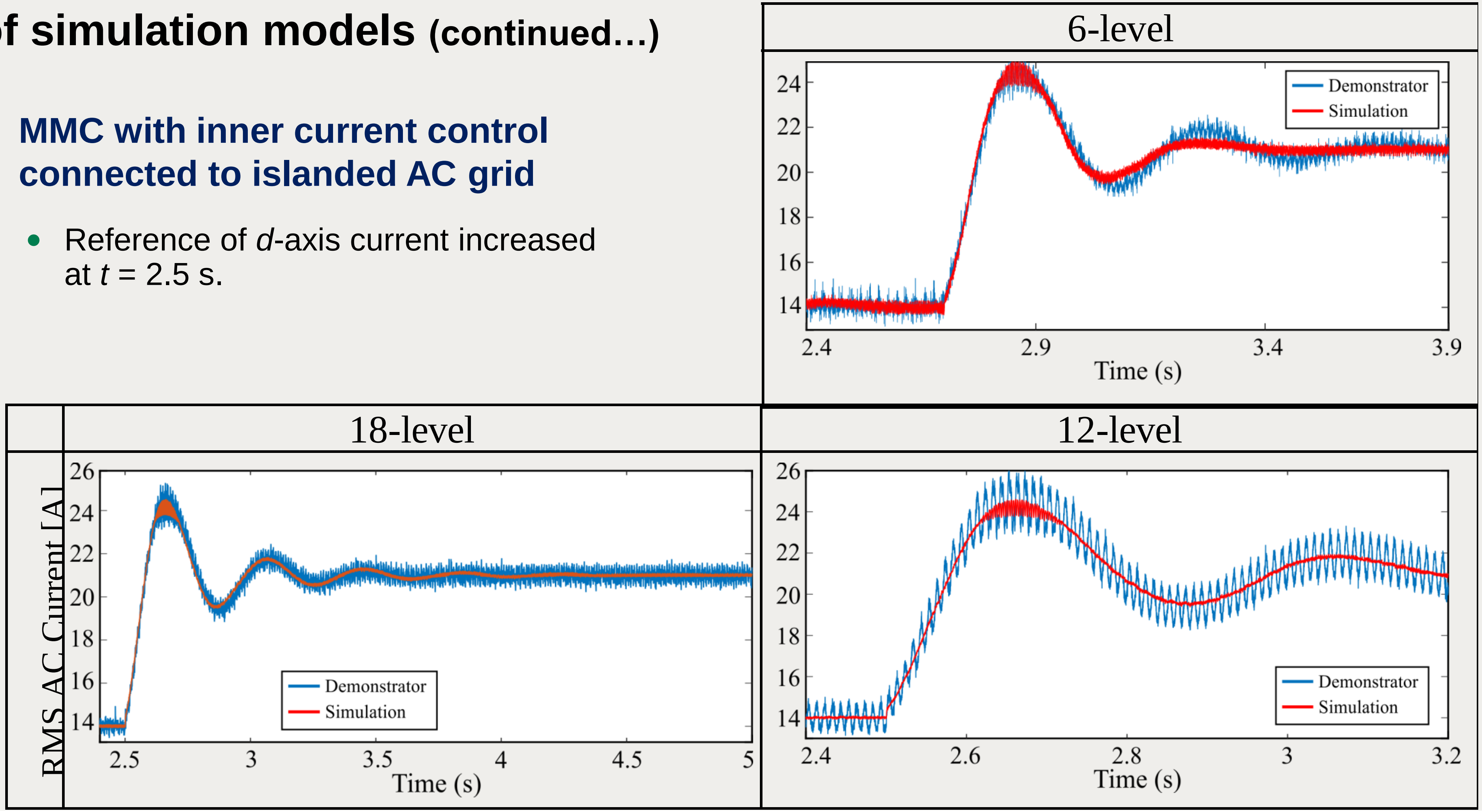


Experimental Results (4)

➢ **Matching converter parameters of demonstrator with those of simulation models (continued…)**

MMC with inner current control connected to islanded AC grid

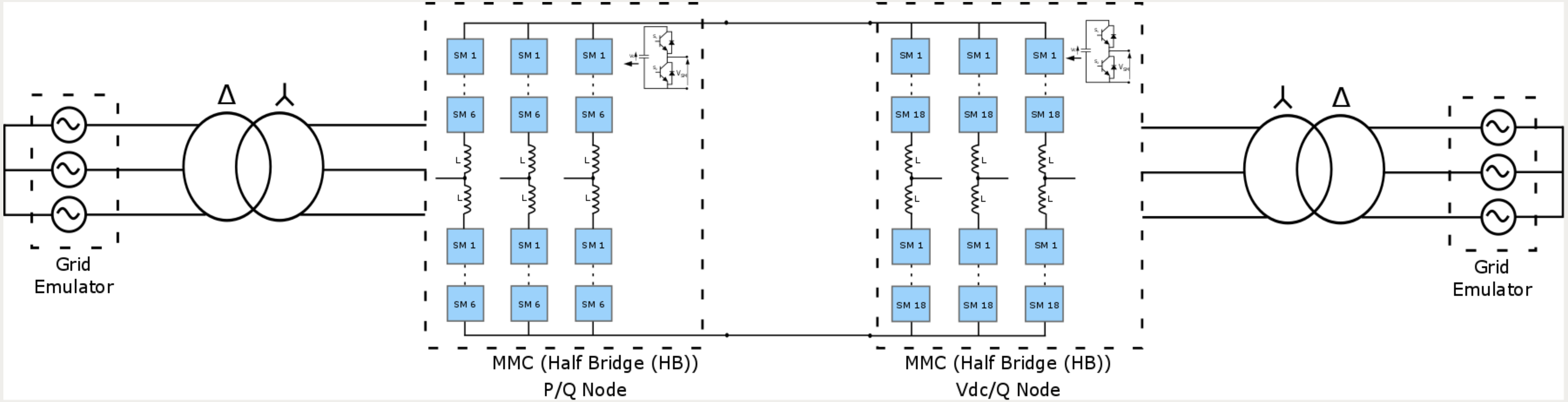
- Reference of *d*-axis current increased at t = 2.5 s.



Experimental Results (5)

➢ Experimental Validation for Topology A

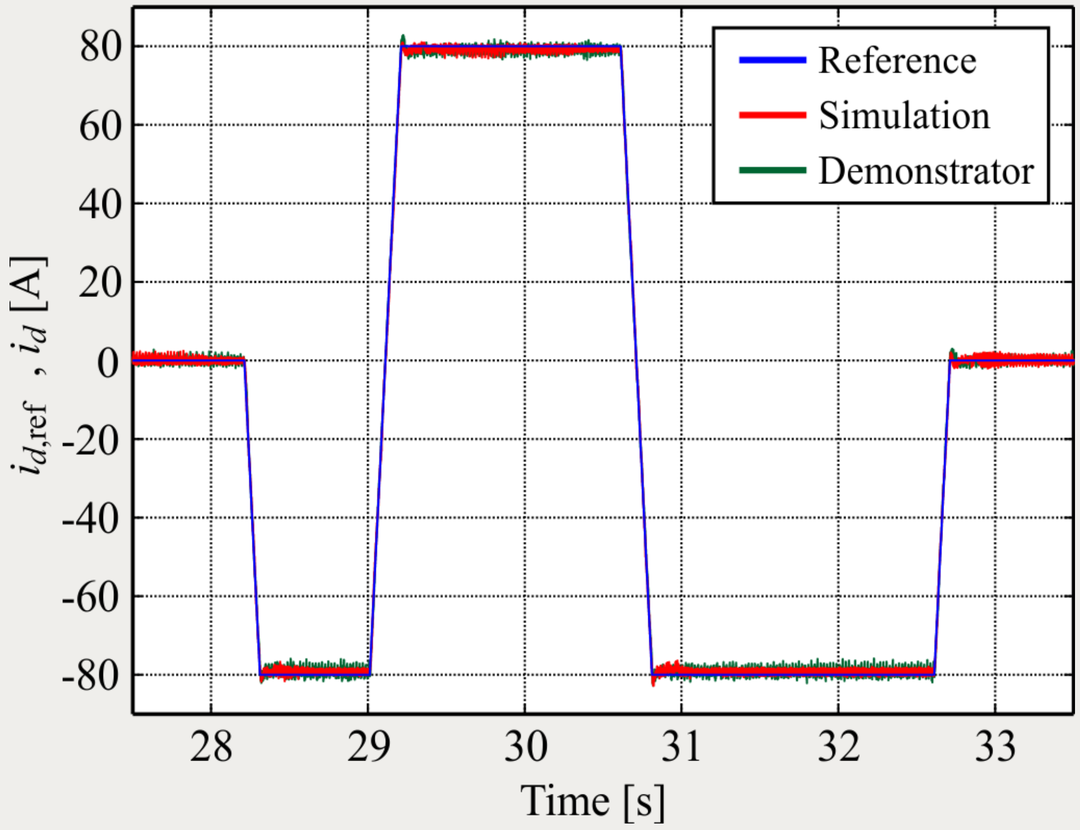
- **Sending converter** (6-level half-bridge) uses a nearest level modulation (NLM) and operates in a ***P*/*Q* mode**.
- **Receiving converter** (18-level half-bridge) uses a phase disposition PWM (PD-PWM) and operates in a **V_{dc}/*Q* mode**.
- Both converters make use of a **circulating current regulator** and **voltage balancing algorithms**.

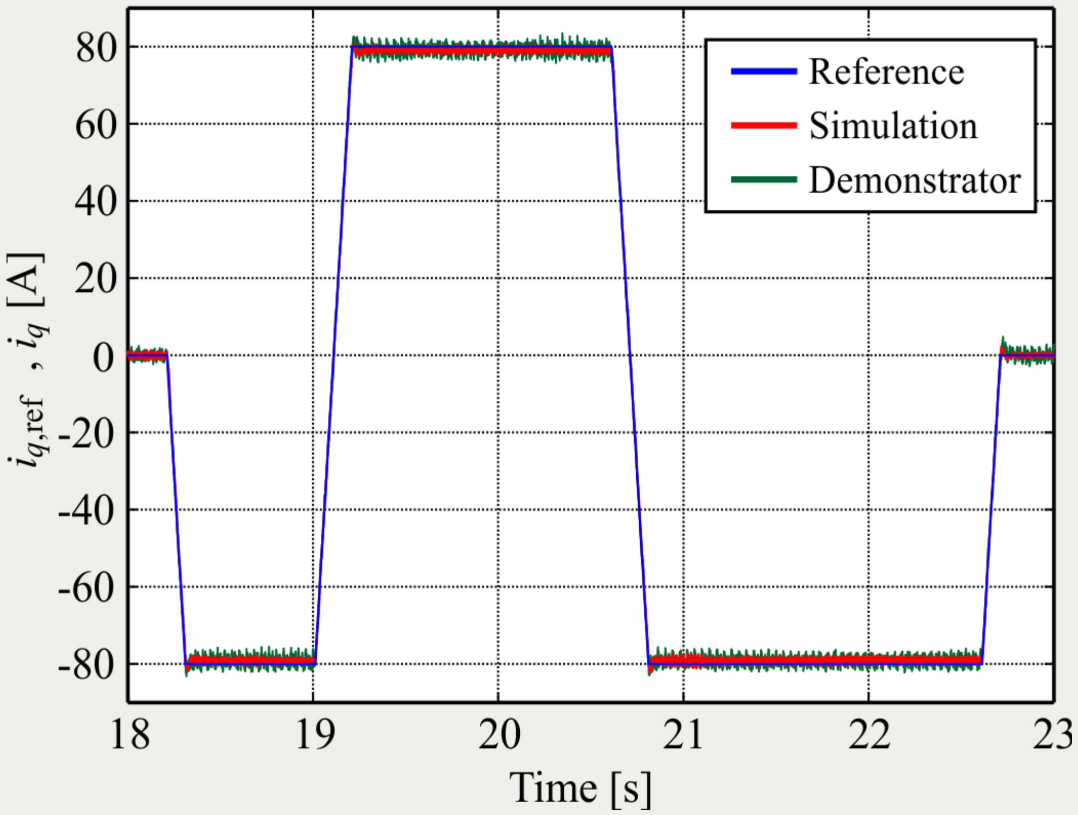


Experimental Results (6)

➢ **Experimental Validation for Topology A (continued…)**

- **Reference currents** at the **sending end**:

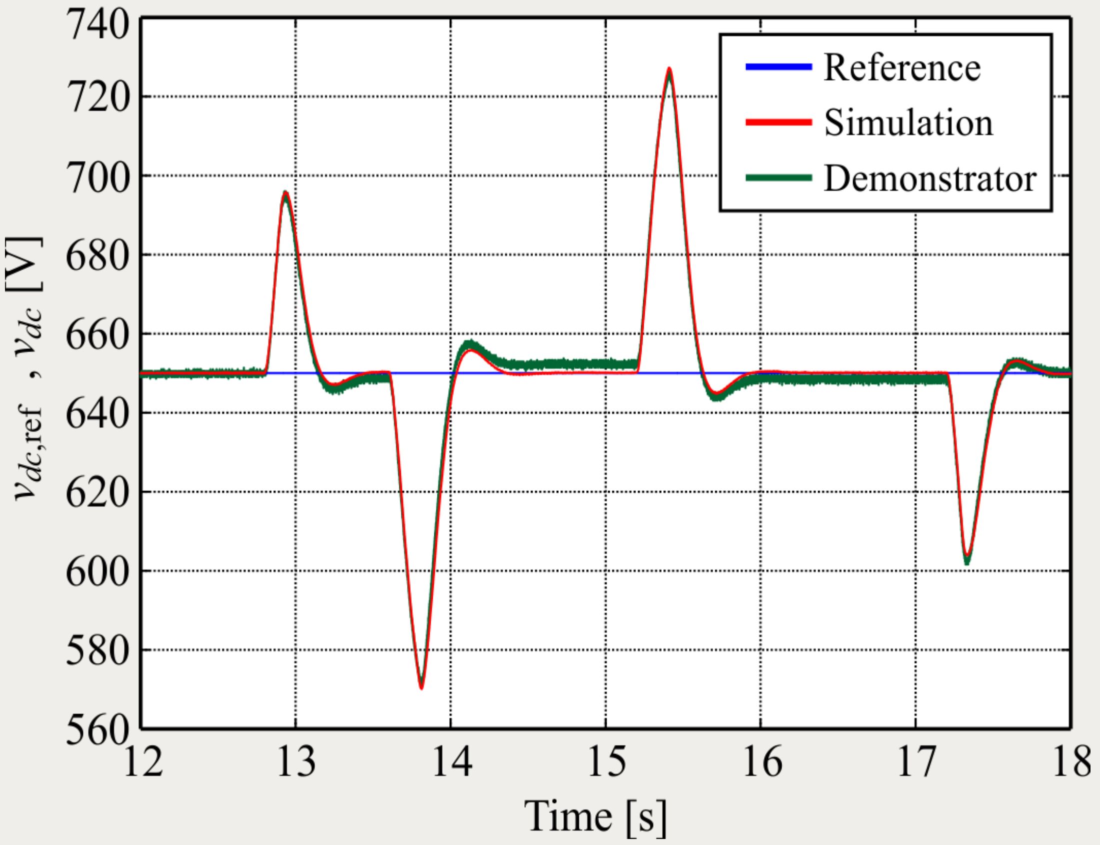


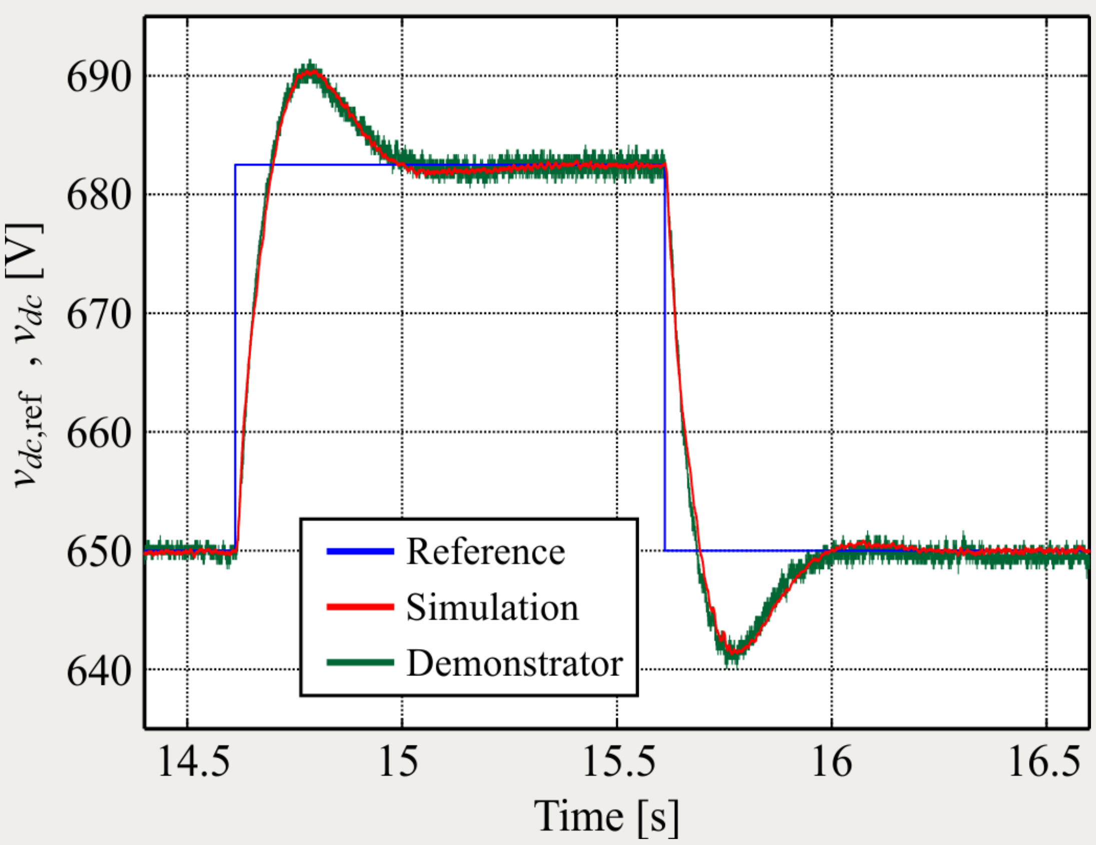


Experimental Results (7)

➢ **Experimental Validation for Topology A (continued…)**

- **DC voltage**. Performance upon changes in current reference i_d and changes in the DC voltage reference:

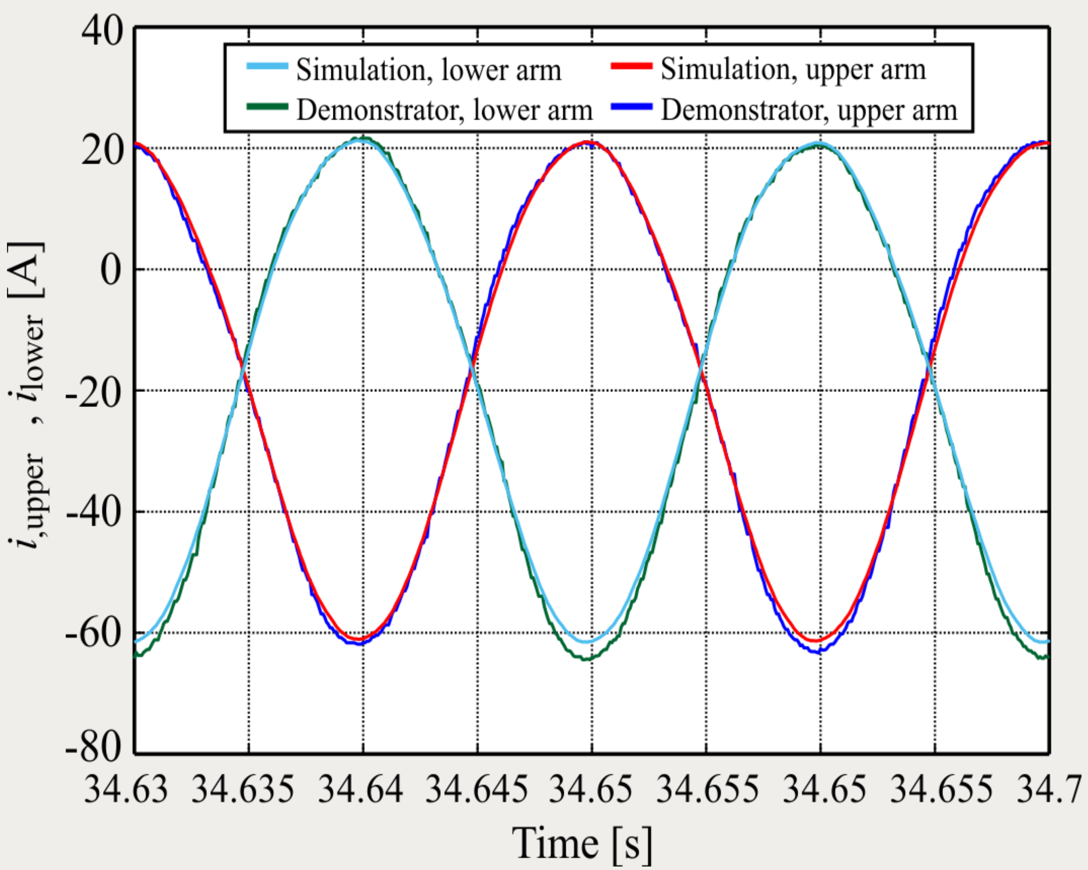


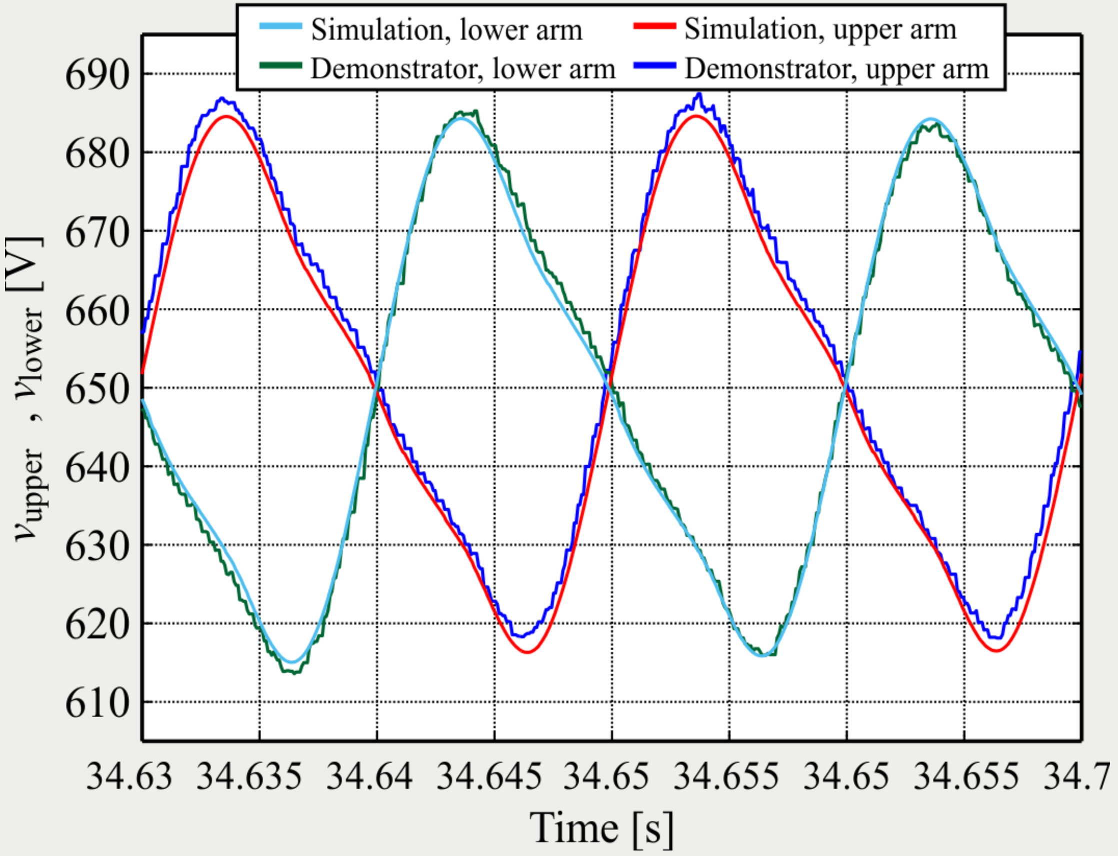


Experimental Results (8)

➢ **Experimental Validation for Topology A (continued…)**

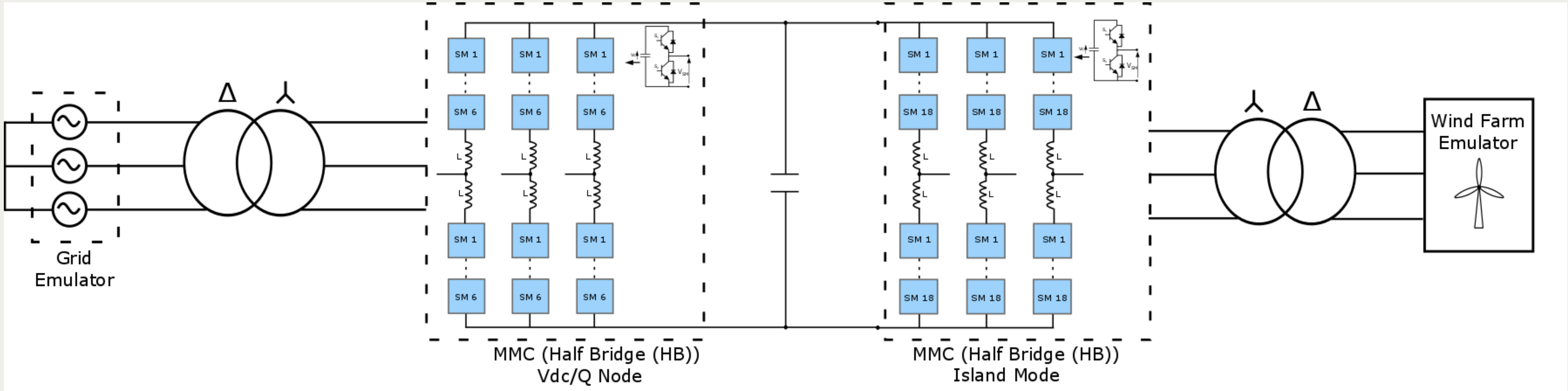
- **Upper & lower arm currents and voltages** at the receiving end converter (steady-state)





Further Work

➢ **Point-to-Point System**



<u>Objective</u>:

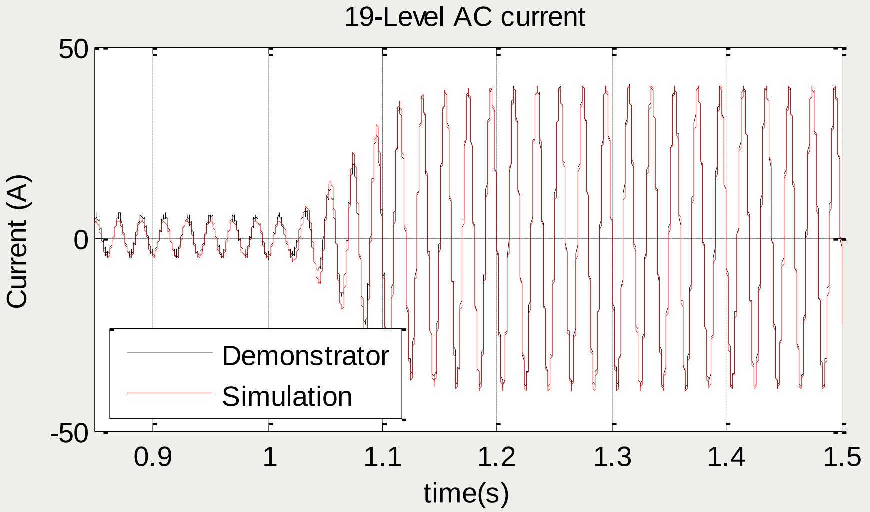
Evaluate the operation of the point-to-point link when the WF power varies.

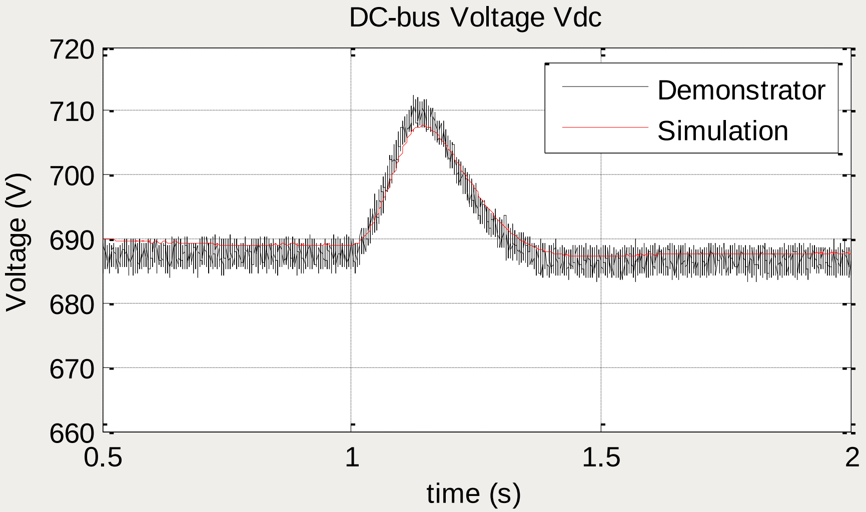
<u>Procedure:</u>

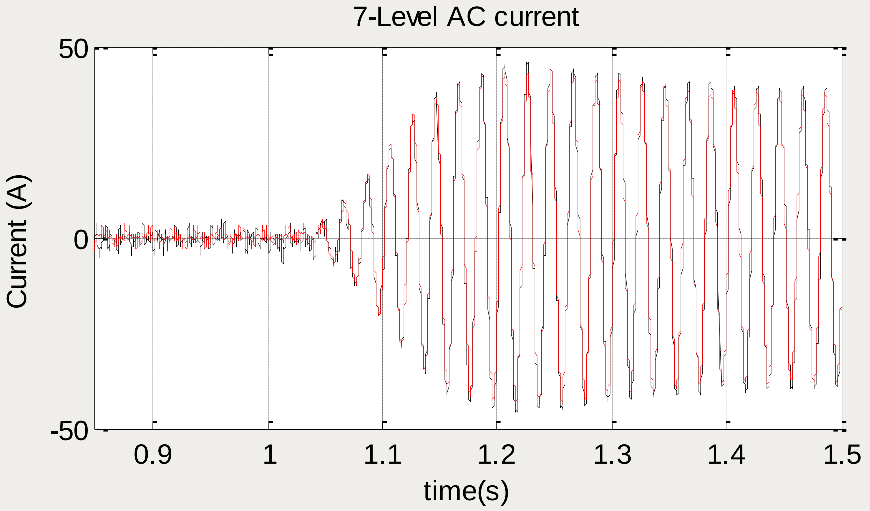
Change active power of the WF from 0 to 1 p.u. with ramp rate limitation of 10 p.u./s.

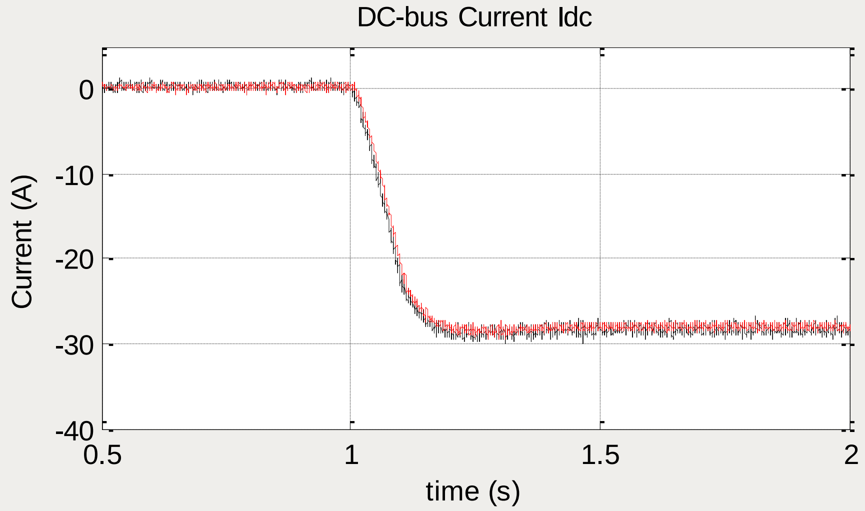
Further Work (2)

➢ Point-to-Point System (continued…)



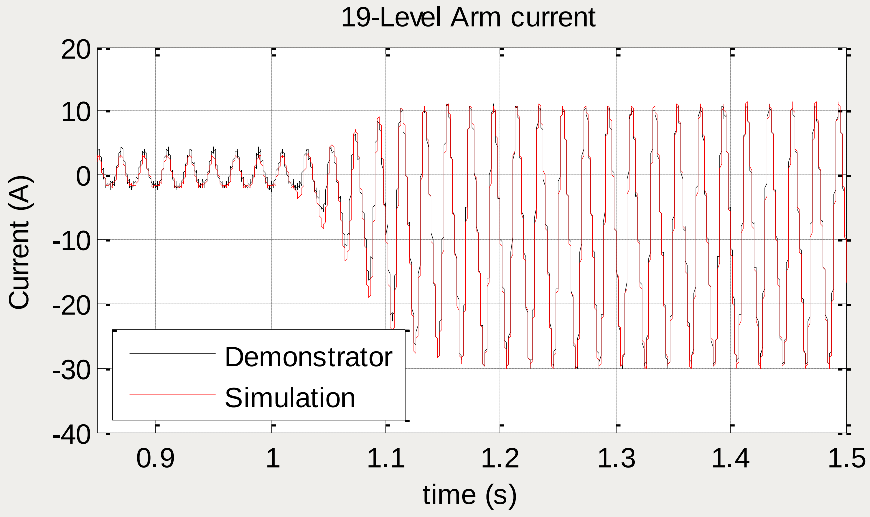


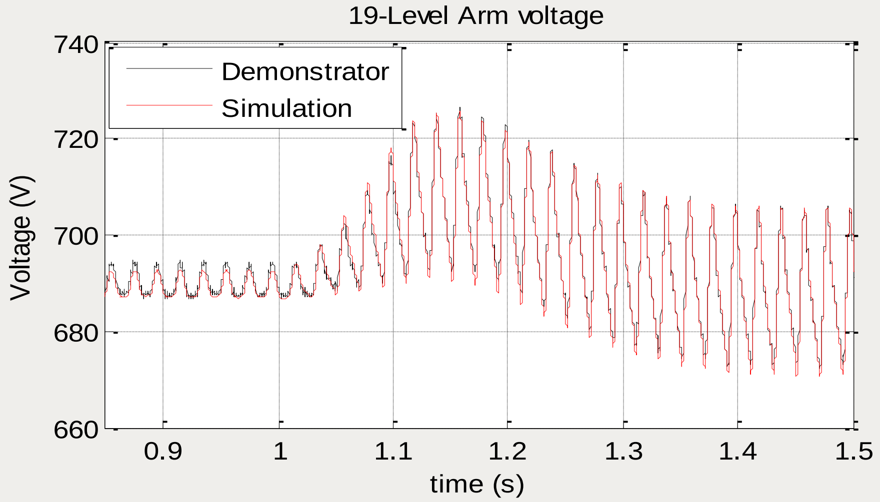


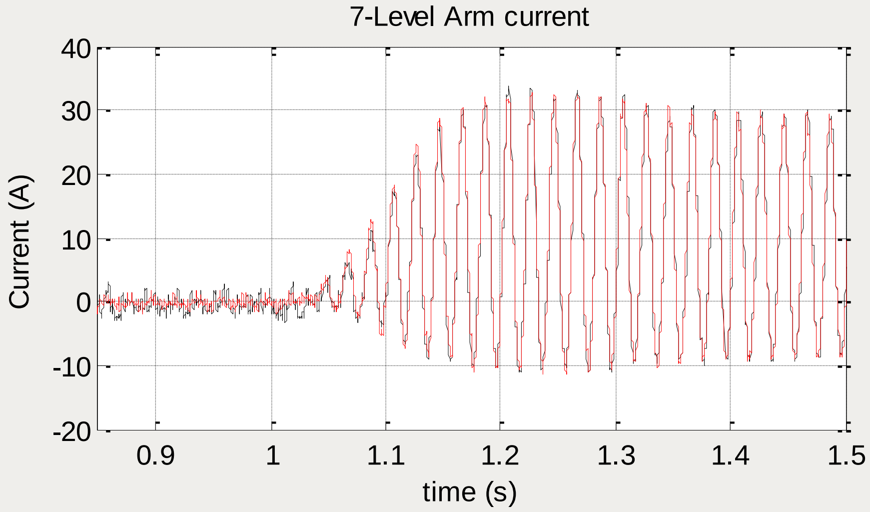


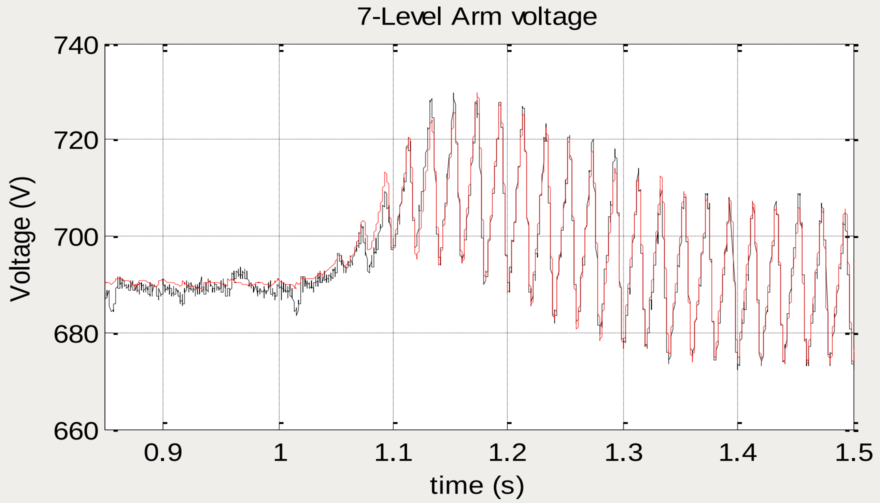
Further Work (3)

➢ **Point-to-Point System (continued…)**



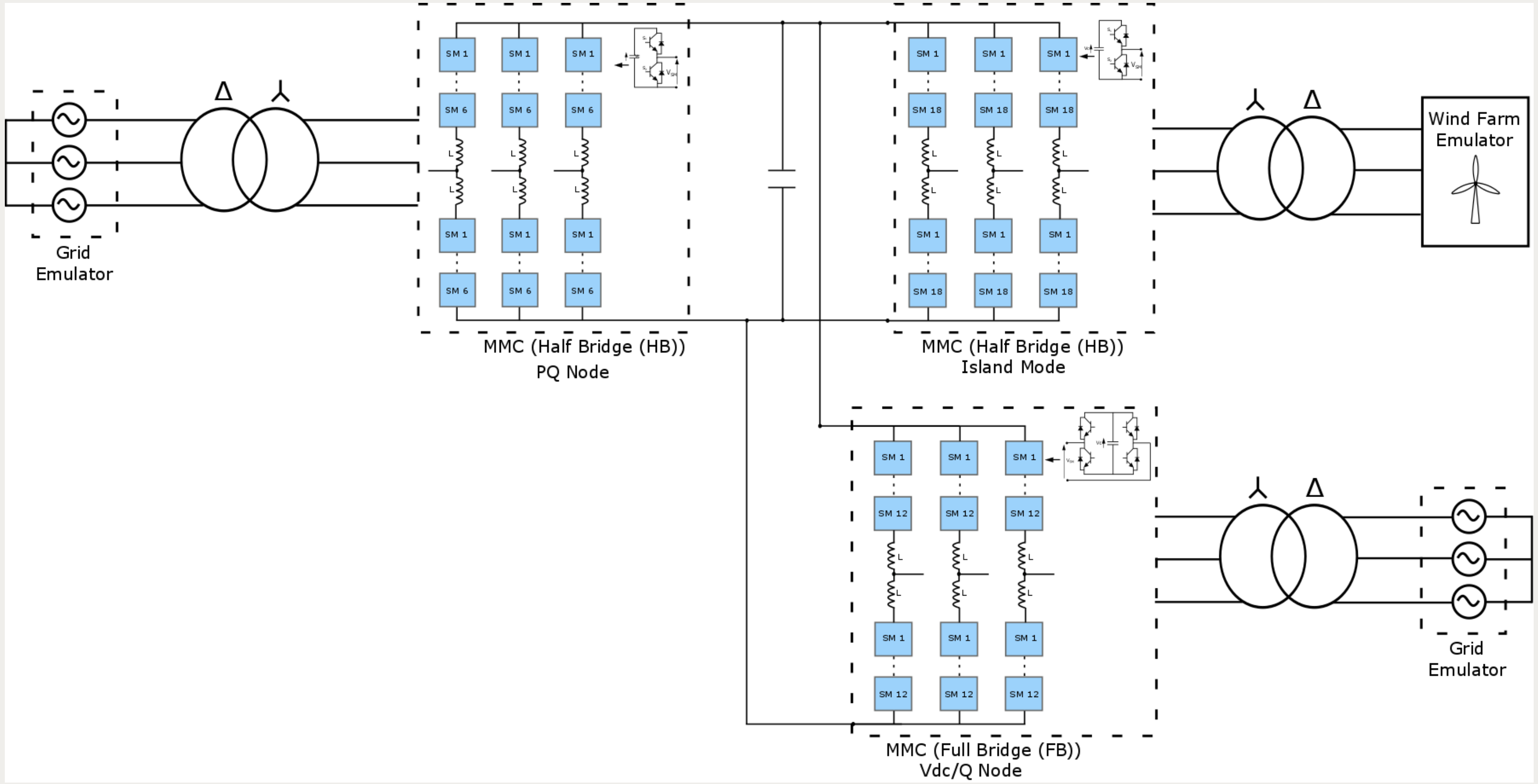






Further Work (4)

➢ Three-Terminal System



Objective:

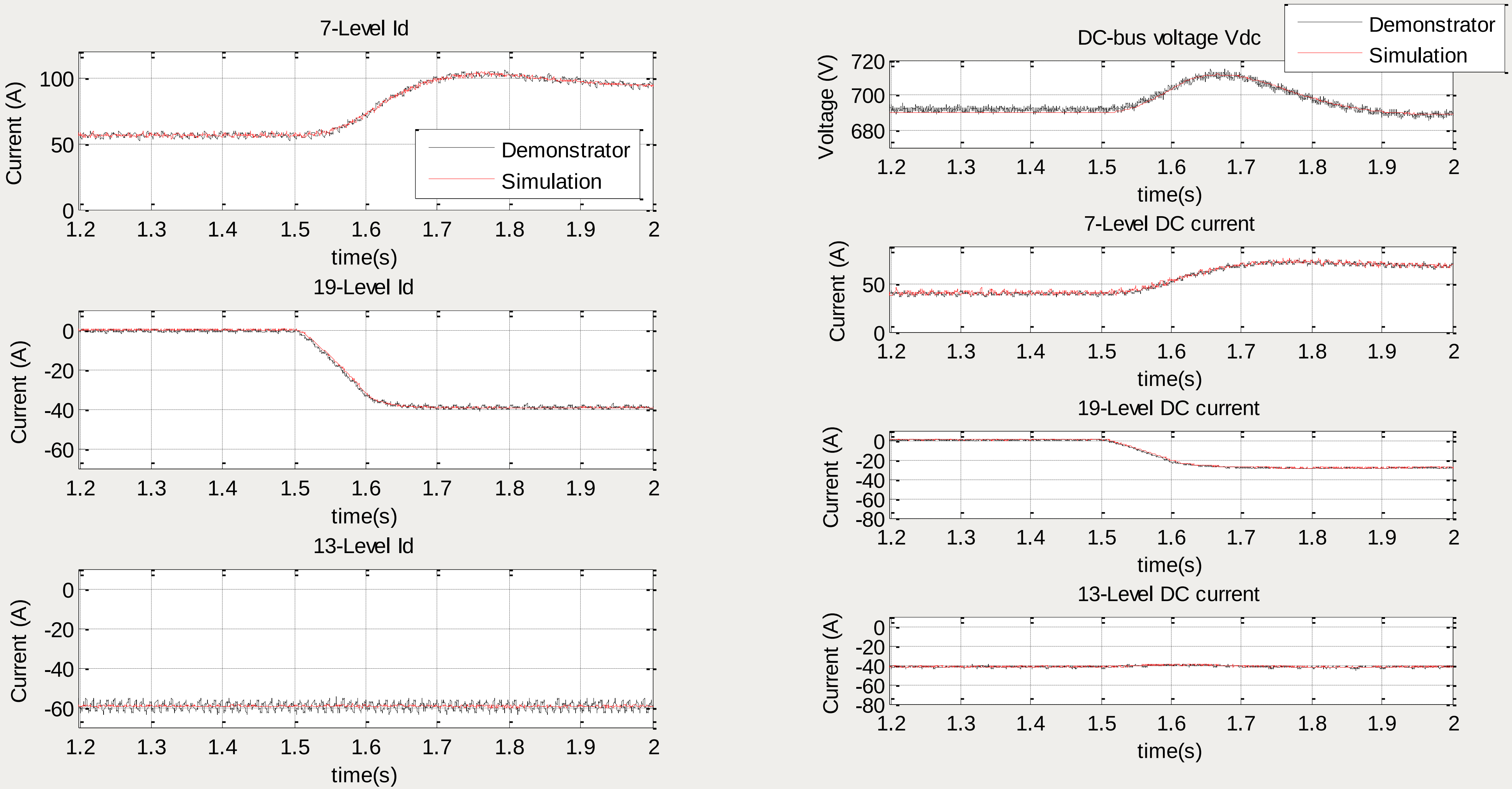
Evaluate the operation of a three-terminal system when the WF power varies.

Procedure:

- Set the power of the PQ node to –0.5 p.u (injecting power into the grid).
- Change active power of the WF from 0 to 1 p.u. with ramp rate limitation 10 p.u./s

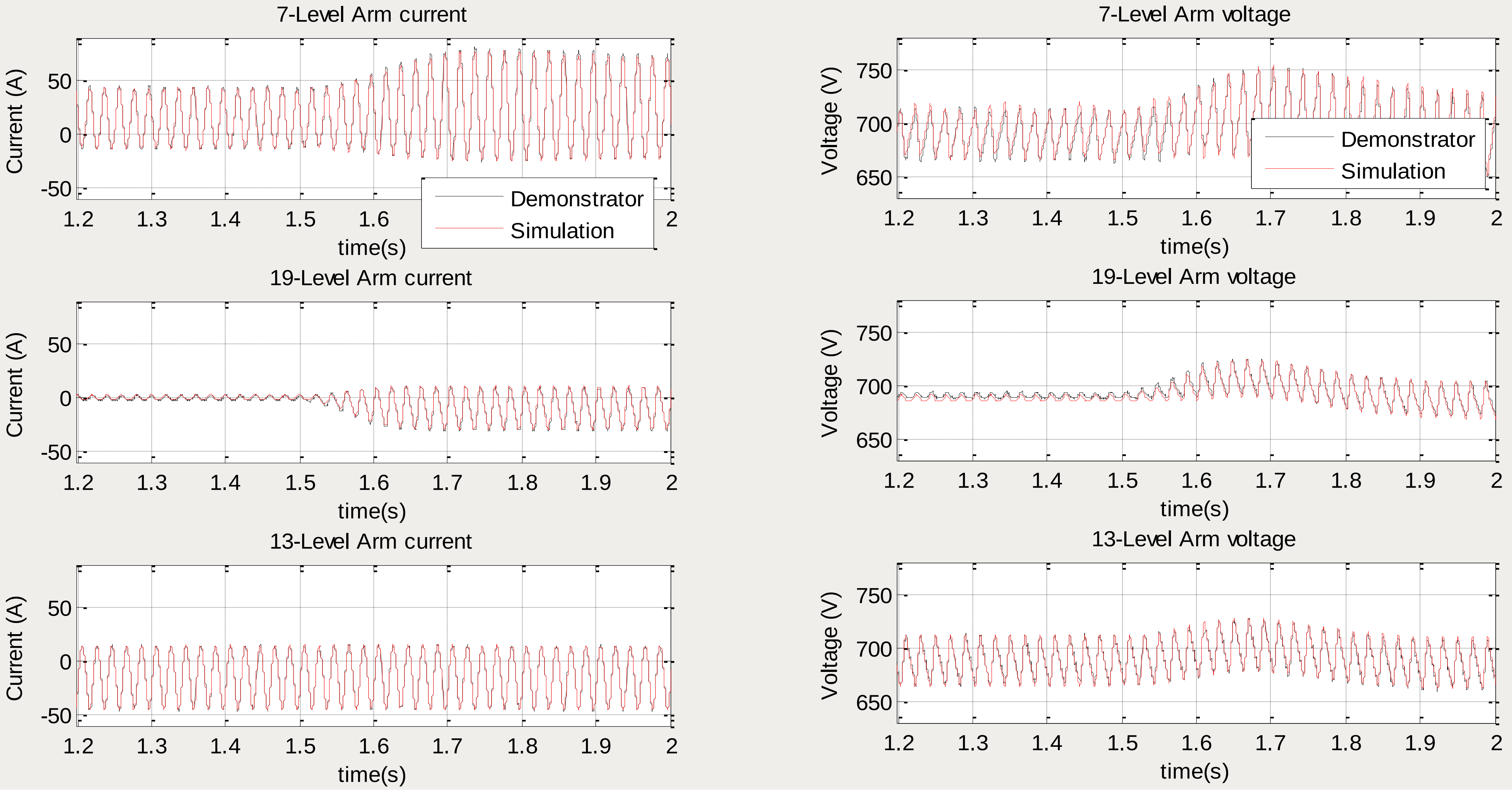
Further Work (5)

➢ Three-Terminal System (continued…)



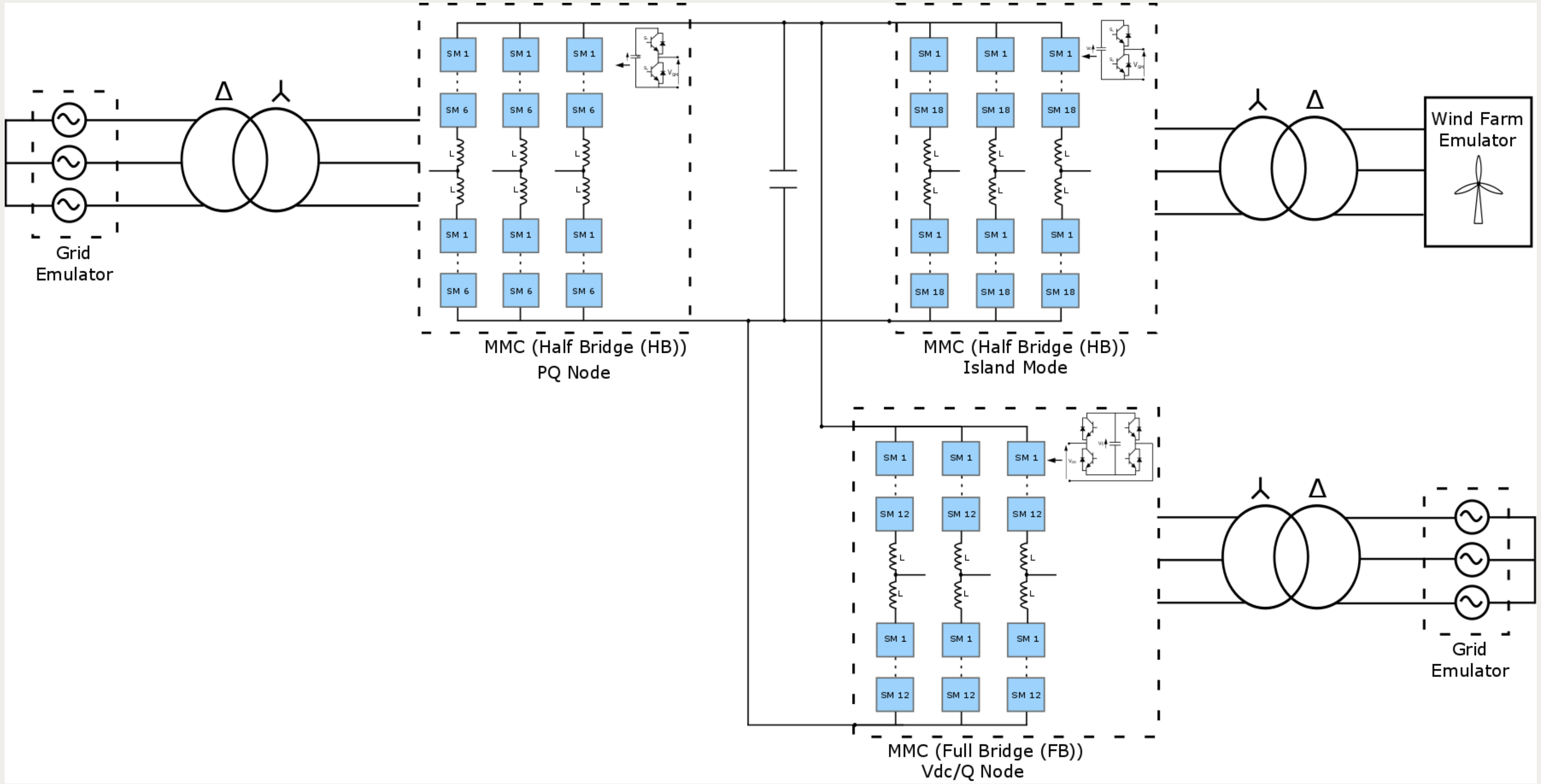
Further Work (6)

➢ Three-Terminal System (continued…)



Further Work (7)

➢ Three-Terminal System – TEST TWO



<u>Objective</u>:

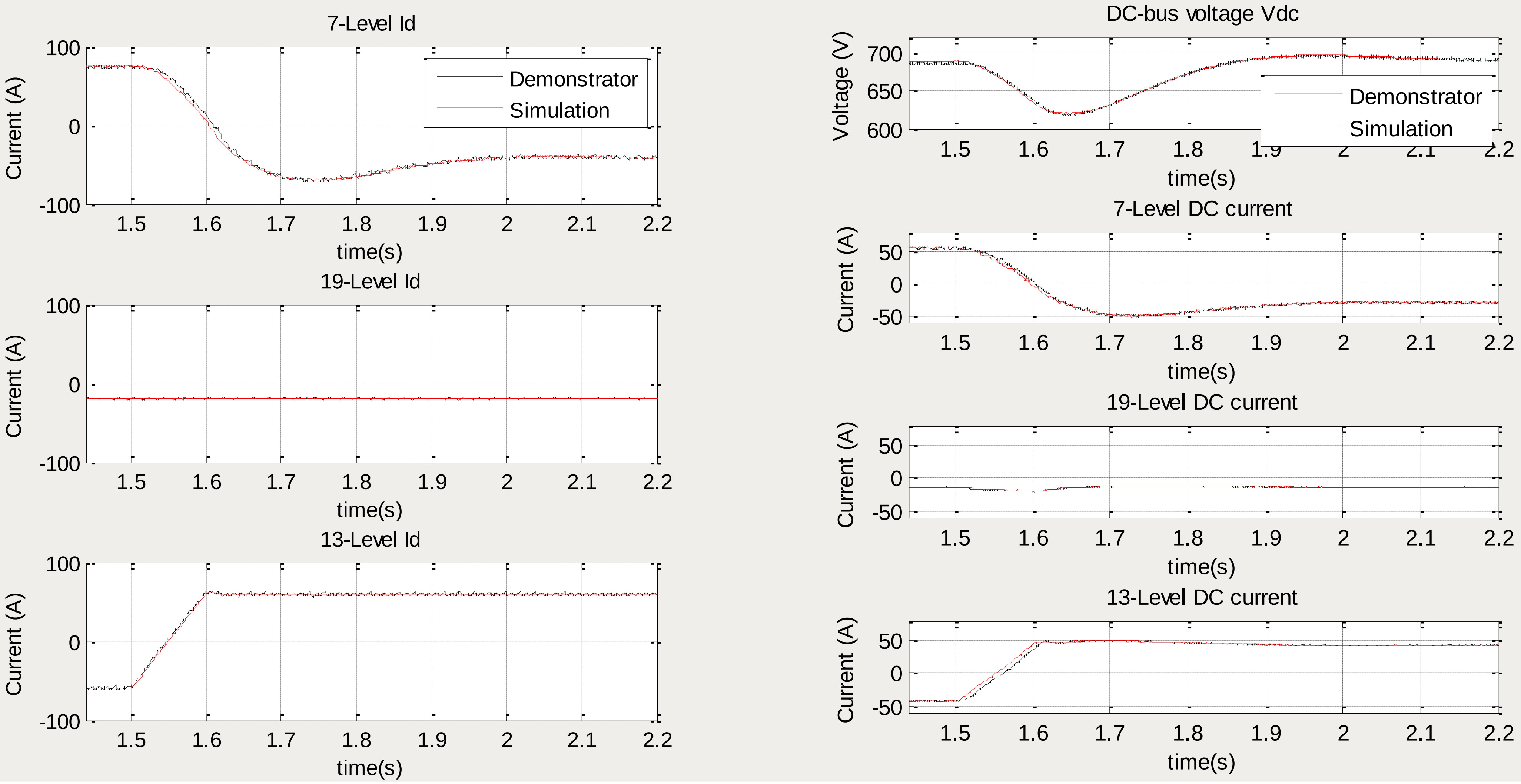
Evaluate the operation of a three-terminal system when the power flow of the PQ node is reversed.

<u>Procedure:</u>

- Set the power of the WF to 0.5 p.u.
- Change the active power of the PQ node from –0.5 to 0.5 p.u. with ramp rate limitation 10 p.u./s.

Further Work (8)

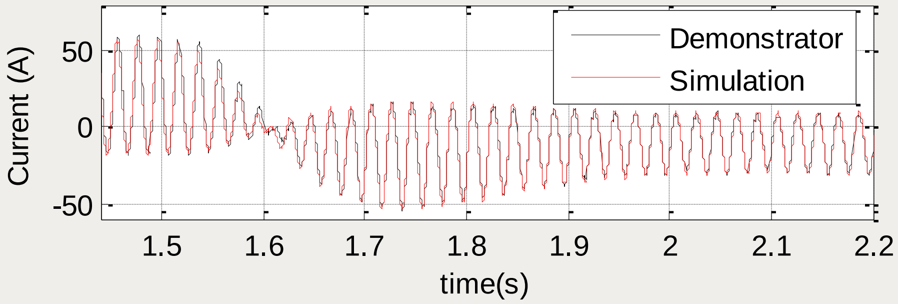
➤ **Three-Terminal System – TEST TWO (continued…)**



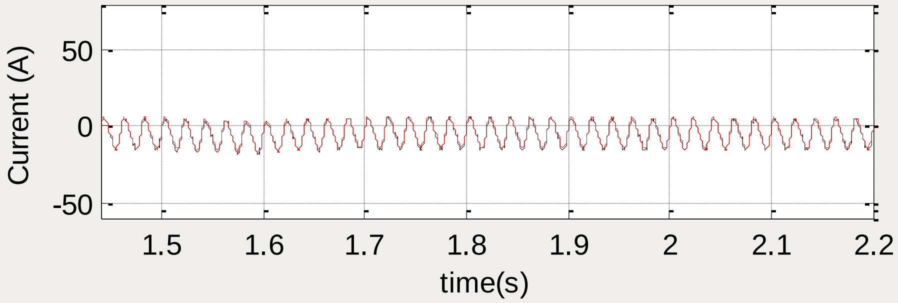
Further Work (9)

➢ Three-Terminal System – TEST TWO (continued…)

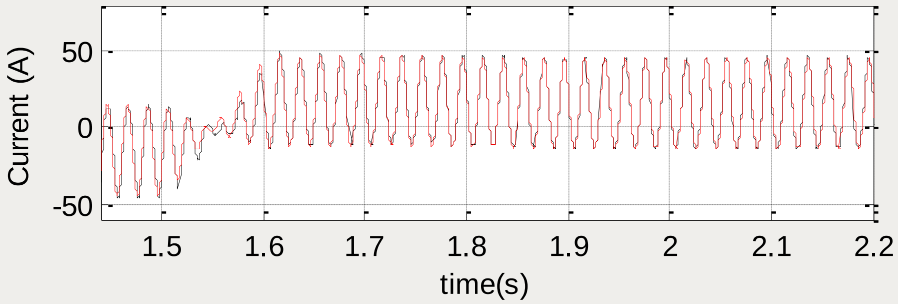
7-Level Arm current



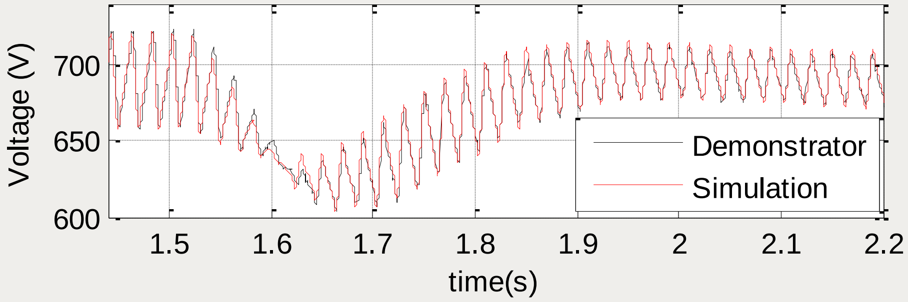
19-Level Arm current



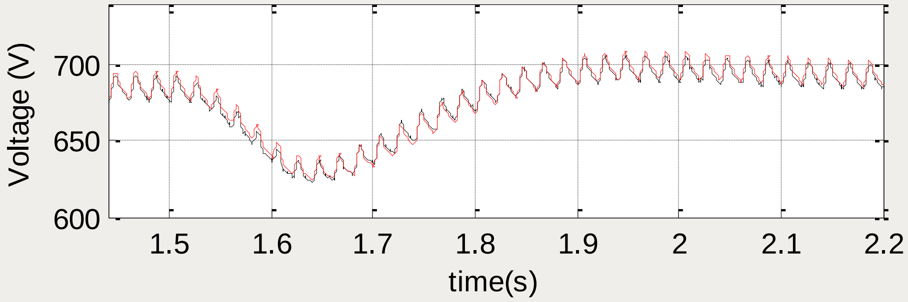
13-Level Arm current



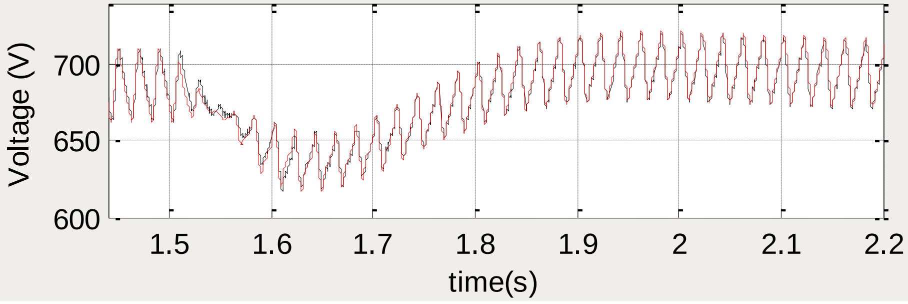
7-Level Arm voltage



19-Level Arm voltage



13-Level Arm voltage



Conclusions

➢ Main Contributions of this Work

- A set of **models** and **control algorithms** has been developed, simulated and assessed. These have been published as an **'Open Access' Toolbox**.
- **Network topologies** constituting likely scenarios for the transmission of offshore wind energy have been proposed.
- To assess the suitability of the models, topologies and control algorithms, **a set of KPIs** have been defined.
- An **experimental demonstrator** for the integration of grid-connected OWFs using HVDC grids has been presented.
- Results demonstrating the capabilities of the demonstrator have been compared against simulation results. **These show good agreement**.

Conclusions

➢ Main Contributions of this Work

- Provision to ***TSOs, utilities, manufacturers and academic institutions*** with simulation and experimental tools to generate the **necessary knowledge for the development, construction and connection of MTDC systems** –aiming to **help de-risking the use of MTDC grids for the connection of OWFs**.

➢ On-Going Work

- Using the demonstrator, conduct tests for different system topologies representing future scenarios to **validate simulation results** obtained using computational tools.
- **Make the demonstrator available to interested parties for R&D activities**.

Conclusions

➢ Some papers linked to this presentation

- Ugalde-Loo CE, *et al.*, "Lessons Learnt from the BEST PATHS Project for the Integration of Offshore Wind Farms using Multi-Terminal HVDC Grids," *47th CIGRE Session 2018*, Paris, France, 26-31 August 2018, pp. 1-10.
- Parker M, Finney S, Holliday D, "DC protection of a multi-terminal HVDC network featuring offshore wind farms," *Energy Procedia*, vol. 142, Dec. 2017, pp. 2195-2201.
- Azpiri I, Ciapessoni E, Cirio D, Glasdam J, Lund P, Pitto P, "Grid code compliant controllers for multi-terminal HVDC grids aimed to integrate wind power: assessing their impact on the operational security of a real-world system," *Energy Procedia*, vol. 142, Dec. 2017, pp. 2165-2170.
- Ciapessoni, *et al.*, "Assessing the impact of multi-terminal HVDC grids for wind integration on future scenarios of a real-world AC power system using grid code compliant open models," *2017 IEEE Power Tech*, Manchester, UK, 18-22 June 2017, pp. 1-6
- Ugalde-Loo CE, *et al.*, "BEST PATHS Project: Real-Time Demonstrator for the Integration of Offshore Wind Farms using Multi-Terminal HVDC Grids," *Offshore Wind Energy (OWE 2017)*, London, UK, 6-8 June 2017, pp. 1-11.
- Ugalde-Loo CE, *et al.*, "Open access simulation toolbox for the grid connection of offshore wind farms using multi-terminal HVDC networks," *13th IET International Conference on AC and DC Power Transmission (ACDC 2017)*, Manchester, UK, 14-16 February 2017, pp. 1-6.

Questions?

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The authors gratefully acknowledge the financial support provided by the EU FP7 Programme through the project "BEyond State of the art Technologies for re-Powering AC corridors & multi-Terminal HVDC Systems" (BEST PATHS), grant agreement number 612748.

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