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Deliverable 3.7: Compliance evaluation results using simulations

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PROMOTioN
PROGRESS ON MESHED HVDC OFFSHORE TRANSMISSION NETWORKS

Deliverable 3.7: Compliance evaluation results using simulations

Part I: WPP/WTG control for Self-Start and Black Start

Part II: WPP/WTG control for DRU Operation

19/2/2020

PROMOTioN – Progress on Meshed HVDC Offshore Transmission Networks
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LIST OF CONTRIBUTORS

Work Package 3 and deliverable 3.7 involve a large number of partners and contributors. The names of the partners, who contributed to the present deliverable, are presented in the following table.

Contributors marked with C provided the content of this deliverable, whereas those marked with R provided review in different stages of the deliverable

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CONTENT

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LIST OF DEFINITIONS / ABBREVIATIONS

Term	Meaning
WT	Wind Turbine
OWF	Offshore Wind Farm
VSC	Voltage Source Converter
DRU	Diode Rectifier Unit
Radial grid	Grid that does not contain a loop
Point-to-Point	(Inter) connection between two points
OTS	Off-shore Transmission System
WFG	Wind Farm Group
TSO	Transport (onshore) System Operator
MOG	Meshed Offshore Grid
Multi Terminal	More than two stations
Cluster	See Figure 2.3 D3.1
Sub-cluster	
Cluster Controller (CLC)	
Master Controller (MC)	
Offsh. HVDC Conv (OFC)	
Onsh. HVDC Conv. (ONC)	

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1. EXECUTIVE SUMMARY

1.1. INTRODUCTION

This report is part of *Task 3.4 "Compliance evaluation based on detailed numerical simulations"*. The main aim of this report is to show the results of the compliance evaluation of the Wind Turbine Generator (WTG) Grid Side Converter (GSC) and WPP controllers, when operating as Grid Forming Converters.

The first part of WP3 was mainly focused on the development and validation of controllers that allow the connection of WTGs to Diode Rectifier based HVDC stations (DRU-HVDC stations).

Grid forming WT controls, such as the ones developed for DRU-HVDC connected wind farms, can be used for OWPP self-energisation and to contribute to black start operation. Developed controllers in D3.4 already include OWPP energisation, islanding operation and synchronisation to weak ac-grids. Due to special industrial interest in WPP self-start to houseload operation and WPP contribution to black-start, the scope of T3.4 was enlarged to cover also self-start and black-start operation.

For the compliance evaluation of WTG controllers for DRU-HVDC integration, there was a large amount of work carried out in previous deliverables, namely, definition of requirements, scenarios, test cases, controller description and compliance evaluation procedures. Therefore, this report includes only the results corresponding to the detailed compliance evaluation.

Similarly, for the newly considered self-start and black-start cases, this report includes the definition of test requirements, HVDC and HVAC scenarios and test cases and, finally, the compliance evaluation of WTG and WPP controllers for self-start and black-start operation when the OWPP is connected via a HVAC export cable and also via a VSC-HVDC connection.

The report consists of two parts:

PART I: Self-start and Black-start operation.

This part includes the statement of requirements, HVAC and HVDC scenarios and test cases and, finally, the results of the compliance evaluation of the GSC controllers based on detailed numerical simulations.

PART II: Compliance evaluation of WPP and WTG controllers for DRU-HVDC integration

This part includes only the compliance evaluation results for WPP and WTG controllers for DRU-HVDC integration, as the requirements were already defined in deliverable D3.1, the test cases defined in deliverable D3.2 and compliance evaluation procedures in deliverable D.3.6, where controller explanation and initial results are covered in deliverable D3.4.

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1.2. BLACK START WTG/WPP CONTROLLER VALIDATION

This document includes the verification procedure of WTG and WPP controllers for HVAC and HVDC based black-start. The verification procedure includes:

a) Definition of functional requirements
b) Definition of HVAC and HVDC scenarios
c) Definition of HVAC and HVDC test cases
d) Test case results

For HVAC connected WPPs, both sequential (using POW switching) and soft-start procedures are considered. The sequential back start procedure includes WPP energisation to islanded (houseload) operation, energisation of off-shore HVAC station, export cable, on-shore HVAC, block load operation and synchronisation to other islands. In order to achieve realistic results, transformer models include detailed saturation characteristics and cables have been modelled using distributed frequency-dependant parameters.

As expected, critical elements in HVAC sequential energisation are the off-shore and on-shore substation transformers and the HVAC export cable. When considering errors in the POW switching arising from wrong residual flux or wrong breaker closing time estimates, relatively large voltage oscillations can appear due to ferromagnetic resonance and/or to sympathetic in-rush. In most cases, the oscillations die away after a reasonable time, but in a small number of cases, the oscillations lead to overvoltage which would trip WTGs or protection equipment.

Reactive power requirement for the WPP is just slightly higher than the reactive power required to compensate array and export cables (or the part which is not compensated by shunt reactors).

The total reactive power required from the WTGs should also consider the reactive power required for energising additional on-shore cables and lines.

It has been shown that soft-energisation both leads to smaller maximum voltages and currents and to faster energisation times. Therefore, soft-energisation is to be preferred when technically available.

Direct connection and disconnection of a 30MW block load did not lead to voltages and frequencies outside of the limits set in the requirements. However, block load ramping up is preferable in order to decrease the impact of sudden loads on the WTG mechanics.

Moreover, it has been found that the system recovers adequately during symmetric on-shore, off-shore and cable faults. Also, the developed controller is capable to synchronise to an existing on-shore electrical island and co-ordinate with the other island the provision of active and reactive power requirements to the joint system.

For HVDC connected WPPs, the energisation of the off-shore WPP to houseload operation is similar to the HVAC case. The sequential connection of the HVDC rectifier station, HVDC export cable and HVDC inverter station has been studied with different values of pre-insertion resistors (PIR).

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It has also been found that, for the HVDC case, the soft-start approach leads to faster energisation times and smaller values of peak voltages and currents.

Direct connection of the 30MW on-shore block load did not lead to voltages and currents outside of those stated in the functional requirements.

The proposed compliance evaluation procedure for HVAC black-start operation has been also applied to a grid-forming black-box controller supplied by MHI-Vestas Offshore Wind. The results show the good performance of the controller during Off-shore Wind Power Plant power to houseload (islanded) operation, energisation of off-shore HVAC substation, export cable and on-shore HVAC substation, and block load delivery, both for sequential and soft-start energisation.

The studies carried out have shown that the proposed controllers are capable of performing both sequential and soft-start energisation of the WPP, export system and on-shore island for both HVAC and HVDC connections.

The stated functional requirements, together with the detailed simulation studies represent the first phases for a full scale black-start validation.

The results presented here will be extended in WP16 where real-time CHiL validation will be carried out for both HVAC and HVDC connected WPPs.

1.3. DRU-ENABLED WTG/WPP CONTROLLER VALIDATION

The detailed validation of the DRU-enabled WTG and WPP controllers has been carried out in this part, considering the functional requirements stated in deliverable D3.1, the scenarios defined in deliverable D3.2 and the controllers included in deliverable D3.4.

The performance of the considered controllers has been validated during normal operation (umbilical start-up, islanded, DRU-connected, power transients, etc) and during faults (off-shore, on-shore, HVDC cable, etc). The operation of a DRU-connected WPP when providing ancillary services has also been shown (frequency support, power oscillation damping). The considered controllers have shown an adequate performance for all the simulated test cases.

Therefore, these detailed simulation studies represent the first phases for a full scale DRU-enabled WTG controller validation.

The results presented here will be extended in WP16 where real-time CHiL validation will be carried out.

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PART I. SELF-START AND BLACK-START OPERATION

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2. OFF-SHORE WIND FARM SELF START

2.1. OPERATIONAL AND STABILITY REQUIREMENTS

This section includes the operation and stability requirements for black start operation for use within task T3.4.

These requirements are to be considered as a reasonable starting point for the validation of the developed control strategies and are not meant to be considered as recommendations for grid codes. Moreover, eventual black-start requirements and qualification procedure is usually agreed with the individual TSO.

The stated requirements should not be considered as hard, validated values. Rather, these values are a guideline for test case validation and will be subject to revision depending on the findings of the black-start studies to be carried out within WP3 and WP16 of the PROMOTioN project.

For the purposes of this section, two modes of operation are defined, namely “household operation” (ISL), where the wind power plant (WPP) is operating as an island and providing only energy for its losses and auxiliary services. The second mode of operation is “black-start”, where third party transmission assets are energised.

Unless otherwise stated, requirements are considered at the corresponding on-shore PCC for both HVAC and HVDC wind power plants.

For houseload operation, the grid code specifications do not apply. However, as an initial investigative step, the same requirements will be used for both houseload and black-start operation, considering that some requirements might be particularly difficult to meet for houseload operation. In this case, some recommendations will be issued based on the results of the test cases.

When not specified, NC RfG will be used as default requirements. Frequency and RMS values are calculated as per IEC61000-4-30.

Besides the operational and stability requirements regarding grid connection, control strategies should not have, as far as possible, negative effects on the WTG. Particularly, control strategies should aim at keeping the same converter characteristics as grid following converters, i.e. unaffected DC link cap and chopper sizes (considering DC link voltage variations to be within +/- 10% rated value) and unaffected grid filter size.
Moreover, developed control strategies should not increase peak and fatigue related drive-train torques.

These two design conditions aim at the use of grid forming converters with self-start capability without requiring modifications to WTG hardware, as far as possible. In any case, any WTG hardware modification should be subject to a cost benefit analysis, which is beyond the scope of this document.

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2.1.1 FREQUENCY RANGES

The frequency range defined here is understood to be the maximum frequency excursion during block load connection/disconnection when the considered wind power plant is the only generation operating in a given island. The frequency range in this specification should not be understood as allowing the WTG to trip if frequency lays outside the frequency range. Therefore, the frequency range stated in this section is a design parameter for the grid-forming wind turbine frequency control, and does not apply for situations other than the WPP being the only generator in an islanded system.

Therefore, the WPP should have the ability to manage the frequency during block load connection/disconnection within the range 49-52Hz as required by Elia (NGESO and NC RfG consider larger frequency ranges, so the considered requirements are relatively stringent on the WTG and WPP control). The studies performed should include the maximum load ramp rate which would keep the frequency within the considered range.

Frequency control will include a selectable droop which could be set at between 2 and 12% and the dead band of which can be set at between 10 to 200 mHz.

2.1.2 VOLTAGE RANGES

Consider initially ±10% voltage variation during block loads as per NGESO requirements. The test case studies will show if these limits should be changed in light of the results.

Voltage control will include a selectable V-Q droop up to 12% with an optional deadband.

2.1.3 BLOCK LOAD SIZE

Block load size is selected to be a maximum of 30 MW, with capability to handle ±30 MW instantaneous load change. The simulation test results will show what is the maximum ramp rate achievable, considering the stated maximum voltage and frequency limits.

2.1.4 REACTIVE POWER CAPACITY

No specific requirement is set for reactive power capacity. Nevertheless, the results will investigate the reactive power needed to perform black-start for different scenarios.

2.1.5 DYNAMIC VOLTAGE CONTROL

The black-start capable wind power plant should be able to control the voltage at the PCC within its operational limits and respond to voltage references.

2.1.6 FREQUENCY CONTROL CAPABILITY

The black-start capable wind power plant should be able to control the frequency at the PCC within its operational limits and respond to frequency references.

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2.1.7 HARMONIC DISTORTION

Voltage distortion requirements for black-start capable units the same as for normal connected units. In this way, equipment compatibility is ensured, as well as making easier synchronisation with other islands during system recovery.

2.1.8 LOW VOLTAGE RIDE-THROUGH

Low voltage ride through profiles will be kept the same as existing profiles as a starting point, with the following considerations:

During black start it is not clear that current can be controlled the way it is specified in grid codes. A recommendation will be issued based on the results of the study.

Transmission system fault clearing times might be larger than usual, as wind power plants will limit their current contribution to the fault to protect themselves and hence relays will see lower fault currents than expected. This issue will also be studied. It is likely that alternative settings to protective relays will have to be used for black-start using WPPs.

2.1.9 OVER-VOLTAGE RIDE THROUGH

Consider Over Voltage Ride Through according to VDE AR-N-4120: i.e 130% for 100 ms and 125% for 60 s. This OVRT requirement is in line with overvoltage events, particularly in HVDC connected wind power plants.

2.1.10 POWER SHARING BETWEEN WIND TURBINES

Wind turbines should be able to share both active and reactive power amongst themselves, with selectable contribution factors. Note this is not a grid compliance requirement. This is rather an operational requirement for the WPP so all WTG contribute to active and reactive power requirements within their operational limits.

2.1.11 SYNCHRONISATION CAPABILITY

Capability to synchronise to another island when the frequency difference is less than 0.1Hz, the angle difference is less than 20º and the voltage difference is less than 1%.

2.1.12 INERTIA RESPONSE

During houseload and black-start operation, inertia response is indirectly set by the block load size, rise time and operational frequency requirements. Therefore, no specific value is set for these cases.

Inertia response might be useful once the WPP island has been synchronised to another (weak) island. In this case, specific TSO requirements will apply.

2.2. CONSIDERED SCENARIOS

This document considers three scenarios for self-start and black start operation:

- Black start by HVAC connected WPP
- Black start by HVDC connected WPP (with intermediate off-shore transformer stations)

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- Black start by HVDC connected WPP (without intermediate off-shore transformer stations)

In all cases, each individual wind power plant consists of 50 8MW wind turbine generators, totalling 400MW rated power. This WPP is the same as used for all the rest of the studies in WP3.

The description of each one of the scenarios is included as follows and the detailed parameters of each one of the components is included in the Appendix of this document.

2.2.1 HVAC CONNECTED WPP

Figure 2-1 shows the HVAC connected WPP base line scenario. It consists of the following components:

- OWF of 400MW, consisting of 50 x 8MW WTGs connected to a 66kV ac collector.
- 460MVA off-shore transformer with a ratio of 66/220 kV.
- 75 km HVAC copper cable with a cross section of 1000mm^2.
- Shunt compensators at the both ends of the cable.
- 460MVA on-shore transformer with a ratio of 220/400 kV.

Array cable and wind turbine characteristics are taken from the OWF defined in Deliverable 3.2.

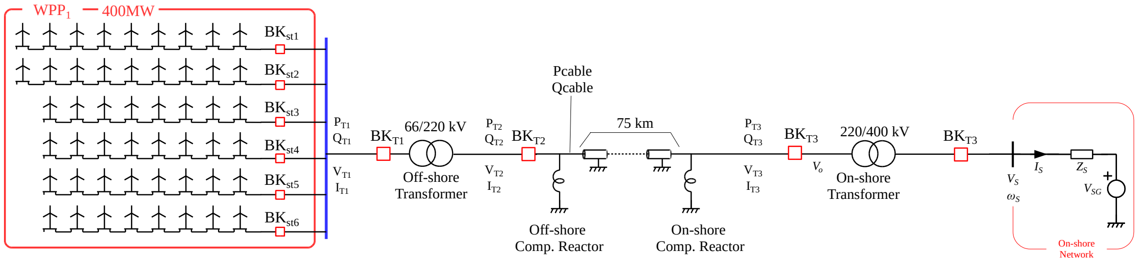

Figure 2-1: HVAC connected WPP baseline scenario

The 75km cable has been selected as being a particularly adverse case regarding cable length without intermediate compensation stations.

The frequency response of the export cable and shunt reactor is shown in Figure 2-2 and Figure 2-3, where the effect of cable grounding is clearly seen. Grounding affects slightly the first resonant frequency. For black-start studies, it is considered that only the on-shore shunt compensation (40%) is connected, in order to avoid current zero misses which would prevent correct protection operation. This kind of compensation would always lead to a resonant frequency around 24Hz, which should be taken into account in order to study possible subsynchronous resonance problems with the rest of the system.

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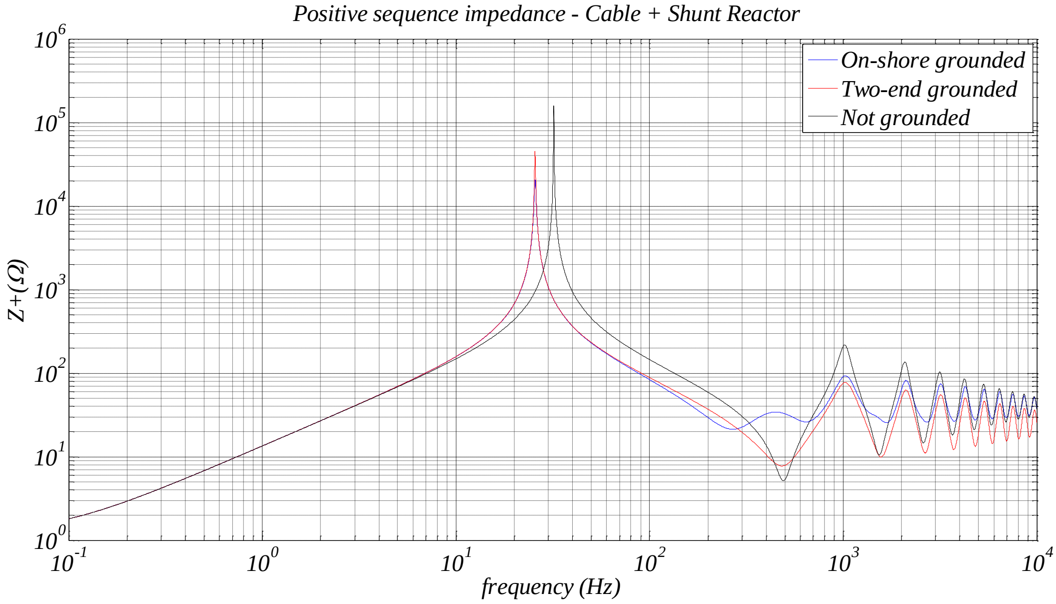

Figure 2-2: Positive sequence impedance of Cable and On-shore shunt compensation depending on cable grounding

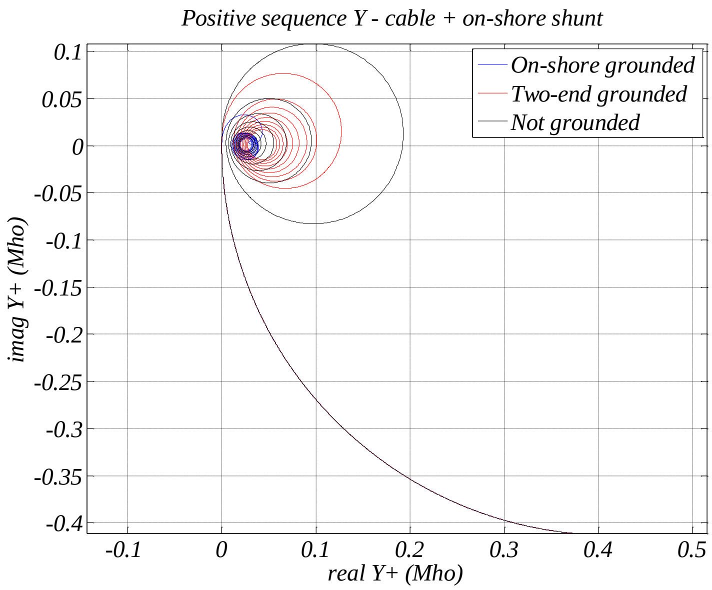

Figure 2-3. Positive sequence admittance of Cable and On-shore shunt compensation depending on cable grounding

When the cable and on-shore transformer are included in the analysis, the first resonant frequency, caused by the cable capacitance and the shunt compensation, remains at around 24Hz (Figure 2-4). However, a new resonance appears at about 180 Hz (or it can be argued that the cable resonant frequency at 480Hz is shifted to 180Hz). Therefore, currents of 180Hz will appear during energisation.

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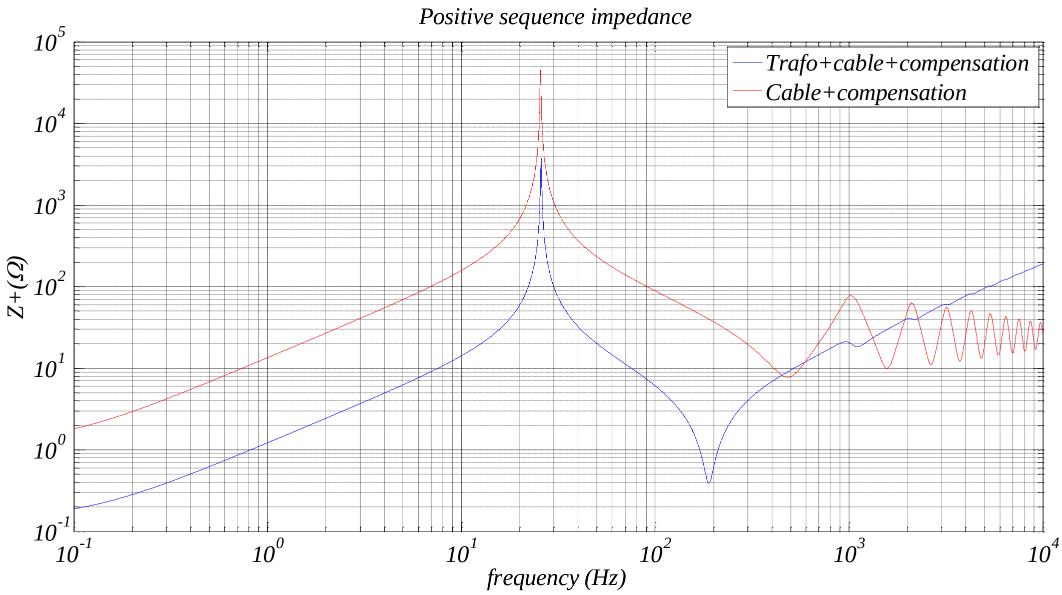

Figure 2-4. Positive sequence impedance of the joint Transformer + cable + on-shore shunt compensation

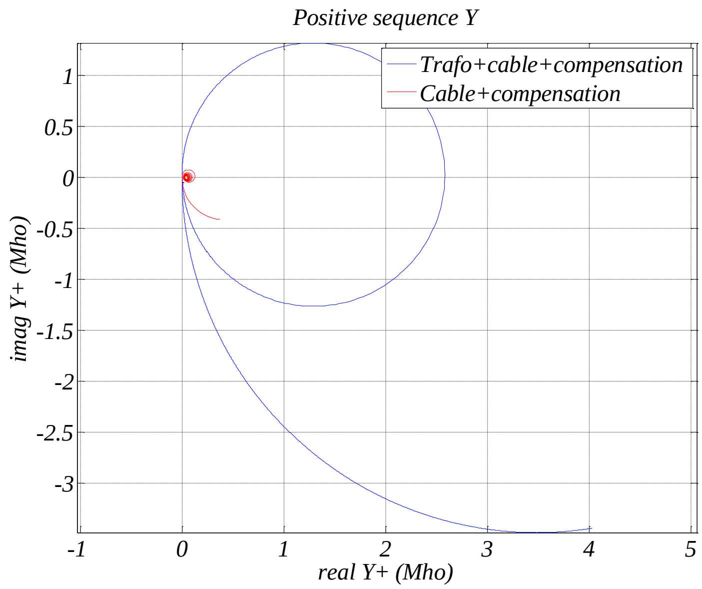

Figure 2-5. Positive sequence admittance of the joint Transformer + cable + on-shore shunt compensation

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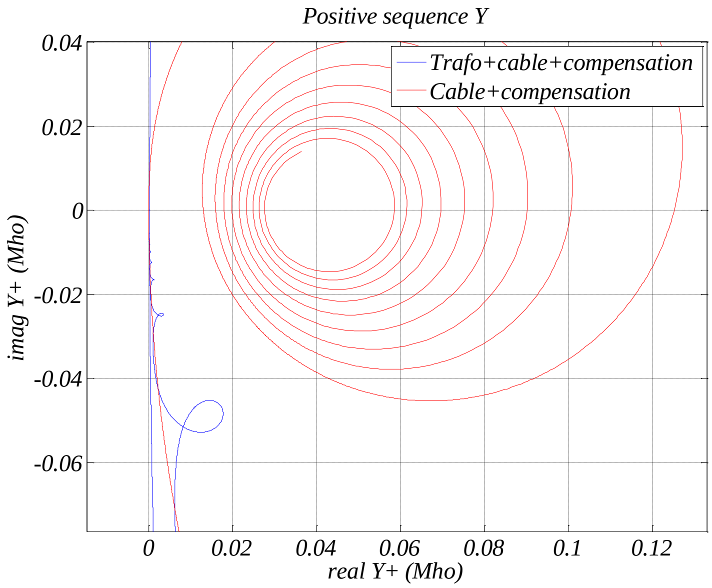

Figure 2-6. Positive sequence admittance of the joint Transformer + cable + on-shore shunt compensation (zoom)

Finally, Figure 2-7 shows the effect of the on-shore shunt compensation on the total impedance. Impedance for frequencies above 100Hz is largely unaffected by the presence of the shunt compensation. However, at low frequencies, a new (parallel) resonance peak appears at around 24Hz (where the cable capacitive reactance matches that of the shunt reactor).

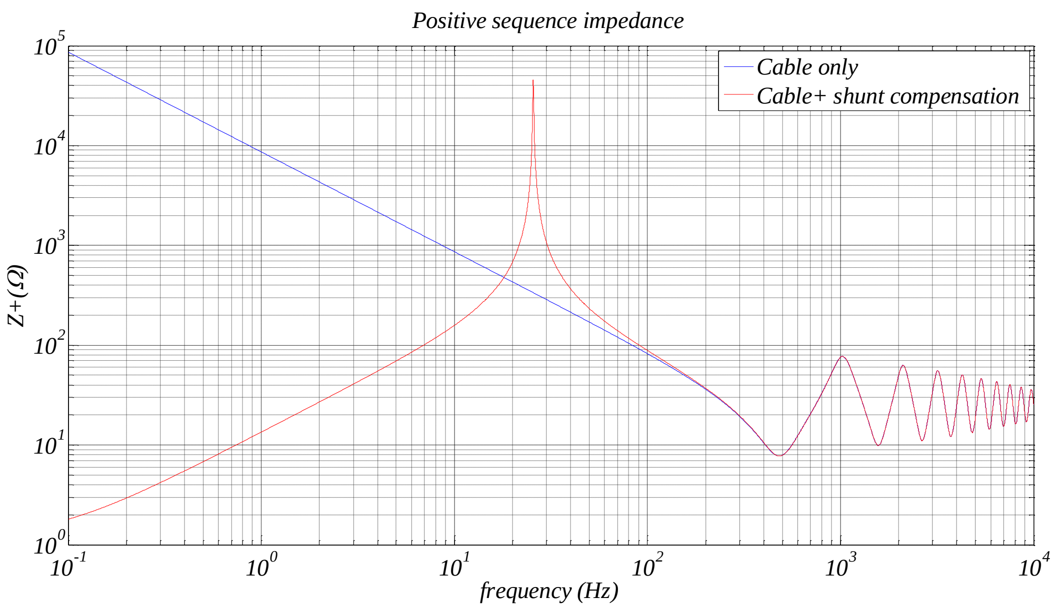

Figure 2-7. Effect of on-shore shunt compensation on positive sequence impedance.

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2.2.2 VSC CONNECTED WPP (WITH/WITHOUT INTERMEDIATE TRANSFORMER STATIONS)

Scenario 1: 3x400MW WPPs, consisting of 8MW WTs connected to a 66kV ac collector and at 120km from shore. WPP definition from D3.2. 1.2 GW VSC stations (symmetric monopole) connected via intermediate 66/155kV transformer stations.

- 3 OWF of each 400MW, consisting of 50 x 8MW WTGs connected to a 66kV ac collector.
- 2 OWF transformer of each 240 MVA with a ratio of 66/155 kV.
- 5, 20, and 40 km of export cables with 155kV rating.
- Shunt compensators at the OWF ends of the cable
- 2 HVDC converter transformer of each 1440 MVA with a ratio of 220/400 kV.

Array cables (66 kV), export cables (155 kV) and wind turbine characteristics are taken from the OWF defined in Deliverable 3.2 and 2.1.

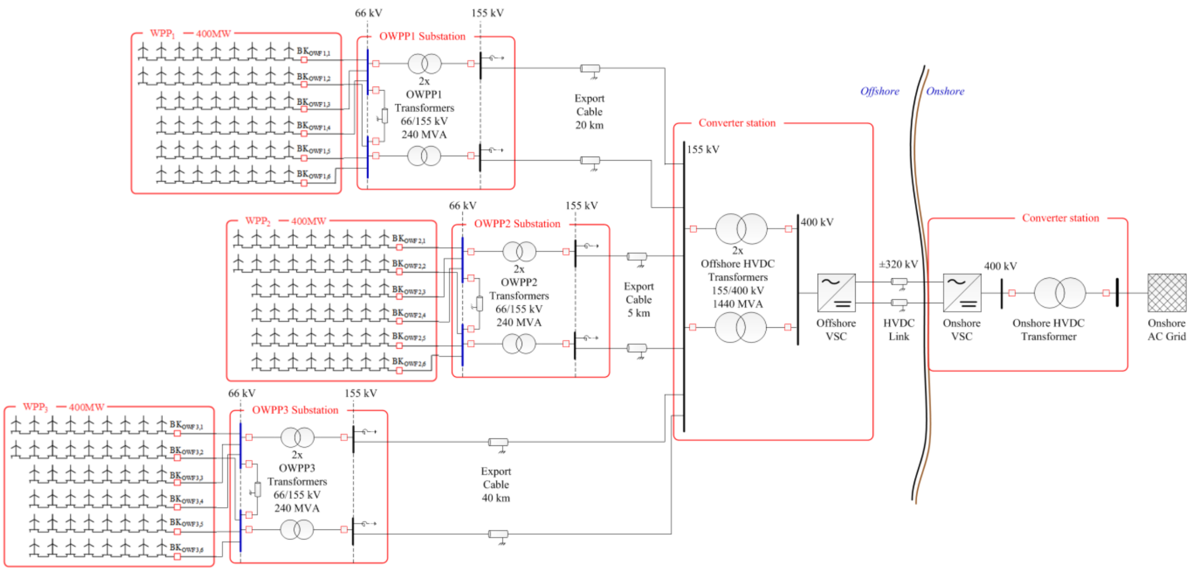

Figure 2-8: Scenario 1: 3x400MW WPPs, consisting of 8MW WTs connected to a 66kV ac collector and at 120km from shore.

Scenario 2: 3x400MW WPPs, consisting of 8MW WTs connected to a 155kV ac collector and at 120km from shore. WPP definition from D3.2. 1.2 GW VSC stations (symmetric monopole) connected without transformer stations.

- 3 OWF of each 400MW, consisting of 50 x 8MW WTGs connected to a 66kV ac collector.
- 2 OWF transformer of each 240 MVA with a ratio of 66/155 kV.
- 5, 20, and 40 km of export cables with 155kV rating.
- Shunt compensators at the OWF ends of the cable
- 2 HVDC converter transformer of each 1440 MVA with a ratio of 220/400 kV.

Array cables (66 kV), export cables (155 kV) and wind turbine characteristics are taken from the OWF defined in Deliverable 3.2 and 2.1.

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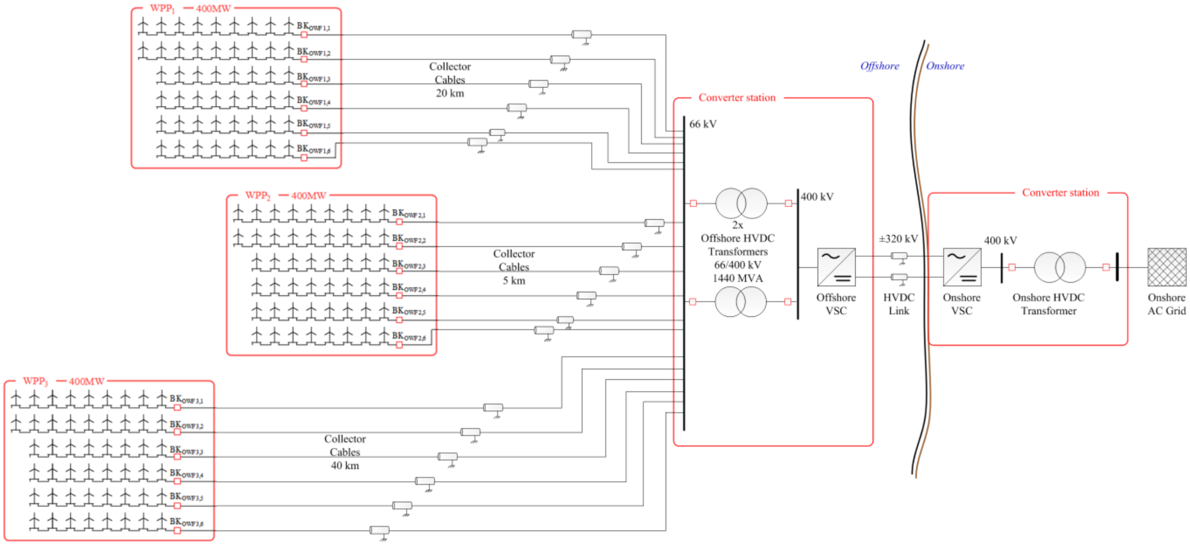

Figure 2-9: 3x400MW WPPs, consisting of 8MW WTs connected to a 155kV ac collector and at 120km from shore.

2.3. SIMULATION TEST CASES

This section includes the simulation test cases to be carried out in the aforementioned scenarios for controller validation for self-start and black-start operation.

It is worth pointing out that some of the HVDC Diode Rectifier connected wind power plant operational modes are directly applicable to both HVAC and HVDC based black-start operation.

These operational modes are covered in Deliverables D3.1 and D3.2:

- **ISL mode - Island operation** (Houseload operation): The WPP is neither connected to a DR nor to an alternate AC system (be it synchronised or unsynchronised) i.e. the WPP is completely islanded and has to maintain its own voltage and frequency control in order to supply the local network load.
- **UAC mode – Unsynchronised AC:** The WPP is connected to an alternate AC system such as a local generator or VSC converter which is not synchronized with the main AC system nor has any other strong frequency control characteristics.
- **SAC mode – Synchronised AC:** The WPP is connected to the main AC system or another AC system with strong frequency control characteristics.

Clearly, these three operational modes, already covered in WP3 are particularly relevant to self-start / black-start operation. Even though test cases defined for DRU based controllers already include transitions between these operational modes, the definition of these test cases will be included here for the sake of completeness.

2.4. NORMAL OPERATION

This section includes the test cases for normal operation.

Self-start and black start operation studies by means of simulation should include both transformer and cable models with sufficient detail. Particularly all transformers should include realistic values for saturation and have the possibility to include residual flux. Phase dependant frequency models should be used for cables longer than 10 km.

2.4.1 OFF-SHORE AC GRID START-UP OPERATION (SELF-START TO HOUSELOAD OPERATION)

The start procedure includes the energisation of all the off-shore system elements, considering that the initial WTG is capable to energise its own auxiliaries using an internal energy source (e.g. UPS). The test case defined in this section will lead to the system end up working in houseload operation (ISL mode). This start-up procedure is common for all scenarios considered in this document regardless of HVAC or HVDC connection.

A proposal of energisation procedure consists of:

1. Energisation of transformer of WT_{1-1} from WT_{1-1}.
2. Energisation of string cable 1 from WT_{1-1}.
3. Sequential synchronisation of the rest of WTs connected to string 1 (first energisation of the transformer from the string and then synchronisation of the WT).
4. Sequential energisation of the rest of strings and synchronisation of the WTs. The sequence to energise the next string consist of:
    a. Energise a string from energised strings.
    b. Energise the WT transformers from the energised strings.
    c. Synchronisation of the WTs.

Off-shore wind farm shall end up in ISL mode with a correct active and reactive power sharing.

2.4.1. OFF-SHORE AC-GRID START-UP OPERATION		
System Configuration	HVAC connected WPP	
Control hierarchy levels affected	OWF controller, WT controller	
Related functional requirements		
Methodology	The considered functional requirements will be validated by means of EMT simulation.	
Minimum simulation detail (maximum level of aggregation)	WTG	Level 4 (from Deliverable 3.2)
	OWF	One complete string and aggregated strings
	MMC	N/A
	On-shore grid	N/A
Case description	The start-up procedure included in the description is carried out. The off-shore wind farm will be completely energised and at the end of the procedure, the OWFs will be in ISL mode. The different elements will be energised sequentially as per the previous description, no pre-insertion resistor (PIR) or point-of-wave (POW) is considered.	
Sensitivity analysis	Number of WT/strings connected (6 cases considering different number of connected strings).	
Result assessment	For each one of the tests, the functional requirements will be evaluated and quantitative and qualitative results will be tabulated and compared with the considered functional requirements.	

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2.4.2 RESPONSE TO CHANGES IN REACTIVE POWER SHARING COMMAND (ISL OPERATION)

2.4.2. RESPONSE TO CHANGES IN REACTIVE POWER SHARING COMMAND (ISL OPERATION)		
System Configuration	HVAC connected WPP	
Control hierarchy levels affected	OWF controller, WT controller	
Related functional requirements		
Methodology	The considered functional requirements will be validated by means of EMT simulation.	
Minimum simulation detail (maximum level of aggregation)	WTG	Level 4 (from Deliverable 3.2)
	OWF	One complete string and aggregated strings
	MMC	N/A
	On-shore grid	N/A
Case description	The OWF controller will send commands to set different sharing coefficients to each WTG. This test will show adequate reactive power sharing between WTGs	
Sensitivity analysis	Number of WT/strings connected (6 cases considering different number of connected strings).	
Result assessment	For each one of the tests, the functional requirements will be evaluated and quantitative and qualitative results will be tabulated and compared with the considered functional requirements.	

2.4.3 RESPONSE TO CHANGES IN FREQUENCY SET-POINT

2.4.3. RESPONSE TO CHANGES IN FREQUENCY SET-POINT		
System Configuration	HVAC connected WPP	
Control hierarchy levels affected	OWF controller, WT controller	
Related functional requirements		
Methodology	The considered functional requirements will be validated by means of EMT simulation.	
Minimum simulation detail (maximum level of aggregation)	WTG	Level 4 (from Deliverable 3.2)
	OWF	One complete string and aggregated strings
	MMC	N/A
	On-shore grid	On-shore substation with/without block load
Case description	The OWF controller will send commands to the WTGs to change the frequency reference to the extreme values of the allowable frequency range.	
Sensitivity analysis	Number of WT/strings connected (6 cases considering different number of connected strings). a) Houseload operation with/without off-shore substation b) Self-start operation (on-shore substation with/without block load).	

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Result assessment	For each one of the tests, the functional requirements will be evaluated and quantitative and qualitative results will be tabulated and compared with the considered functional requirements.

2.4.4 DYNAMIC VOLTAGE CONTROL

2.4.4. DYNAMIC VOLTAGE CONTROL		
System Configuration	HVAC connected WPP	
Control hierarchy levels affected	OWF controller, WT controller	
Related functional requirements		
Methodology	The considered functional requirements will be validated by means of EMT simulation.	
Minimum simulation detail (maximum level of aggregation)	WTG	Level 4 (from Deliverable 3.2)
	OWF	One complete string and aggregated strings
	MMC	N/A
	On-shore grid	On-shore substation with/without block load
Case description	The OWF controller will send commands to the WTGs to change the voltage reference to the extreme values of the allowable voltage range.	
Sensitivity analysis	Number of WT/strings connected (6 cases considering different number of connected strings). a) Houseload operation. b) Self-start operation.	
Result assessment	For each one of the tests, the functional requirements will be evaluated and quantitative and qualitative results will be tabulated and compared with the considered functional requirements.	

2.4.5 HARMONIC COMPLIANCE (TO BE CARRIED OUT IN WP16)

2.4.5. HARMONIC COMPLIANCE (TO BE COVERED IN WP16)		
System Configuration	HVAC connected WPP	
Control hierarchy levels affected	OWF controller, WT controller	
Related functional requirements		
Methodology	The considered functional requirements will be validated by means of EMT simulation.	
Minimum simulation detail (maximum level of aggregation)	WTG	Level 4 (from Deliverable 3.2)
	OWF	One complete string and aggregated strings
	MMC	N/A
	On-shore grid	On-shore substation with/without block load
Case description	The system will be operated at different power levels and its harmonic compliance will be tested. Usually, EMT simulations	

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	are not practical to be run to achieve adequate time samples for harmonic analysis without correlation between wind turbines. This test case will be tried with the real time CHiL system developed in WP16.
Sensitivity analysis	Number of WT/strings connected (6 cases considering different number of connected strings). a) Houseload operation. b) Self-start operation.
Result assessment	For each one of the tests, the functional requirements will be evaluated and quantitative and qualitative results will be tabulated and compared with the considered functional requirements.

2.4.6 OFF-SHORE HVAC SUBSTATION ENERGISATION

2.4.6. OFF-SHORE HVAC SUBSTATION ENERGISATION		
System Configuration	HVAC connected WPP	
Control hierarchy levels affected	OWF controller, WT controller	
Related functional requirements		
Methodology	The considered functional requirements will be validated by means of EMT simulation.	
Minimum simulation detail (maximum level of aggregation)	WTG	Level 4 (from Deliverable 3.2)
	OWF	One complete string and aggregated strings. Transformer models will include detailed in-rush and saturation characteristics.
	MMC	N/A
	On-shore grid	N/A
Case description	The offshore HVAC transformer (or transformers) will be energised, considering possible shunt compensation elements present in the substation. Use of PIRs is not considered Different POW switching instants will be considered.	
Sensitivity analysis	Number of WT/strings connected (6 cases considering different number of connected strings). Different POW switching instants will be considered.	
Result assessment	For each one of the tests, the functional requirements will be evaluated and quantitative and qualitative results will be tabulated and compared with the considered functional requirements.	

2.4.7 HVAC EXPORT CABLE ENERGISATION

2.4.7. HVAC EXPORT CABLE ENERGISATION	
System Configuration	HVAC connected WPP
Control hierarchy levels affected	OWF controller, WT controller
Related functional requirements	
Methodology	The considered functional requirements will be validated by means of EMT simulation.

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Minimum simulation detail (maximum level of aggregation)	WTG	Level 4 (from Deliverable 3.2)
	OWF	One complete string and aggregated strings. Transformer models will include detailed in-rush and saturation characteristics. Export cables will be modelled as a phase dependant distributed model.
	MMC	N/A
	On-shore grid	N/A
Case description	The export cable will be energised, considering possible shunt compensation elements present in the off-shore and on-shore substations.	
Sensitivity analysis	Number of WT/strings connected (6 cases considering different number of connected strings). Different POW switching instants will be considered.	
Result assessment	For each one of the tests, the functional requirements will be evaluated and quantitative and qualitative results will be tabulated and compared with the considered functional requirements.	

2.4.8 OFF-SHORE HVDC STATION ENERGISATION

2.4.8 OFF-SHORE HVDC STATION ENERGISATION		
System Configuration	VSC-HVDC connected WPP	
Control hierarchy levels affected	Offshore and onshore MMC station, WT controller	
Related functional requirements		
Methodology	The offshore HVDC substation energization will be validated by means of EMT simulation.	
Minimum simulation detail (maximum level of aggregation)	WTG	Level 4 (Perfect DC link control is assumed)
	OWF	Level 6 (One complete string, aggregated strings and aggregated clusters)
	MMC	Level 1 (Corresponding to Type 4 as defined by Cigre WG B4.57)
	On-shore grid	Level 3 (Thevenin equivalent)
Case description	There will be two cases; 1. The OWF (WTs) will ramp up the offshore AC grid voltage in the OWF, while the HVDC transformer and converter are not connected. Then the HVDC transformer and converter will be switched in via using a Pre-Insertion Resistor (PIR) that will be bypassed after a certain Pre-Insertion Time (PIT). 2. The OWF (WTs) will ramp up the offshore AC grid voltage in the OWF, while the HVDC transformer and converter are connected without any PIR) The offshore MMC cells will be charged from the offshore AC side.	
Sensitivity analysis	Rate of voltage ramp-up by the OWF will be tested for different values.	
Result assessment	The maximum rate of voltage ramp-up value, which doesn't cause oscillations or overshoot will be identified. Offshore AC	

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	grid voltage, WTs' and MMC's AC currents will be observed to be within the limits and controlled properly.

2.4.9 HVDC CABLE ENERGISATION

2.4.9 HVDC CABLE ENERGISATION		
System Configuration	VSC-HVDC connected WPP	
Control hierarchy levels affected	Offshore and onshore MMC station, WT controller	
Related functional requirements		
Methodology	The HVDC cable energization will be validated by means of EMT simulation.	
Minimum simulation detail (maximum level of aggregation)	WTG	Level 4 (Perfect DC link control is assumed)
	OWF	Level 6 (One complete string, aggregated strings and aggregated clusters)
	MMC	Level 2 (Averaged model, corresponding to a Type 5)
	On-shore grid	Level 3 (Thevenin equivalent)
Case description	Once the offshore MMC cells are charged from the offshore AC grid side by the OWF, the offshore HVDC converter will be de-blocked and start regulating HVDC link voltage.	
Sensitivity analysis	The HVDC link voltage setpoint will be slightly varied within the limits.	
Result assessment	Offshore AC grid voltage, HVDC link voltage, WTs' and offshore MMC's AC currents will be observed to be within the limits and controlled properly.	

2.4.10 ON-SHORE HVDC STATION ENERGISATION

2.4.10 ON-SHORE HVDC STATION ENERGISATION		
System Configuration	VSC-HVDC connected WPP	
Control hierarchy levels affected	Offshore and onshore MMC station, WT controller	
Related functional requirements		
Methodology	The onshore HVDC station (converter and transformer) energization will be validated by means of EMT simulation.	
Minimum simulation detail (maximum level of aggregation)	WTG	Level 4 (Perfect DC link control is assumed)
	OWF	Level 6 (One complete string, aggregated strings and aggregated clusters)
	MMC	Level 1 (Corresponding to Type 4 as defined by Cigre WG B4.57)
	On-shore grid	Level 3 (Thevenin equivalent). Only on-shore loads as no on-shore generation has been considered.
Case description	Once the HVDC link is energized by the offshore side, first the	

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	onshore HVDC MMC cells will be charged to their rated DC voltage (from the HVDC link side) and then the onshore MMC will be de-blocked and start creating the onshore AC grid voltage via a ramp-up, while the onshore grid (beyond the HVDC transformer) is not connected. The onshore MMC will regulate the onshore AC grid voltage to the rated value.
Sensitivity analysis	Rate of onshore AC grid voltage ramp-up by the onshore MMC will be tested for different values.
Result assessment	Onshore AC grid voltage, offshore AC grid voltage, HVDC link voltage, WTs' and MMCs' AC currents, MMC cell voltages and HVDC current will be observed to be within the limits and controlled properly.

2.4.11 ON-SHORE HVAC SUBSTATION ENERGISATION

2.4.11. ON-SHORE HVAC SUBSTATION ENERGISATION		
System Configuration	HVAC connected WPP	
Control hierarchy levels affected	OWF controller, WT controller	
Related functional requirements		
Methodology	The considered functional requirements will be validated by means of EMT simulation.	
Minimum simulation detail (maximum level of aggregation)	WTG	Level 4 (from Deliverable 3.2)
	OWF	One complete string and aggregated strings. Transformer models will include detailed in-rush and saturation characteristics. Export cables will be modelled as a phase dependant distributed model.
	MMC	N/A
	On-shore grid	Transformer models will include detailed in-rush and saturation characteristics. Include possible substation compensation elements.
Case description	The onshore HVAC transformer (or transformers) will be energised, considering possible shunt compensation elements present in the substation.	
Sensitivity analysis	Number of WT/strings connected (6 cases considering different number of connected strings). Different POW switching instants will be considered.	
Result assessment	For each one of the tests, the functional requirements will be evaluated and quantitative and qualitative results will be tabulated and compared with the considered functional requirements.	

2.4.12 SYNCHRONISATION TO ON SHORE GRID

2.4.12. SYNCHRONISATION TO ONSHORE GRID	
System Configuration	HVAC connected WPP
Control hierarchy levels affected	OWF controller, WT controller

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Related functional requirements		
Methodology	The considered functional requirements will be validated by means of EMT simulation.	
Minimum simulation detail (maximum level of aggregation)	WTG	Level 4 (from Deliverable 3.2)
	OWF	Level 4 (from Deliverable 3.2) One complete string and aggregated strings. Transformer models will include detailed in-rush and saturation characteristics.
	MMC	N/A
	On-shore grid	Transformer models will include detailed in-rush and saturation characteristics. Include possible substation compensation elements. Rest of the grid will be Level 3 (as defined in Deliverable 3.2)
Case description	The OWPP created on-shore island will be synchronised to another island, as part of the restoration process. Once synchronised, different references of active/reactive power will be sent to the OWPP.	
Sensitivity analysis	Number of WT/strings connected (6 cases considering different number of connected strings). Different angle, frequency and magnitude differences will be considered.	
Result assessment	For each one of the tests, the functional requirements will be evaluated and quantitative and qualitative results will be tabulated and compared with the considered functional requirements.	

2.4.13 POWER BLOCK DELIVERY

2.4.13. POWER BLOCK DELIVERY		
System Configuration	HVAC/HVDC connected WPP	
Control hierarchy levels affected	OWF controller, WT controller	
Related functional requirements		
Methodology	The considered functional requirements will be validated by means of EMT simulation.	
Minimum simulation detail (maximum level of aggregation)	WTG	Level 4 (from Deliverable 3.2)
	OWF	One complete string and aggregated strings. Transformer models will include detailed saturation and residual flux characteristics.
	MMC	N/A
	On-shore grid	Transformer models will include detailed saturation characteristics and residual flux. Include possible substation compensation elements.
Case description	A 30 MW active power block will be applied to the on-shore island created by the OWPP (without synchronisation to any	

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	other AC grid). Different ramp rates will be considered. As a second step the 30MW active power block will be disconnected by tripping the corresponding breaker.
Sensitivity analysis	Number of WT/strings connected (6 cases considering different number of connected strings). Different POW switching instants will be considered.
Result assessment	For each one of the tests, the functional requirements will be evaluated and quantitative and qualitative results will be tabulated and compared with the considered functional requirements.

2.4.14 SOFT ENERGISATION (FROM HOUSELOAD TO POWER BLOCK)

Considering that the WPP is already in houseload operation, this test cases covers the soft-start procedure of the rest of the system up to the on-shore HVAC substation. Therefore, all the considered elements (off-shore substation, HVAC export cable, onshore substation) are connected simultaneously at zero or a very low voltage (e.g. 0.2 pu) and then the WPP ramps up its voltage to 1pu. The test case ends with a power block delivery.

For HVDC connected WPP, the off-shore grid voltage is ramped up to carry out the soft-start energisation of the off-shore HVDC transformer and charge the off-shore converter cells simultaneously, without a PIR. Then the off-shore converter is de-blocked to energize the HVDC cable followed by the DC-side pre-charging of the on-shore converter cells and de-blocking to control the on-shore AC voltage, ending with power block delivery, identical to sections 2.4.9, 2.4.10 & 2.4.13, respectively.

2.4.14. SOFT ENERGISATION		
System Configuration	HVAC connected WPP	
Control hierarchy levels affected	OWF controller, WT controller	
Related functional requirements		
Methodology	The considered functional requirements will be validated by means of EMT simulation.	
Minimum simulation detail (maximum level of aggregation)	WTG	Level 4 (from Deliverable 3.2)
	OWF	One complete string and aggregated strings
	MMC	N/A
	On-shore grid	Transformer models will include detailed saturation and residual flux characteristics. Include possible substation compensation elements.
Case description	The black start operation included in the description is carried out when the off-shore wind farm is in ILS mode. Soft energisation shall be carried out as considered in the description.	
Sensitivity analysis	Number of WT/strings connected (6 cases considering different number of connected strings).	
Result assessment	For each one of the tests, the functional requirements will be evaluated and quantitative and qualitative results will be	

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	tabulated and compared with the considered functional requirements.

2.5. FAULT RIDE-THROUGH AND PROTECTION

Various fault cases that need to be tested are defined in this section, including onshore grid faults, HVAC cable faults and offshore AC faults. The aggregation level of the adopted model for WTG, OWF, MMC and onshore grid are specified and the procedures to carry on the test cases of fault operation are described. The required sensitivity analysis and the approach to assess the test results are provided.

2.5.1 ONSHORE GRID FAULTS

2.5.1 ONSHORE GRID FAULTS		
System Configuration	HVAC connected WPP	
Control hierarchy levels affected	OWF controller, WT controller	
Related functional requirements		
Methodology	The considered fault ride-through requirements will be validated by means of EMT simulation.	
Minimum simulation detail (maximum level of aggregation)	WTG	Level 4 (from Deliverable 3.2)
	OWF	One complete string and aggregated strings
	MMC	N/A
	On-shore grid	Transformer models will include detailed saturation and residual flux characteristics. Include possible substation compensation elements.
Case description	After the occurrence of onshore AC faults, the offshore WTs will operate on current limiting mode to avoid overcurrent. When the onshore AC fault is cleared, the offshore WPP should restore the system to the previous state (connected/unconnected load).	
Sensitivity analysis	Number of WT/strings connected (6 cases considering different number of connected strings).	
Result assessment	For each one of the tests, the functional requirements will be evaluated and quantitative and qualitative results will be tabulated and compared with the considered functional requirements.	

2.5.2 HVAC CABLE FAULTS

2.5.2 HVAC CABLE FAULTS	
System Configuration	HVAC connected WPP
Control hierarchy levels affected	OWF controller, WT controller
Related functional requirements	
Methodology	The considered fault ride-through requirements will be validated by means of EMT simulation.

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Minimum simulation detail (maximum level of aggregation)	WTG	Level 4 (from Deliverable 3.2)
	OWF	One complete string and aggregated strings
	MMC	N/A
	On-shore grid	Transformer models will include detailed saturation and residual flux characteristics. Include possible substation compensation elements.
Case description	After the occurrence of HVAC cable faults, the offshore WTs will operate on current limiting mode to avoid overcurrent. When the umbilical AC fault is cleared, the offshore WPP should restore the system to the previous state (connected/unconnected load).	
Sensitivity analysis	Number of WT/strings connected (6 cases considering different number of connected strings). Various fault locations along the HVAC cable will be tested.	
Result assessment	For each one of the tests, the functional requirements will be evaluated and quantitative and qualitative results will be tabulated and compared with the considered functional requirements.	

2.5.3 OFFSHORE AC FAULTS

2.5.3.1 OFFSHORE AC FAULTS		
System Configuration	HVAC connected WPP	
Control hierarchy levels affected	OWF controller, WT controller	
Related functional requirements		
Methodology	The considered fault ride-through requirements will be validated by means of EMT simulation.	
Minimum simulation detail (maximum level of aggregation)	WTG	Level 4 (from Deliverable 3.2)
	OWF	One complete string and aggregated strings
	MMC	N/A
	On-shore grid	Transformer models will include detailed saturation and residual flux characteristics. Include possible substation compensation elements.
Case description	After the occurrence of symmetrical offshore AC faults, the offshore WTs will operate on current limiting mode to avoid overcurrent. After fault clearance, the offshore WPP should restore the system to the previous state (connected/unconnected load).	
Sensitivity analysis	Number of WT/strings connected (6 cases considering different number of connected strings). Offshore AC busbar fault will be tested.	
Result assessment	For each one of the tests, the fault ride-through requirements will be evaluated and compared with the considered functional requirements. Typical simulation results will be presented.	

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3. COMPLIANCE EVALUATION RESULTS OF OWF AND WPP CONTROLLERS FOR SELF-START AND BLACK START OPERATION

This point includes de the compliance evaluation results of the test cases that have been defined above. These results shall include a table with the compliance evaluation and detailed results as the Deliverable 3.4.

3.1. HVAC CONNECTED WTG CONTROL

The wind turbine control in normal operation and in fault operation for each individual wind turbine is shown below [Martinez-Turegano 2018].

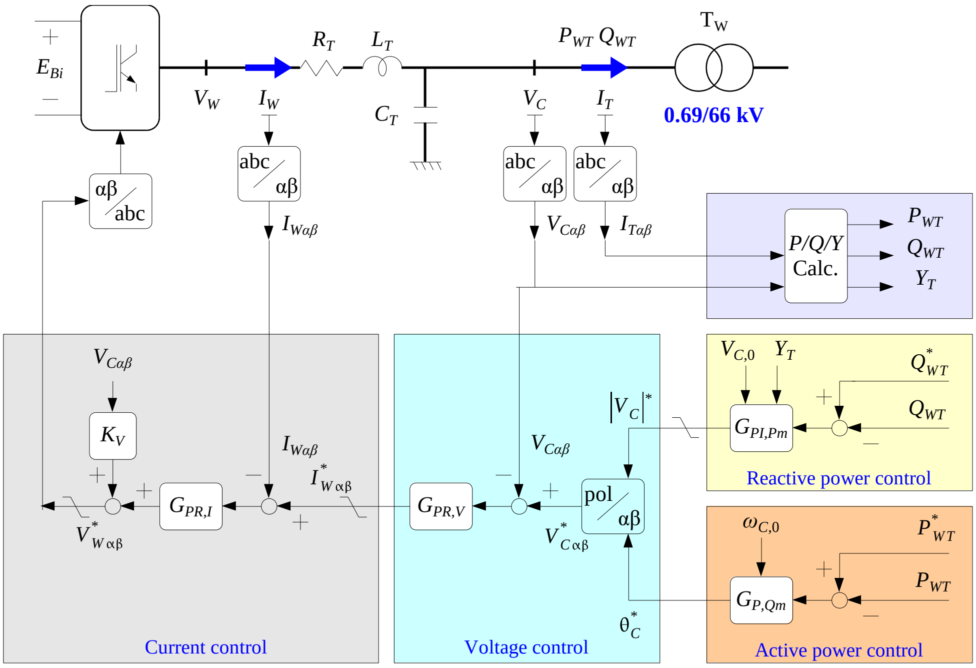

Figure 3-1: WTG grid side converter control for HVAC connected WPP.

The proposed control consists of an inner proportional-resonant (PR) current control loop, an outer PR voltage control loop, outer P/w, Q/V droops. The operation of the aforementioned blocks will be explained in detail as follows.

The proposed distributed control technique is based on a cascaded control approach, with an inner PR current control loop in the stationary α-β frame. The outer PR control loop is responsible for the control of the VT voltage magnitude and angle control. The bandwidth of the control loops is 200 Hz and 40 Hz, respectively. The

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internal PR current loop allows for control of positive and negative sequence WTG currents and voltages and allow for both current and voltage limitation.

Active and reactive power sharing between wind turbines is carried out by means of P/w and Q/V droops:

$$\omega = \omega^* - m(P - P^*) - m_d \frac{d}{dt}(P - P^*)$$

$$V_c = V_{C\,0} - n(Q - Q^*)$$

where m and m_d are the proportional and derivate coefficients of active power P, and n is the proportional coefficient of the reactive power Q.

3.2. VSC CONNECTED WPP CONTROL

The wind turbine control in normal operation for each individual wind turbine is shown below.

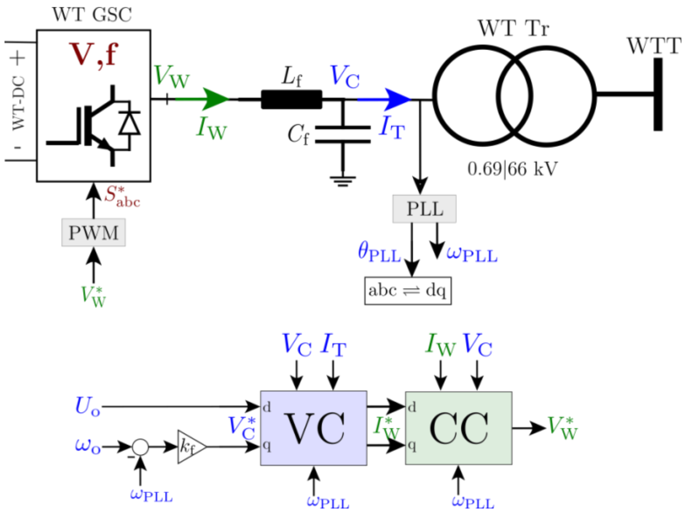

Figure 3-2: WTG grid side converter (GSC) control for HVDC connected WPP.

The above grid-forming control is based on the distributed phase-locked-loop (PLL)-based frequency control as proposed in [Yu 2018] that uses a cascaded control approach.

- The inner loop is a classical synchronous reference frame based current control (CC) that has been widely used for controlling VSCs with benefit of fast response and current limitation.
- The voltage control (VC) loop is responsible for forming the grid i.e. controlling the voltage magnitude, by the *d*-axis & *q*-axis voltage references. Normally, the *q*-axis reference is set to 0 in isolated converter based networks. However, the output of PLL can be used as an indication of frequency deviation, and thus a proportional frequency loop is used to generate the q-axis voltage reference, as explained in more detail in [Yu 2018].

- Since during the energization of the grid-forming HVDC connected WPP, the grid PCC is not available and the WPP is in *islanded* operation, the real (P) & reactive (Q) power flows are set by the load demand plus losses. Thus the outer loops for active power control and reactive power sharing control, as shown in [Yu 2018] are not used here, similar to what has been used in [Sakamuri 2019].

3.3. NORMAL OPERATION

3.3.1 OFF-SHORE AC GRID START-UP OPERATION (SELF-START TO HOUSELOAD OPERATION)

The sensitivity analysis for the off-shore AC grid start-up operation just includes one simulation with the synchronisation of the all WTGs. It is done because the simulations with less strings/WTGs connected are a part of the complete off-shore AC grid start-up operation.

Test case	2.4.1. OFF-SHORE AC-GRID START-UP OPERATION		
Simulation detail	WT	Level 4: Perfect DC link control is assumed	
	OWF	Level 4: One detailed string and aggregated strings.	
	On-shore grid	Level 3: Thevenin equivalent	
	Configuration (connected strings)	Compliance	Comments
Simulations (sensitivity analysis)	6 Strings	pass	P_{TOT}= 400 MW; **WTG (max values):** V= 1.14 pu; I = 0.83 pu; P_{WT} = 0.07 pu; Q_{WT} = -0.81 pu; Δf = 1.25 Hz; df/dt = 3.03 Hz/s; **PCC (max values):** V = 1.19 pu; I = 0.0 pu; P = 0 pu; Q = 0 pu; The WTG voltage is exceeded a few milliseconds during the string cable energisation, which can be avoided by carrying out a soft-energisation of the string cable by the first connected WTG or by energising the first string cable in sections.
Comments	The start-up process consists on the following basic steps: • $WTG\text{-}_{1,1}$ energizes its transformer. • $WTG\text{-}_{1,1}$ energizes the string 1. • Synchronisation of WTGs connected to string 1. • Connected WTGs energize the string n. • Synchronisation of WTGs connected to string n.		

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Sample result	 Figure 3-3: Sequential connection of WTGs in string 1: (a) active power (pu); (b) reactive power (pu); (c) voltage (pu); (d) off-shore ac frequency (Hz). (magnitudes shown at the low voltage terminals of the WTG transformer).

The first string cable requires 0.8 pu reactive power for its energisation. Therefore, the first string cable can be energised from a single WTG. String cables with higer reactive power requirements should be energised in sections. The voltages and currents of the WTG during the string energisation are shown in Figure 3-4. As mentioned in the comment, voltage exceeds 1.1 pu for a few milliseconds during string cable hard energisation, which can be avoided by carrying out a soft-energisation of the string cable by the first connected WTG or by energising the first string cable in smaller sections.

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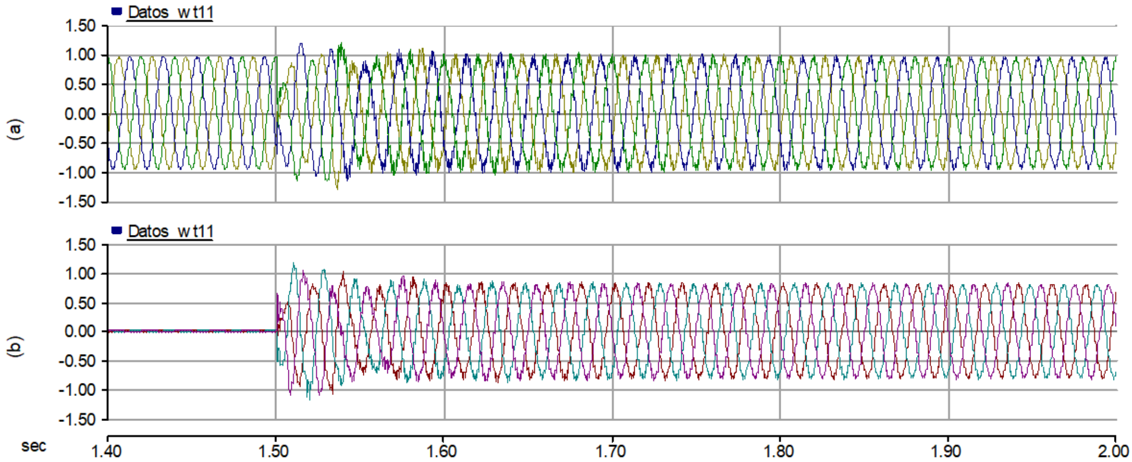

Figure 3-4: $WTG_{1,1}$ during the string1 energisation (at the low voltage terminals of the WTG transformer): (a) voltage (pu); (b) current (pu).

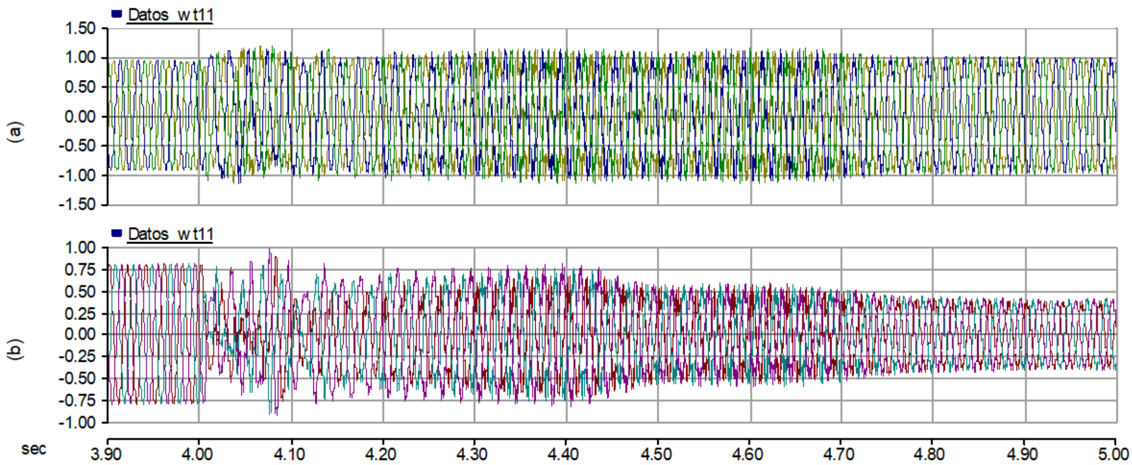

Figure 3-5: $WTG_{1,1}$ during the $WTG_{1,2}$ transformer energisation (at the low voltage terminals of the WTG transformer): (a) voltage (pu); (b) current (pu).

Then, the synchronisation of the rest of WTGs is carried out sequentially energising the WTG transformer from the connected WTGs and synchronising the WTG. WTG-1,1 energizes the transformer of WTG-1,2 in-rush currents appear. Those currents are mitigated in 1.5 seconds. As the in-rush current is mitigated the WTG-1,2 synchronises and contributes to the reactive power sharing (see as the current of the WTG-1,2 decreases).
After the synchronisation of the connected WTS to the string 1, the synchronisation of the remaining strings and aggregated WTGs is carried out.

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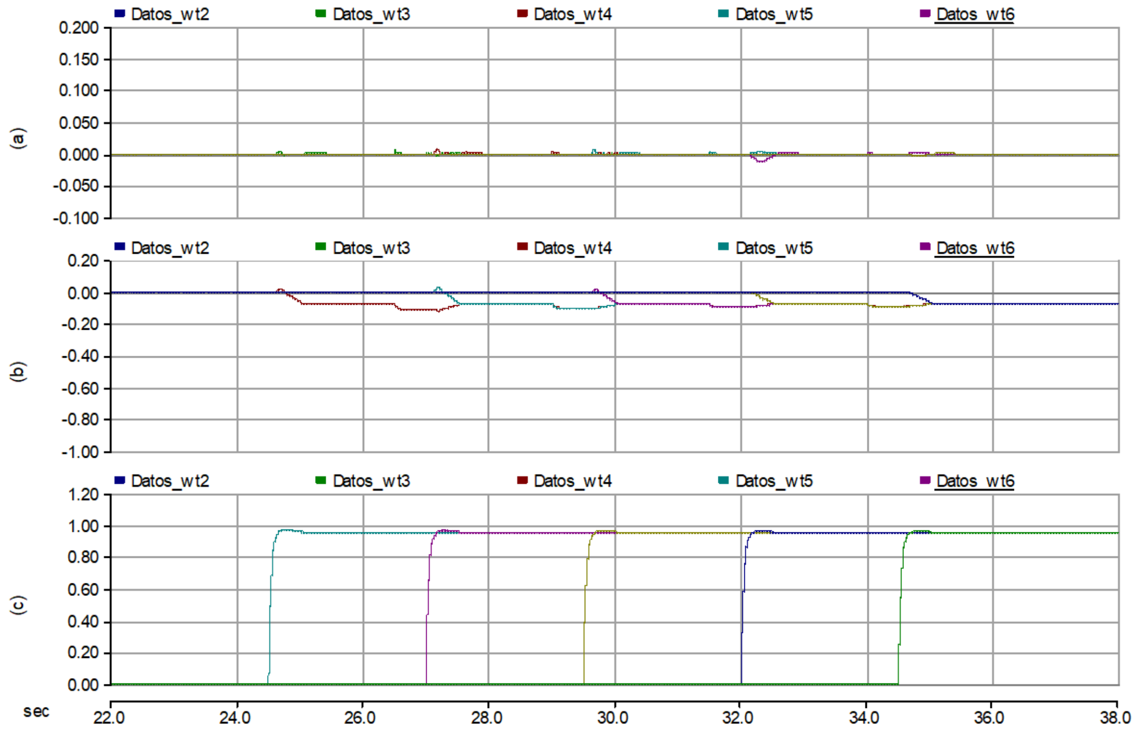

Figure 3-6: Aggregated WTGs: (a) active power (pu); (b) reactive power (pu); (c) voltage (pu) (magnitudes shown at the low voltage terminals of the WTG transformer).

3.3.2 RESPONSE TO CHANGES IN REACTIVE POWER SHARING COMMAND (ISL OPERATION)

This test case is equal than the tested test case "4.2.7. RESPONSE TO REACTIVE POWER SHARING COMMAND" for the DRU scenario. Thus, the results are included in section 6.1.6.

3.3.3 RESPONSE TO CHANGES IN FREQUENCY SET-POINT

Test case	2.4.3. RESPONSE TO CHANGES IN FREQUENCY SET-POINT		
Simulation detail	WT	Level 4: Perfect DC link control is assumed	
	OWF	Level 4: One detailed string and aggregated strings.	
	On-shore grid	Level 3: Thevenin equivalent	
	Configuration (connected strings)	Compliance	Comments
Simulations (sensitivity analysis)	6 Strings	pass	P_{TOT}= 400 MW; **WTG(max values):** V = 0.97 pu; I = 0.08 pu; P = 0.0 pu; Q = -0.08 pu; Δf = 1.0 Hz; df/dt = 2.5 Hz/s; **PCC(max values):** V = 0.98 pu; I = 0.0 pu; P = 0 pu; Q = 0 pu;

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	5 Strings	pass	P_{TOT}= 336 MW; **WTG(max values):** V = 0.97 pu; I = 0.09 pu; P = 0.0 pu; Q = -0.08 pu; Δf = 1.0 Hz; df/dt = 2.5 Hz/s; **PCC(max values):** V = 0.98 pu; I = 0.0 pu; P = 0 pu; Q = 0 pu;
	4 Strings	pass	P_{TOT}= 272 MW; **WTG(max values):** V = 0.97 pu; I = 0.09 pu; P = 0.0 pu; Q = -0.08 pu; Δf = 1.0 Hz; df/dt = 2.5 Hz/s; **PCC(max values):** V = 0.98 pu; I = 0.0 pu; P = 0 pu; Q = 0 pu;
	3 Strings	pass	P_{TOT}= 208 MW; **WTG(max values):** V = 0.97 pu; I = 0.09 pu; P_{WT} = 0.0 pu; Q_{WT} = -0.08 pu; Δf = 1.0 Hz; df/dt = 2.5 Hz/s; **PCC(max values):** V = 0.98 pu; I = 0.0 pu; P = 0 pu; Q = 0 pu;
	2 Strings	pass	P_{TOT}= 144 MW; **WTG(max values):** V = 0.97 pu; I = 0.09 pu; P = 0.0 pu; Q = -0.08 pu; Δf = 1.0 Hz; df/dt = 2.5 Hz/s; **PCC(max values):** V = 0.98 pu; I = 0.0 pu; P = 0 pu; Q = 0 pu;
	1 Strings	pass	P_{TOT}= 72 MW; **WTG(max values):** V = 0.97 pu; I = 0.09 pu; P = 0.0 pu; Q = -0.08 pu; Δf = 1.0 Hz; df/dt = 2.5 Hz/s; **PCC(max values):** V = 0.98 pu; I = 0.0 pu; P = 0 pu; Q = 0 pu;
Comments	This test case consist of changing the frequency set-point. It is carried out changing it as follows: • 1.5 seconds: frequency set-point from 50 to 49 Hz. • 2.5 seconds: frequency set-point from 49 to 51 Hz. • 3.5 seconds: frequency set-point from 51 to 50 Hz. The test case shows the capability of the WPP to remain stable when the frequency set-point change.		

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Sample result

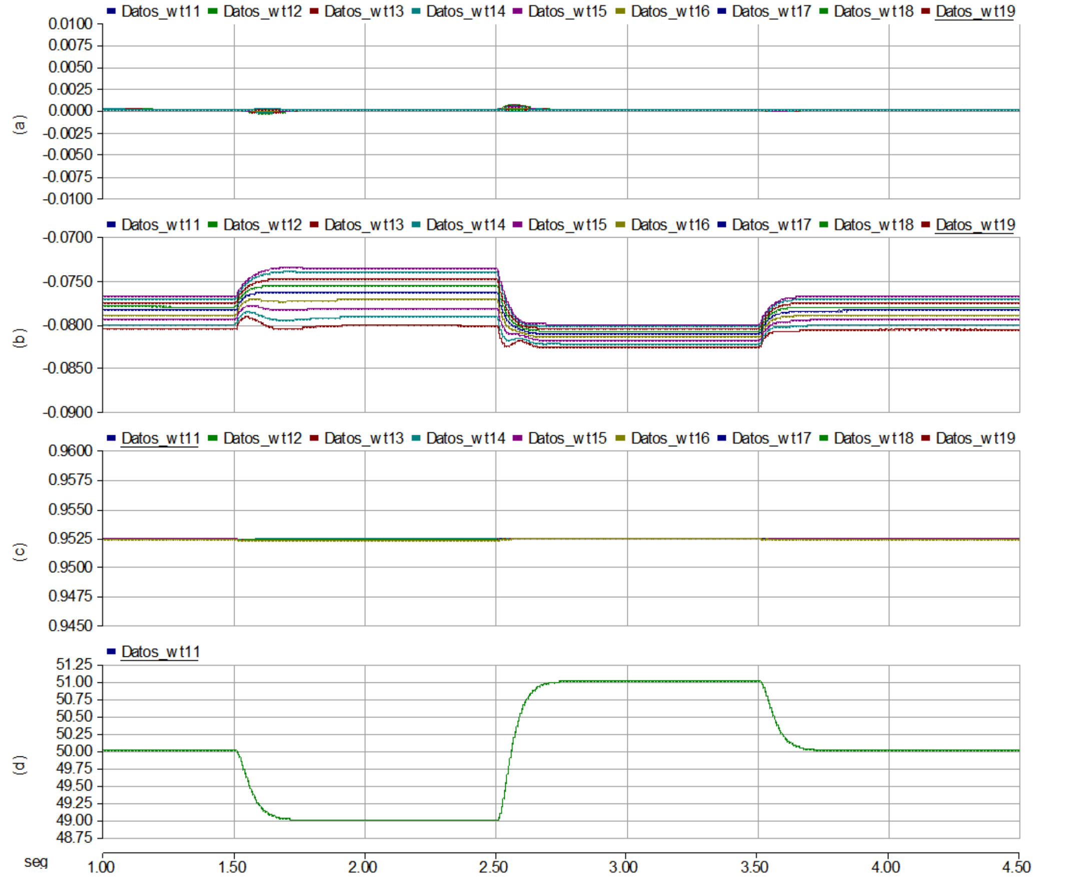

Figure 3-7: WTGs of string 1 in OWF: (a) active power (pu); (b) reactive power (pu); (c) voltage (pu); (d) off-shore ac frequency (Hz). (magnitudes shown at the low voltage terminals of the WTG transformer).

3.3.4 DYNAMIC VOLTAGE CONTROL

This test case is equal than the tested test case “4.2.4. DYNAMIC VOLTAGE CONTROL” for the DRU scenario. Thus, the results are included in section 6.1.4.

3.3.5 HARMONIC COMPLIANCE

This test case will be analysed in WP16 using a real-time simulator (RTS).

3.3.6 OFF-SHORE HVAC SUBSTATION ENERGISATION

This test case consists of the energisation of the off-shore transformer (66/220 kV) from the off-shore WPP using the POW. The energisation of the transformer using POW close each pole as follows:

- Pole A: at maximum voltage A.
- Pole B: 5 ms after the pole A closes.

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- Pole C: 5 ms after the pole A closes.

A Gaussian error with 2 σ=±2.5 ms has been included for the closing time of each one of the poles.

Test case	2.4.6. OFF-SHORE HVAC SUBSTATION ENERGISATION		
Simulation detail	WT	Level 4: Perfect DC link control is assumed	
	OWF	Level 4: One detailed string and aggregated strings.	
	On-shore grid	Level 3: Thevenin equivalent	
	Configuration (connected strings)	Compliance	Comments
Simulations (sensitivity analysis)	6 Strings	pass	P_{TOT}= 400 MW; Pole error (BK_T1): A=0.6 ms; B=-0.7 ms; C=-0.1 ms; **WTG (max values):** V = 0.96 pu; I= 0.09 pu; P = 0.0 pu; Q = -0.08 pu; Δf = 0.01 Hz; df/dt = 0.05 Hz/s; **PCC (max values):** V = 0.97 pu; I = 0.02 pu; P = 0.0 pu; Q = 0.02 pu;
	5 Strings	pass	P_{TOT}= 336 MW; Pole error (BK_T1): A=-0.3 ms; B=-0.4 ms; C=-2.3 ms; **WTG (max values):** V =0.97 pu; I = 0.13 pu; Max P = 0.0 pu; Max Q = -0.09 pu; Max Δf = 0.01 Hz; Max df/dt = 0.09 Hz/s; **PCC (max values):** V = 0.98 pu; I = 0.05 pu; P = 0.0 pu; Q = -0.01 pu;
	4 Strings	pass	P_{TOT}= 272 MW; Pole error (BK_T1): A=-1.3 ms; B=1.1 ms; C=-1.2 ms; **WTG (max values):** V =0.98 pu; I = 0.16 pu; P = 0.01 pu; Q = -0.08 pu; Δf = 0.01 Hz; df/dt = 0.04 Hz/s; **PCC (max values):** V = 1.02 pu; I = 0.12 pu; P = 0.0 pu; Q = 0.01 pu;
	3 Strings	pass	P_{TOT}= 208 MW; Pole error (BK_T1): A=-2.1 ms; B=0.1 ms; C=0.0 ms; **WTG (max values):** V= 1.0 pu; I = 0.19 pu; P = 0.01 pu; Q = -0.08 pu; Δf = 0.1 Hz; df/dt = 0.09 Hz/s; **PCC (max values):** V = 1.07 pu; I = 0.11 pu; Max P_{WT} = 0.0 pu; Max Q_{WT} = -0.01 pu;
	2 Strings	pass	P_{TOT}= 144 MW; Pole error(BK_T1): A=-1.8 ms; B=-1.6 ms; C=2.2 ms; **WTG (max values):** V= 0.97 pu; I = 0.12 pu; P = 0.01 pu; Q = -0.08 pu; Δf = 0.01 Hz; df/dt = 0.05 Hz/s; **PCC (max values):** V = 0.97 pu; I = 0.02 pu; P = 0.0 pu; Q = 0.0 pu;
	1 Strings	pass	P_{TOT}= 72 MW; Pole error (BK_T1): A=2.0 ms; B=0.7 ms; C=-0.6 ms; **WTG (max values):** V = 0.99 pu; I= 0.17 pu; P = 0.01 pu; Q = -0.08 pu; Δf = 0.01 Hz; df/dt = 0.06 Hz/s; **PCC (max values):** V = 0.99 pu; I = 0.02 pu; P = 0.01 pu; Q = 0.01 pu;

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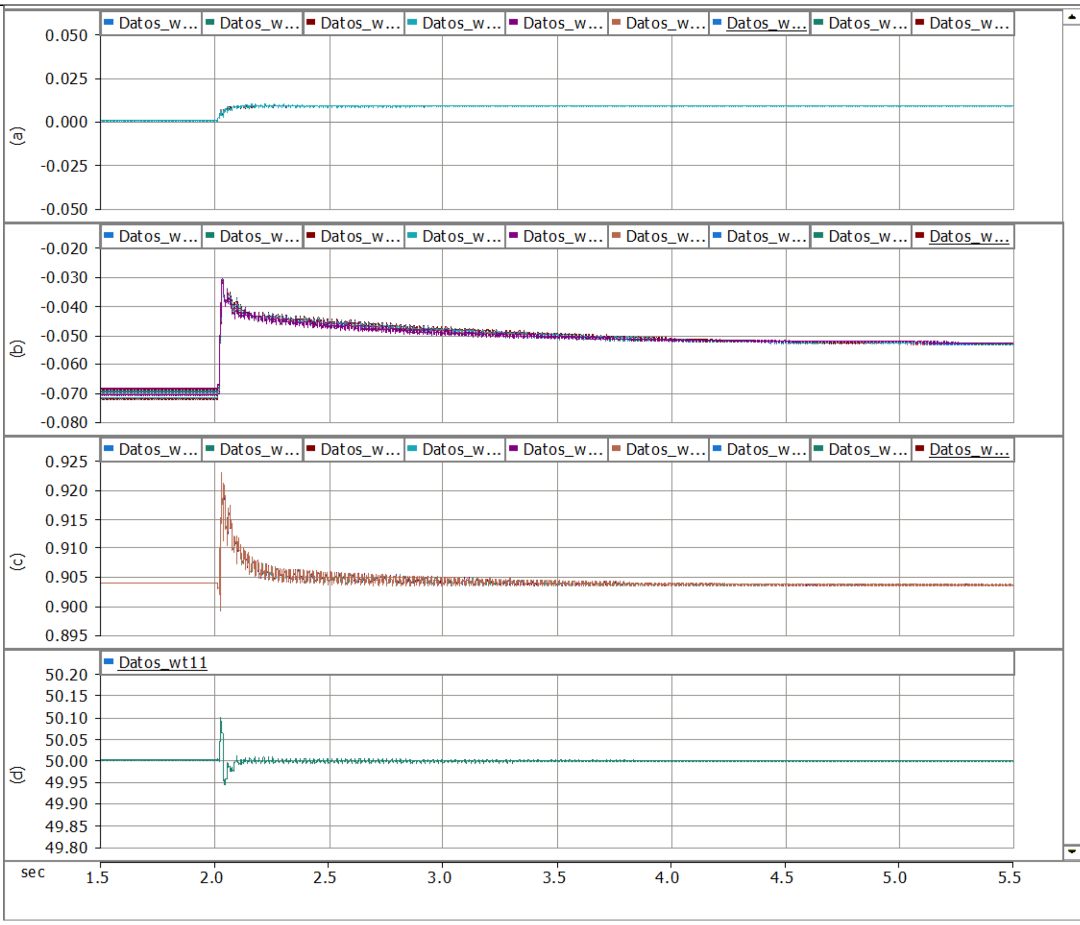
Comments	The sample result shows the energisation of the off-shore transformer (66/220 kV) with only one detailed string connected (considered the most unfavourable case).
Sample result	 Figure 3-8: OWF string 1 WTGs during off-shore HVAC transformer energisation: (a) active power (pu); (b) reactive power (pu); (c) voltage (pu); (d) off-shore ac frequency (Hz). (magnitudes shown at the low voltage terminals of the WTG transformer).

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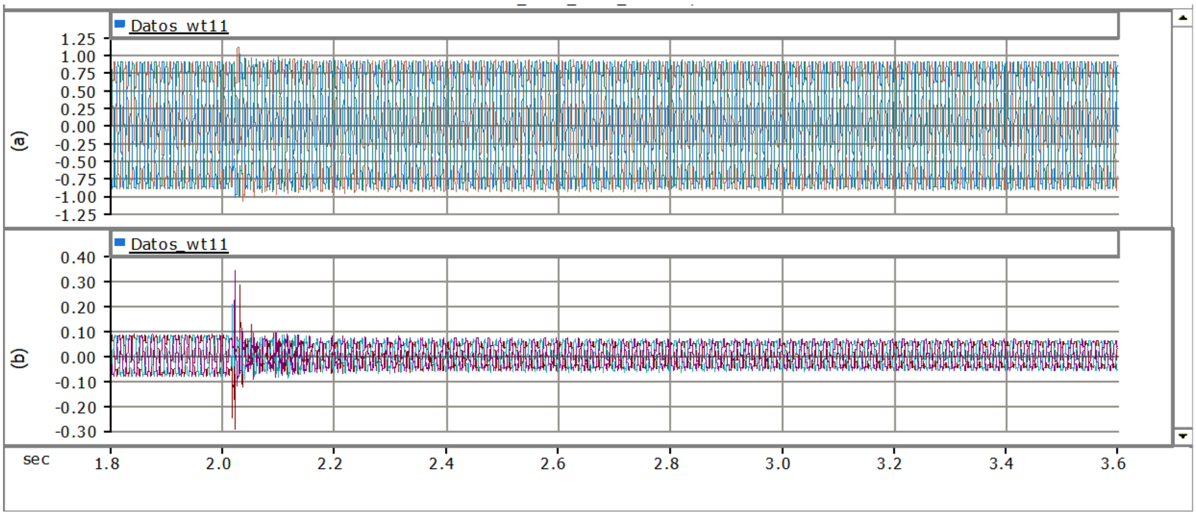

Figure 3-9: $WTG_{1,1}$ during the off-shore transformer energisation (at the low voltage terminals of the WTG transformer): (a) voltage (pu); (b) current (pu).

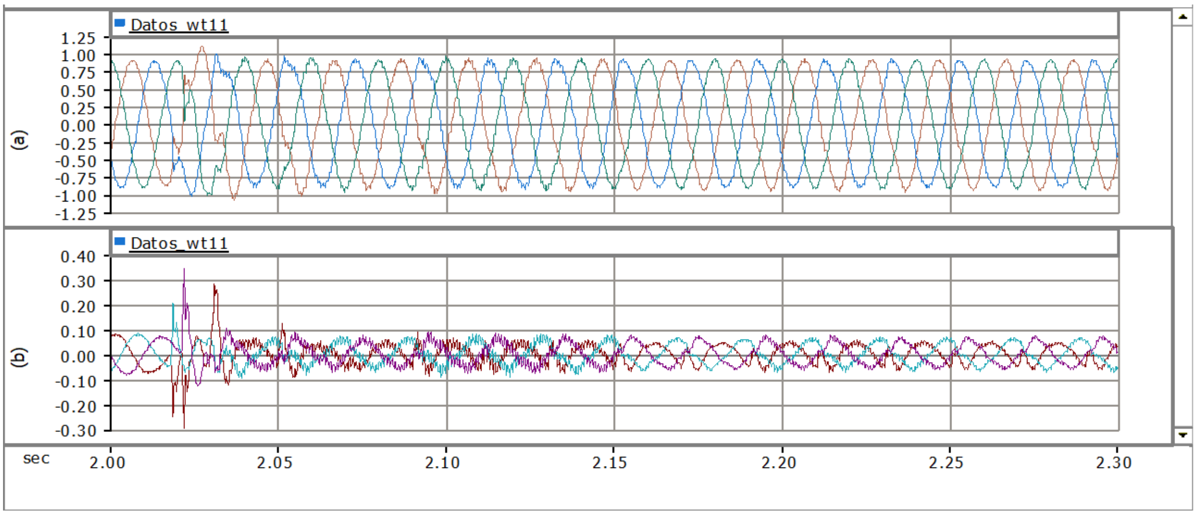

Figure 3-10: $WTG_{1,1}$ during the off-shore transformer energisation (at the low voltage terminals of the WTG transformer): (a) voltage (pu); (b) current (pu).

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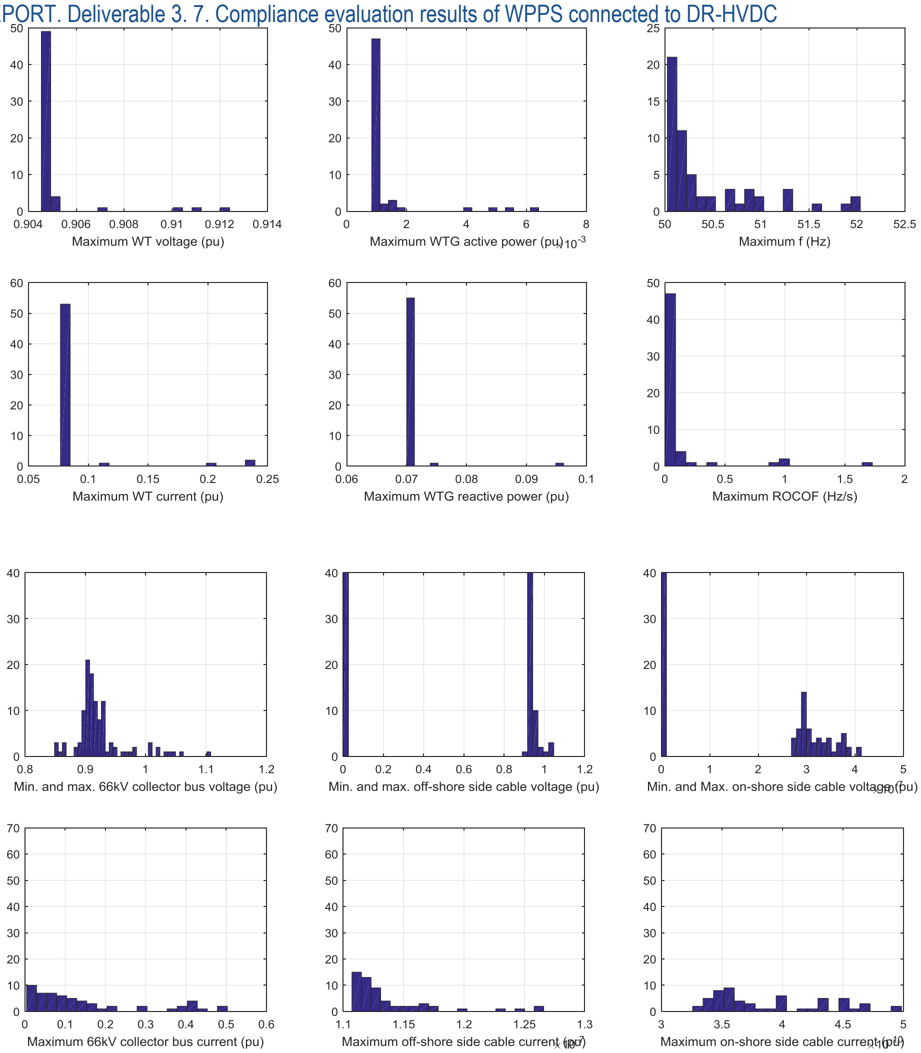

Figure 3-11. Distribution of Monte Carlo test case results for off-shore HVAC transformer energisation with random POW pole spread

The sensitivity to different delays errors for the pole closing of the point of wave (POW) breaker has been carried out by means of a Monte Carlo analysis, considering a gaussian distributed random error of +-2.5ms (2 σ). A total of 100 cases has been run to study the influence of POW switching error during energisation.

Figure Figure 3-11 shows the distribution of the test case results, where the Y axis shows the number of cases in each class. It is worth noting that the minimum voltage in the 66kV collector but is slightly smaller than 0.9 pu in some cases. This undervoltage only lasts for a few milliseconds and is due to the WTG reference voltage being set at about 0.9 pu, in order to avoid overvoltages when large capacitive cables are connected due to Ferranti effect.

The peak active current required for off-shore transformer energisation is about 7%, although in some cases, it can go up to 23%. The maximum reactive power peak is also 7% most of the cases, as the active power delivered by the WTG is very small. PCC frequency is always within limits and rocof maximum is below 0.5 Hz/s most of the cases, with some cases being up to 1.6 Hz/s.

Also, it is worth noting that there are a few cases (not included in the Monte Carlo results), which show ferromagnetic resonances that might cause unacceptable over-voltage and could lead WTG or protective equipment tripping. Ferromagnetic resonance effects are greatly reduced when sequential energisation is carried out at reduced voltage level (e.g. 0.9pu) and have not been seen when using soft-start energisation.

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3.3.7 HVAC EXPORT CABLE ENERGISATION

This test case consists on the energisation of the HVAC export cable plus the shunt compensator at the off-shore end of the cable. The shunt compensation is designed to compensate a 40% of the reactive power that the export cable produce (40% of 190 MVA). Just a 40% is compensated in order to avoid zero losing in any current that could damage any element of the system if any fault appear.

Compensate just the 40% of the 190 MVA means that the off-shore WPP shall absorb at least 114 MVA that the export cable produces. A string with 9 WTGs just is able to absorb 72 MVA, thus a minimum of 2 strings are needed to energise the export cable plus the shunt compensation.

The energisation of the export cable using POW close each pole of the breaker as follows:

- Pole A: at 0 V in phase A.
- Pole B: at 0 V in phase B.
- Pole C: at 0 V in phase C.

As in the off-shore substation energisation, a Gaussian distributed random error with 2 sigma=+-2.5 ms is considered for each pole closing time.

<table>
<tr><td>Test case</td><td colspan="3">2.4.7. HVAC EXPORT CABLE ENERGISATION</td></tr>
<tr><td rowspan="3">Simulation detail</td><td>WT</td><td colspan="2">Level 4: Perfect DC link control is assumed</td></tr>
<tr><td>OWF</td><td colspan="2">Level 4: One detailed string and aggregated strings.</td></tr>
<tr><td>On-shore grid</td><td colspan="2">Level 3: Thevenin equivalent</td></tr>
<tr><td></td><td>Configuration (connected strings)</td><td>Compliance</td><td>Comments</td></tr>
<tr><td rowspan="2">Simulations (sensitivity analysis)</td><td>6 Strings</td><td>Pass</td><td>P_{TOT}= 400 MW; Pole error (BK_T2): A=-1.7 ms; B=-0.8 ms; C=1.7 ms;
WTG (max values): V = 1.0 pu; I = 0.4pu; P = 0.06 pu; Q = -0.35 pu;
Δf = 0.05 Hz; df/dt = 0.06 Hz/s;
PCC (max values): V = 1.05 pu; I = 0.19 pu; P = 0.03 pu; Q = -0.15 pu;
Export cable (max values):
-off-shore: V = 1.1 pu; I = 0.19 pu;
-on-shore: V = 1.1 pu; I = 0.0 pu;</td></tr>
<tr><td>5 Strings</td><td>Pass</td><td>P_{TOT}= 336 MW; Pole error (BK_T2): A=1.3 ms; B=0.4 ms; C=0.4 ms;
WTG (max values): V = 1.01 pu; I = 0.45pu; P = 0.08 pu; Q = -0.46 pu;
Δf = 0.06 Hz; df/dt = 0.10 Hz/s;
PCC (max values): V = 1.11 pu; I = 0.53 pu; P = 0.06 pu; Q = -0.29 pu;
Export cable (max values):
-off-shore: V = 1.12 pu; I = 0.67 pu;
-on-shore: V = 1.12 pu; I = 0.0 pu;</td></tr>
</table>

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	4 Strings	Pass	P_{TOT}= 272 MW; Pole error (BK_T2): A=1.0 ms; B=1.6 ms; C=-0.7 ms; **WTG (max values):** V = 0.98 pu; I = 0.93pu; P = 0.13 pu; Q = -0.43 pu; Δf = 0.02 Hz; df/dt = 0.12 Hz/s; **PCC (max values):** V = 1.05 pu; I = 0.53 pu; P = 0.08 pu; Q = -0.22 pu; **Export cable (max values):** **-off-shore:** V = 1.1 pu; I = 0.6 pu; **-on-shore:** V = 1.09 pu; I = 0.0 pu;
	3 Strings	Pass	P_{TOT}= 208 MW; Pole error (BK_T2): A=1.6 ms; B=0.8 ms; C=-1.4 ms; **WTG (max values):** V = 0.96 pu; I = 0.65pu; P = 0.12 pu; Q = -0.52 pu; Δf = 0.02 Hz; df/dt = 0.12 Hz/s; **PCC (max values):** V = 1.01 pu; I = 0.26 pu; P = 0.06 pu; Q = -0.23 pu; **Export cable (max values):** **-off-shore:** V = 1.10 pu; I = 0.35 pu; **-on-shore:** V = 1.08 pu; I = 0.0 pu;
	2 Strings	Pass	P_{TOT}= 144 MW; Pole error (BK_T2): A=-0.9 ms; B=1.5 ms; C=0.7 ms; **WTG (max values):** V = 0.97 pu; I =0.84 pu; P = 0.17 pu; Q = -0.73 pu; Δf = 0.08 Hz; df/dt = 0.41 Hz/s; **PCC (max values):** V = 1.04 pu; I = 0.25 pu; P = 0.06 pu; Q = -0.22 pu; **Export cable (max values):** **-off-shore:** V = 1.10 pu; I = 0.34 pu; **-on-shore:** V = 1.10 pu; I = 0.0 pu;
	1 Strings	Fail	P_{TOT}= 72 MW; Not enough capacity to compensate the reactive power produced by the export cable.
Comments	Sample results correspond to the case with only two strings connected.		

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Sample result

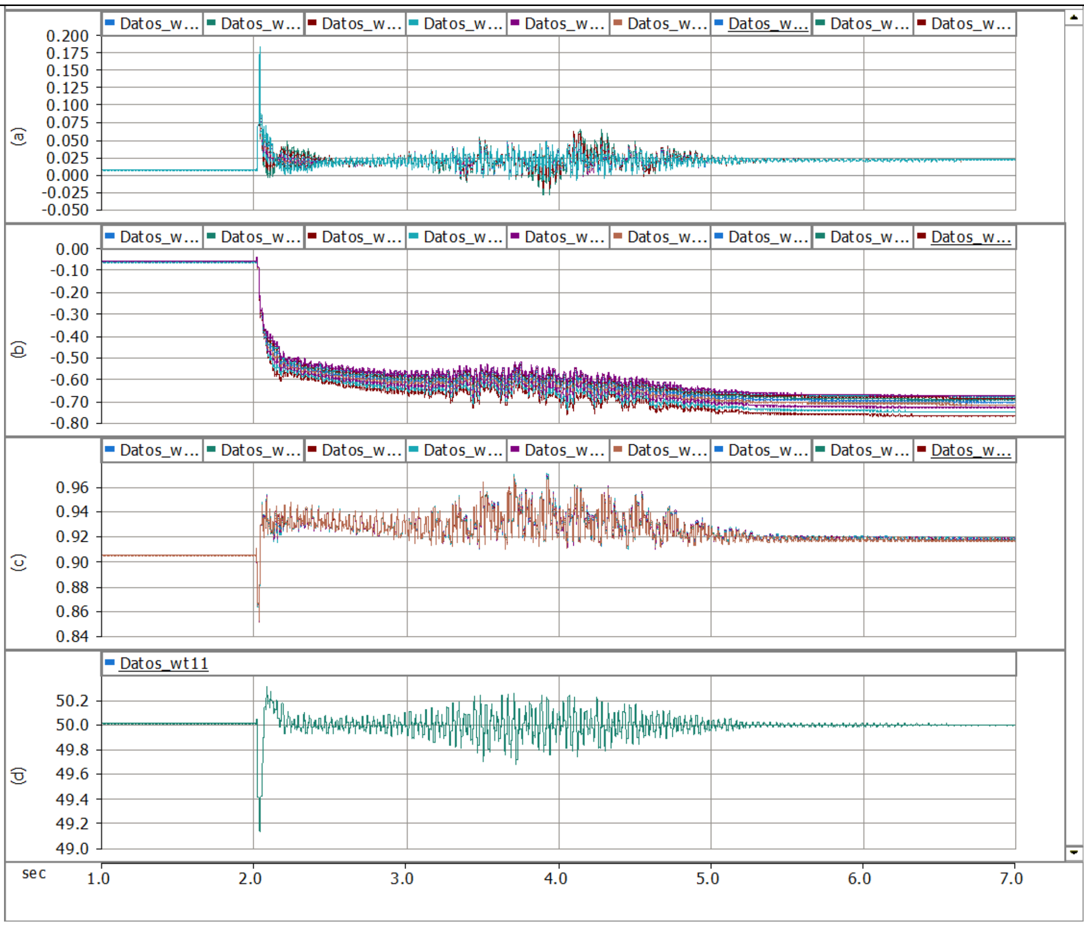

Figure 3-12: WTGs of string 1 in OWF (at the low voltage terminals of the WTG transformer): (a) active power (pu); (b) reactive power (pu); (c) voltage (pu); (d) off-shore ac frequency (Hz).

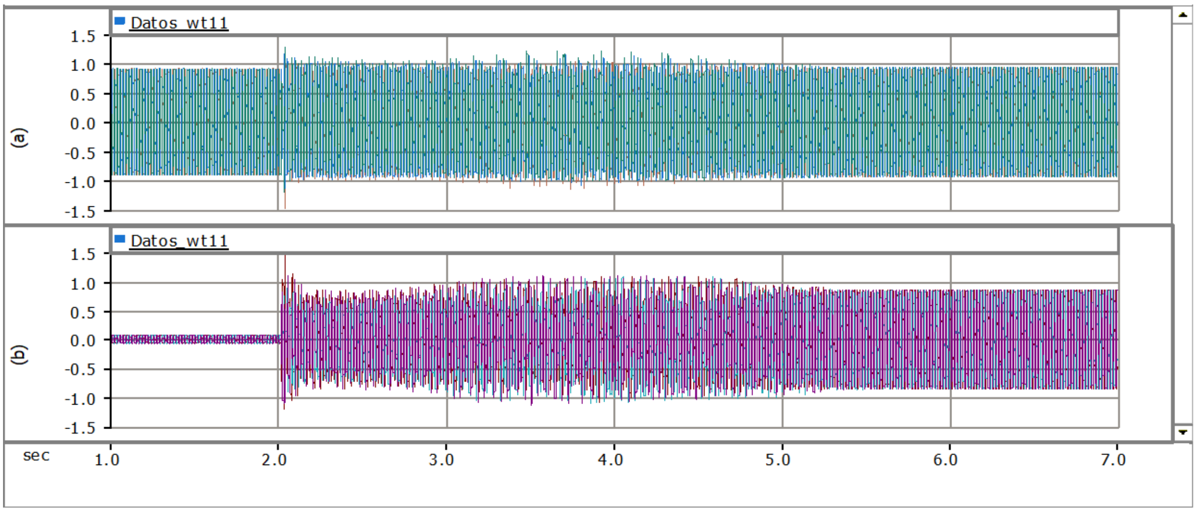

Figure 3-13: $WTG_{1,1}$ during the export cable energisation (at the low voltage terminals of the WTG transformer): (a) voltage (pu); (b) current (pu).

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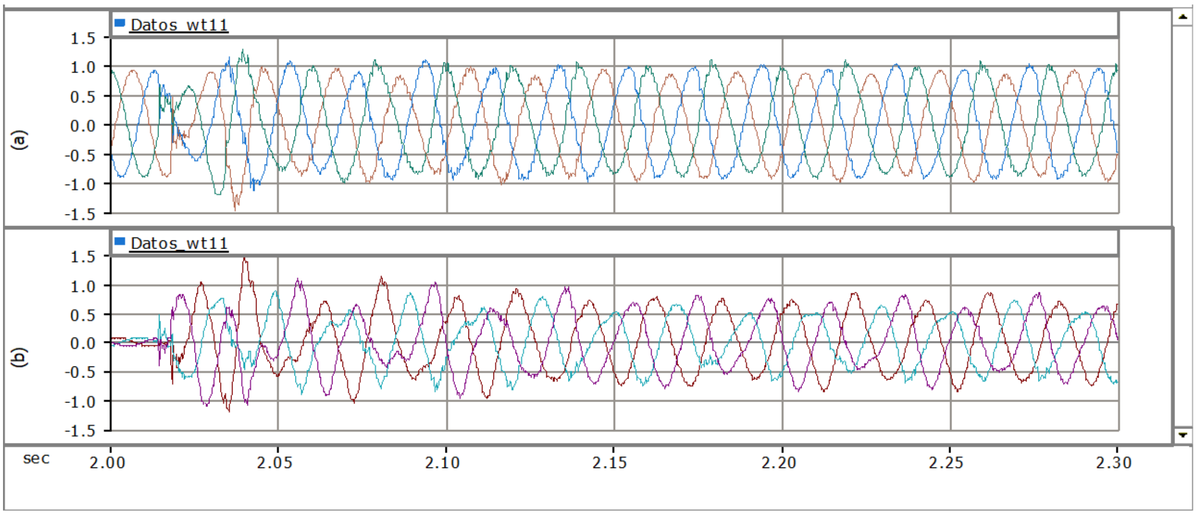

Figure 3-14: $WTG_{1,1}$ during HVAC export cable energisation (at the low voltage terminals of the WTG transformer): (a) voltage (pu); (b) current (pu).

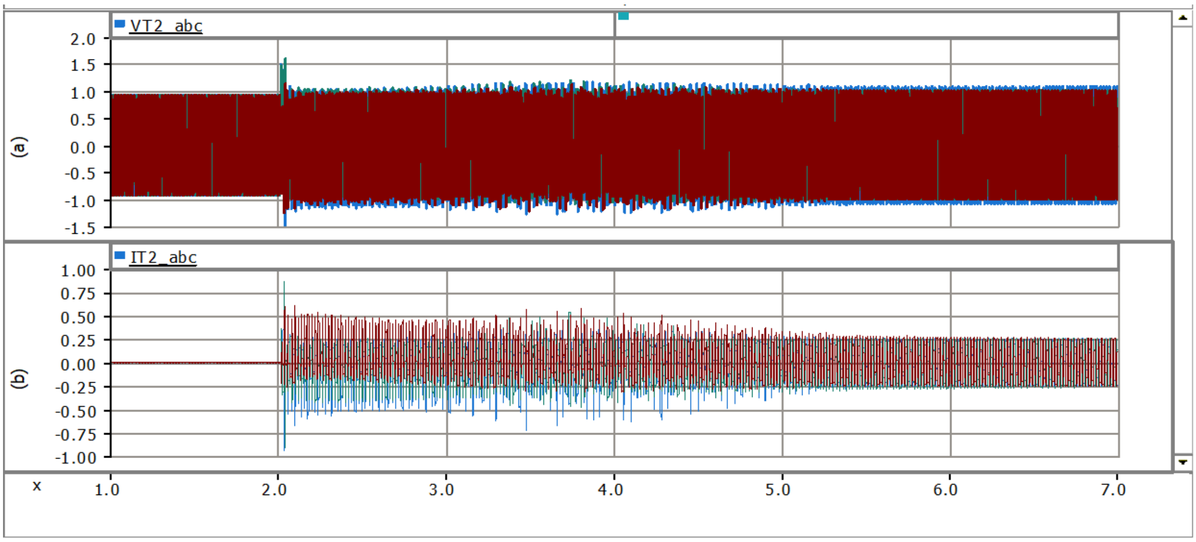

Figure 3-15: Voltage and current at the off-shore terminals of the export cable during HVAC export cable energisation: (a) voltage (pu); (b) current (pu).

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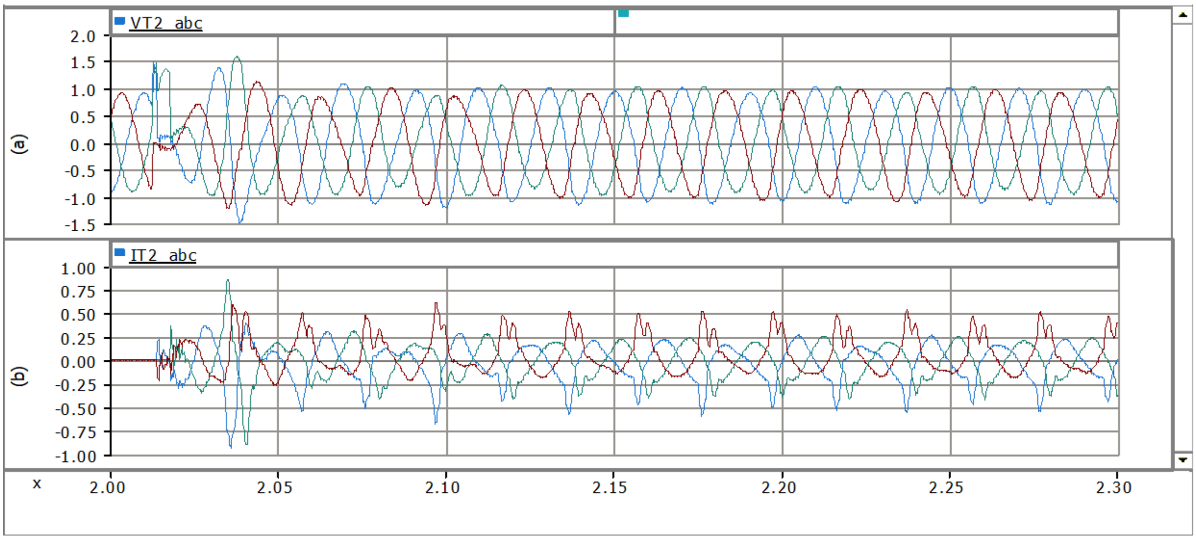

Figure 3-16: Voltage and current at the off-shore terminals of the export cable during HVAC export cable energisation, showing off-shore transformer sympathetic resonance: (a) voltage (pu); (b) current (pu).

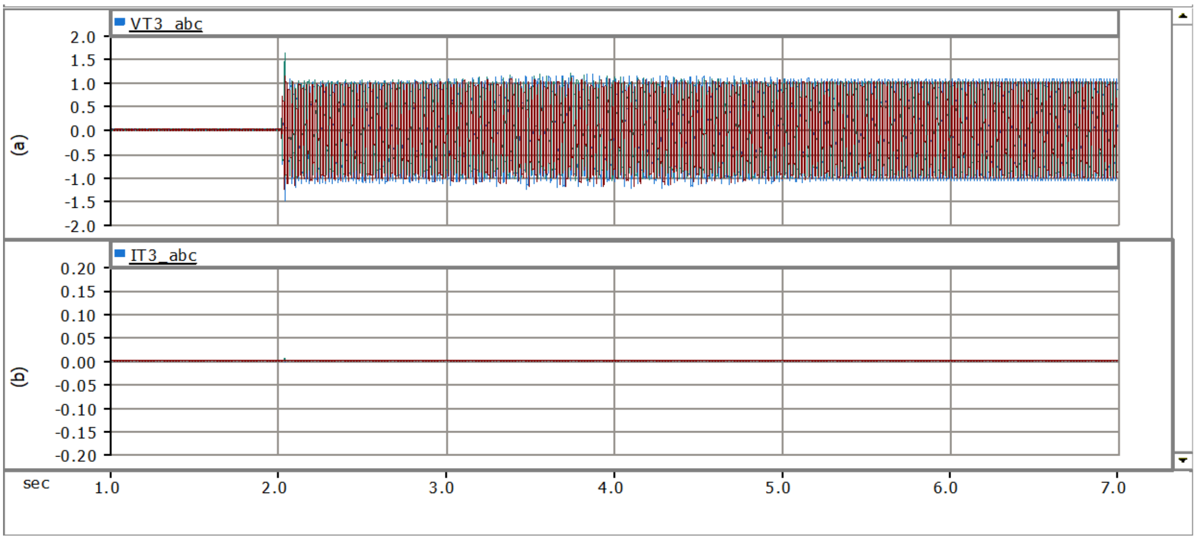

Figure 3-17: Voltage and current at the on-shore side of the export cable during HVAC export cable energisation: (a) voltage (pu); (b) current (pu).

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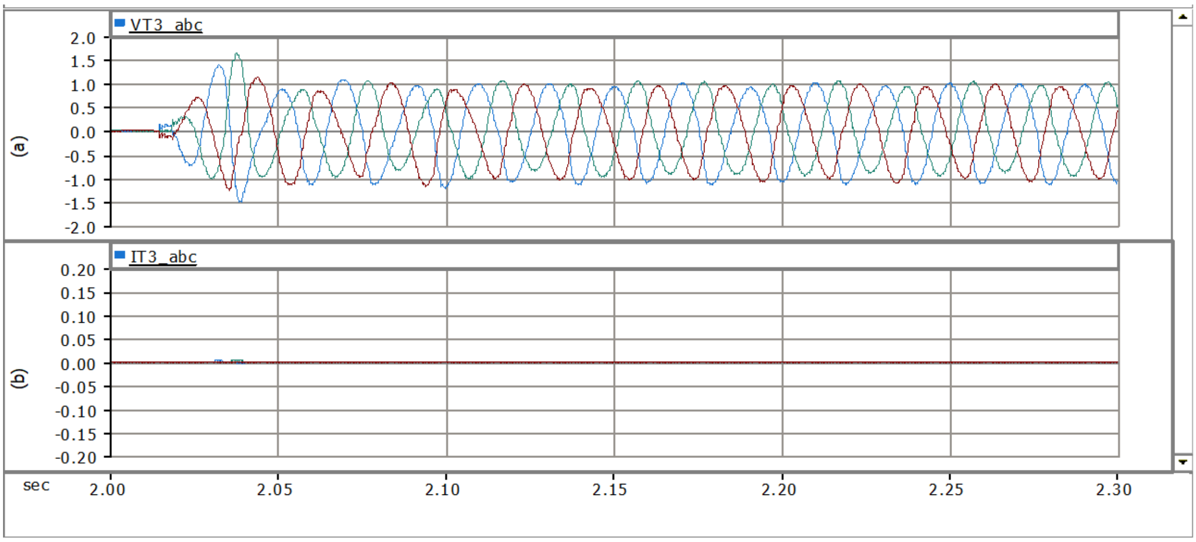

Figure 3-18: Voltage and current at the on-shore side of the export cable during HVAC export cable energisation: (a) voltage (pu); (b) current (pu).

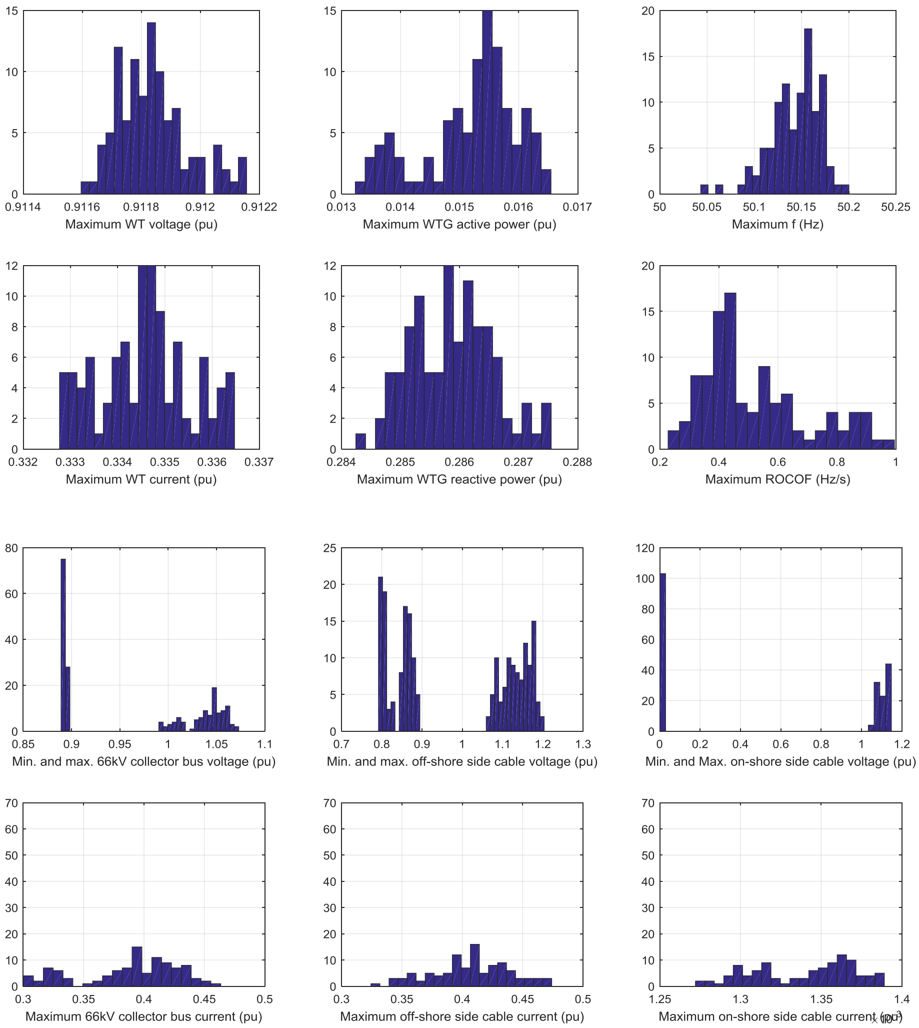

Figure 3-19. Distribution of Monte Carlo test case results for off-shore HVAC export cable energisation with random POW pole spread

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Figure Figure 3-19 shows the sensitivity analysis to random errors in POW switching during HVAC export cable energisation. A total of 100 cases have been simulated with random errors on breaker switching time (±2.5ms Gaussian distribution σ=2).

WTG voltages are within the considered margins, whereas maximum current could reach up to 0.35 pu. Maximum reactive power requirement is below 0.3 pu. Frequency is within the 50.25 Hz range and maximum rocof is always below 1 Hz/s.

The 66kV collector bus voltages are always within the +-10% limits. However, the off-shore side cable voltage and, particularly, the on-shore side cable voltage, in some cases, are above 1.1 pu. The relatively large voltage at the on-shore side of the cable is expected due to the Ferranti effect and considering that the only the 0.4 pu on-shore shunt compensation is connected. In any case, the voltage at the considered busses was always within the 1.3 pu for less than 100 ms limit.

In a few cases (around 1%-2%) a relatively large harmonic resonance between the cable and off-shore transformer could observed, leading to overvoltages that could trip the WTGs grid side converter transformer or other equipment.

3.3.8 OFF-SHORE HVDC STATION ENERGISATION

This test case consists of the energisation of the off-shore HVDC transformer (66/390 kV) and the AC-side pre-charging of the off-shore converter submodule cells from the off-shore WPP. For Hard Switching using a pre-insertion resistor (PIR), which is bypassed after a certain pre-insertion time (PIT), different values of PIR & PIT are tested. For Soft Start without a PIR, different values of the ramp-rate of the WPP voltage are tested.

Test case	2.4.8. OFF-SHORE HVDC SUBSTATION ENERGISATION	
Simulation detail	WT	Level 4: Perfect DC link control is assumed
	OWF	Level 4: One detailed string and aggregated strings.
	MMC	Level 1 (Corresponding to Type 4 as defined by Cigre WG B4.57)
	On-shore grid	Level 3: Thevenin equivalent
	Configuration	Comments
Hard Switching (sensitivity analysis)	PIR = 100, 200, 300 Ω PIT = 0.01, 0.1, 0.3 s	Different values of PIR are tested for different values of PIT.
Soft Start (sensitivity analysis)	Ramp-rate (100%) = 0.5, 1, 2 s	Different ramp-rates are tested for off-shore grid voltage ramp-up.

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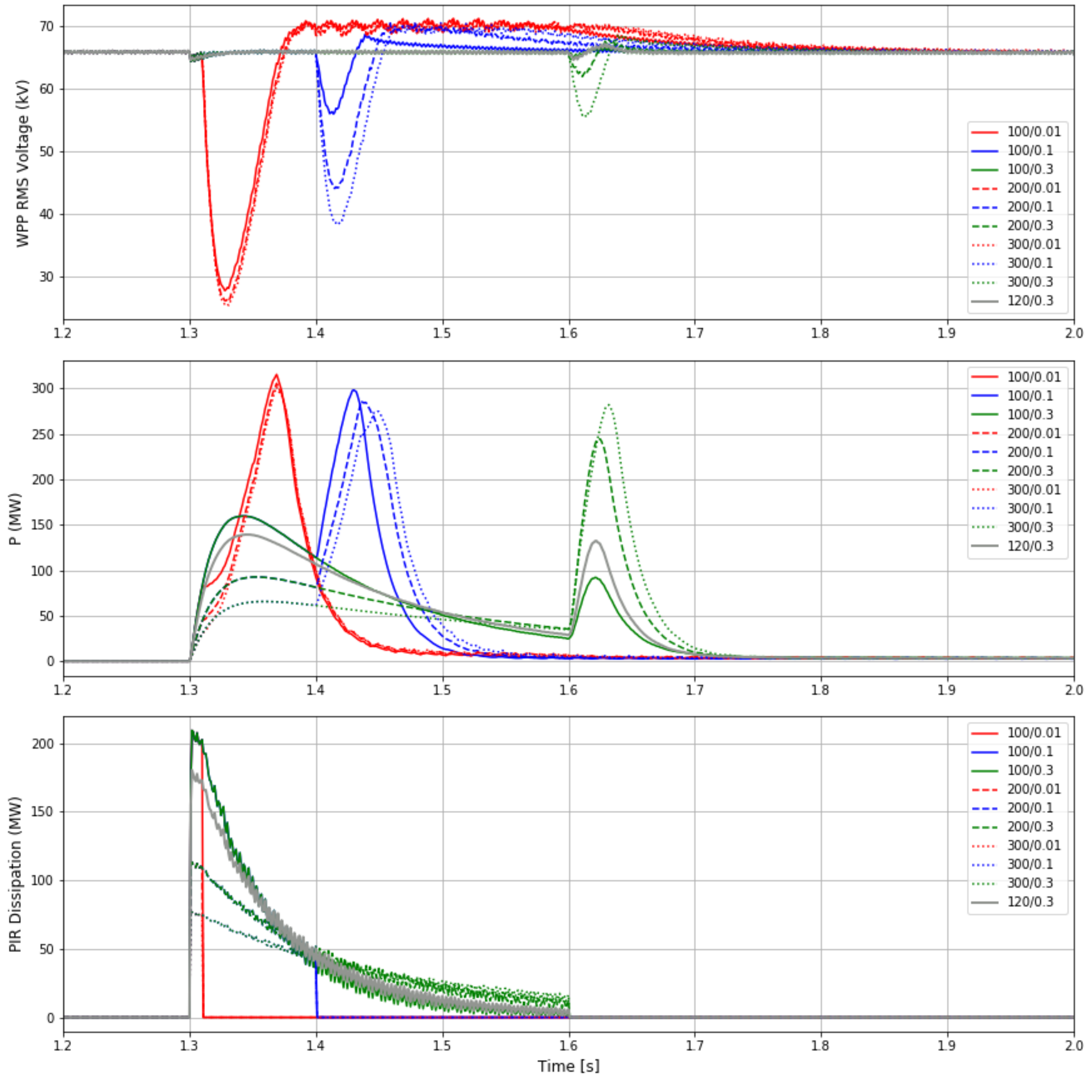
Hard Switching Sensitivity Analysis	 Figure 3-20: Waveforms for Hard Switching sensitivity analysis for PIR values of 100, 200 & 300 Ω and PIT values of 0.01, 0.1 & 0.3 s: WPP Terminal RMS Voltage (kV), WPP output Power (MW) and Power dissipated across PIR during PIT in MW. [Red: 0.01s, Blue: 0.1s, Green: 0.3s; Solid: 100Ω, Dashed: 200Ω, Dotted: 300Ω]
Comment	From Figure 3-20, it is clear that when the PIR is bypassed, there is a voltage dip associated with the transient (energization) power peak. For a given PIR, a lower PIT value increases the transient dip, while for a given PIT value, a lower PIR reduces the transient dip. However, for lower PIT value (eg. 0.01s), the value of PIR doesn't cause a significant reduction in the voltage dip.

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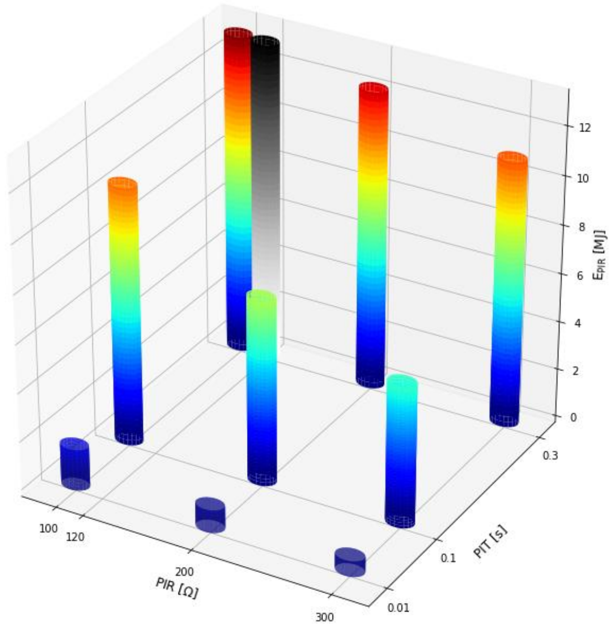
<table>
<tr><td>Hard Switching Sensitivity Analysis</td><td>

Figure 3-21: Energy dissipated across different PIR values of 100, 200 & 300 Ω for different PIT values of 0.01, 0.1 & 0.3 s, during offshore hard-switching energisation.</td></tr>
<tr><td>Comment</td><td>In simulation, the PIR/PIT value of 120Ω/0.3s has been chosen to limit the voltage dip due to the transient (energization) power peak, as shown from the sensitivity analysis results in Figure 3-20. However, in practice, due to high cost of real estate on the offshore platform, the sizing of PIR must be done according to its duty cycle of operation to limit the energy dissipated during PIT, for example say, 3 operations in 10s and then 30 min off for cooling. With that in consideration, a value of 300Ω/0.1s might be more practical.</td></tr>
</table>

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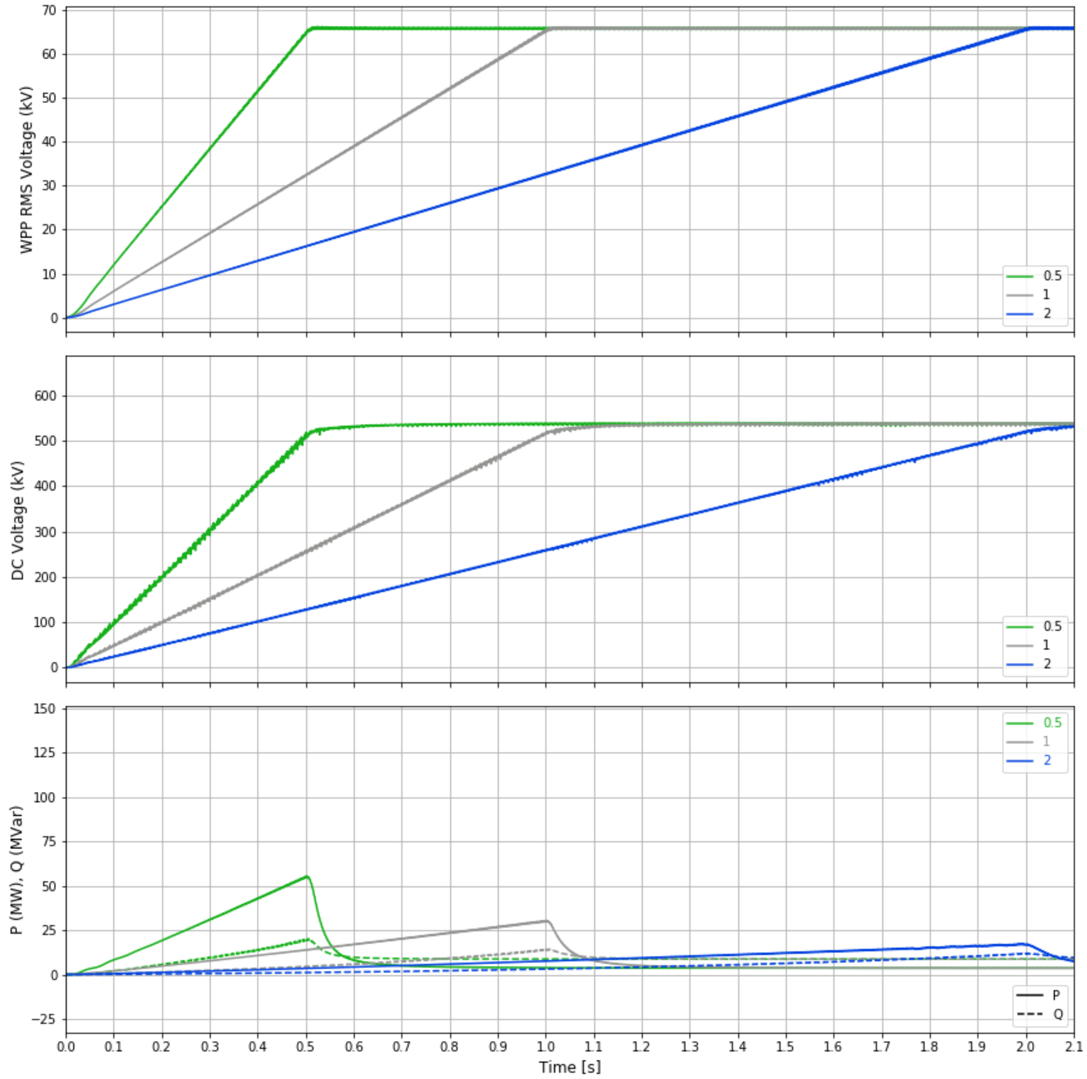
Soft Start Sensitivity Analysis	 Figure 3-22: Waveforms for Soft Start sensitivity analysis for offshore voltage (100%) ramp-rate values of 0.5, 1 & 2s: WPP Terminal RMS Voltage (kV), HVDC link voltage (kV) and Real (MW) & Reactive (Mvar) Power output of WPP.
Comments	For faster ramp-rate values, a higher charging peak of about 60 MW, only 15% of the WPP rated capacity, is seen. However, no transients are observed during the soft-start, even with a 100%/0.5s ramp-rate, in theory allowing an even faster ramp-rate. Thus, soft-start is preferable to the hard-switching case, as it allows faster energisation without any of the transient issues.

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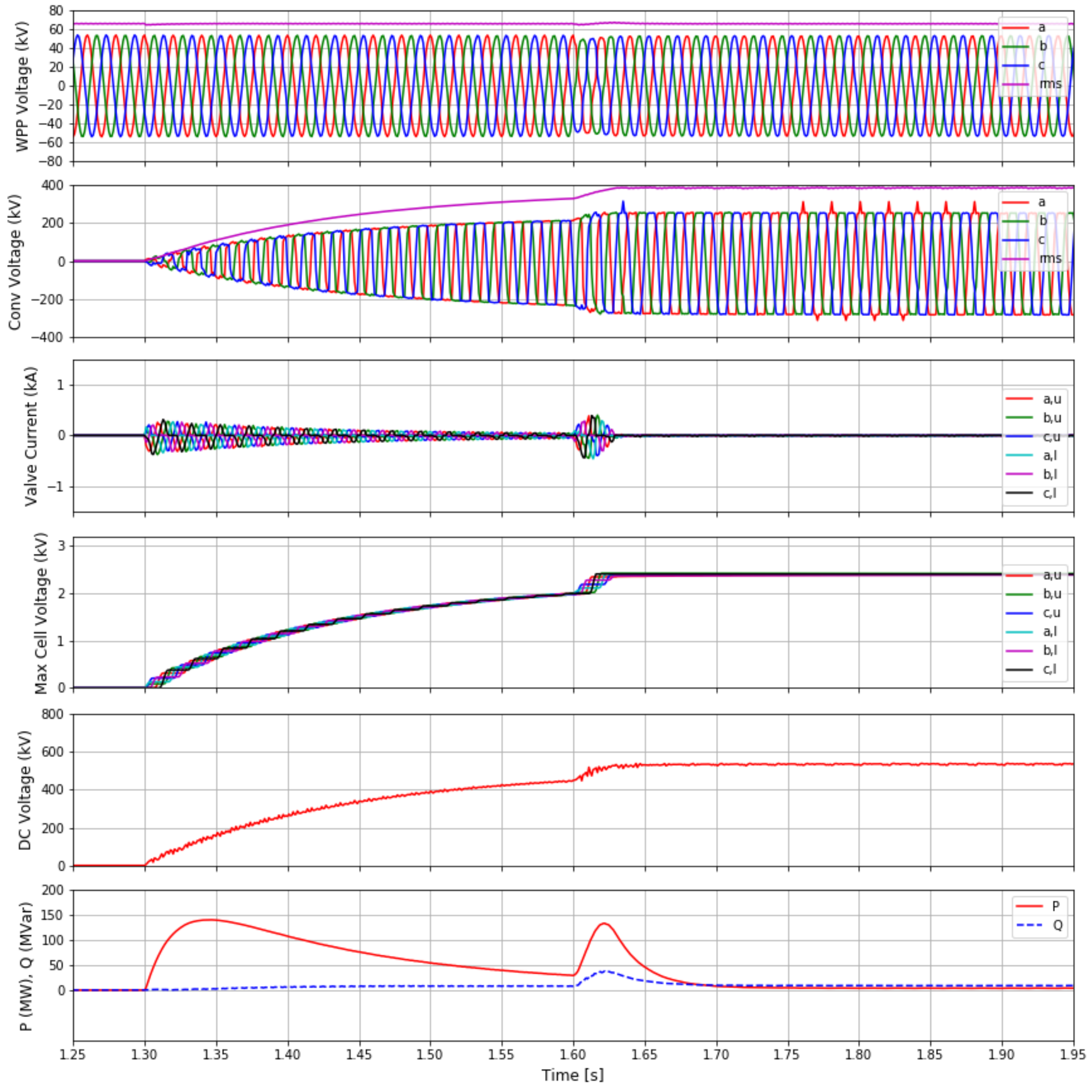
Results	 Figure 3-23: Waveforms for Hard Switching energisation of the offshore HVDC transformer and converter with PIR of 120Ω that is inserted at 1.3s and bypassed after PIT of 0.3s: WPP Terminal Phase & RMS voltage (kV), Offshore Converter Voltage (kV), Offshore converter Upper/Lower arm Valve Currents for all Phases (kA), Max Cell Voltages of Upper/Lower arm in all Phases for Offshore converter (kV), HVDC link voltage (kV), Real (MW) & Reactive (Mvar) Power output of WPP.
Comment	The results shows the energisation of the off-shore transformer (66/390 kV) along with the AC-side uncontrolled pre-charging of the off-shore converter cells by the grid-forming OWF with a PIR that is bypassed after PIT (Hard Switching).

3.3.9 HVDC CABLE ENERGISATION

This test case consists of the energisation of the ±320 kV HVDC export cable by de-blocking the offshore converter to control the HVDC link voltage.

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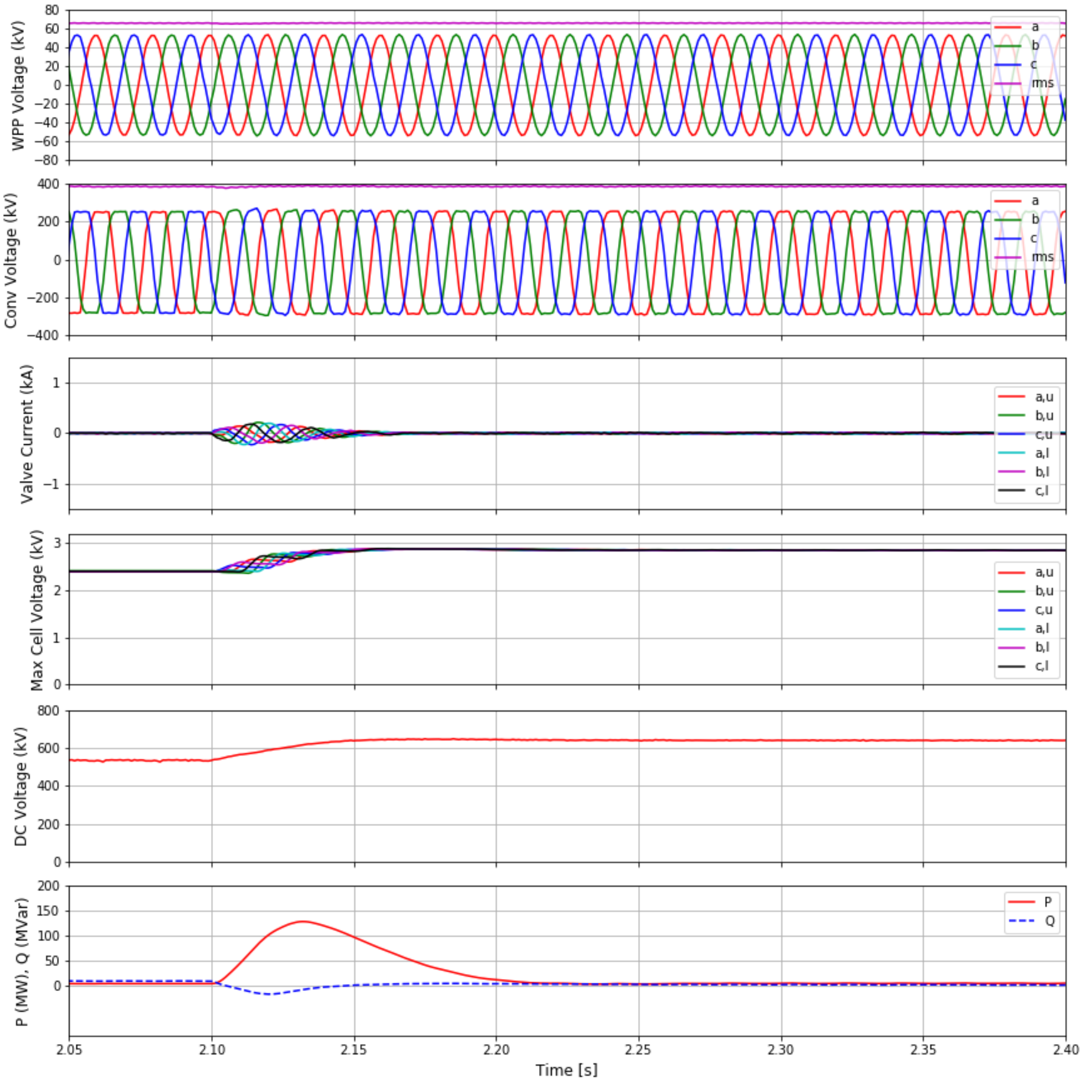
Test case	2.4.9. HVDC CABLE ENERGISATION	
Simulation detail	WT	Level 4: Perfect DC link control is assumed
	OWF	Level 4: One detailed string and aggregated strings.
	MMC	Level 1 (Corresponding to Type 4 as defined by Cigre WG B4.57)
	On-shore grid	Level 3: Thevenin equivalent
Comments	The results shows the off-shore converter regulating the HVDC link voltage to 640 kV.	
Results	 Figure 3-24: Waveforms for Hard Switching energisation of the HVDC cable when the off-shore converter is de-blocked at 2.1s: WPP Terminal Phase & RMS voltage (kV), Offshore Converter Voltage (kV), Offshore converter Upper/Lower arm Valve Currents for all Phases (kA), Max Cell Voltages of Upper/Lower arm in all Phases for Offshore converter (kV), HVDC link voltage (kV), Real (MW) & Reactive (Mvar) Power output of WPP.	

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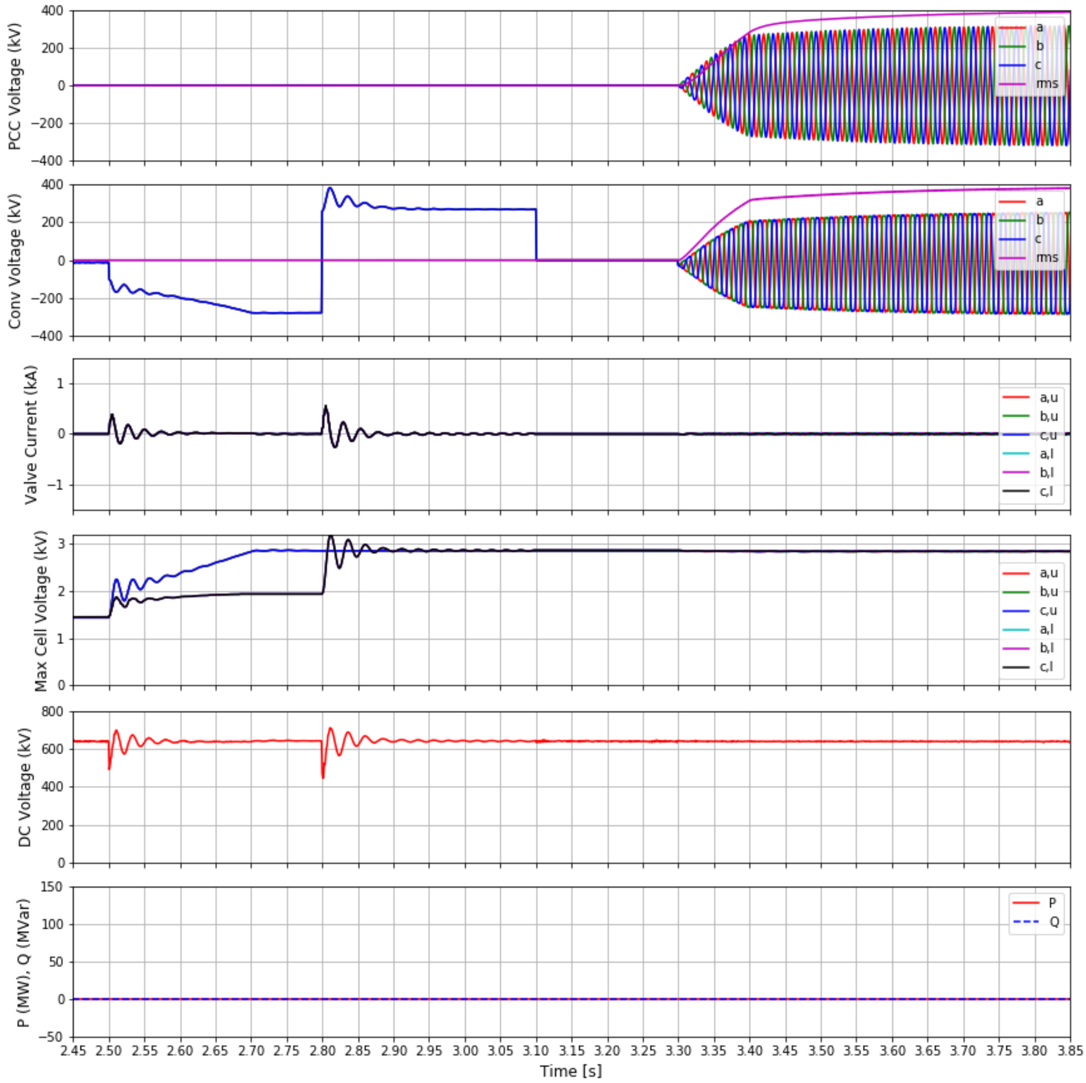
3.3.10 ON-SHORE HVDC STATION ENERGISATION

This test case consists of the DC-side controlled pre-charging of the on-shore converter submodule cells after which the on-shore converter is de-blocked to control the on-shore PCC AC voltage.

Test case	2.4.10. ON-SHORE HVDC SUBSTATION ENERGISATION	
Simulation detail	WT	Level 4: Perfect DC link control is assumed
	OWF	Level 4: One detailed string and aggregated strings.
	MMC	Level 1 (Corresponding to Type 4 as defined by Cigre WG B4.57)
	On-shore grid	Level 3: Thevenin equivalent
Controlled Pre-charging Sequence	Compared to the AC-side pre-charging of the off-shore converter cells in 3.1.8, the DC-side pre-charging of the on-shore converter cells is more challenging. Before the Controlled Pre-charging is started at 2.5s, the onshore converter submodule cells are charged *uncontrollably* to 1.42 kV, half of the nominal, as the 640 kV HVDC voltage is divided equally between 450 (225 per arm) capacitors in the whole leg, when blocked. When the converter is de-blocked, its submodules (now only 225 inserted in total in a leg, at any time) charge *uncontrollably* from 1.42 kV to the desired nominal cell voltage of 2.85 kV, from the DC-side 640 kV, leading to a huge transient charging current that causes a large dip in the HVdc link voltage and an undesirable disturbance in the offshore converter submodule cell voltages. Thus, *open-loop* **controlled pre-charging** (Yu et al., 2013) of the onshore converter submodule cells is implemented, to charge the submodule capacitors to the nominal 2.85 kV, before they can be switched for the onshore grid-forming control when de-blocked. This is done by the following steps: 1. First the upper arm is inserted & the lower arm is bypassed, to fully charge all the 225 cells of the upper arm. To control the charging current (and the resulting transients in the DC voltage & offshore submodule cell voltages), the lower arm cells are bypassed one-by-one, in a ramp and not all at once. 2. Then the upper arm is bypassed & the lower arm inserted, so the upper arm cells hold their charge while the lower arm cells charge fully. 3. Lastly, both the upper & lower arms are blocked (now the fully charged cells hold their charge), before the converter is de-blocked for controlling the on-shore AC-voltage at its terminals. The pre-charging control described above is *open-loop* because no closed-loop control of the charging current, for example as proposed in Li et al., 2015, is implemented.	

Results	 Figure 3-25: Waveforms for DC-side pre-charging of the on-shore converter & de-blocking: Onshore PCC Phase & RMS voltage (kV), Onshore Converter Voltage (kV), Onshore converter Upper/Lower arm Valve Currents for all Phases (kA), Max Cell Voltages of Upper/Lower arm in all Phases for Onshore converter (kV), HVDC link voltage (kV), Real (MW) & Reactive (Mvar) Power injection at Onshore PCC.

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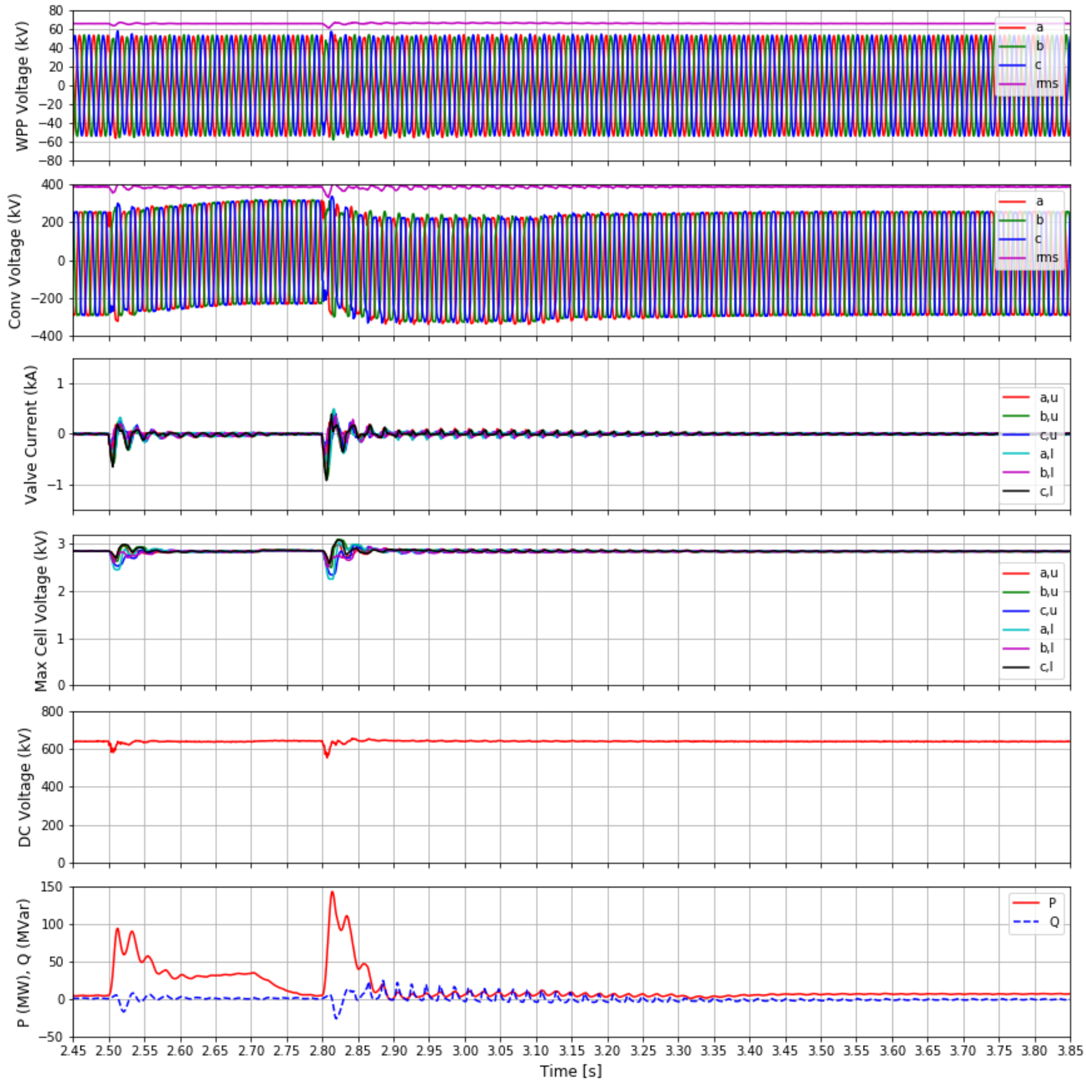

Figure 3-26: Waveforms for DC-side pre-charging of the on-shore converter & de-blocking: WPP Terminal Phase & RMS voltage (kV), Offshore Converter Voltage (kV), Offshore converter Upper/Lower arm Valve Currents for all Phases (kA), Max Cell Voltages of Upper/Lower arm in all Phases for Offshore converter (kV), HVDC link voltage (kV), Real (MW) & Reactive (Mvar) Power output of WPP.

Comments	The results show the controlled DC-side pre-charging of the on-shore converter from 2.5s to 3.1s, with the upper arm charging (lower arm bypassed) started at 2.5s, the lower arm charging (upper arm bypassed) started at 2.8s, then both arms blocked from 3.1-3.3s. The energy stored in the cells of the off-shore converter is used during the pre-charging of the on-shore converter cells, resulting in a voltage transient in the HVDC link. Finally, the on-shore converter is de-blocked at 3.3s for on-shore AC voltage control.

3.3.11 ON-SHORE HVAC SUBSTATION ENERGISATION

This test case consists of the energisation of the on-shore transformer (220/400 kV) from the off-shore WPP using the POW. The energisation of the transformer using POW close each pole as follows:

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- Pole A: at maximum voltage A.
- Pole B: 5 ms after the pole A closes.
- Pole C: 5 ms after the pole A closes.

A Gaussian error with 2σ = ±2.5 ms has been included in the closing times of each one of the poles.

Test case	2.4.11. ON-SHORE HVAC SUBSTATION ENERGISATION		
Simulation detail	WT	Level 4: Perfect DC link control is assumed	
	OWF	Level 4: One detailed string and aggregated strings.	
	On-shore grid	Level 3: Thevenin equivalent	
	Configuration (connected strings)	Compliance	Comments
Simulations (sensitivity analysis)	6 Strings	Pass	P_{TOT}= 400 MW; Pole error (BK_T3): A=1.9 ms; B=-0.6 ms; C=0.8 ms; **WTG (max values):** V = 0.93 pu; I = 0.63pu; P = 0.02 pu; Q = -0.30 pu; Δf = 0.01 Hz; df/dt = 0.03 Hz/s; **PCC (max values):** V = 0.97 pu; I = 0.23 pu; P = 0.01 pu; Q = -0.22 pu; **Export cable (max values):** **-off-shore:** V = 1.01 pu; I = 0.24 pu; **-on-shore:** V = 1.01 pu; I = 0.17 pu;
	5 Strings	Pass	P_{TOT}= 336 MW; Pole error (BK_T3): A=1.2 ms; B=-0.2 ms; C=0.5 ms; **WTG (max values):** V = 0.98 pu; I = 0.69pu; P = 0.02 pu; Q = -0.4 pu; Δf = 0.02 Hz; df/dt = 0.1 Hz/s; **PCC (max values):** V = 1.0 pu; I = 0.24 pu; P = 0.01 pu; Q = -0.22 pu; **Export cable (max values):** **-off-shore:** V = 1.09 pu; I = 0.28 pu; **-on-shore:** V = 1.09 pu; I = 0.19 pu;
	4 Strings	Pass	P_{TOT}= 272 MW; Pole error (BK_T3): A=1.6 ms; B=1.4 ms; C=0.5 ms; **WTG (max values):** V = 1.0 pu; I = 0.87pu; P = 0.02 pu; Q = -0.42 pu; Δf = 0.01 Hz; df/dt = 0.06 Hz/s; **PCC (max values):** V = 1.08 pu; I = 0.34 pu; P = 0.01 pu; Q = -0.25 pu; **Export cable (max values):** **-off-shore:** V = 1.09 pu; I = 0.25 pu; **-on-shore:** V = 1.09 pu; I = 0.18 pu;
	3 Strings	Pass	P_{TOT}= 208 MW; Pole error (BK_T3): A=-1.5 ms; B=-0.5 ms; C=-0.1 ms; **WTG (max values):** V = 0.95 pu; I = 0.61pu; P = 0.03 pu; Q = -0.54 pu; Δf = 0.03 Hz; df/dt = 0.07 Hz/s; **PCC (max values):** V = 1.0 pu; I = 0.25 pu; P = 0.01 pu; Q = -0.23 pu; **Export cable (max values):** **-off-shore:** V = 1.09 pu; I = 0.25 pu; **-on-shore:** V = 1.09 pu; I = 0.16 pu;

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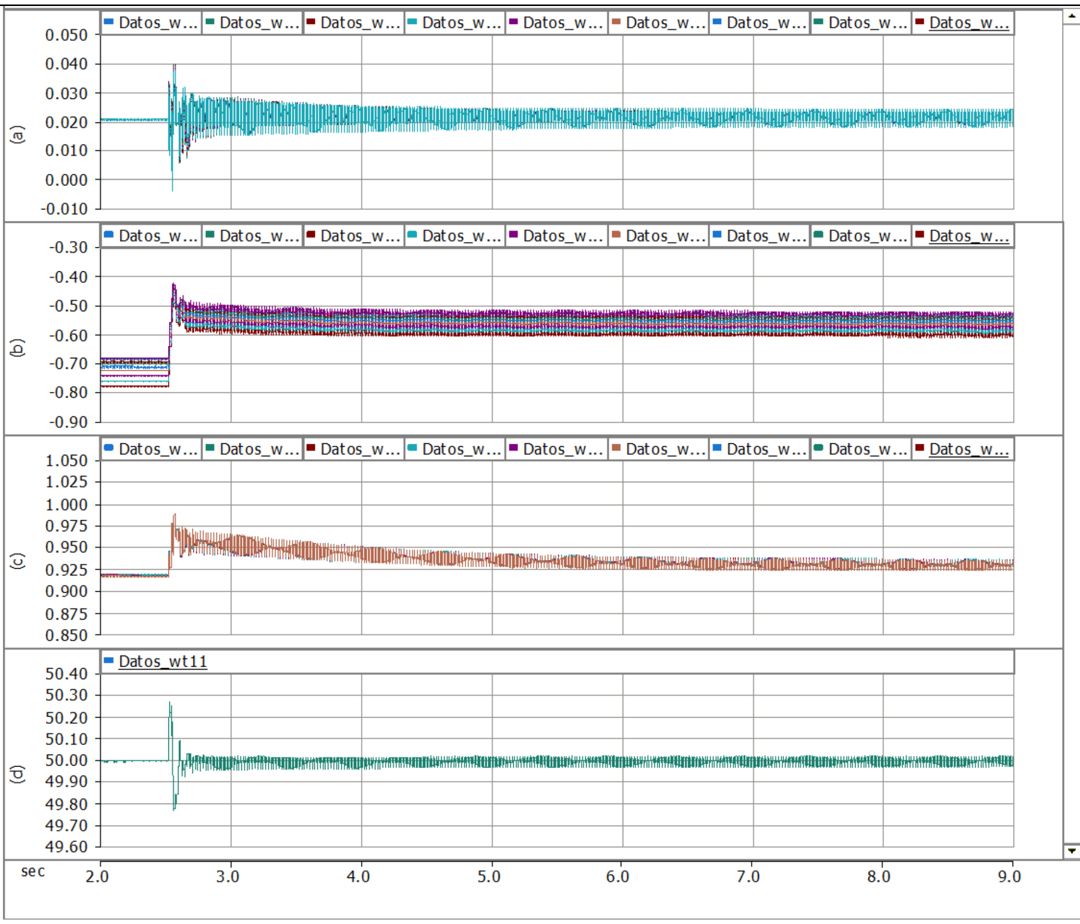
	2 Strings	Pass	P_{TOT}= 144 MW; Pole error (BK_T3): A=1.3 ms; B=-0.5 ms; C=-1.2 ms; **WTG (max values):** V= 0.99 pu; I = 0.85 pu; P = 0.04 pu; Q = -0.79 pu; Δf = 0.02 Hz; df/dt = 0.3 Hz/s; **PCC (max values):** V = 1.04 pu; I = 0.25 pu; P = 0.01 pu; Q = -0.25 pu; **Export cable (max values):** **-off-shore:** V = 1.07 pu; I = 0.25 pu; **-on-shore:** V = 1.07 pu; I = 0.25 pu;
	1 Strings	Fail	P_{TOT}= 72 MW; Not enough capacity to compensate the reactive power produced by the export cable.
Comments	Sample results correspond to the case with only two strings connected.		
Sample result	 Figure 3-27: On-shore HVAC transformer energisation: String 1 WTGs (at the low voltage terminals of the WTG transformer): (a) active power (pu); (b) reactive power (pu); (c) voltage (pu); (d) off-shore ac frequency (Hz).		

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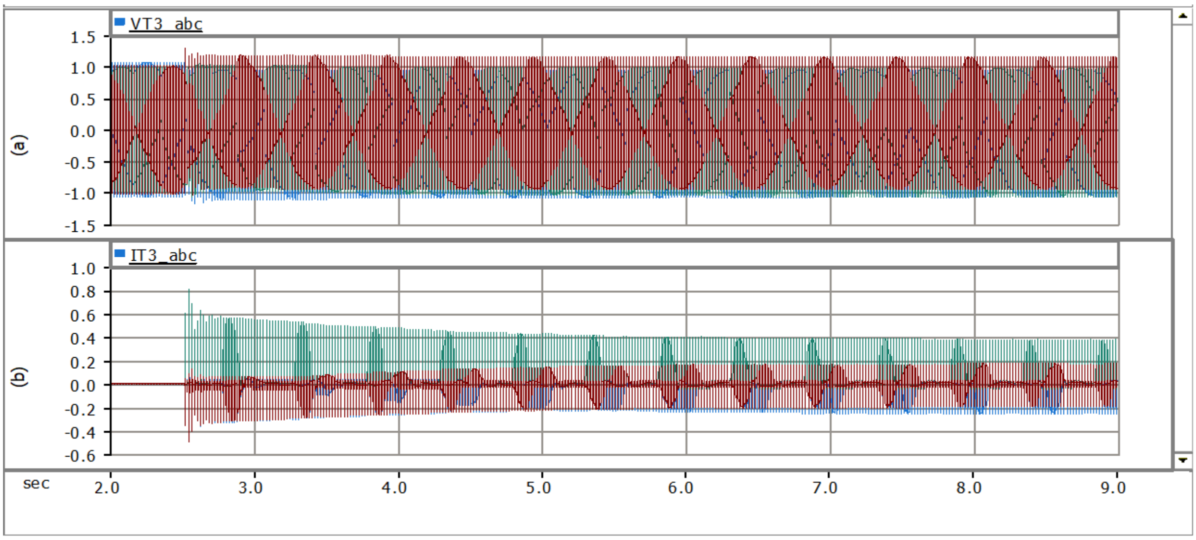

Figure 3-28: On-shore HVAC transformer energisation: Voltage and current at the 220kV terminals of the onshore transformer: (a) voltage (pu); (b) current (pu).

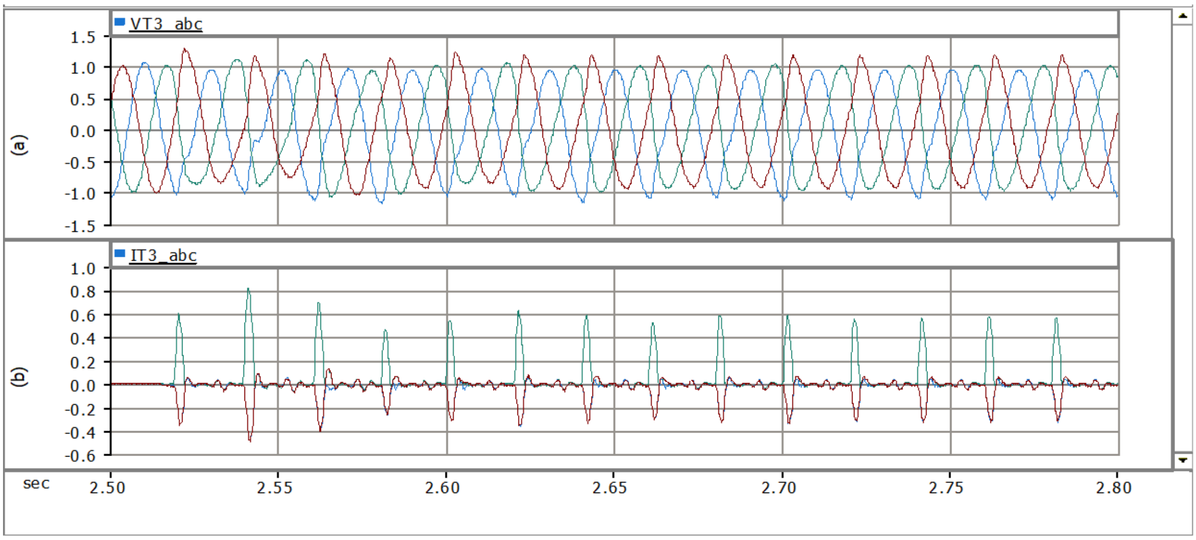

Figure 3-29: On-shore HVAC transformer energisation: Voltage and current at the 220kV terminals of the onshore transformer: (a) voltage (pu); (b) current (pu) (detail).

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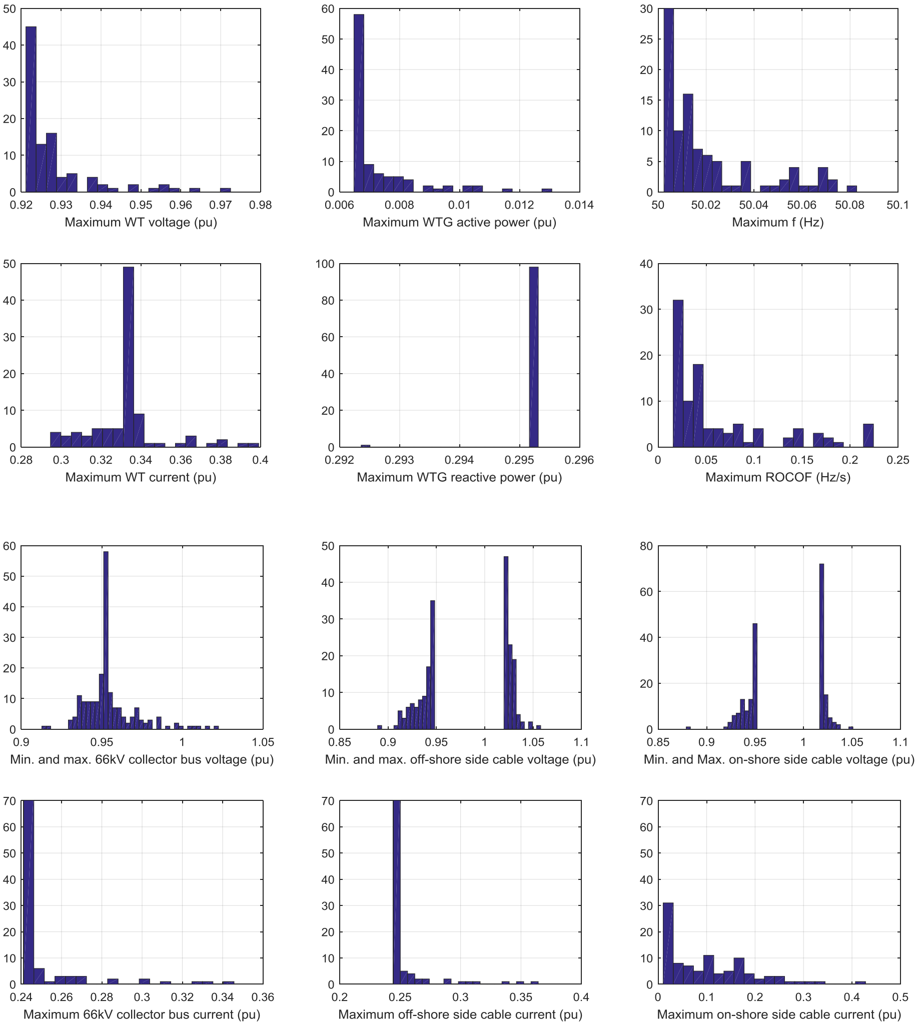

Figure 3-30. Distribution of Monte Carlo test case results for on-shore HVAC transformer energisation with random POW pole spread

Figure Figure 3-30 shows the sensitivity analysis to errors in POW breaker closing times. A total of 100 simulations have been carried out considering a random, Gaussian distributer error in POW closing times 2σ = ±2.5 ms).

Voltages at the WTG transformer low voltage side, 66kV collector bus and both sides of the export cable are within the considered requirements during transients and during steady state operation.

Maximum reactive power delivered by the WTGs is 0.3pu, whereas maximum WTG current is always below 0.4pu. Maximum frequency is always below 50.1Hz and rocof is always below 0.25 Hz/s.

Maximum currents in the 66kV collector bus and cable off-shore end are below 0.4 pu for most cases, with average values around 0.25 pu which is consistent with the WPP carrying out a large part of the cable compensation.

It is worth stressing that direct connection of the on-shore transformer, even when using POW, usually leads to sympathetic in-rush from the off-shore transformer, enhanced by the large cable capacitance. In most cases, this resonance dies away in a relatively short period of time, without voltages or currents exceeding their limits, however, in very few cases (less than 2%), harmonic voltages and currents caused by ferromagnetic resonance were large enough to cause WTG or protection equipment tripping. Ferromagnetic resonance effects are greatly reduced when sequential energisation is carried out at reduced voltage level (e.g. 0.9pu) and have not been seen when using soft-start energisation.

3.3.12 SYNCHRONISATION TO ON-SHORE GRID

This test case consists of the synchronisation of the HVAC system (off-shore WPP, off-shore and on-shore substations and HVAC cable) to an external grid. The synchronisation is carried out at the on-shore substation on the 400 kV ac grid. The synchronisation procedure consists of controls the voltage amplitude and the frequency through a WPP control that's synchronises both grids. When the difference between the dq components of both grids is lower than 1.5% the breaker between both grids is closed automatically.

Test case	2.4.12. SYNCHRONISATION TO ON SHORE GRID		
Simulation detail	WT	Level 4: Perfect DC link control is assumed	
	OWF	Level 4: One detailed string and aggregated strings.	
	On-shore grid	Level 3: Thevenin equivalent	
	Configuration (connected strings)	Compliance	Comments
Simulations (sensitivity analysis)	6 Strings	Pass	P_{TOT}= 400 MW; **WTG (max values):** V = 0.96 pu; I = 0.36pu; P = 0.01 pu; Q = -0.34 pu; Δf = 0.25 Hz; df/dt = 0.88 Hz/s; **PCC (max values):** V = 0.99 pu; I = 0.14 pu; P = 0.01 pu; Q = -0.14 pu; **Export cable (max values):** **-off-shore:** V = 1.02 pu; I = 0.14 pu; **-on-shore:** V = 1.03 pu; I = 0.05 pu;
	5 Strings	Pass	P_{TOT}= 336 MW; **WTG (max values):** V = 0.96 pu; I = 0.41pu; P = 0.01 pu; Q = -0.4 pu; Δf = 0.25 Hz; df/dt = 0.88 Hz/s; **PCC (max values):** V = 1.0 pu; I = 0.15 pu; P = 0.01 pu; Q = -0.15 pu; **Export cable (max values):** **-off-shore:** V = 1.02 pu; I = 0.15 pu; **-on-shore:** V = 1.04 pu; I = 0.05 pu;
	4 Strings	Pass	P_{TOT}= 272 MW; **WTG (max values):** V = 0.97 pu; I = 0.5 pu; P = 0.02 pu; Q = -0.47 pu; Δf = 0.25 Hz; df/dt = 0.91 Hz/s; **PCC (max values):** V = 1.01 pu; I = 0.15 pu; P = 0.01 pu; Q = -0.15 pu; **Export cable (max values):** **-off-shore:** V = 1.04 pu; I = 0.15 pu; **-on-shore:** V = 1.05 pu; I = 0.06 pu;

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	3 Strings	Pass	P_{TOT}= 208 MW; **WTG (max values):** V = 0.97 pu; I = 0.63pu; P = 0.02 pu; Q = -0.61 pu; Δf = 0.25 Hz; df/dt = 0.9 Hz/s; **PCC (max values):** V = 1.03 pu; I = 0.15 pu; P = 0.01 pu; Q = -0.15 pu; **Export cable (max values):** **-off-shore:** V = 1.05 pu; I = 0.15 pu; **-on-shore:** V = 1.07 pu; I = 0.07 pu;
	2 Strings	Pass	P_{TOT}= 144 MW; **WTG (max values):** V= 0.98 pu; I = 0.9 pu; P = 0.04 pu; Q = -0.88 pu; Δf = 0.25 Hz; df/dt = 0.88 Hz/s; **PCC (max values):** V = 1.06 pu; I = 0.16 pu; P = 0.01 pu; Q = -0.16 pu; **Export cable (max values):** **-off-shore:** V = 1.09 pu; I = 0.16 pu; **-on-shore:** V = 1.1 pu; I = 0.09 pu;
	1 Strings	Fail	P_{TOT}= 72 MW; Not enough capacity to compensate the reactive power produced by the export cable.
Comments	The sample results show the energisation of the export cable with just 2 strings connected. The sample results show that the voltage is reduced when the synchronisation starts. Voltage reduction is required to synchronise to an external grid of 1pu voltage due to the Ferranti effect caused by the non-fully compensated HVAC export cable. As mentioned in other tests, this reduction can be minimised by including a tap changer in the off-shore HVAC transformer. When both grids are synchronised the voltage rises close to the voltage reference, but not to the voltage before the synchronisation. This is possible now as part of the HVAC cable reactive power requirements now come from the connected grid. This behaviour can be changed by modifying the WTG Q/V droop coefficient. The same applies to the active power reference, which is set to zero after synchronisation. The power injected by the WPP can be set to a different value by changing the appropriate P/ω droop coefficient or by changing the active power reference P*.		

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Sample result

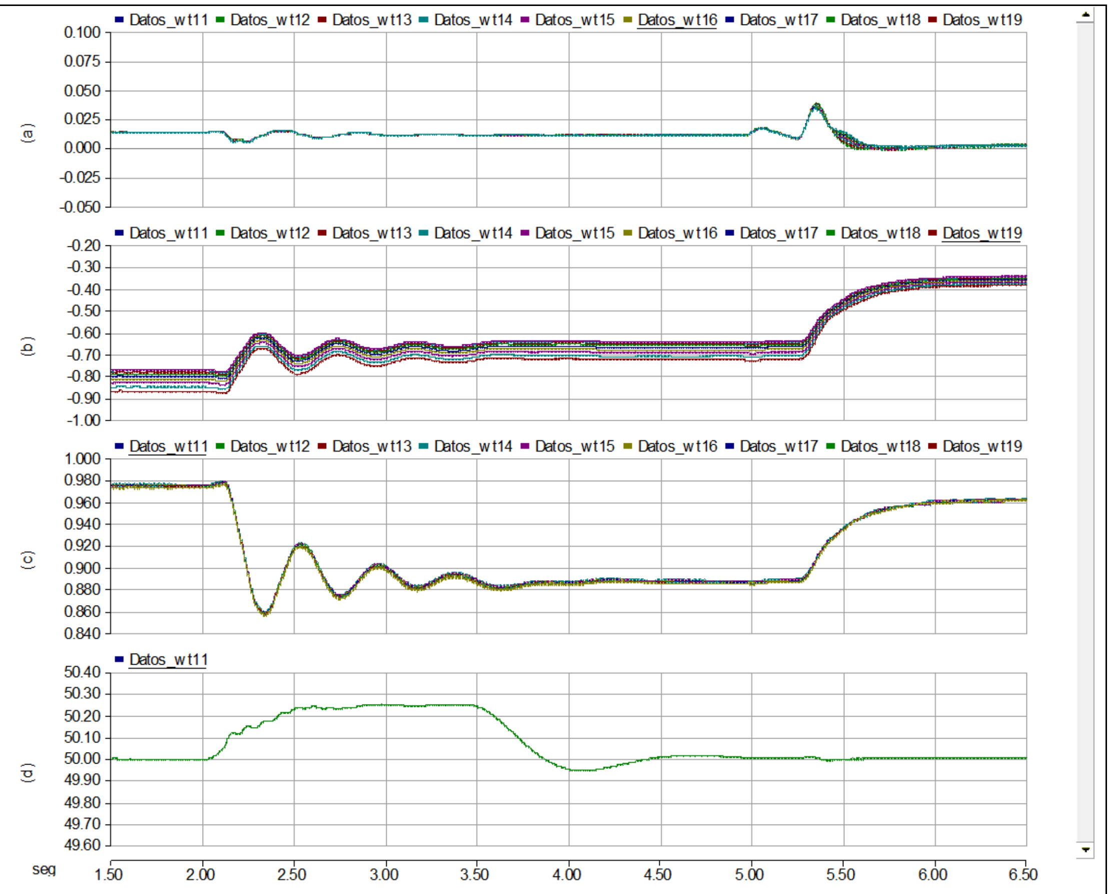

Figure 3-31: WTGs of string 1 in OWF (at the low voltage terminals of the WTG transformer): (a) active power (pu); (b) reactive power (pu); (c) voltage (pu); (d) off-shore ac frequency (Hz).

3.3.13 POWER BLOCK DELIVERY

This test case consist of the connection of a 30 MW load applied to the on-shore island. After the connection, when the grid is in steady state, the load is disconnected. The charge has been applied considering the maximum ramp possible rate (i.e. direct connect/disconnect of the 30MW load).

Test case	2.4.13a. POWER BLOCK DELIVERY (HVAC)		
Simulation detail	WT	Level 4: Perfect DC link control is assumed	
	OWF	Level 4: One detailed string and aggregated strings.	
	On-shore grid	Level 3: Thevenin equivalent	
	Configuration (connected strings)	Compliance	Comments

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691714.

Simulations (sensitivity analysis)	6 Strings	Pass	P_{TOT}= 400 MW; **WTG (max values):** V = 0.98 pu; I = 0.37pu; P = 0.08 pu; Q = -0.36 pu; Δf = 0.12 Hz; df/dt = 0.37 Hz/s; **PCC (max values):** V = 1.01 pu; I = 0.16 pu; P = 0.05 pu; Q = -0.15 pu; **Export cable (max values):** **-off-shore:** V = 1.04 pu; I = 0.16 pu; **-on-shore:** V = 1.05 pu; I = 0.05 pu;
	5 Strings	Pass	P_{TOT}= 336 MW; **WTG (max values):** V = 0.99 pu; I = 0.43pu; P = 0.1 pu; Q = -0.41 pu; Δf = 0.15 Hz; df/dt = 0.4 Hz/s; **PCC (max values):** V = 1.03 pu; I = 0.16 pu; P = 0.05 pu; Q = -0.16 pu; **Export cable (max values):** **-off-shore:** V = 1.05 pu; I = 0.16 pu; **-on-shore:** V = 1.06 pu; I = 0.05 pu;
	4 Strings	Pass	P_{TOT}= 272 MW; **WTG (max values):** V = 1.0 pu; I = 0.52 pu; P = 0.12 pu; Q = -0.5 pu; Δf = 0.19 Hz; df/dt = 0.7 Hz/s; **PCC (max values):** V = 1.04 pu; I = 0.16 pu; P = 0.05 pu; Q = -0.16 pu; **Export cable (max values):** **-off-shore:** V = 1.07 pu; I = 0.16 pu; **-on-shore:** V = 1.08 pu; I = 0.05 pu;
	3 Strings	Pass	P_{TOT}= 208 MW; **WTG (max values):** V = 1.01 pu; I = 0.66pu; P = 0.17 pu; Q = -0.65 pu; Δf = 0.26 Hz; df/dt = 0.76 Hz/s; **PCC (max values):** V = 1.07 pu; I = 0.16 pu; P = 0.05 pu; Q = -0.16 pu; **Export cable (max values):** **-off-shore:** V = 1.1 pu; I = 0.16 pu; **-on-shore:** V = 1.11 pu; I = 0.05 pu;
	2 Strings	Pass	P_{TOT}= 144 MW; **WTG (max values):** V= 1.05 pu; I = 0.93 pu; P = 0.26 pu; Q = -0.91 pu; Δf = 0.4 Hz; df/dt = 0.98 Hz/s; **PCC (max values):** V = 1.13 pu; I = 0.16 pu; P = 0.05 pu; Q = -0.17 pu; **Export cable (max values):** **-off-shore:** V = 1.15 pu; I = 0.17 pu; **-on-shore:** V = 1.17 pu; I = 0.06 pu;
	1 Strings	Fail	P_{TOT}= 72 MW; Not enough capacity to compensate the reactive power produced by the export cable.
Comments	The sample results show the energisation of the export cable using just 2 string connected. Using more WTGs the oscillations when the load is disconnected disappear.		

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Sample result

Figure 3-32: WTGs of string 1 in OWF (at the low voltage terminals of the WTG transformer): (a) active power (pu); (b) reactive power (pu); (c) voltage (pu); (d) off-shore ac frequency (Hz).

Test case	2.4.13b. POWER BLOCK DELIVERY (HVDC)	
Simulation detail	WT	Level 4: Perfect DC link control is assumed
	OWF	Level 4: One detailed string and aggregated strings.
	On-shore grid	Level 3: Thevenin equivalent
	MMC	Level 1 (Corresponding to Type 4 as defined by Cigre WG B4.57)

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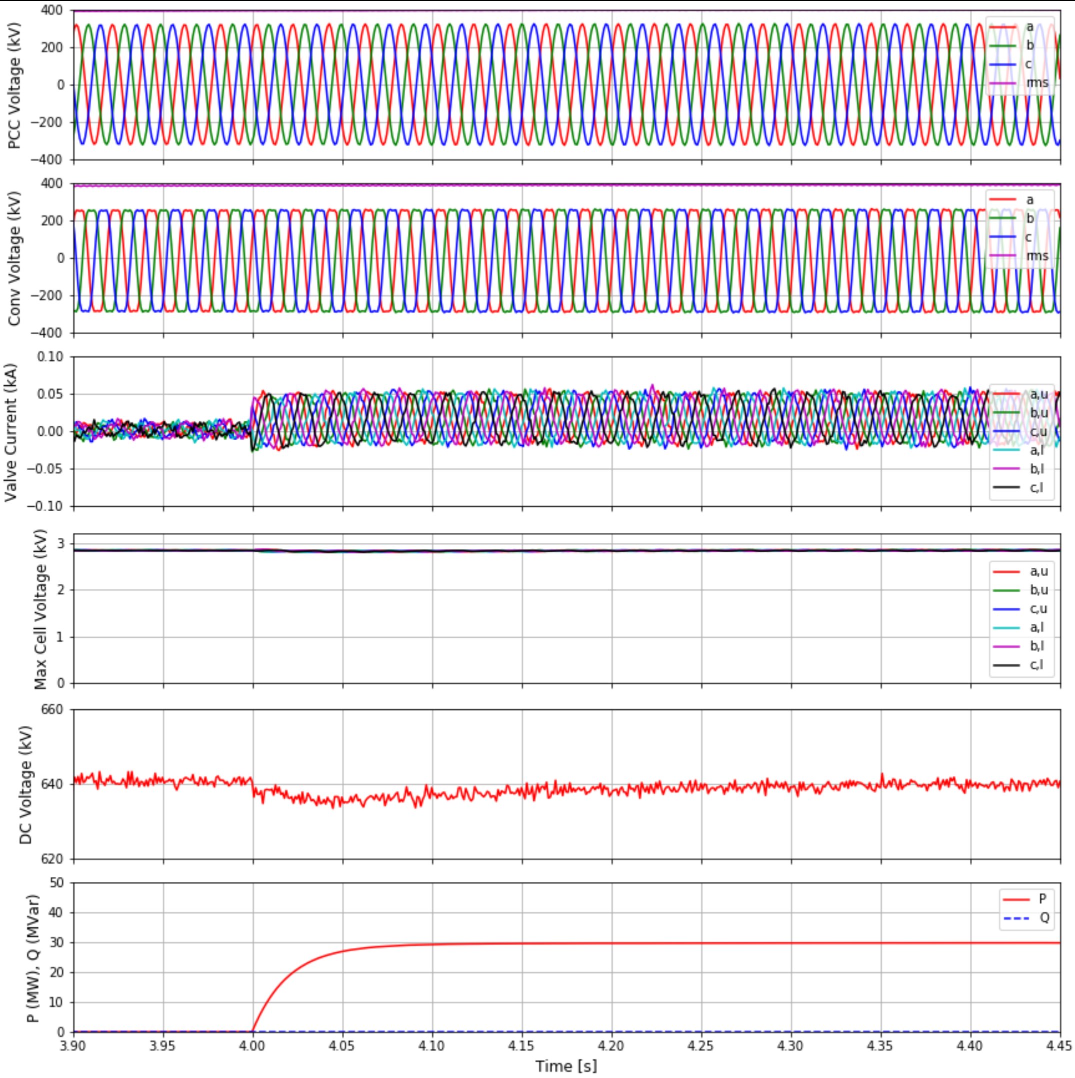
HVDC connected WPP	 Figure 3-33: Waveforms for Power Block Delivery by HVDC-connected WPP: Onshore PCC Phase & RMS voltage (kV), Onshore Converter Voltage (kV), Onshore converter Upper/Lower arm Valve Currents for all Phases (kA), Max Cell Voltages of Upper/Lower arm in all Phases for Onshore converter (kV), HVDC link voltage (kV), Real (MW) & Reactive (MVAr) Power injection at Onshore PCC.
Comment	The results show that the HVDC link voltage drops about 1.5% when the block load is picked-up, before the offshore converter regulates it back to the reference value.

3.3.14 SOFT ENERGISATION (FROM HOUSELOAD TO POWER BLOCK)

Test case	2.4.14a. SOFT ENERGISATION (FROM HOUSELOAD TO POWER BLOCK) HVAC	
Simulation detail	WT	Level 4: Perfect DC link control is assumed
	OWF	Level 4: One detailed string and aggregated strings.
	On-shore grid	Level 3: Thevenin equivalent

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	Configuration (connected strings)	Compliance	Comments
Simulations (sensitivity analysis)	6 Strings	Pass	P_{TOT}= 400 MW; **WTG (max values):** V = 0.98 pu; I = 0.37pu; P = 0.08 pu; Q = -0.35 pu; Δf = 0.31 Hz; df/dt = 0.83 Hz/s; **PCC (max values):** V = 1.01 pu; I = 0.16 pu; P = 0.05 pu; Q = -0.16 pu; **Export cable (max values):** **-off-shore:** V = 1.03 pu; I = 0.16 pu; **-on-shore:** V = 1.05 pu; I = 0.05 pu;
	5 Strings	Pass	P_{TOT}= 336 MW; **WTG (max values):** V = 0.98 pu; I = 0.43pu; P = 0.1 pu; Q = -0.41 pu; Δf = 0.3 Hz; df/dt = 0.78 Hz/s; **PCC (max values):** V = 1.03 pu; I = 0.16 pu; P = 0.05 pu; Q = -0.16 pu; **Export cable (max values):** **-off-shore:** V = 1.025 pu; I = 0.16 pu; **-on-shore:** V = 1.06 pu; I = 0.05 pu;
	4 Strings	Pass	P_{TOT}= 272 MW; **WTG (max values):** V = 1.0 pu; I = 0.52 pu; P = 0.13 pu; Q = -0.5 pu; Δf = 0.34 Hz; df/dt = 0.82 Hz/s; **PCC (max values):** V = 1.04 pu; I = 0.16 pu; P = 0.05 pu; Q = -0.16 pu; **Export cable (max values):** **-off-shore:** V = 1.07 pu; I = 0.16 pu; **-on-shore:** V = 1.08 pu; I = 0.05 pu;
	3 Strings	Pass	P_{TOT}= 208 MW; **WTG (max values):** V = 1.01 pu; I = 0.66pu; P = 0.17 pu; Q = -0.64 pu; Δf = 0.5 Hz; df/dt = 1.2 Hz/s; **PCC (max values):** V = 1.07 pu; I = 0.16 pu; P = 0.05 pu; Q = -0.17 pu; **Export cable (max values):** **-off-shore:** V = 1.1 pu; I = 0.17 pu; **-on-shore:** V = 1.12 pu; I = 0.05 pu;
	2 Strings	Pass	P_{TOT}= 144 MW; **WTG (max values):** V= 1.05 pu; I = 0.93 pu; P = 0.27 pu; Q = -0.92 pu; Δf = 0.6 Hz; df/dt = 1.5 Hz/s; **PCC (max values):** V = 1.13 pu; I = 0.16 pu; P = 0.05 pu; Q = -0.17 pu; **Export cable (max values):** **-off-shore:** V = 1.15 pu; I = 0.17 pu; **-on-shore:** V = 1.18 pu; I = 0.07 pu;
	1 Strings	Fail	P_{TOT}= 72 MW; Not enough capacity to compensate the reactive power produced by the export cable.
Comments	The sample results show the HVAC export cable energisation and direct on line (DOL) load connection and disconnection with just 2 strings connected. Note both voltage and frequency limits are met both during energisation and also during DOL load connection and disconnection.		

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691714.

Sample result

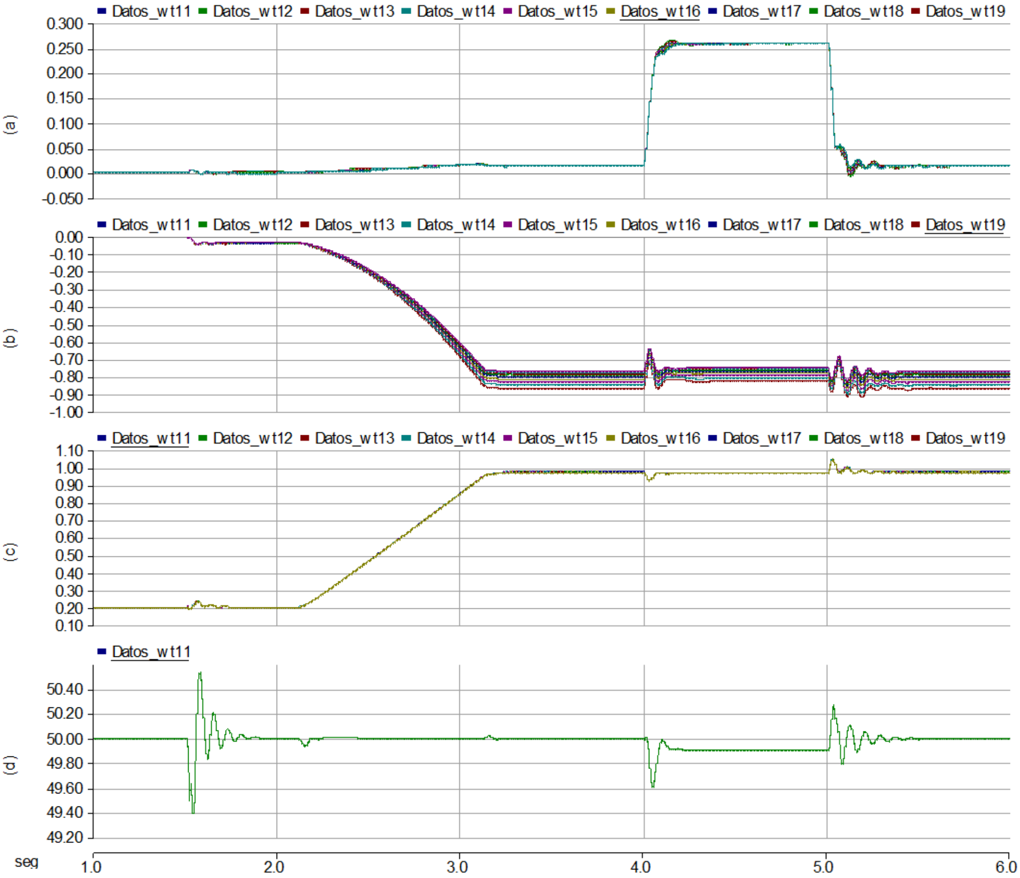

Figure 3-34: WTGs of string 1 in OWF (at the low voltage terminals of the WTG transformer): (a) active power (pu); (b) reactive power (pu); (c) voltage (pu); (d) off-shore ac frequency (Hz).

Test case	2.4.14b. SOFT ENERGISATION (FROM HOUSELOAD TO POWER BLOCK) HVDC		
Simulation detail	WT	Level 4: Perfect DC link control is assumed	
	OWF	Level 4: One detailed string and aggregated strings.	
	MMC	Level 1 (Corresponding to Type 4 as defined by Cigre WG B4.57)	
	On-shore grid	Level 3: Thevenin equivalent	

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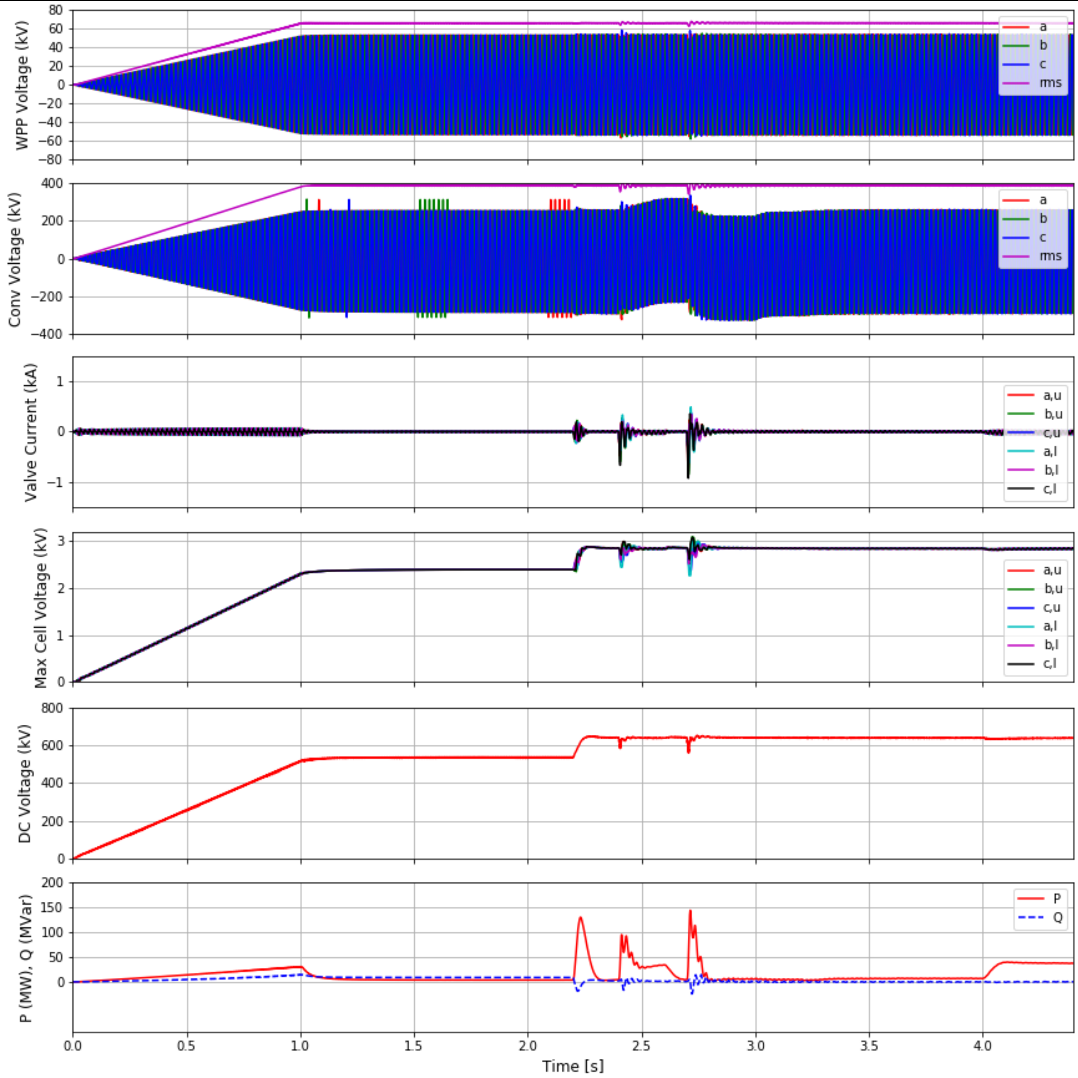
HVDC connected WPP	 Figure 3-35: Waveforms for Soft Start of HVDC-connected WPP: Onshore PCC Phase & RMS voltage (kV), Onshore Converter Voltage (kV), Onshore converter Upper/Lower arm Valve Currents for all Phases (kA), Max Cell Voltages of Upper/Lower arm in all Phases for Onshore converter (kV), HVDC link voltage (kV), Real (MW) & Reactive (MVAr) Power injection at Onshore PCC.
Comment	The results show the complete Soft Start energisation sequence of an HVDC-connected WPP from offshore grid-forming to transformer, converter, export cable energisation and finally onshore power block delivery.

3.4. FAULT RIDE-THROUGH AND PROTECTION

This section shows the compliance evaluation results for fault ride-through and protection tested on the HVAC black start scenario. On-shore, off-shore and cable faults have been checked. All faults have been tested over the WPP with off-shore transformer, the HVAC cable and the On-shore transformer energised. Additionally, the faults have been tested with and without load. Just symmetric faults have been tested. A short circuit resistance of 1 Ω has been used for all fault test cases.

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3.4.1 ONSHORE GRID FAULTS

This test case consists of a short-circuit fault at the on-shore 400 kV grid. The duration of the short-circuit is set to 0.4s in both cases (with and without load).

3.4.1.1 CONNECTED LOAD

Test case	2.5.1 ONSHORE GRID FAULTS		
Simulation detail	WT	Level 4: Perfect DC link control is assumed	
	OWF	Level 4: One detailed string and aggregated strings.	
	On-shore grid	Level 3: Thevenin equivalent	
	Configuration (connected strings)	Compliance	Comments
Simulations (sensitivity analysis)	6 Strings	Pass	P_{TOT}= 400 MW; **WTG (max values):** V = 0.96 pu; I = 1.12pu; P = 0.08 pu; Q = -0.44 pu; Δf = 0.28 Hz; df/dt = 2.27 Hz/s; **PCC (max values):** V = 0.99 pu; I = 1.16 pu; P = 0.08 pu; Q = -0.34 pu; **Export cable (max values):** **-off-shore:** V = 1.01 pu; I = 1.15 pu; **-on-shore:** V = 1.01 pu; I = 1.23 pu;
	5 Strings	Pass	P_{TOT}= 336 MW; **WTG (max values):** V = 0.97 pu; I = 1.12pu; P = 0.1 pu; Q = -0.39 pu; Δf = 0.35 Hz; df/dt = 2.25 Hz/s; **PCC (max values):** V = 0.99 pu; I = 0.97 pu; P = 0.08 pu; Q = -0.25 pu; **Export cable (max values):** **-off-shore:** V = 1.02 pu; I = 0.96 pu; **-on-shore:** V = 1.02 pu; I = 1.04 pu;
	4 Strings	Pass	P_{TOT}= 272 MW; **WTG (max values):** V = 0.97 pu; I= 1.12 pu; P = 0.13 pu; Q = -0.45 pu; Δf = 0.5 Hz; df/dt = 2.26 Hz/s; **PCC (max values):** V = 1.01 pu; I = 0.78 pu; P = 0.08 pu; Q = -0.25 pu; **Export cable (max values):** **-off-shore:** V = 1.03 pu; I = 0.77 pu; **-on-shore:** V = 1.03 pu; I = 0.86 pu;
	3 Strings	Pass	P_{TOT}= 208 MW; **WTG (max values):** V = 0.97 pu; I = 1.12pu; P = 0.17 pu; Q = -0.57 pu; Δf = 0.46 Hz; df/dt = 2.27 Hz/s; **PCC (max values):** V = 1.03 pu; I = 0.59 pu; P = 0.09 pu; Q = -0.25 pu; **Export cable (max values):** **-off-shore:** V = 1.05 pu; I = 0.59 pu; **-on-shore:** V = 1.05 pu; I = 0.68 pu;

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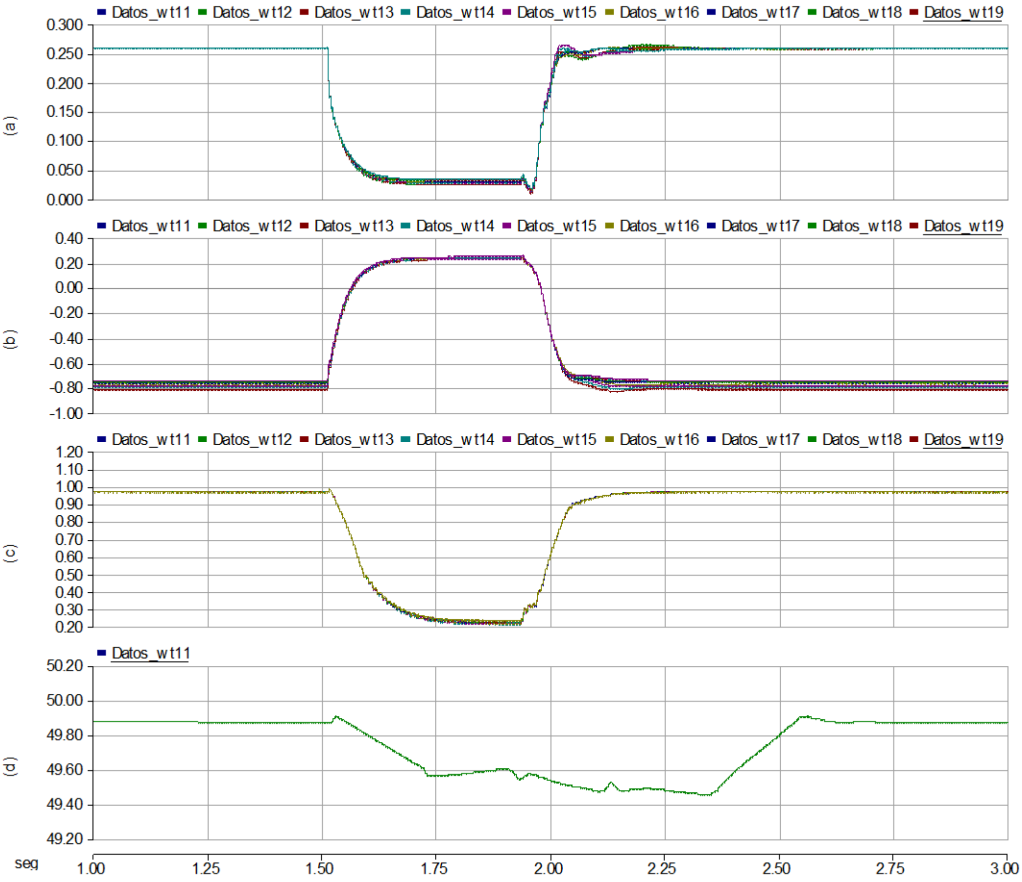
	2 Strings	Pass	P_{TOT}= 144 MW; **WTG (max values):** V= 0.98 pu; I = 1.12 pu; P = 0.26 pu; Q = -0.83 pu; Δf = 0.54 Hz; df/dt = 2.3 Hz/s; **PCC (max values):** V = 1.05 pu; I = 0.41 pu; P = 0.09 pu; Q = -0.26 pu; **Export cable (max values):** **-off-shore:** V = 1.07 pu; I = 0.41 pu; **-on-shore:** V = 1.07 pu; I = 0.52 pu;
	1 Strings	Fail	P_{TOT}= 72 MW; Not enough capacity to compensate the reactive power produced by the export cable.
Comments	The sample results show the most unfavourable case, i.e. only 2 strings connected.		
Sample result	 Figure 3-36: 400kV on-shore grid fault: String1 WTGs (at the low voltage terminals of the WTG transformer): (a) active power (pu); (b) reactive power (pu); (c) voltage (pu); (d) off-shore ac frequency (Hz).		

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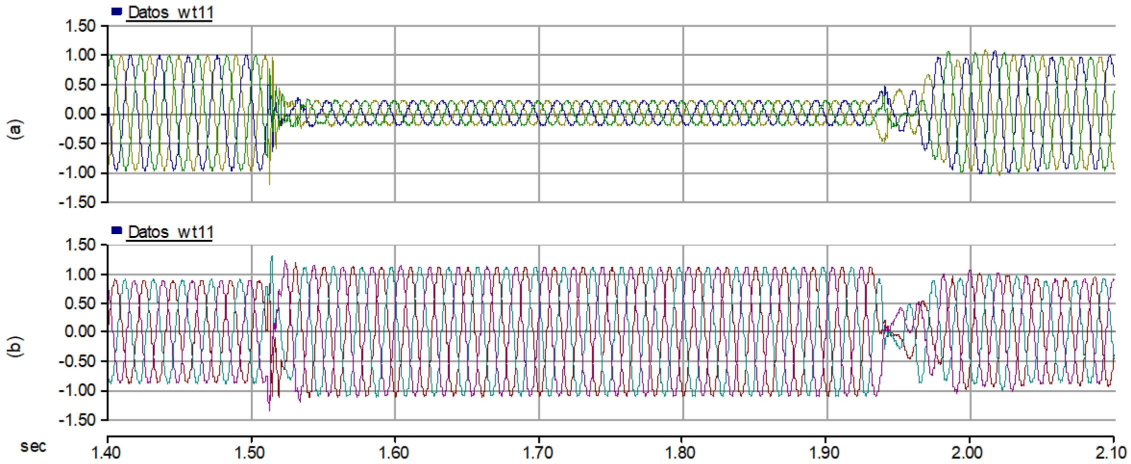

Figure 3-37: 400kV on-shore grid fault: $WTG_{1,1}$ during an on-shore fault (at the low voltage terminals of the WTG transformer): (a) voltage (pu); (b) current (pu).

3.4.1.2 UNCONNECTED LOAD

Test case	2.5.1 ONSHORE GRID FAULTS		
Simulation detail	WT	Level 4: Perfect DC link control is assumed	
	OWF	Level 4: One detailed string and aggregated strings.	
	On-shore grid	Level 3: Thevenin equivalent	
	Configuration (connected strings)	Compliance	Comments
Simulations (sensitivity analysis)	6 Strings	Pass	P_{TOT}= 400 MW; **WTG (max values):** V = 0.96 pu; I = 1.12pu; P = 0.06 pu; Q = -0.44 pu; Δf = 0.28 Hz; df/dt = 2.27 Hz/s; **PCC (max values):** V = 0.99 pu; I = 1.16 pu; P = 0.04 pu; Q = -0.34 pu; **Export cable (max values):** **-off-shore:** V = 1.02 pu; I = 1.15 pu; **-on-shore:** V = 1.02 pu; I = 1.22 pu;
	5 Strings	Pass	P_{TOT}= 336 MW; **WTG (max values):** V = 0.96 pu; I = 1.12pu; P = 0.05 pu; Q = -0.39 pu; Δf = 0.33 Hz; df/dt = 2.25 Hz/s; **PCC (max values):** V = 1.02 pu; I = 0.97 pu; P = 0.03 pu; Q = -0.25 pu; **Export cable (max values):** **-off-shore:** V = 1.02 pu; I = 0.96 pu; **-on-shore:** V = 1.02 pu; I = 1.03 pu;

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	4 Strings	Pass	P_{TOT}= 272 MW; **WTG (max values):** V = 0.97 pu; I= 1.12 pu; P = 0.06 pu; Q = -0.547 pu; Δf = 0.38 Hz; df/dt = 2.26 Hz/s; **PCC (max values):** V = 1.03 pu; I = 0.78 pu; P = 0.03 pu; Q = -0.25 pu; **Export cable (max values):** **-off-shore:** V = 1.03 pu; I = 0.77 pu; **-on-shore:** V = 1.03 pu; I = 0.84 pu;
	3 Strings	Pass	P_{TOT}= 208 MW; **WTG (max values):** V = 0.97 pu; I = 1.12pu; P = 0.07 pu; Q = -0.56 pu; Δf = 0.41 Hz; df/dt = 2.27 Hz/s; **PCC (max values):** V = 1.03 pu; I = 0.59 pu; P = 0.03 pu; Q = -0.25 pu; **Export cable (max values):** **-off-shore:** V = 1.05 pu; I = 0.59 pu; **-on-shore:** V = 1.05 pu; I = 0.67 pu;
	2 Strings	Pass	P_{TOT}= 144 MW; **WTG (max values):** V= 0.98 pu; I = 1.12 pu; P = 0.09 pu; Q = -0.91 pu; Δf = 0.45 Hz; df/dt = 2.3 Hz/s; **PCC (max values):** V = 1.13 pu; I = 0.16 pu; P = 0.05 pu; Q = -0.17 pu; **Export cable (max values):** **-off-shore:** V = 1.15 pu; I = 0.17 pu; **-on-shore:** V = 1.18 pu; I = 0.07 pu; In this case, voltages are above 1.1 pu for less than 100 ms. They comply with the criteria of not exceeding 1.3pu for 100 ms.
	1 Strings	Fail	P_{TOT}= 72 MW; Not enough capacity to compensate the reactive power produced by the export cable.
Comments	The sample results have been obtained with 2 strings connected.		

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Sample result

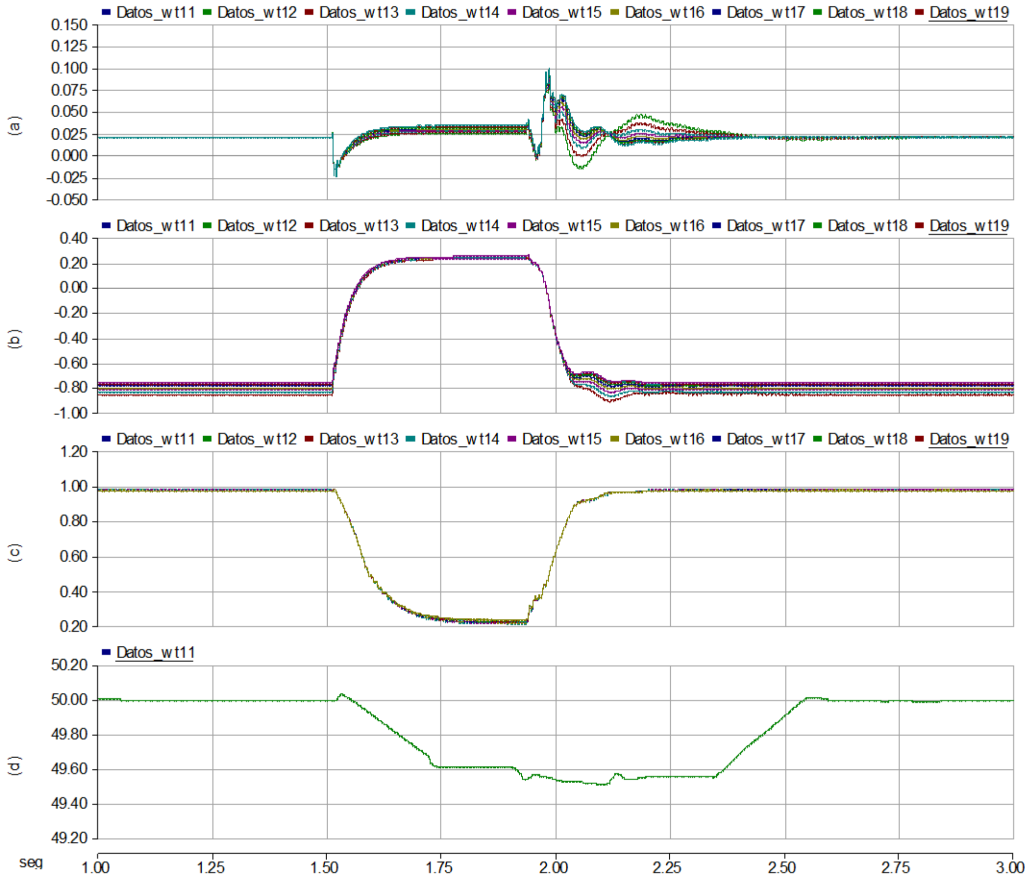

Figure 3-38: 400kV on-shore grid fault: string 1 WTGs (at the low voltage terminals of the WTG transformer): (a) active power (pu); (b) reactive power (pu); (c) voltage (pu); (d) off-shore ac frequency (Hz).

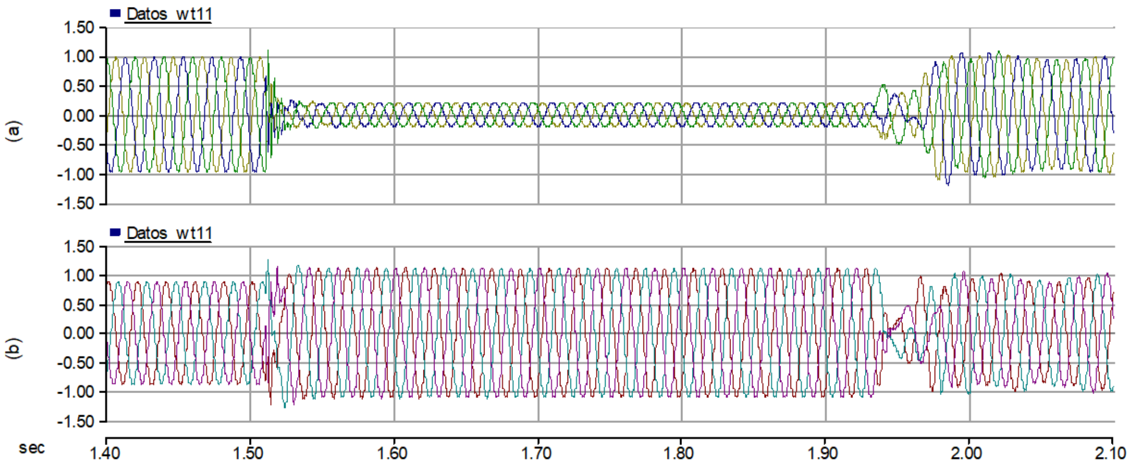

Figure 3-39: 400kV on-shore grid fault: $WTG_{1,1}$ during an on-shore fault (at the low voltage terminals of the WTG transformer): (a) voltage (pu); (b) current (pu).

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3.4.2 HVAC EXPORT CABLE FAULTS

This test case consists of a short-circuit at the middle of the HVAC 220KV cable with and without load. The duration of the short-circuit is set to 0.4s in both cases (with and without load).

3.4.2.1 CONNECTED LOAD

Test case	2.5.1 ONSHORE GRID FAULTS		
Simulation detail	WT	Level 4: Perfect DC link control is assumed	
	OWF	Level 4: One detailed string and aggregated strings.	
	On-shore grid	Level 3: Thevenin equivalent	
	Configuration (connected strings)	Compliance	Comments
Simulations (sensitivity analysis)	6 Strings	Pass	P_{TOT}= 400 MW; **WTG (max values):** V = 0.96 pu; I = 1.12pu; P = 0.08 pu; Q = -0.33 pu; Δf = 0.45 Hz; df/dt = 2.11 Hz/s; **PCC (max values):** V = 0.99 pu; I = 1.13 pu; P = 0.08 pu; Q = -0.24 pu; **Export cable (max values):** **-off-shore:** V = 1.01 pu; I = 1.13 pu; **-on-shore:** V = 1.01 pu; I = 0.16 pu;
	5 Strings	Pass	P_{TOT}= 336 MW; **WTG (max values):** V = 0.96 pu; I = 1.12pu; P = 0.1 pu; Q = -0.38 pu; Δf = 0.45 Hz; df/dt = 2.12 Hz/s; **PCC (max values):** V = 0.99 pu; I = 0.95 pu; P = 0.08 pu; Q = -0.25 pu; **Export cable (max values):** **-off-shore:** V = 1.02 pu; I = 0.95 pu; **-on-shore:** V = 1.02 pu; I = 0.15 pu;
	4 Strings	Pass	P_{TOT}= 272 MW; **WTG (max values):** V = 0.96 pu; I= 1.12 pu; P = 0.13 pu; Q = -0.45 pu; Δf = 0.5 Hz; df/dt = 2.26 Hz/s; **PCC (max values):** V = 1.0 pu; I = 0.77 pu; P = 0.08 pu; Q = -0.25 pu; **Export cable (max values):** **-off-shore:** V = 1.03 pu; I = 0.77 pu; **-on-shore:** V = 1.03 pu; I = 0.14 pu;
	3 Strings	Pass	P_{TOT}= 208 MW; **WTG (max values):** V = 0.97 pu; I = 1.12pu; P = 0.17 pu; Q = -0.57 pu; Δf = 0.55 Hz; df/dt = 2.27 Hz/s; **PCC (max values):** V = 1.03 pu; I = 0.59 pu; P = 0.08 pu; Q = -0.25 pu; **Export cable (max values):** **-off-shore:** V = 1.04 pu; I = 0.59 pu; **-on-shore:** V = 1.04 pu; I = 0.13 pu;

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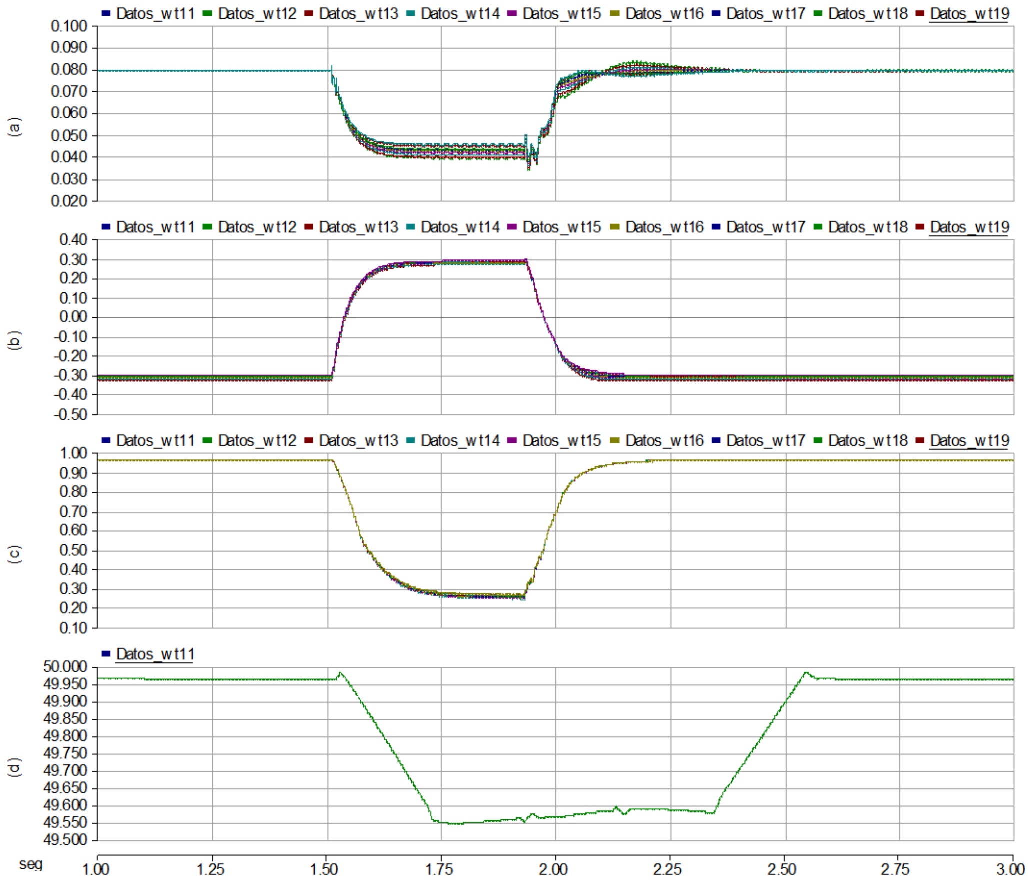
	2 Strings	Pass	P_{TOT}= 144 MW; **WTG (max values):** V= 0.97 pu; I = 1.12 pu; P = 0.26 pu; Q = -0.83 pu; Δf = 0.64 Hz; df/dt = 2.3 Hz/s; **PCC (max values):** V = 1.05 pu; I = 0.41 pu; P = 0.09 pu; Q = -0.26 pu; **Export cable (max values):** **-off-shore:** V = 1.07 pu; I = 0.41 pu; **-on-shore:** V = 1.07 pu; I = 0.12 pu;
	1 Strings	Fail	P_{TOT}= 72 MW; Not enough capacity to compensate the reactive power produced by the export cable.
Comments	The sample results have been obtained with all strings connected.		
Sample result	 Figure 3-40: 220kV HVAC mid-point cable fault: String 1 WTGs (at the low voltage terminals of the WTG transformer): (a) active power (pu); (b) reactive power (pu); (c) voltage (pu); (d) off-shore ac frequency (Hz).		

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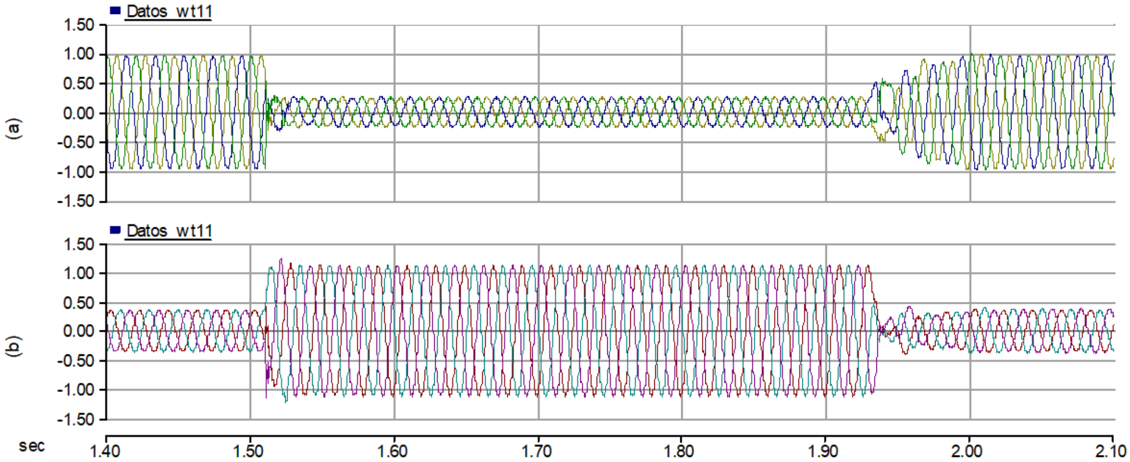

Figure 3-41: 220kV HVAC mid-point cable fault: $WTG_{1,1}$ during an on-shore fault (at the low voltage terminals of the WTG transformer): (a) voltage (pu); (b) current (pu).

3.4.2.2 UNCONNECTED LOAD

Test case	2.5.1 ONSHORE GRID FAULTS		
Simulation detail	WT	Level 4: Perfect DC link control is assumed	
	OWF	Level 4: One detailed string and aggregated strings.	
	On-shore grid	Level 3: Thevenin equivalent	
	Configuration (connected strings)	Compliance	Comments
Simulations (sensitivity analysis)	6 Strings	Pass	P_{TOT}= 400 MW; **WTG (max values):** V = 0.96 pu; I = 1.12pu; P = 0.04 pu; Q = -0.33 pu; Δf = 0.45 Hz; df/dt = 2.21 Hz/s; **PCC (max values):** V = 0.99 pu; I = 1.13 pu; P = 0.04 pu; Q = -0.24 pu; **Export cable (max values):** **-off-shore:** V = 1.02 pu; I = 1.13 pu; **-on-shore:** V = 1.02 pu; I = 0.15 pu;
	5 Strings	Pass	P_{TOT}= 336 MW; **WTG (max values):** V = 0.96 pu; I = 1.12pu; P = 0.04 pu; Q = -0.39 pu; Δf = 0.43 Hz; df/dt = 2.14 Hz/s; **PCC (max values):** V = 1.0 pu; I = 0.95 pu; P = 0.03 pu; Q = -0.25 pu; **Export cable (max values):** **-off-shore:** V = 1.02 pu; I = 0.95 pu; **-on-shore:** V = 1.02 pu; I = 0.15 pu;

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	4 Strings	Pass	P_{TOT}= 272 MW; **WTG (max values):** V = 0.97 pu; I= 1.12 pu; P = 0.04 pu; Q = -0.46 pu; Δf = 0.50 Hz; df/dt = 2.2 Hz/s; **PCC (max values):** V = 1.01 pu; I = 0.77 pu; P = 0.03 pu; Q = -0.25 pu; **Export cable (max values):** **-off-shore:** V = 1.03 pu; I = 0.77 pu; **-on-shore:** V = 1.03 pu; I = 0.14 pu;
	3 Strings	Pass	P_{TOT}= 208 MW; **WTG (max values):** V = 0.97 pu; I = 1.12pu; P = 0.06 pu; Q = -0.60 pu; Δf = 0.55 Hz; df/dt = 2.27 Hz/s; **PCC (max values):** V = 1.03 pu; I = 0.59 pu; P = 0.03 pu; Q = -0.25 pu; **Export cable (max values):** **-off-shore:** V = 1.05 pu; I = 0.59 pu; **-on-shore:** V = 1.05 pu; I = 0.12 pu;
	2 Strings	Pass	P_{TOT}= 144 MW; **WTG (max values):** V= 0.98 pu; I = 1.12 pu; P = 0.09 pu; Q = -0.90 pu; Δf = 0.6 Hz; df/dt = 2.3 Hz/s; **PCC (max values):** V = 1.06 pu; I = 0.41 pu; P = 0.03 pu; Q = -0.28 pu; **Export cable (max values):** **-off-shore:** V = 1.08 pu; I = 0.41 pu; **-on-shore:** V = 1.08 pu; I = 0.11 pu;
	1 Strings	Fail	P_{TOT}= 72 MW; Not enough capacity to compensate the reactive power produced by the export cable.
Comments	The sample results have been obtained with all strings connected.		

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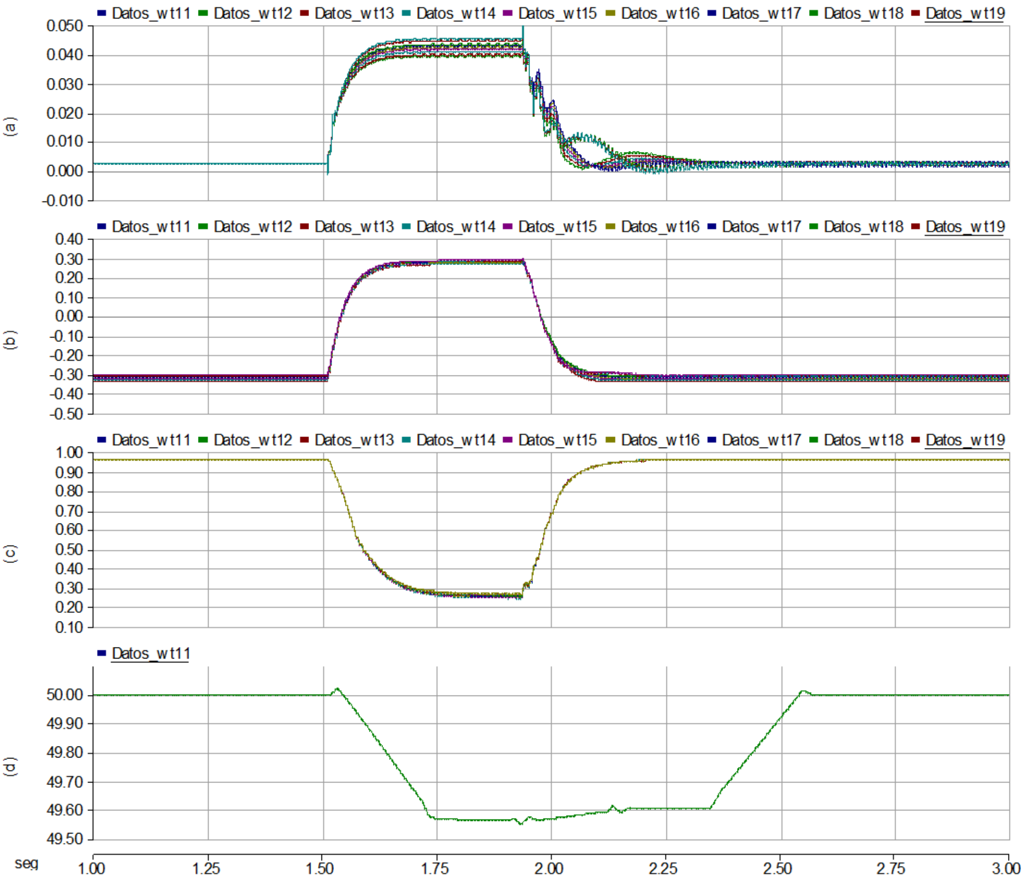
Sample result	 Figure 3-42: 220kV HVAC mid-point cable fault: String 1 WTGs (at the low voltage terminals of the WTG transformer): (a) active power (pu); (b) reactive power (pu); (c) voltage (pu); (d) off-shore ac frequency (Hz).

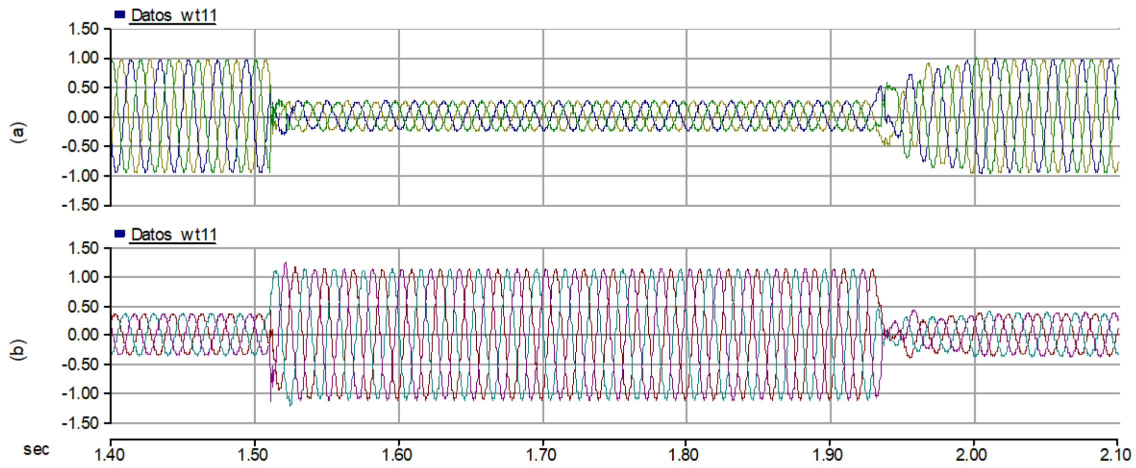


Figure 3-43: 220kV HVAC mid-point cable fault: $WTG_{1,1}$ during an on-shore fault (at the low voltage terminals of the WTG transformer): (a) voltage (pu); (b) current (pu).

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3.4.3 OFFSHORE AC FAULTS

This test case consists of a short-circuit at the off-shore 66kV collector bus with and without on-shore load. The duration of the short-circuit is set to 0.4s in both cases (with and without load).

3.4.3.1 CONNECTED LOAD

Test case	2.5.1 ONSHORE GRID FAULTS		
Simulation detail	WT	Level 4: Perfect DC link control is assumed	
	OWF	Level 4: One detailed string and aggregated strings.	
	On-shore grid	Level 3: Thevenin equivalent	
	Configuration (connected strings)	Compliance	Comments
Simulations (sensitivity analysis)	6 Strings	Pass	P_{TOT}= 400 MW; **WTG (max values):** V = 0.96 pu; I = 1.12pu; P = 0.12 pu; Q = -0.33 pu; Δf = 0.26 Hz; df/dt = 2.27 Hz/s; **PCC (max values):** V = 0.99 pu; I = 0.44 pu; P = 0.08 pu; Q = -0.24 pu; **Export cable (max values):** **-off-shore:** V = 1.01 pu; I = 0.44 pu; **-on-shore:** V = 1.01 pu; I = 0.08 pu;
	5 Strings	Pass	P_{TOT}= 336 MW; **WTG (max values):** V = 0.96 pu; I = 1.12pu; P = 0.11 pu; Q = -0.38 pu; Δf = 0.30 Hz; df/dt = 2.25 Hz/s; **PCC (max values):** V = 0.99 pu; I = 0.45 pu; P = 0.08 pu; Q = -0.25 pu; **Export cable (max values):** **-off-shore:** V = 1.02 pu; I = 0.44 pu; **-on-shore:** V = 1.02 pu; I = 0.08 pu;
	4 Strings	Pass	P_{TOT}= 272 MW; **WTG (max values):** V = 0.96 pu; I= 1.12 pu; P = 0.13 pu; Q = -0.46 pu; Δf = 0.54 Hz; df/dt = 2.26 Hz/s; **PCC (max values):** V = 1.01 pu; I = 0.46 pu; P = 0.08 pu; Q = -0.25 pu; **Export cable (max values):** **-off-shore:** V = 1.02 pu; I = 0.44 pu; **-on-shore:** V = 1.02 pu; I = 0.08 pu;
	3 Strings	Pass	P_{TOT}= 208 MW; **WTG (max values):** V = 0.97 pu; I = 1.12pu; P = 0.17 pu; Q = -0.57 pu; Δf = 0.50 Hz; df/dt = 2.27 Hz/s; **PCC (max values):** V = 1.02 pu; I = 0.46 pu; P = 0.09 pu; Q = -0.25 pu; **Export cable (max values):** **-off-shore:** V = 1.02 pu; I = 0.44 pu; **-on-shore:** V = 1.02 pu; I = 0.08 pu;

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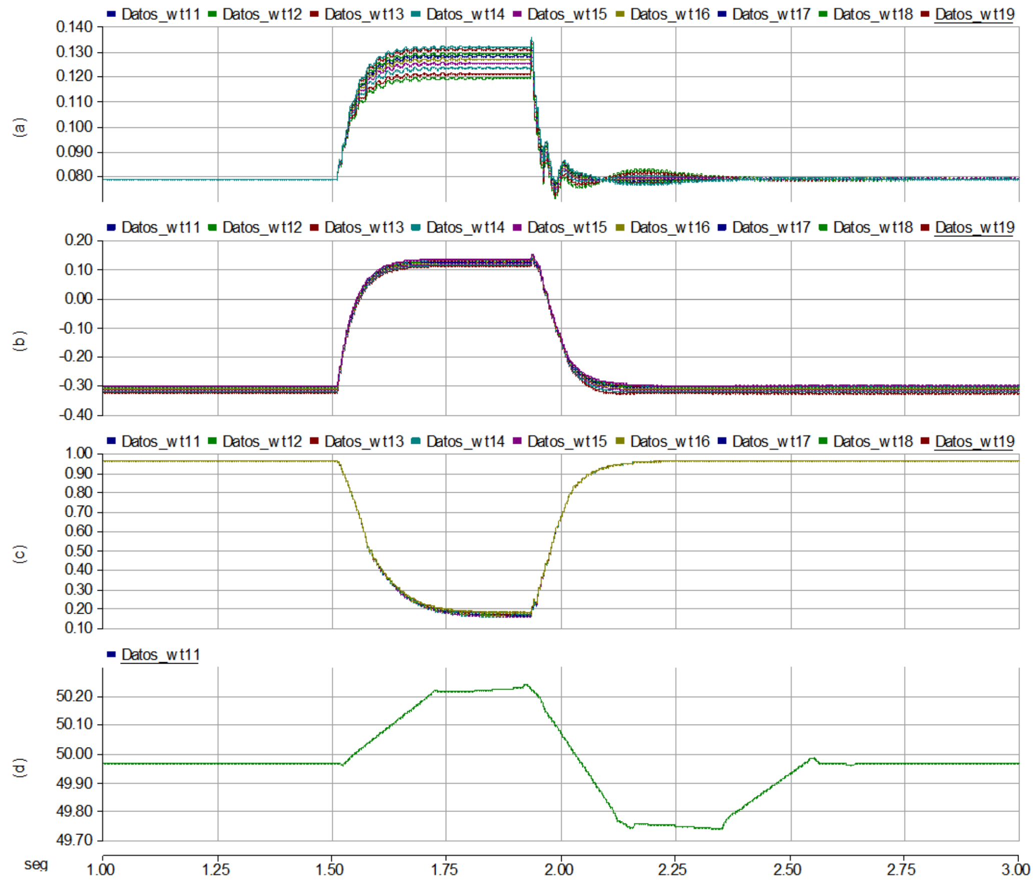
	2 Strings	Pass	P_{TOT}= 144 MW; **WTG (max values):** V= 0.97 pu; I = 1.12 pu; P = 0.25 pu; Q = -0.82 pu; Δf = 0.54 Hz; df/dt = 2.3 Hz/s; **PCC (max values):** V = 1.05 pu; I = 0.46 pu; P = 0.09 pu; Q = -0.26 pu; **Export cable (max values):** **-off-shore:** V = 1.02 pu; I = 0.44 pu; **-on-shore:** V = 1.02 pu; I = 0.08 pu;
	1 Strings	Fail	P_{TOT}= 72 MW; Not enough capacity to compensate the reactive power produced by the export cable.
Comments	The sample results have been obtained with all strings connected.		
Sample result	 Figure 3-44: 66kV off-shore collector bus fault: String 1 WTGs (at the low voltage terminals of the WTG transformer): (a) active power (pu); (b) reactive power (pu); (c) voltage (pu); (d) off-shore ac frequency (Hz).		

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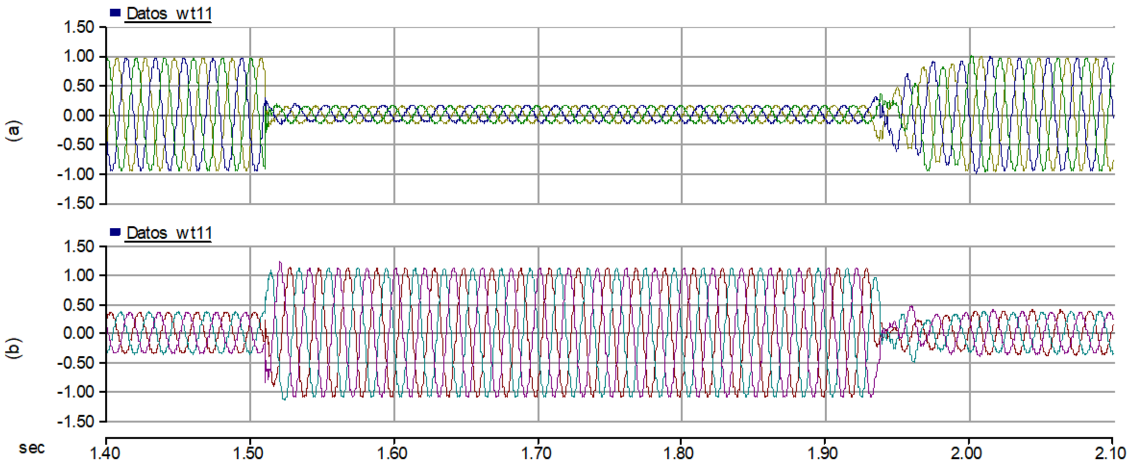

Figure 3-45: 66kV off-shore collector bus fault: $WTG_{1,1}$ during an on-shore fault (at the low voltage terminals of the WTG transformer): (a) voltage (pu); (b) current (pu).

3.4.3.2 UNCONNECTED LOAD

Test case	2.5.1 ONSHORE GRID FAULTS		
Simulation detail	WT	Level 4: Perfect DC link control is assumed	
	OWF	Level 4: One detailed string and aggregated strings.	
	On-shore grid	Level 3: Thevenin equivalent	
	Configuration (connected strings)	Compliance	Comments
Simulations (sensitivity analysis)	6 Strings	Pass	P_{TOT}= 400 MW; **WTG (max values):** V = 0.96 pu; I = 1.12pu; P = 0.12 pu; Q = -0.34 pu; Δf = 0.24 Hz; df/dt = 2.27 Hz/s; **PCC (max values):** V = 0.99 pu; I = 0.45 pu; P = 0.02 pu; Q = -0.25 pu; **Export cable (max values):** **-off-shore:** V = 1.02 pu; I = 0.48 pu; **-on-shore:** V = 1.02 pu; I = 0.05 pu;
	5 Strings	Pass	P_{TOT}= 336 MW; **WTG (max values):** V = 0.96 pu; I = 1.12pu; P = 0.11 pu; Q = -0.40 pu; Δf = 0.27 Hz; df/dt = 2.25 Hz/s; **PCC (max values):** V = 1.0 pu; I = 0.45 pu; P = 0.03 pu; Q = -0.25 pu; **Export cable (max values):** **-off-shore:** V = 1.02 pu; I = 0.48 pu; **-on-shore:** V = 1.02 pu; I = 0.01 pu;

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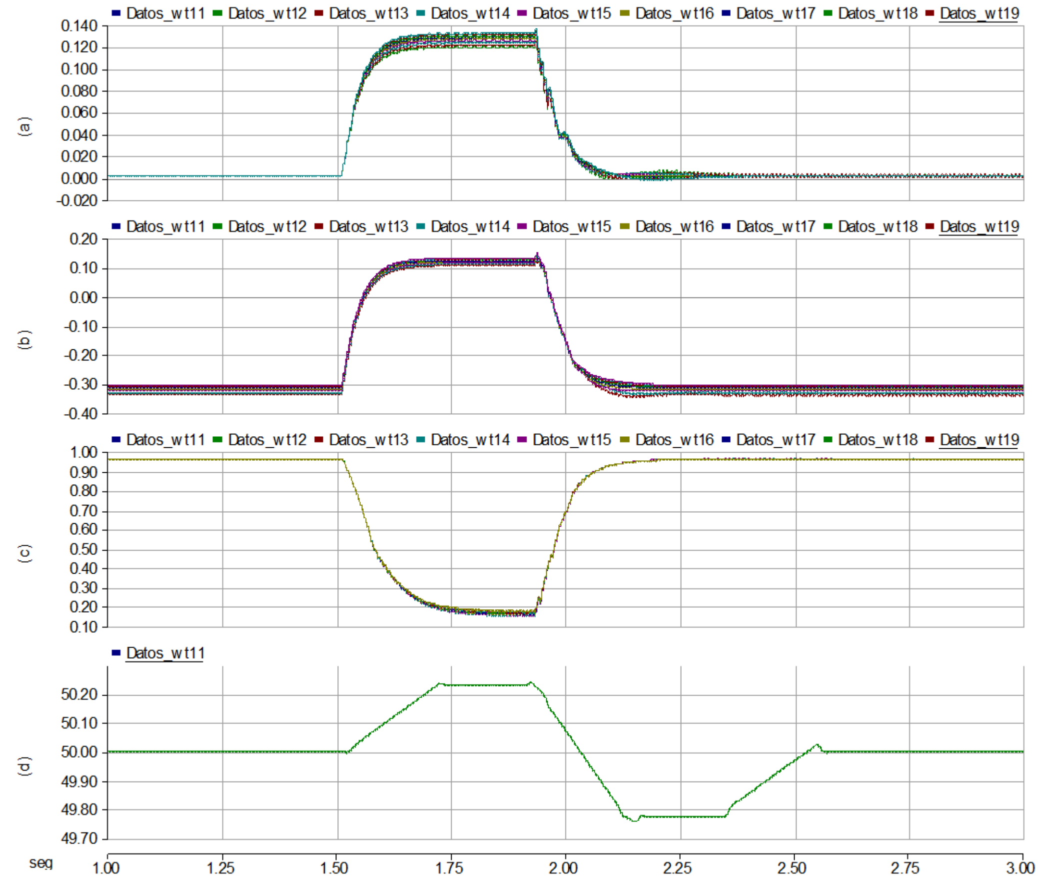
	4 Strings	Pass	P_{TOT}= 272 MW; **WTG (max values):** V = 0.97 pu; I= 1.12 pu; P = 0.09 pu; Q = -0.47 pu; Δf = 0.38 Hz; df/dt = 2.26 Hz/s; **PCC (max values):** V = 1.03 pu; I = 0.45 pu; P = 0.03 pu; Q = -0.25 pu; **Export cable (max values):** **-off-shore:** V = 1.02 pu; I = 0.48 pu; **-on-shore:** V = 1.02 pu; I = 0.01 pu;
	3 Strings	Pass	P_{TOT}= 208 MW; **WTG (max values):** V = 0.97 pu; I = 1.12pu; P = 0.09 pu; Q = -0.60 pu; Δf = 0.41 Hz; df/dt = 2.27 Hz/s; **PCC (max values):** V = 1.03 pu; I = 0.46 pu; P = 0.03 pu; Q = -0.26 pu; **Export cable (max values):** **-off-shore:** V = 1.05 pu; I = 0.50 pu; **-on-shore:** V = 1.05 pu; I = 0.02 pu;
	2 Strings	Pass	P_{TOT}= 144 MW; **WTG (max values):** V= 0.98 pu; I = 1.12 pu; P = 0.11 pu; Q = -0.89 pu; Δf = 0.45 Hz; df/dt = 2.3 Hz/s; **PCC (max values):** V = 1.06 pu; I = 0.47 pu; P = 0.03 pu; Q = -0.26 pu; **Export cable (max values):** **-off-shore:** V = 1.05 pu; I = 0.50 pu; **-on-shore:** V = 1.05 pu; I = 0.02 pu;
	1 Strings	Fail	P_{TOT}= 72 MW; Not enough capacity to compensate the reactive power produced by the export cable.
Comments	The sample results have been obtained with all strings connected.		

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691714.

Sample result	 Figure 3-46: 66kV off-shore collector bus fault: String 1 WTGs (at the low voltage terminals of the WTG transformer): (a) active power (pu); (b) reactive power (pu); (c) voltage (pu); (d) off-shore ac frequency (Hz).

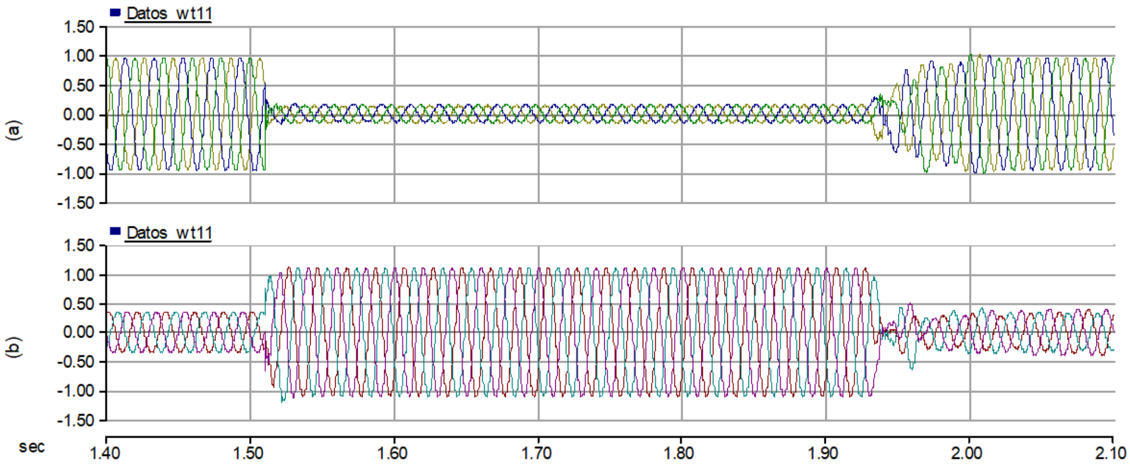


Figure 3-47: 66kV off-shore collector bus fault: $WTG_{1,1}$ during an on-shore fault (at the low voltage terminals of the WTG transformer): (a) voltage (pu); (b) current (pu).

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4. BLACK-BOX SIMULATION RESULTS

This section includes the compliance study of a black-box grid forming controller provided by MHI Vestas Offshore Wind.

The test cases and scenarios are exactly the same as those used for the compliance evaluation tests carried out with the controllers published by the academic partners.

The following HVAC black-start test cases have been selected from the considered test cases defined in D3.7 to test the MVOW WTG control:

- 2.4.1. OFF-SHORE AC-GRID START-UP OPERATION
- 2.4.3. RESPONSE TO CHANGES IN FREQUENCY SET-POINT
- 2.4.6. OFF-SHORE HVAC SUBSTATION ENERGISATION
- 2.4.7. HVAC EXPORT CABLE ENERGISATION
- 2.4.11. ON-SHORE HVAC SUBSTATION ENERGISATION
- 2.4.13. POWER BLOCK DELIVERY
- 2.4.14. SOFT ENERGISATION (FROM HOUSELOAD TO POWER BLOCK)

4.1. OFF-SHORE –GRID START-UP OPERATION

The start procedure includes the energisation of all the off-shore system elements, considering that the initial WTG is capable to energise its own auxiliaries using an internal energy source (e.g. UPS). The test case defined in this section will lead to the system end up working in houseload operation (ISL mode). This start-up procedure is common for all scenarios considered in this document regardless of HVAC or HVDC connection.

A proposal of energisation procedure consists of:

1. Energisation of transformer of WT_{1-1} from WT_{1-1}.
2. Energisation of string cable 1 from WT_{1-1}.
3. Sequential synchronisation of the rest of WTs connected to string 1 (first energisation of the transformer from the string and then synchronisation of the WT).
4. Sequential energisation of the rest of strings and synchronisation of the WTs. The sequence to energise the next string consist of:
    a. Energise a string from energised strings.
    b. Energise the WT transformers from the energised strings.
    c. Synchronisation of the WTs.

At the end of this test, the off-shore wind farm ends up in ISL mode with correct active and reactive power sharing.

<table>
<tr><td>Test case</td><td colspan="2">2.4.1. OFF-SHORE AC-GRID START-UP OPERATION</td></tr>
<tr><td rowspan="2">Simulation detail</td><td>WT</td><td>Level 4: Perfect DC link control is assumed</td></tr>
<tr><td>OWF</td><td>Level 4: One detailed string and aggregated strings.</td></tr>
</table>

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	On-shore grid	Level 3: Thevenin equivalent	
	Configuration (connected strings)	Compliance	Comments
Simulations (sensitivity analysis)	6 Strings	pass	P_{TOT}= 400 MW; **WTG (max values):** V= 1.14 pu; I = 0.96 pu; P_{WT} = 0.07 pu; Q_{WT} = -0.75 pu; Δf = 0.02 Hz; df/dt = 0.1 Hz/s; **PCC (max values):** V = 1.19 pu; I = 0.0 pu; P = 0 pu; Q = 0 pu;
Comments	The start-up process consists on the following basic steps: • WTG-$_{1,1}$ energizes its transformer. • WTG-$_{1,1}$ energizes the string 1. • Synchronisation of WTGs connected to string 1. • Connected WTGs energize the string n. • Synchronisation of WTGs connected to string n.		
Sample result	 Figure 4-1: String 1 WTGs during sequential start-up: (a) active power (pu); (b) reactive power (pu); (c) voltage (pu); (d) off-shore ac frequency (Hz).		

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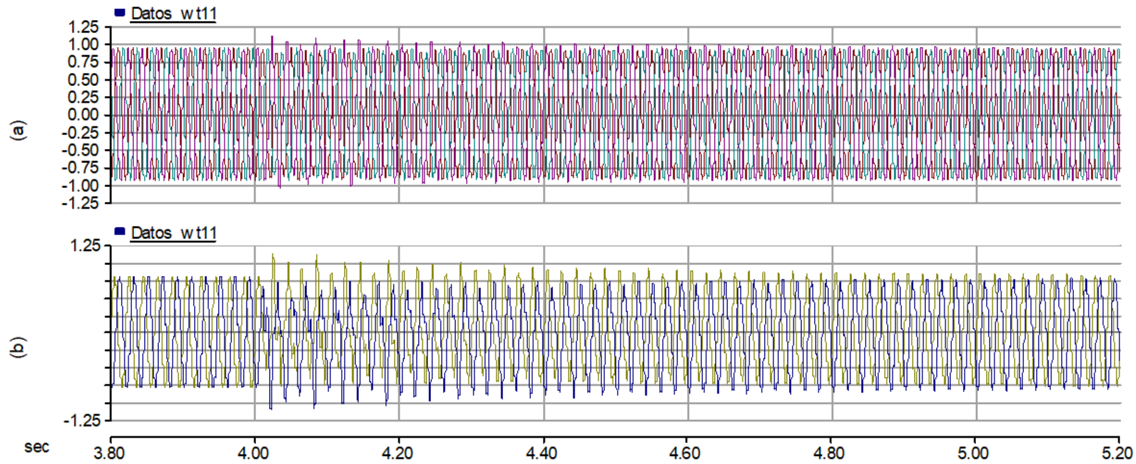

Figure 4-2: $WTG_{1,1}$ during $WTG_{1,2}$ transformer energisation: (a) voltage (pu); (b) current (pu).

4.2. RESPONSE TO CHANGES IN FREQUENCY SET-POINT

Test case	2.4.3. RESPONSE TO CHANGES IN FREQUENCY SET-POINT		
Simulation detail	WT	Level 4: Perfect DC link control is assumed	
	OWF	Level 4: One detailed string and aggregated strings.	
	On-shore grid	Level 3: Thevenin equivalent	
	Configuration (connected strings)	Compliance	Comments
Simulations (sensitivity analysis)	6 Strings	pass	P_{TOT}= 400 MW; **WTG(max values):** V = 0.96 pu; I = 0.08 pu; P = 0.0 pu; Q = -0.08 pu; Δf = 1.0 Hz; df/dt = 2.5 Hz/s; **PCC(max values):** V = 0.99 pu; I = 0.0 pu; P = 0 pu; Q = 0 pu;
	5 Strings	pass	P_{TOT}= 336 MW; **WTG(max values):** V = 0.96 pu; I = 0.09 pu; P = 0.0 pu; Q = -0.08 pu; Δf = 1.0 Hz; df/dt = 2.5 Hz/s; **PCC(max values):** V = 0.99 pu; I = 0.0 pu; P = 0 pu; Q = 0 pu;
	4 Strings	pass	P_{TOT}= 272 MW; **WTG(max values):** V = 0.97 pu; I = 0.09 pu; P = 0.0 pu; Q = -0.08 pu; Δf = 1.0 Hz; df/dt = 2.5 Hz/s; **PCC(max values):** V = 0.99 pu; I = 0.0 pu; P = 0 pu; Q = 0 pu;

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	3 Strings	pass	P_{TOT}= 208 MW; **WTG(max values):** V = 0.97 pu; I = 0.09 pu; P_{WT} = 0.0 pu; Q_{WT} = -0.08 pu; Δf = 1.0 Hz; df/dt = 2.5 Hz/s; **PCC(max values):** V = 0.99 pu; I = 0.0 pu; P = 0 pu; Q = 0 pu;
	2 Strings	pass	P_{TOT}= 144 MW; **WTG(max values):** V = 0.97 pu; I = 0.09 pu; P = 0.0 pu; Q = -0.08 pu; Δf = 1.0 Hz; df/dt = 2.5 Hz/s; **PCC(max values):** V = 0.99 pu; I = 0.0 pu; P = 0 pu; Q = 0 pu;
	1 Strings	pass	P_{TOT}= 72 MW; **WTG(max values):** V = 0.97 pu; I = 0.09 pu; P = 0.0 pu; Q = -0.08 pu; Δf = 1.0 Hz; df/dt = 2.5 Hz/s; **PCC(max values):** V = 0.99 pu; I = 0.0 pu; P = 0 pu; Q = 0 pu;
Comments	The frequency set point is changed as follows: • 1.5 seconds: frequency set-point from 50 to 49 Hz. • 2.5 seconds: frequency set-point from 49 to 51 Hz. • 3.5 seconds: frequency set-point from 51 to 50 Hz. The test case shows the capability of the WPP to remain stable for large frequency set point changes.		

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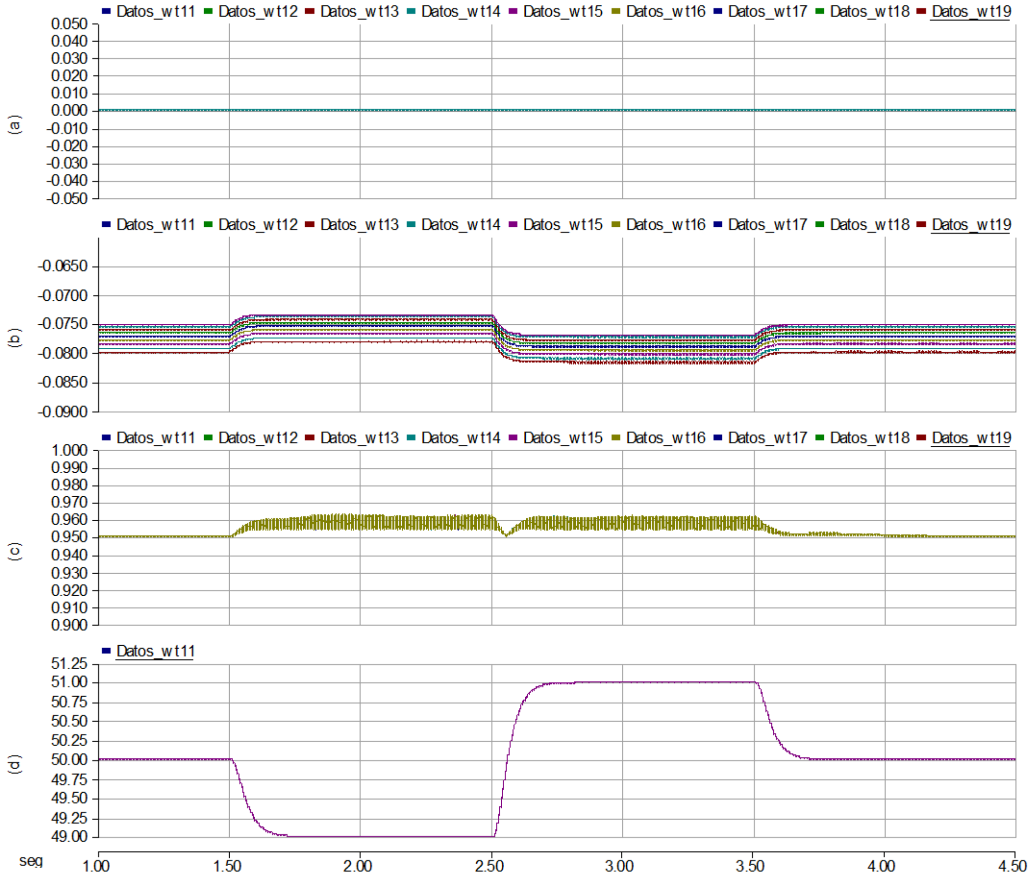
Sample result	 Figure 4-3: String 1 WTGs during changes in frequency set point: (a) active power (pu); (b) reactive power (pu); (c) voltage (pu); (d) off-shore ac frequency (Hz).

4.3. OFF-SHORE HVAC SUBSTATION ENERGISATION

This test case shows the energisation of the off-shore transformer (66/220 kV) from the off-shore WPP using POW switching. The considered POW closing times for each pole are as follows:

- Pole A: at maximum voltage A.
- Pole B: 5 ms after the pole A closes.
- Pole C: 5 ms after the pole A closes.

A random Gaussian error with $2\sigma=\pm2.5$ms is considered for the closing times of each pole.

Test case	2.4.6. OFF-SHORE HVAC SUBSTATION ENERGISATION

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Simulation detail	WT	Level 4: Perfect DC link control is assumed	
	OWF	Level 4: One detailed string and aggregated strings.	
	On-shore grid	Level 3: Thevenin equivalent	
	Configuration (connected strings)	Compliance	Comments
Simulations (sensitivity analysis)	6 Strings	pass	P_{TOT}= 400 MW; Pole error (BK_T1): A=1.8 ms; B=-0.8 ms; C=1.0 ms; **WTG (max values):** V = 0.96 pu; I= 0.14 pu; P = 0.01 pu; Q = -0.07 pu; Δf = 0.01 Hz; df/dt = 0.05 Hz/s; **PCC (max values):** V = 0.97 pu; I = 0.08 pu; P = 0.0 pu; Q = 0.017 pu;
	5 Strings	pass	P_{TOT}= 336 MW; Pole error (BK_T1): A=0.3 ms; B=0.7 ms; C=-1.0 ms; **WTG (max values):** V =0.95 pu; I = 0.11 pu; Max P = 0.01 pu; Max Q = -0.07 pu; Max Δf = 0.01 Hz; Max df/dt = 0.04 Hz/s; **PCC (max values):** V = 1.02 pu; I = 0.06 pu; P = 0.0 pu; Q = -0.01 pu;
	4 Strings	pass	P_{TOT}= 272 MW; Pole error (BK_T1): A=0.5 ms; B=1.2 ms; C=-0.8 ms; **WTG (max values):** V =0.95 pu; I = 0.10 pu; P = 0.01 pu; Q = -0.07 pu; Δf = 0.01 Hz; df/dt = 0.05 Hz/s; **PCC (max values):** V = 1.02 pu; I = 0.4 pu; P = 0.0 pu; Q = -0.01 pu;
	3 Strings	pass	P_{TOT}= 208 MW; Pole error (BK_T1): A=-1.3 ms; B=1.2 ms; C=-0.8 ms; **WTG (max values):** V= 0.96 pu; I = 0.16 pu; P = 0.01 pu; Q = -0.07 pu; Δf = 0.01 Hz; df/dt = 0.03 Hz/s; **PCC (max values):** V = 1.02 pu; I = 0.08 pu; Max P_{WT} = 0.0 pu; Max Q_{WT} = -0.01 pu;
	2 Strings	pass	P_{TOT}= 144 MW; Pole error(BK_T1): A=-1.1 ms; B=0.9 ms; C=0.0 ms; **WTG (max values):** V= 0.96 pu; I = 0.14 pu; P = 0.0 pu; Q = -0.07 pu; Δf = 0.01 Hz; df/dt = 0.04 Hz/s; **PCC (max values):** V = 1.2 pu; I = 0.06 pu; P = 0.0 pu; Q = 0.0 pu;
	1 Strings	pass	P_{TOT}= 72 MW; Pole error (BK_T1): A=-1.0 ms; B=1.4 ms; C=1.1 ms; **WTG (max values):** V = 0.95 pu; I= 0.10 pu; P = 0.01 pu; Q = -0.07 pu; Δf = 0.02 Hz; df/dt = 0.05 Hz/s; **PCC (max values):** V = 1.02 pu; I = 0.02 pu; P = 0.0 pu; Q = 0.0 pu;
Comments	The sample results show the energisation of the off-shore transformer (66/220 kV) with only one string connected (considered the most unfavourable case).		

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Sample result

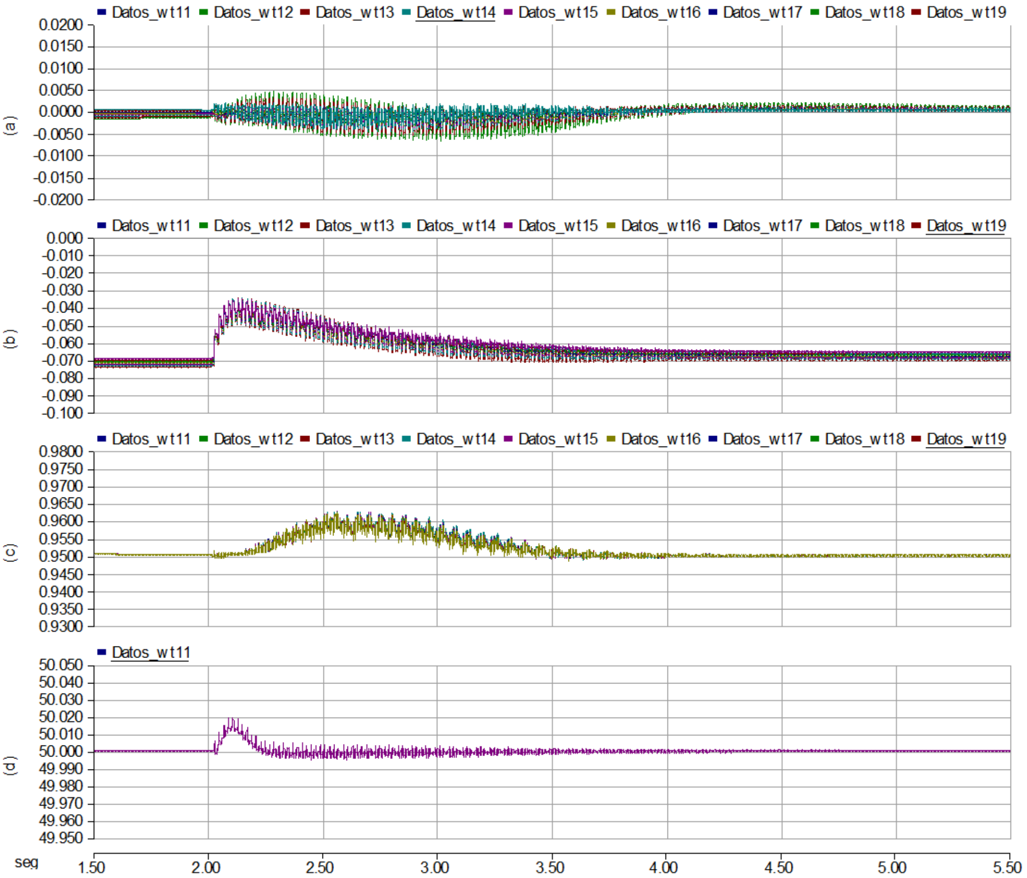

Figure 4-4: String 1 WTGs during off-shore transformer energisation: (a) active power (pu); (b) reactive power (pu); (c) voltage (pu); (d) off-shore ac frequency (Hz).

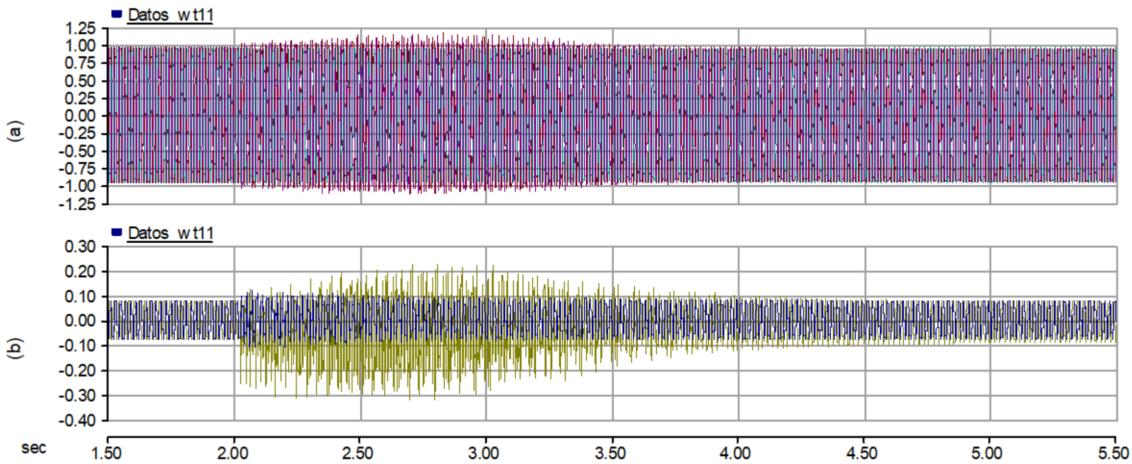

Figure 4-5: Voltage and current at the terminals of the off-shore transformer during off-shore HVAC transformer energisation: (a) voltage (pu); (b) current (pu).

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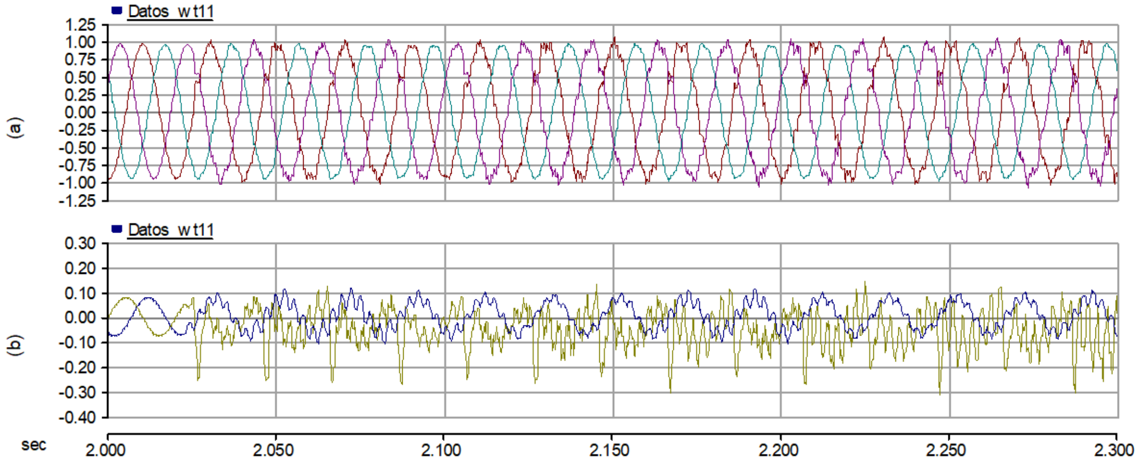

Figure 4-6: Voltage and current at the terminals of the off-shore transformer during off-shore HVAC transformer energisation (detail): (a) voltage (pu); (b) current (pu).

Additionally, a Monte-Carlo sensitivity analysis of 100 cases has been carried out, considering a normal distributed error on pole closing time of 2σ equal to ±2.5ms. The Monte-Carlo simulations have been carried out using the UPV “Rigel” computing cluster, which consists of a total of 2176 Xeon cores with 9364 Gb of memory and a total computing capability of 40 TFLOPS. The results are shown in Figure 4-7 and Figure 4-8.

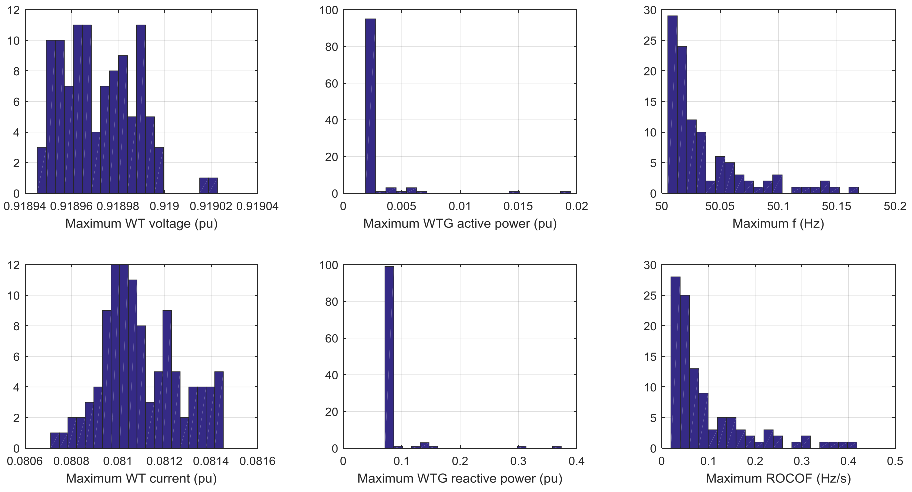

Figure 4-7. Off-shore HVAC substation energisation: Sensitivity analysis to different pole delays for POW switching during sequential start-up (WTG terminals)

Figure 4-7 shows the frequency plots of the 100 cases. The x axis show the class of each result and the y axis shows the number of simulations having results into each class. Figure 4-7 shows that the WTG terminal voltage is always within the ±10% range during off-shore transformer energisation. Peak WTG current is around 8%, required peak active power is relatively small and maximum reactive power is around 8%. This result is

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expected as active power loads are very small during houseload operation and hence, most of the delivered current is reactive. Both frequency deviation and ROCOF are within the required limits.

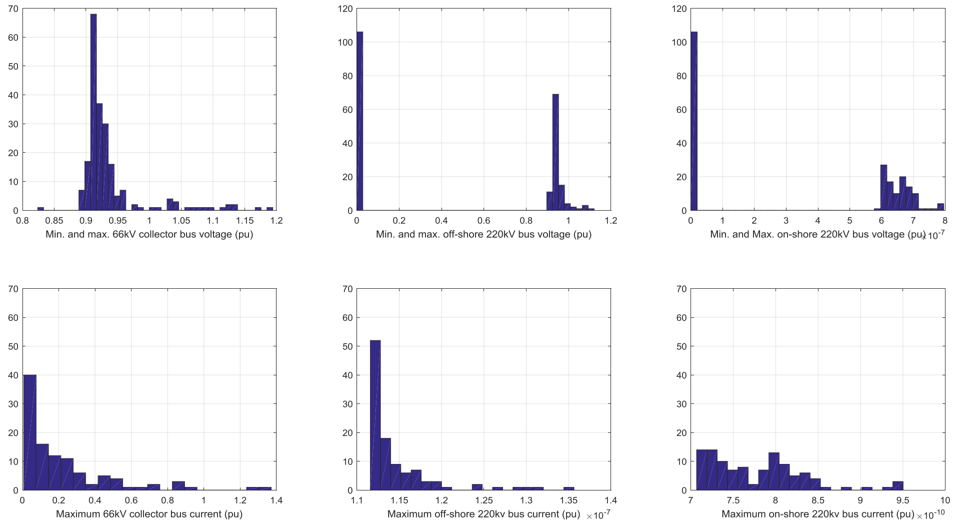

Figure 4-8. Off-shore HVAC substation energisation: Sensitivity analysis to different pole delays for POW switching during sequential start-up (66kV collector bus and 220kV off-shore and on-shore buses)

Figure 4-8 shows the behaviour of the 66kV collector bus and both ends of the export cable. In a very small number of cases, the minimum voltage reaches values below 0.9 pu, whereas the maximum voltage exceeds 1.1pu also for a very small number of cases. Note collector voltage never reaches values above 1.2 pu. The 66kV collector current reaches 1.35 pu (for 100ms and for a single case out of 100). This value is acceptable as it is not large enough to trip the transformer protections.

4.4. HVAC EXPORT CABLE ENERGISATION

Test case	2.4.7. HVAC EXPORT CABLE ENERGISATION		
Simulation detail	WT	Level 4: Perfect DC link control is assumed	
	OWF	Level 4: One detailed string and aggregated strings.	
	On-shore grid	Level 3: Thevenin equivalent	
	Configuration (connected strings)	Compliance	Comments

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Simulations (sensitivity analysis)	6 Strings	Pass	P_{TOT}= 400 MW; Pole error (BK_T2): A=1.0 ms; B=0.3 ms; C=1.7 ms; **WTG (max values):** V = 1.01 pu; I = 0.45pu; P = 0.07 pu; Q = -0.39 pu; Δf = 0.04 Hz; df/dt = 0.19 Hz/s; **PCC (max values):** V = 1.05 pu; I = 0.18 pu; P = 0.03 pu; Q = -0.14 pu; **Export cable (max values):** **-off-shore:** V = 1.12 pu; I = 0.46 pu; **-on-shore:** V = 1.14 pu; I = 0.0 pu;
	5 Strings	Pass	P_{TOT}= 336 MW; Pole error (BK_T2): A=1.4 ms; B=-1.2 ms; C=0.6 ms; **WTG (max values):** V = 1.02 pu; I = 0.93pu; P = 0.12 pu; Q = -0.43 pu; Δf = 0.04 Hz; df/dt = 0.22 Hz/s; **PCC (max values):** V = 1.12 pu; I = 0.46 pu; P = 0.06 pu; Q = -0.22 pu; **Export cable (max values):** **-off-shore:** V = 1.12 pu; I = 0.46 pu; **-on-shore:** V = 1.14 pu; I = 0.0 pu;
	4 Strings	Pass	P_{TOT}= 272 MW; Pole error (BK_T2): A=1.2 ms; B=1.6 ms; C=2.0 ms; **WTG (max values):** V = 1.03 pu; I = 1.04pu; P = 0.08 pu; Q = -0.45 pu; Δf = 0.05 Hz; df/dt = 0.21 Hz/s; **PCC (max values):** V = 1.15 pu; I = 0.41 pu; P = 0.06 pu; Q = -0.15 pu; **Export cable (max values):** **-off-shore:** V = 1.13 pu; I = 0.44 pu; **-on-shore:** V = 1.12 pu; I = 0.0 pu;
	3 Strings	Pass	P_{TOT}= 208 MW; Pole error (BK_T2): A=0.2 ms; B=-2.0 ms; C=-2.0 ms; **WTG (max values):** V = 1.06 pu; I = 1.08pu; P = 0.19 pu; Q = -0.58 pu; Δf = 0.07 Hz; df/dt = 0.28 Hz/s; **PCC (max values):** V = 1.1 pu; I = 0.4 pu; P = 0.06 pu; Q = -0.16 pu; **Export cable (max values):** **-off-shore:** V = 1.10 pu; I = 0.44 pu; **-on-shore:** V = 1.152 pu; I = 0.0 pu;
	2 Strings	Pass	P_{TOT}= 144 MW; Pole error (BK_T2): A=1.3 ms; B=1.5 ms; C=-0.3 ms; **WTG (max values):** V = 1.07 pu; I =1.09 pu; P = 0.24 pu; Q = -0.83 pu; Δf = 0.0 Hz; df/dt = 0.29 Hz/s; **PCC (max values):** V = 1.09 pu; I = 0.3 pu; P = 0.06 pu; Q = -0.18 pu; **Export cable (max values):** **-off-shore:** V = 1.16 pu; I = 0.4 pu; **-on-shore:** V = 1.18 pu; I = 0.0 pu;
	1 Strings	Fail	P_{TOT}= 72 MW; Not enough capacity to compensate the reactive power produced by the export cable.

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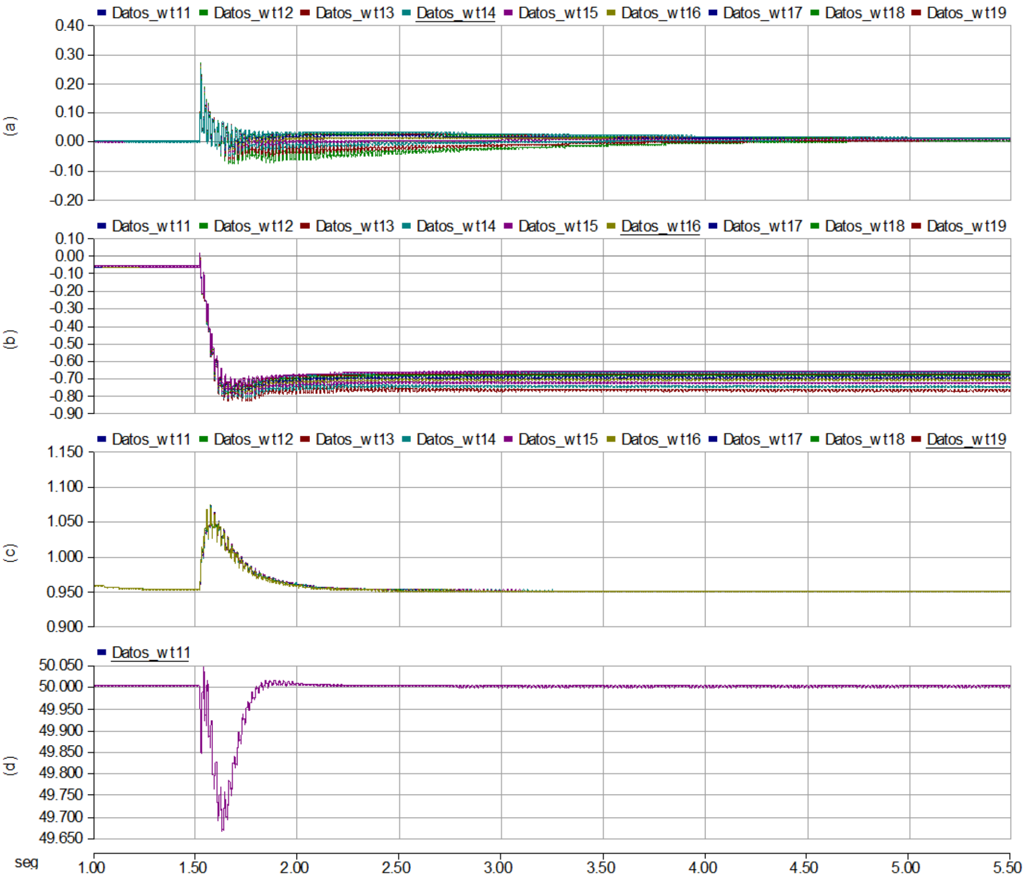
<table>
<tr><td>Comments</td><td>The sample results show the export cable energisation with 2 strings connected.</td></tr>
<tr><td>Sample result</td><td>


Figure 4-9: Export cable energisation: String 1 WTGs: (a) active power (pu); (b) reactive power (pu); (c) voltage (pu); (d) off-shore ac frequency (Hz).
</td></tr>
</table>

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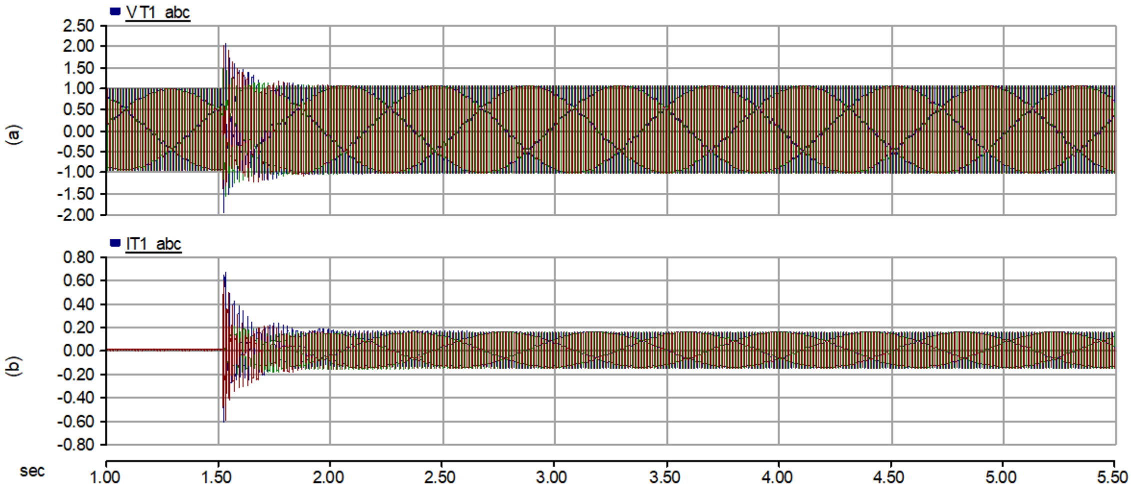

Figure 4-10: Export cable energisation: Voltage and current at the terminals of the offshore transformer: (a) voltage (pu); (b) current (pu).

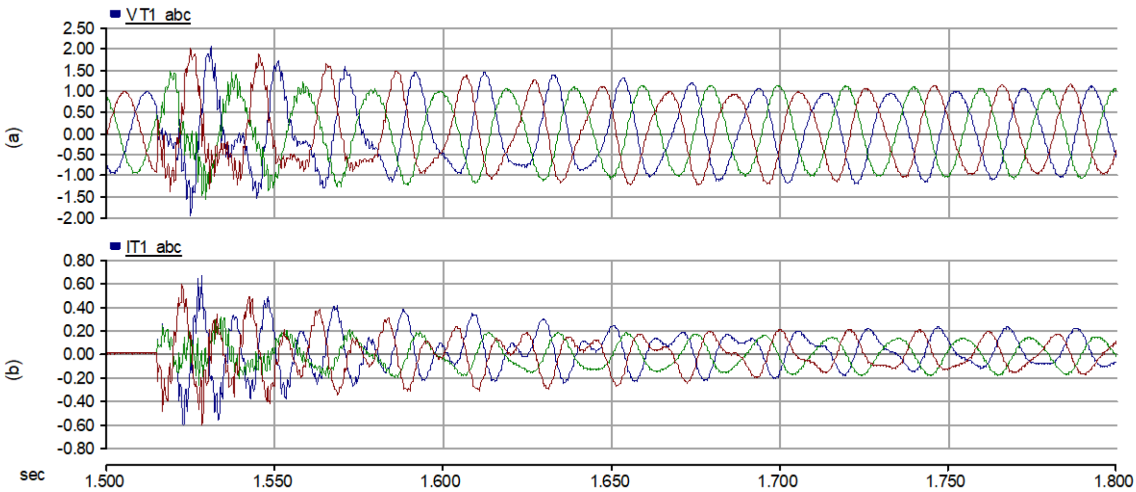

Figure 4-11: Export cable energisation: Voltage and current at the terminals of the offshore transformer (detail): (a) voltage (pu); (b) current (pu).

The results of the sensitivity analysis of the HVAC export cable energisation, considering a normal distributed error on pole closing time of $2\sigma=\pm2.5$ms are shown in Figure 4-12 and Figure 4-13.

Figure 4-12 shows the voltages and currents at the WTG 66kV terminals. Maximum WTG terminal voltage is always below 0.95 pu for all simulations carried out, whereas WTG current is always below 0.35pu. Most of this current is reactive, as the active power loads are relatively small. The maximum reactive power consumed is always below 0.3 pu and matches the reactive power left to compensate for the array and export cables. Both frequency and rocof are within the considered requirements.

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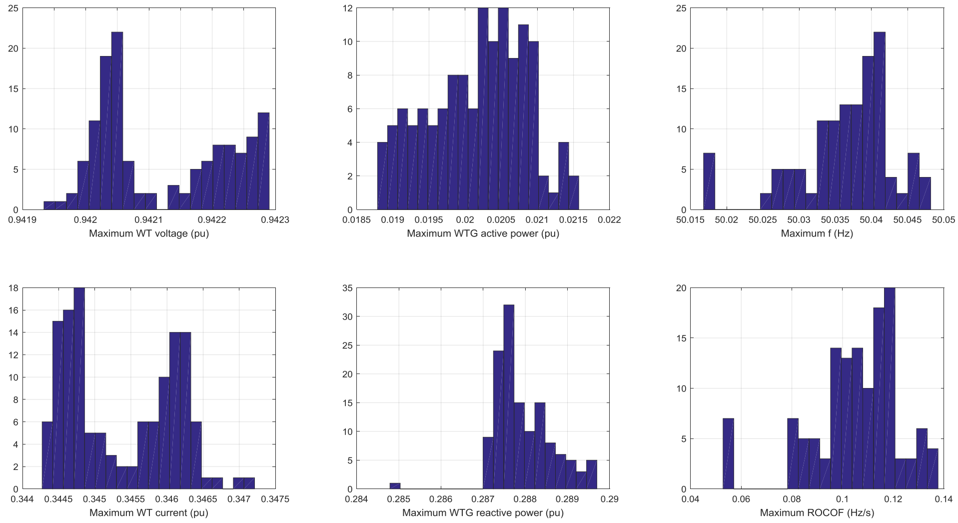

Figure 4-12. Export cable energisation: Sensitivity analysis to different pole delays for POW switching during sequential start-up (WTG terminals)

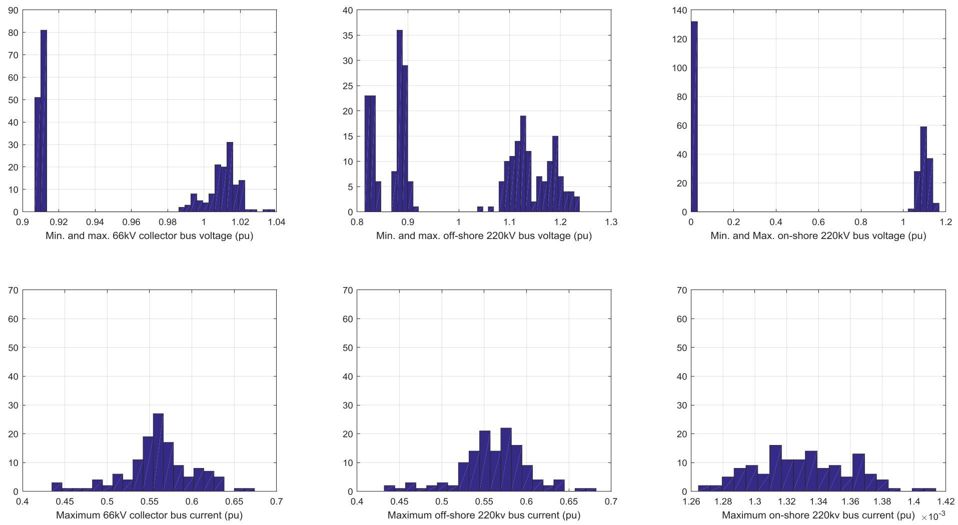

Figure 4-13. Export cable energisation: Sensitivity analysis to different pole delays for POW switching during sequential start-up (66kV collector bus and 220kV off-shore and on-shore buses)

Figure 4-13 shows the results of the sensitivity Monte-Carlo analysis for the export cable energisation at the off-shore 66kV collector bus and 220kV off-shore and on-shore buses. Voltages are, in most cases, within ±0.1 pu of the rated value. In some cases, the off-shore 220kV bus voltage is outside this range. Voltages outside the ±0.1 pu occur for less than 100ms and they are never above the 1.3 pu transient over-voltage limit.

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4.5. ON-SHORE HVAC SUBSTATION ENERGISATION

Test case	2.4.11. ON-SHORE HVAC SUBSTATION ENERGISATION		
Simulation detail	WT	Level 4: Perfect DC link control is assumed	
	OWF	Level 4: One detailed string and aggregated strings.	
	On-shore grid	Level 3: Thevenin equivalent	
	Configuration (connected strings)	Compliance	Comments
Simulations (sensitivity analysis)	6 Strings	Pass	P_{TOT}= 400 MW; Pole error (BK_T3): A=0.2 ms; B=-1.9 ms; C=-0.8 ms; **WTG (max values):** V = 0.96 pu; I = 0.66pu; P = 0.04 pu; Q = -0.31 pu; Δf = 0.01 Hz; df/dt = 0.06 Hz/s; **PCC (max values):** V = 1.05 pu; I = 0.36 pu; P = 0.03 pu; Q = -0.15 pu; **Export cable (max values):** **-off-shore:** V = 1.09 pu; I = 0.34 pu; **-on-shore:** V = 1.09 pu; I = 0.21 pu;
	5 Strings	Pass	P_{TOT}= 336 MW; Pole error (BK_T3): A=1.3 ms; B=1.9 ms; C=-1.5 ms; **WTG (max values):** V = 0.96 pu; I = 0.65pu; P = 0.03 pu; Q = -0.36 pu; Δf = 0.01 Hz; df/dt = 0.05 Hz/s; **PCC (max values):** V = 1.03 pu; I = 0.26 pu; P = 0.01 pu; Q = -0.15 pu; **Export cable (max values):** **-off-shore:** V = 1.07 pu; I = 0.28 pu; **-on-shore:** V = 1.07 pu; I = 0.19 pu;
	4 Strings	Pass	P_{TOT}= 272 MW; Pole error (BK_T3): A=-1.3 ms; B=-2.1 ms; C=-0.6 ms; **WTG (max values):** V = 0.98 pu; I =0.83 pu; P = 0.05 pu; Q = -0.43 pu; Δf = 0.01 Hz; df/dt = 0.05 Hz/s; **PCC (max values):** V = 1.08 pu; I = 0.32 pu; P = 0.02 pu; Q = -0.15 pu; **Export cable (max values):** **-off-shore:** V = 1.1 pu; I = 0.31 pu; **-on-shore:** V = 1.1 pu; I = 0.12 pu;
	3 Strings	Pass	P_{TOT}= 208 MW; Pole error (BK_T3): A=0.5 ms; B=-0.1 ms; C=-2.1 ms; **WTG (max values):** V = 0.96 pu; I = 0.66pu; P = 0.03 pu; Q = -0.55 pu; Δf = 0.05 Hz; df/dt = 0.05 Hz/s; **PCC (max values):** V = 1.03 pu; I = 0.17 pu; P = 0.01 pu; Q = -0.16 pu; **Export cable (max values):** **-off-shore:** V = 1.1 pu; I = 0.18 pu; **-on-shore:** V = 1.09 pu; I = 0.05 pu;

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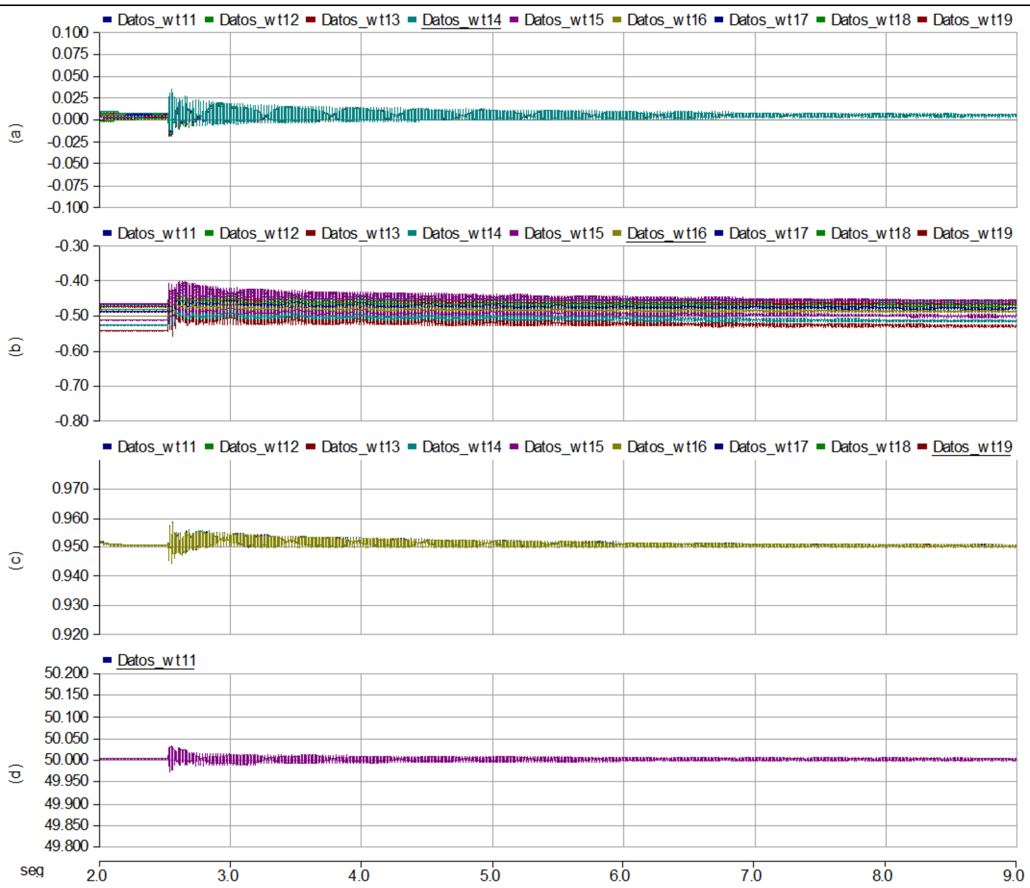
	2 Strings	Pass	P_{TOT}= 144 MW; Pole error (BK_T3): A=-0.5 ms; B=0.0 ms; C=1.2 ms; **WTG (max values):** V = 0.99 pu; I = 0.82pu; P = 0.04 pu; Q = -0.75 pu; Δf = 0.03 Hz; df/dt = 0.1 Hz/s; **PCC (max values):** V = 1.04 pu; I = 0.24 pu; P = 0.01 pu; Q = -0.18 pu; **Export cable (max values):** **-off-shore:** V = 1.1 pu; I = 0.18 pu; **-on-shore:** V = 1.09 pu; I = 0.05 pu;
	1 Strings	Fail	P_{TOT}= 72 MW; Not enough capacity to compensate the reactive power produced by the export cable.
Comments	The sample results show the energisation of the on-shore HVAC transformer with 3 strings connected.		
Sample result	 Figure 4-14: On-shore HVAC substation energisation: String 1 WTGs: (a) active power (pu); (b) reactive power (pu); (c) voltage (pu); (d) off-shore ac frequency (Hz).		

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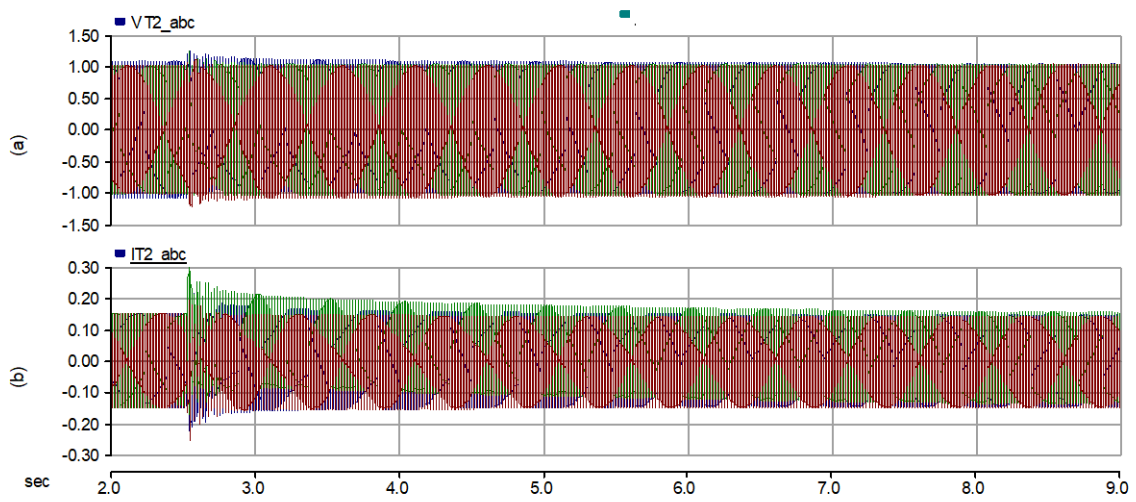

Figure 4-15: On-shore HVAC substation energisation: Voltage and current at the off-shore terminals of the export cable: (a) voltage (pu); (b) current (pu).

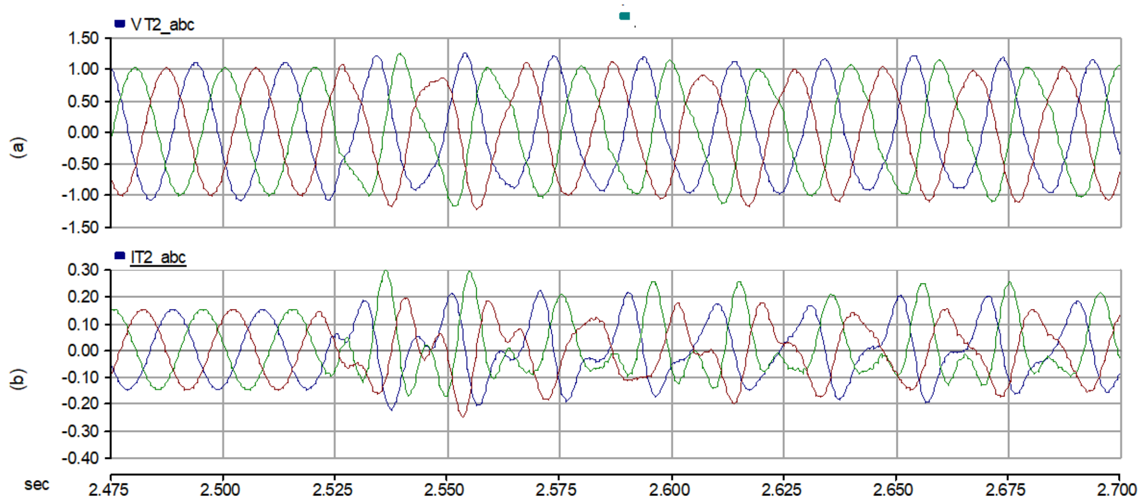

Figure 4-16: On-shore HVAC substation energisation: Voltage and current at the terminals of the export cable (detail): (a) voltage (pu); (b) current (pu).

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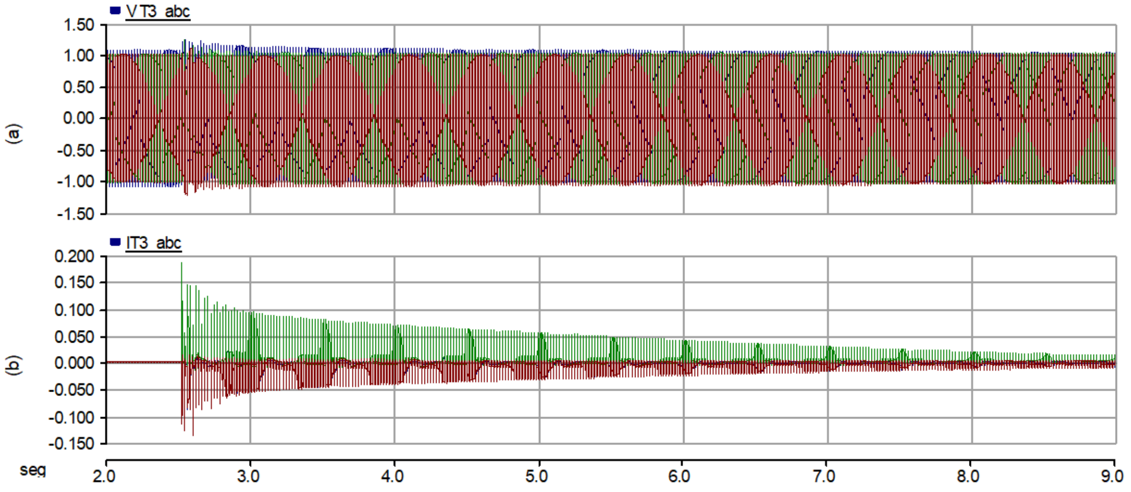

Figure 4-17: On-shore HVAC substation energisation: Voltage and current at the terminals of the onshore transformer: (a) voltage (pu); (b) current (pu).

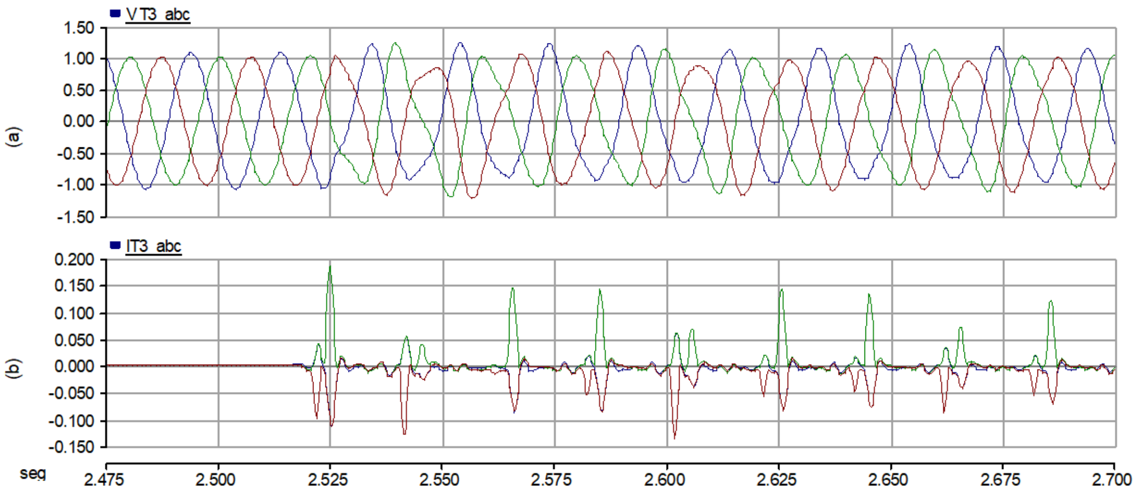

Figure 4-18: On-shore HVAC substation energisation: Voltage and current at the terminals of the onshore transformer (detail): (a) voltage (pu); (b) current (pu).

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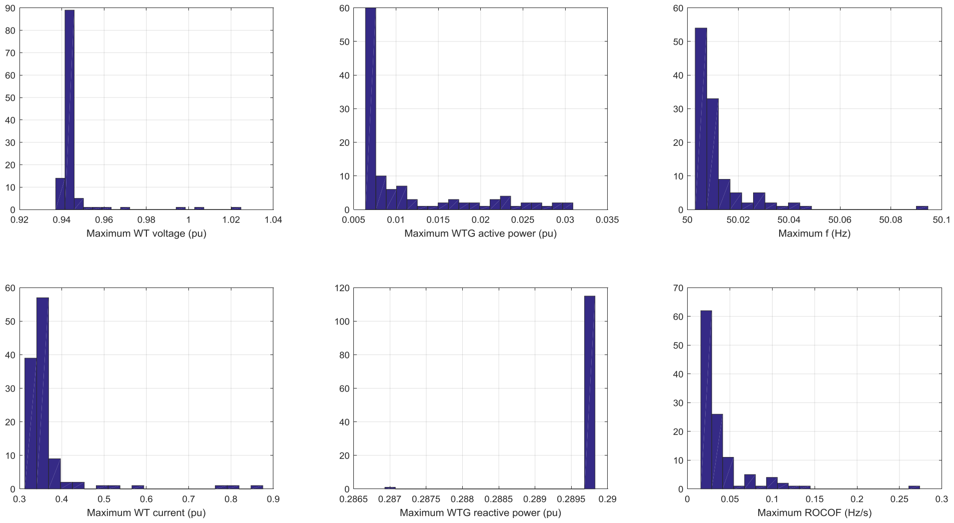

Figure 4-19. On-shore HVAC substation energisation: Sensitivity analysis to different pole delays for POW switching during sequential start-up (WTG terminals)

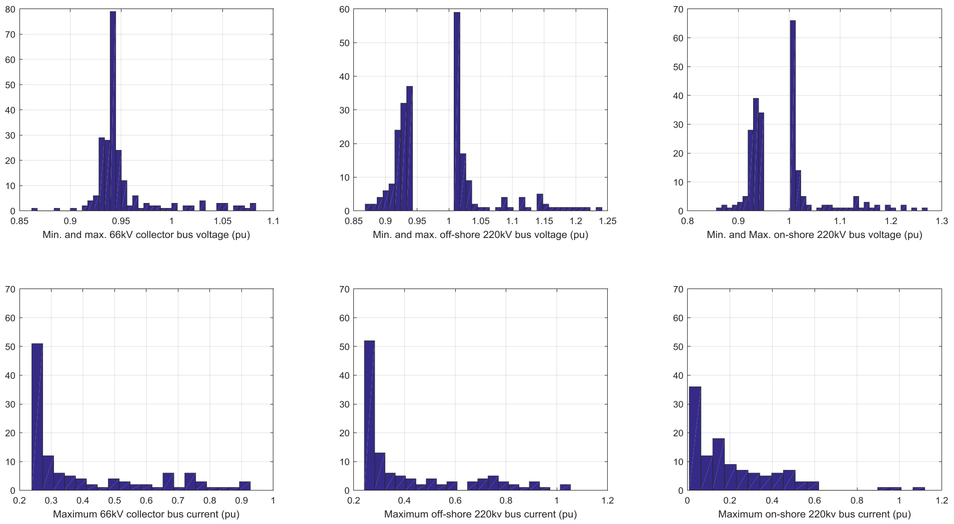

Figure 4-20. On-shore HVAC substation energisation: Sensitivity analysis to different pole delays for POW switching during sequential start-up (66kV collector bus terminals and export cable)

The results of Monte Carlo the sensitivity analysis of on-shore HVAC substation energisation, considering a normal distributed error on pole closing time of $2\sigma=\pm 2.5$ms are shown in Figure 4-19 and Figure 4-20.

Figure 4-19 shows the voltages and currents at the WTG 66kV terminals. Maximum WTG terminal voltage is always below 1.02 pu for all simulations carried out, whereas WTG current is below 0.5 pu for the most part of the cases, with a few cases having a maximum current up to 0.85 pu. Most of this current is reactive, as the active power loads are relatively small. Both frequency and rocof are within the considered requirements.

Figure 4-20 shows the results of the sensitivity Monte-Carlo analysis for the on-shore HVAC substation energisation at the off-shore 66kV collector bus and 220kV off-shore and on-shore buses. Voltages are, in most

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cases, within ±0.1 pu of the rated value. In some cases, the off-shore 220kV bus voltage is outside this range. Voltages outside the ±0.1 pu occur for less than 100ms and they are never above the 1.3 pu transient over-voltage limit.

4.6. POWER BLOCK DELIVERY

Test case	2.4.13. POWER BLOCK DELIVERY		
Simulation detail	WT	Level 4: Perfect DC link control is assumed	
	OWF	Level 4: One detailed string and aggregated strings.	
	On-shore grid	Level 3: Thevenin equivalent	
	Configuration (connected strings)	Compliance	Comments
Simulations (sensitivity analysis)	6 Strings	Pass	P_{TOT}= 400 MW; **WTG (max values):** V = 0.95 pu; I = 0.37pu; P = 0.08 pu; Q = -0.34 pu; Δf = 0.02 Hz; df/dt = 0.05 Hz/s; **PCC (max values):** V = 1.01 pu; I = 0.15 pu; P = 0.05 pu; Q = -0.15 pu; **Export cable (max values):** **-off-shore:** V = 1.03 pu; I = 0.15 pu; **-on-shore:** V = 1.05 pu; I = 0.05 pu;
	5 Strings	Pass	P_{TOT}= 336 MW; **WTG (max values):** V = 0.99 pu; I = 0.43pu; P = 0.1 pu; Q = -0.41 pu; Δf = 0.02 Hz; df/dt = 0.05 Hz/s; **PCC (max values):** V = 1.02 pu; I = 0.16 pu; P = 0.05 pu; Q = -0.15 pu; **Export cable (max values):** **-off-shore:** V = 1.04 pu; I = 0.16 pu; **-on-shore:** V = 1.05 pu; I = 0.05 pu;
	4 Strings	Pass	P_{TOT}= 272 MW; **WTG (max values):** V = 0.95 pu; I = 0.5 pu; P = 0.13 pu; Q = -0.47 pu; Δf = 0.02 Hz; df/dt = 0.05 Hz/s; **PCC (max values):** V = 1.02 pu; I = 0.15 pu; P = 0.05 pu; Q = -0.15 pu; **Export cable (max values):** **-off-shore:** V = 1.04 pu; I = 0.16 pu; **-on-shore:** V = 1.06 pu; I = 0.05 pu;
	3 Strings	Pass	P_{TOT}= 208 MW; **WTG (max values):** V = 0.95 pu; I = 0.64pu; P = 0.17 pu; Q = -0.60 pu; Δf = 0.02 Hz; df/dt = 0.05 Hz/s; **PCC (max values):** V = 1.03 pu; I = 0.16 pu; P = 0.05 pu; Q = -0.16 pu; **Export cable (max values):** **-off-shore:** V = 1.06 pu; I = 0.16 pu; **-on-shore:** V = 1.07 pu; I = 0.05 pu;

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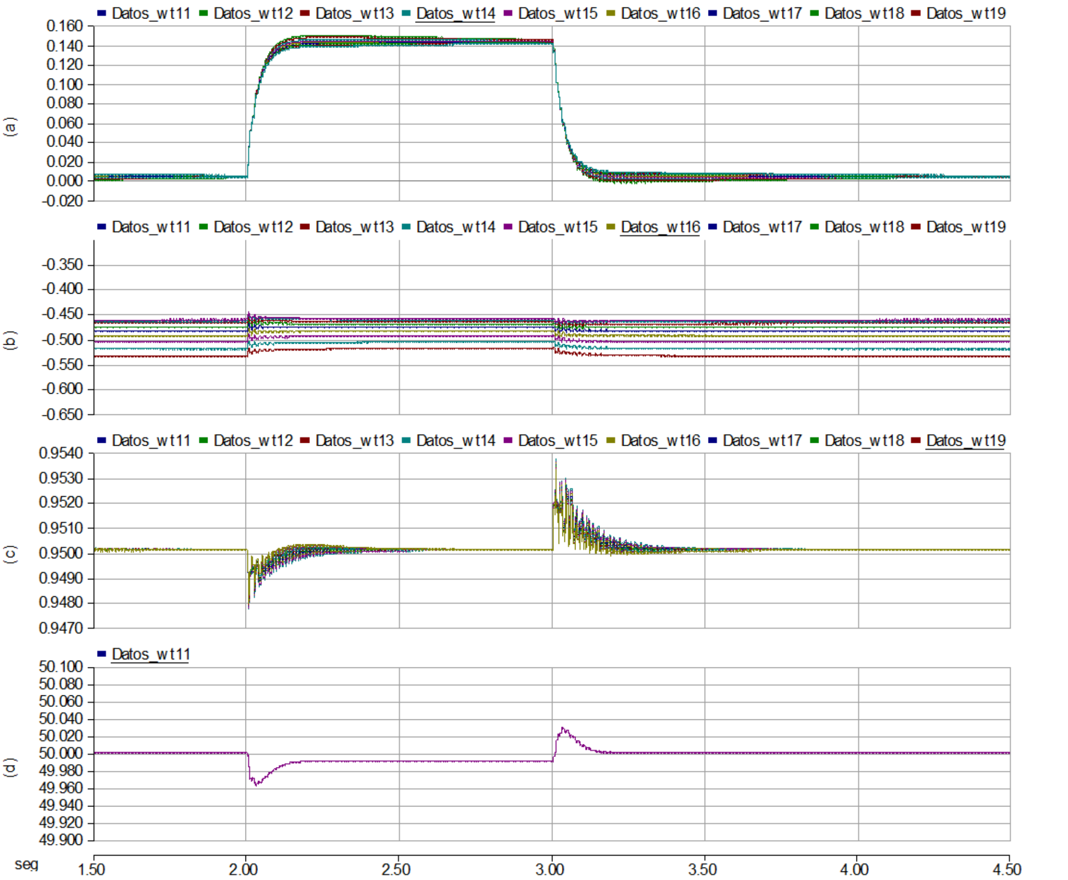
<table>
<tr><td rowspan="2"></td><td>2 Strings</td><td>Pass</td><td>P_{TOT}= 144 MW;
WTG (max values): V = 0.97 pu; I = 0.83pu;
P = 0.22 pu; Q = -0.79 pu;
Δf = 0.02 Hz; df/dt = 0.05 Hz/s;
PCC (max values): V = 1.06 pu; I = 0.16 pu;
P = 0.05 pu; Q = -0.16 pu;
Export cable (max values):
-off-shore: V = 1.08 pu; I = 0.16 pu;
-on-shore: V = 1.08 pu; I = 0.05 pu;</td></tr>
<tr><td>1 Strings</td><td>Fail</td><td>P_{TOT}= 72 MW;
Not enough capacity to compensate the reactive power produced by the export cable.</td></tr>
<tr><td>Comments</td><td colspan="3">The sample results show the export cable energisation considering 3 connected strings.</td></tr>
<tr><td>Sample result</td><td colspan="3">


Figure 4-21: Power block delivery: String 1 WTGs: (a) active power (pu); (b) reactive power (pu); (c) voltage (pu); (d) off-shore ac frequency (Hz).
</td></tr>
</table>

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4.7. SOFT ENERGISATION (FROM HOUSELOAD TO POWER BLOCK)

Test case	2.4.14. SOFT ENERGISATION (FROM HOUSELOAD TO POWER BLOCK)		
Simulation detail	WT	Level 4: Perfect DC link control is assumed	
	OWF	Level 4: One detailed string and aggregated strings.	
	On-shore grid	Level 3: Thevenin equivalent	
	Configuration (connected strings)	Compliance	Comments
Simulations (sensitivity analysis)	6 Strings	Pass	P_{TOT}= 400 MW; **WTG (max values):** V = 0.96 pu; I = 0.33pu; P = 0.08 pu; Q = -0.31 pu; Δf = 0.02 Hz; df/dt = 0.05 Hz/s; **PCC (max values):** V = 0.99 pu; I = 0.15 pu; P = 0.05 pu; Q = -0.15 pu; **Export cable (max values):** **-off-shore:** V = 1.02 pu; I = 0.15 pu; **-on-shore:** V = 1.02 pu; I = 0.05 pu;
	5 Strings	Pass	P_{TOT}= 336 MW; **WTG (max values):** V = 0.96 pu; I = 0.38pu; P = 0.08 pu; Q = -0.36 pu; Δf = 0.02 Hz; df/dt = 0.05 Hz/s; **PCC (max values):** V = 1.01 pu; I = 0.15 pu; P = 0.05 pu; Q = -0.15 pu; **Export cable (max values):** **-off-shore:** V = 1.03 pu; I = 0.15 pu; **-on-shore:** V = 1.06 pu; I = 0.05 pu;
	4 Strings	Pass	P_{TOT}= 272 MW; **WTG (max values):** V = 0.96 pu; I = 0.45 pu; P = 0.11 pu; Q = -0.43 pu; Δf = 0.02 Hz; df/dt = 0.05 Hz/s; **PCC (max values):** V = 1.01 pu; I = 0.15 pu; P = 0.05 pu; Q = -0.15 pu; **Export cable (max values):** **-off-shore:** V = 1.04 pu; I = 0.15 pu; **-on-shore:** V = 1.04 pu; I = 0.05 pu;
	3 Strings	Pass	P_{TOT}= 208 MW; **WTG (max values):** V = 0.97 pu; I = 0.58pu; P = 0.15 pu; Q = -0.55 pu; Δf = 0.02 Hz; df/dt = 0.05 Hz/s; **PCC (max values):** V = 1.03 pu; I = 0.16 pu; P = 0.05 pu; Q = -0.16 pu; **Export cable (max values):** **-off-shore:** V = 1.05 pu; I = 0.16 pu; **-on-shore:** V = 1.05 pu; I = 0.05 pu;

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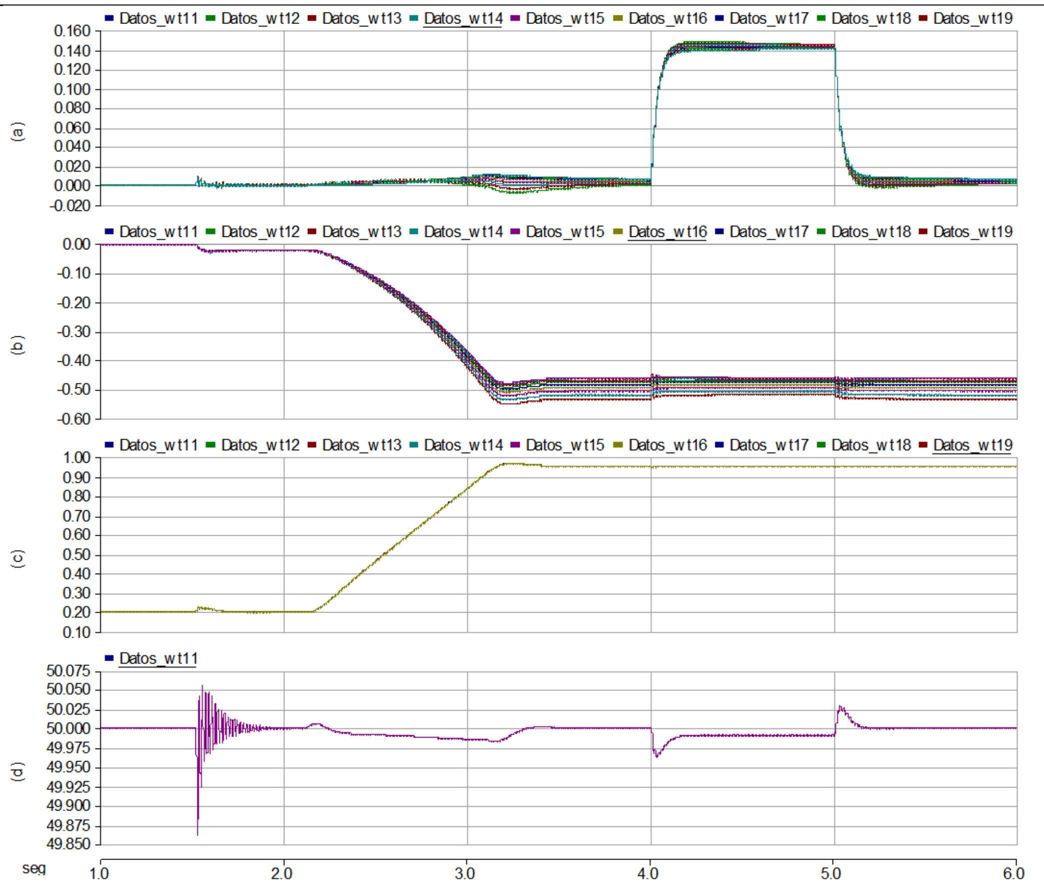
	2 Strings	Pass	P_{TOT}= 144 MW; **WTG (max values):** V = 0.97 pu; I = 0.83pu; P = 0.22 pu; Q = -0.78 pu; Δf = 0.02 Hz; df/dt = 0.06 Hz/s; **PCC (max values):** V = 1.05 pu; I = 0.16 pu; P = 0.05 pu; Q = -0.16 pu; **Export cable (max values):** **-off-shore:** V = 1.07 pu; I = 0.16 pu; **-on-shore:** V = 1.07 pu; I = 0.05 pu;
	1 Strings	Fail	P_{TOT}= 72 MW; Not enough capacity to compensate the reactive power produced by the export cable.
Comments	The sample result shows the export cable energisation considering 3 connected strings.		
Sample result	 Figure 4-22: Soft-energisation: String 1 WTGs: (a) active power (pu); (b) reactive power (pu); (c) voltage (pu); (d) off-shore ac frequency (Hz).		

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5. BLACK-START DISCUSSION AND CONCLUSIONS

This part has included the verification procedure of WTG and WPP controllers for HVAC and HVDC based black-start. The verification procedure included:

a) Definition of functional requirements
b) Definition of HVAC and HVDC scenarios
c) Definition of HVAC and HVDC test cases
d) Test case results

For the controller validation based on simulations, it is very important to use realistic models of transformers, cables and converters.

For HVAC connected WPPs, considered back start procedure included the WPP energisation to islanded (houseload) operation, energisation of off-shore HVAC station, export cable, on-shore HVAC, block load operation and synchronisation to other island. Both sequential energisation (using POW switching) and soft energisation have been tested.

As expected, critical elements in sequential energisation are the off-shore and on-shore substation transformers and the HVAC export cable. When considering errors in the POW switching arising from wrong residual flux or wrong breaker closing time estimates, relatively large voltage oscillations can appear due to ferromagnetic resonance and/or to sympathetic in-rush. In most cases, the oscillations die away, but in a minority of the cases, the oscillations lead to overvoltage which would trip WTGs or protection equipment.

Reactive power requirement for the WPP is just slightly higher than the reactive power required to compensate array and export cables (or the part which is not compensated by shunt reactors), the small additional reactive power being required only during transients.

The total reactive power required from the WTGs should also consider the reactive power required for energising additional on-shore cables and lines.

It has been shown that soft-energisation both leads to smaller maximum voltages and currents and to faster energisation times. Therefore, soft-energisation is to be preferred when technically available.

Direct connection and disconnection of a 30MW block load did not lead to voltages and frequencies outside of the limits set in the requirements. However, block load ramping up is preferable in order to decrease the impact of sudden loads on the WTG mechanics.

Moreover, it has been found that the system recovers adequately during symmetric on-shore, off-shore and cable faults. Also, the developed controller is capable to synchronise to an existing on-shore electrical island and co-ordinate with the other island the provision of active and reactive power requirements to the joint system.

For HVDC connected WPPs, the energisation of the off-shore WPP to houseload operation is similar to the HVAC case. The sequential connection of the HVDC rectifier station, HVDC export cable and HVDC inverter station has been studied with different values of pre-insertion resistors (PIR).

It has also been found that, for the HVDC case, the soft-start approach leads to faster energisation times and smaller values of peak voltages and currents.

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Direct connection of the 30MW on-shore block load did not lead to voltages and currents outside of those stated in the functional requirements.

The proposed compliance evaluation procedure for HVAC black-start operation has been also applied to a grid-forming black-box controller supplied by MHI-Vestas Offshore Wind. The results show the good performance of the controller during Off-shore Wind Power Plant power to houseload (islanded) operation, energisation of off-shore HVAC substation, export cable and on-shore HVAC substation, and block load delivery, both for sequential and soft-start energisation.

The studies carried out have shown that the proposed controllers are capable of performing both sequential and soft-start energisation of the WPP, export system and on-shore island for both HVAC and HVDC connections.

The stated functional requirements, together with the detailed simulation studies represent the first phases for a full black-start validation.

The results presented here will be extended in WP16 where real-time CHiL validation will be carried out.

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PART II. COMPLIANCE EVALUATION OF WPP AND WTG CONTROLLERS FOR DRU-HVDC INTEGRATION

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6. COMPLIANCE EVALUATION OF OWF AND WPP CONTROLLERS FOR DRU-HVDC OPERATION

This section includes a summary of the compliance evaluation results of the test cases corresponding to a DRU-HVDC system shown in Figure 6-1.

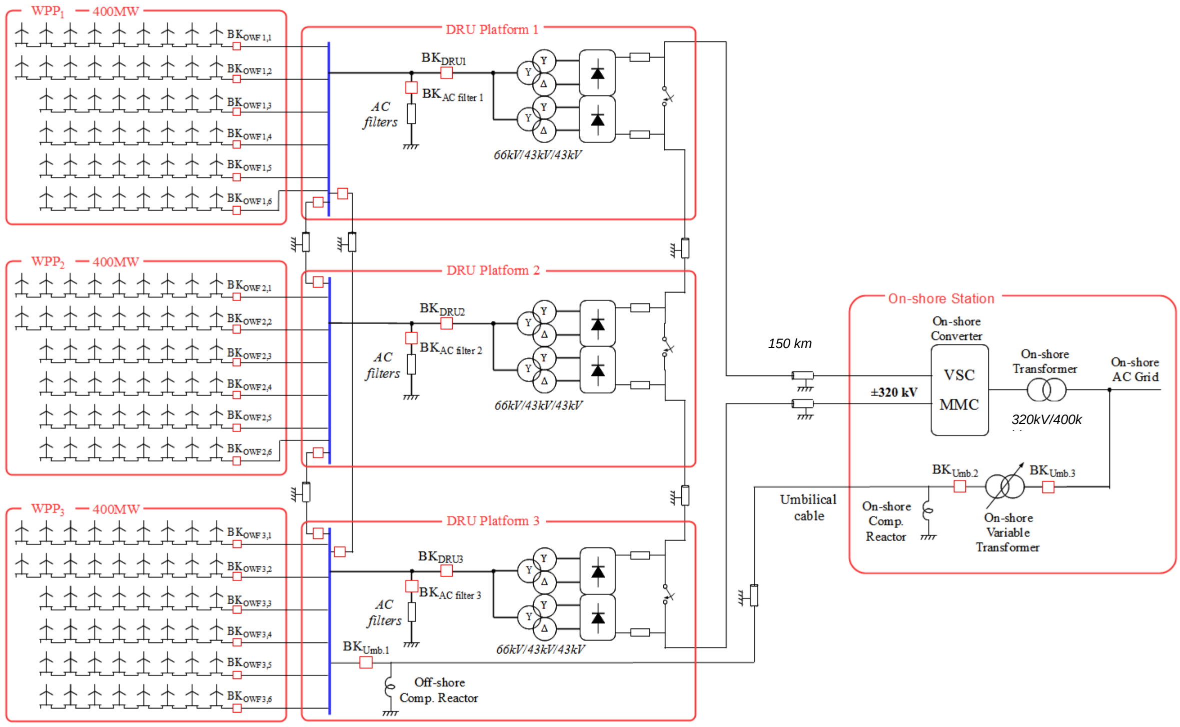

Figure 6-1: Base line scenario with three DRU platforms (from D3.2)

As previously mentioned, the functional specifications for DRU-HVDC controllers and system parameters are in Deliverable D3.1, the test cases in D3.2 and the compliance procedure in D3.6.
For each one of the test cases, a table summarizing the compliance evaluation results has been included, as well as an individual relevant result.

6.1. NORMAL OPERATION

Within all normal operation test cases the compliance evaluation of the following requirements has been checked:

- Voltage envelope: consider a 10-cycle window (200 ms). The calculated voltage shall be within the limits described in Deliverable 3.1.
- Voltage unbalance: calculated as U^{-}/U^{+}. The unbalance shall be lower than 0.05% as defined in Deliverable 3.6.

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- Frequency envelope: consider a 10-cycle window (200 ms). The calculated frequency shall be within the limits described in Deliverable 3.1.
- ROCOF: consider a 10-cycle window (200 ms). The calculated df/dt shall be within the limits described in Deliverable 3.1.

Additionally, specific requirements have been checked for each test case.

6.1.1 HVDC LINK AND OFF-SHORE AC GRID START-UP OPEARTION

The objective of the start procedure includes the energisation of all the off-shore system elements and all other steps needed for the wind farm to start normal production, provided that enough transmission capability is available. The start-up procedure is as defined in Deliverable 3.2 (see Figure 6-2 below).

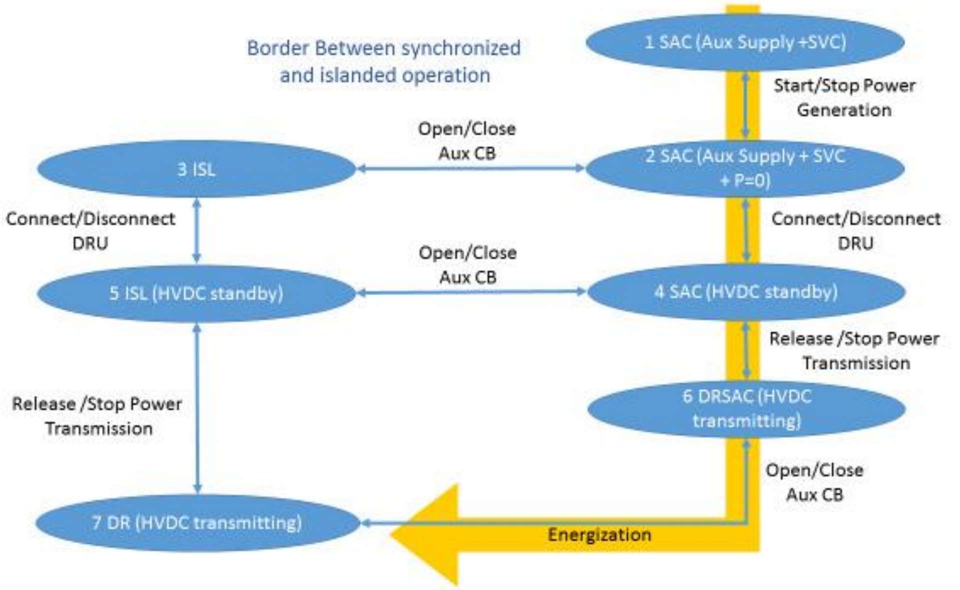

Figure 6-2: Energization procedure.

Besides voltage requirements, this test case validates the following requirements (as defined in D3.2):

- 3.3.2 Frequency ranges.
- 3.4.6 Minimum production limit.
- 4.2.7 Rate of change of frequency (ROCOF) limits.
- 4.3.2 Reactive power/current capabilities.

Test case	4.2.1. HVDC LINK AND OFF-SHORE AC-GRID START-UP OPERATION	
Simulation detail	WT	Level 4: Perfect DC link control is assumed
	OWF	Level 4: One detailed string and aggregated strings.
	On-shore MMC	Level 2: Averaged model
	On-shore grid	Level 3: Thevenin equivalent

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	Configuration (connected strings)	Compliance	Comments
ºSimulations (sensitivity analysis)	6 Strings + 6 Strings + 6 Strings	pass	P_{TOT}= 1200 MW; Max U^-/U^+ = 0.01; Max Δf = 0.2 Hz; Max df = 1.98 Hz/s
	6 Strings + 3 Strings + 1 String	pass	P_{TOT}= 680 MW; Max U^-/U^+ = 0.013; Max Δf = 0.2 Hz; Max df = 1.98 Hz/s
	6 Strings + 1 String + 1 String	pass	P_{TOT}= 544 MW; Max U^-/U^+ = 0.015; Max Δf = 0.2 Hz; Max df = 1.98 Hz/s
	3 Strings + 3 Strings + 3 Strings	pass	P_{TOT}= 624 MW; Max U^-/U^+ = 0.014; Max Δf = 0.2 Hz; Max df = 1.98 Hz/s
	3 Strings + 3 Strings + 1 String	pass	P_{TOT}= 488 MW; Max U^-/U^+ = 0.015; Max Δf = 0.2 Hz; Max df = 1.98 Hz/s
	3 Strings + 1 String + 1 String	pass	P_{TOT}= 352 MW; Max U^-/U^+ = 0.016; Max Δf = 0.2 Hz; Max df = 1.98 Hz/s
	1 String + 1 String + 1 String	pass	P_{TOT}= 260 MW; Max U^-/U^+ = 0.016; Max Δf = 0.2 Hz; Max df = 1.98 Hz/s
Comments	Considering that the umbilical cable is energised, the start-up process consists on the following basic steps: • Energization of strings. • Synchronisation of WTGs. • Enable WTG reactive power sharing, considering the voltage reference that each WTG receives from the WPP controller. • Enable of the centralised control of the umbilical active power transmission. • Enable of the centralised control of offshore ac. Each WTG synchronises as soon as possible in order to reduce simulation times. The requirements related to voltage, frequency and ROCOF have all been passed for all considered cases. The worst case regarding voltage limits occurs when the umbilical cable energises the offshore ac grid, as a relatively large voltage is present due to the Ferranti effect of both umbilical and array cables, even when the umbilical transformer tap changer is at its lowest possible position. Maximum voltage unbalance is produced when WTG transformers are energised. Note that full saturation models have been used for the transformers of individual WTGs. However, the transformers of aggregated strings have their saturation model disabled, as it is not realistic to assume that all WTG transformers in a string will be energised simultaneously. The most adverse instant regarding frequency and ROCOF is connection of the DRU filters. Each DRU platform includes three filters (9 filters in total). The filters are connected sequentially and the first filter to be connected causes the maximum frequency deviation and ROCOF.		

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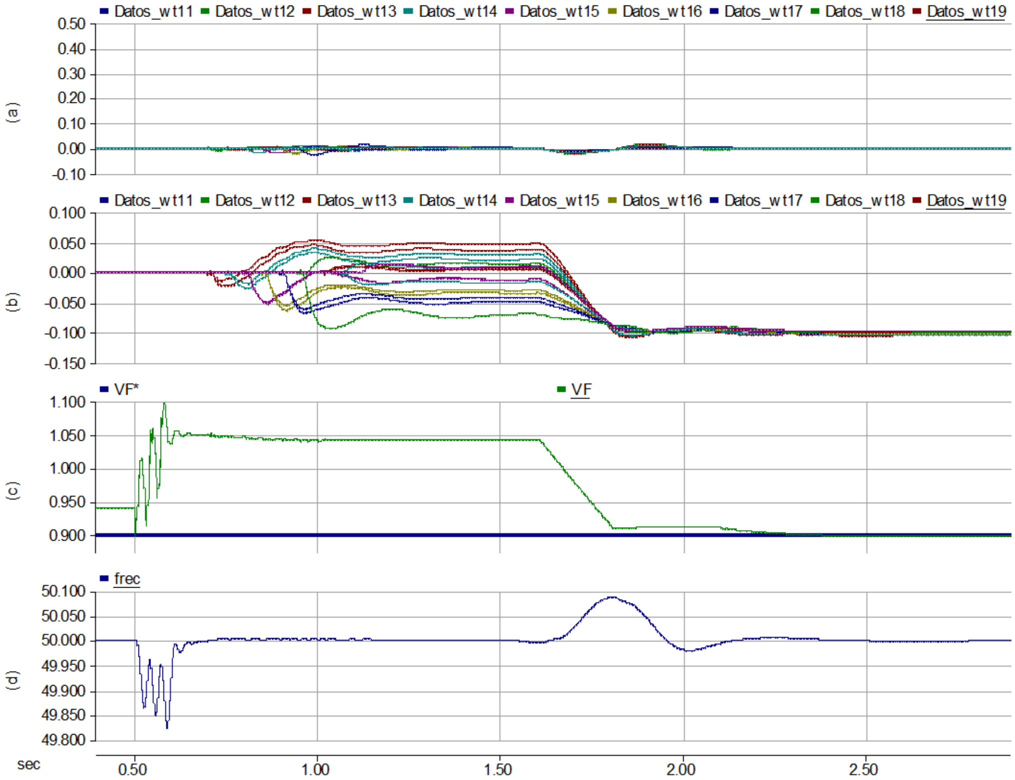
<table>
<tr>
<td>Sample result</td>
<td>


Figure 6-3: WTGs of string 1 in OWF1: (a) active power (pu); (b) reactive power (pu); (c) off-shore ac voltage (pu); (d) off-shore ac frequency (Hz).

Note the relatively high voltage and frequency peaks when the filters are connected. The connection of the individual WTGs and string aggregated WTGs and the correct voltage control and reactive power sharing once voltage control mode is enabled for all connected WTGs.
</td>
</tr>
</table>

6.1.2 HVDC LINK AND OFF-SHORE AC GRID DISCONNECTION OPERATION

At the beginning of this test case, all the connected WTGs are producing its rated active power. Then the active power production of the WTGs is ramped down to 0.2 pu. Then, the DRU filters are disconnected sequentially. After that, the active power production of the WTGs are ramped down to 0.0 pu, and the WPP starts working in ISL mode. The next step is to synchronise the offshore ac grid with the umbilical cable (WPP goes to SAC mode). Finally, the WTGs are disconnected and the offshore ac grid is disconnected.

Additionally, this test case validates the following requirements:

- 3.3.2 Frequency ranges.
- 3.4.6 Minimum production limit.
- 4.2.7 Rate of change of frequency (ROCOF) limits.
- 4.3.2 Reactive power/current capabilities.

Test case	4.2.2. HVDC LINK AND OFF-SHORE AC-GRID DISCONNECTION OPERATION

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Simulation detail	WT	Level 4: Perfect DC link control is assumed	
	OWF	Level 4: One detailed string and aggregated strings…	
	On-shore MMC	Level 2: Averaged model	
	On-shore grid	Level 3: Thevenin equivalent	
	Configuration (connected strings)	Compliance	Comments
Simulations (sensitivity analysis)	6 Strings + 6 Strings + 6 Strings	pass	P_{TOT}= 1200 MW; Max U^-/U^+ = 0.012; Max Δf = 0.2 Hz; Max df = 0.9 Hz/s
	6 Strings + 3 Strings + 1 String	pass	P_{TOT}= 680 MW; Max U^-/U^+ = 0.013; Max Δf = 0.2 Hz; Max df = 0.9 Hz/s
	6 Strings + 1 String + 1 String	pass	P_{TOT}= 544 MW; Max U^-/U^+ = 0.015; Max Δf = 0.2 Hz; Max df = 0.9 Hz/s
	3 Strings + 3 Strings + 3 Strings	pass	P_{TOT}= 624 MW; Max U^-/U^+ = 0.014; Max Δf = 0.2 Hz; Max df = 0.9 Hz/s
	3 Strings + 3 Strings + 1 String	pass	P_{TOT}= 488 MW; Max U^-/U^+ = 0.015; Max Δf = 0.2 Hz; Max df = 0.9 Hz/s
	3 Strings + 1 String + 1 String	pass	P_{TOT}= 352 MW; Max U^-/U^+ = 0.016; Max Δf = 0.2 Hz; Max df = 0.9 Hz/s
	1 String + 1 String + 1 String	pass	P_{TOT}= 260 MW; Max U^-/U^+ = 0.016; Max Δf = 0.2 Hz; Max df = 0.9 Hz/s
Comments	A fast disconnection of the WTGs is carried out in order to reduce the simulation time. Each WTG is disconnected every 0.1 seconds. Regarding operational requirements, the worst case regarding voltage magnitude occurs when only the umbilical cable is keeping the voltage of the offshore grid, without any reactive power control from the WTGs. At this stage, the Ferranti effect causes a relatively large voltage at the end of the off-shore array cables. The maximum voltage unbalance is produced when the WTGs are being disconnected. The worse frequency and ROCOF results have been detected during DRU filter disconnection. The sample result shows the active and reactive power of the WTGs connected to a string. As WTGs are disconnected, the reactive power is shared between the WTGs that remain connected. Hence, the reactive power of the connected WTGs keeps increasing as WTGs are disconnected. Finally, the string cables are disconnected and hence the reactive power provided by the umbilical cable decreases.		

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Sample result

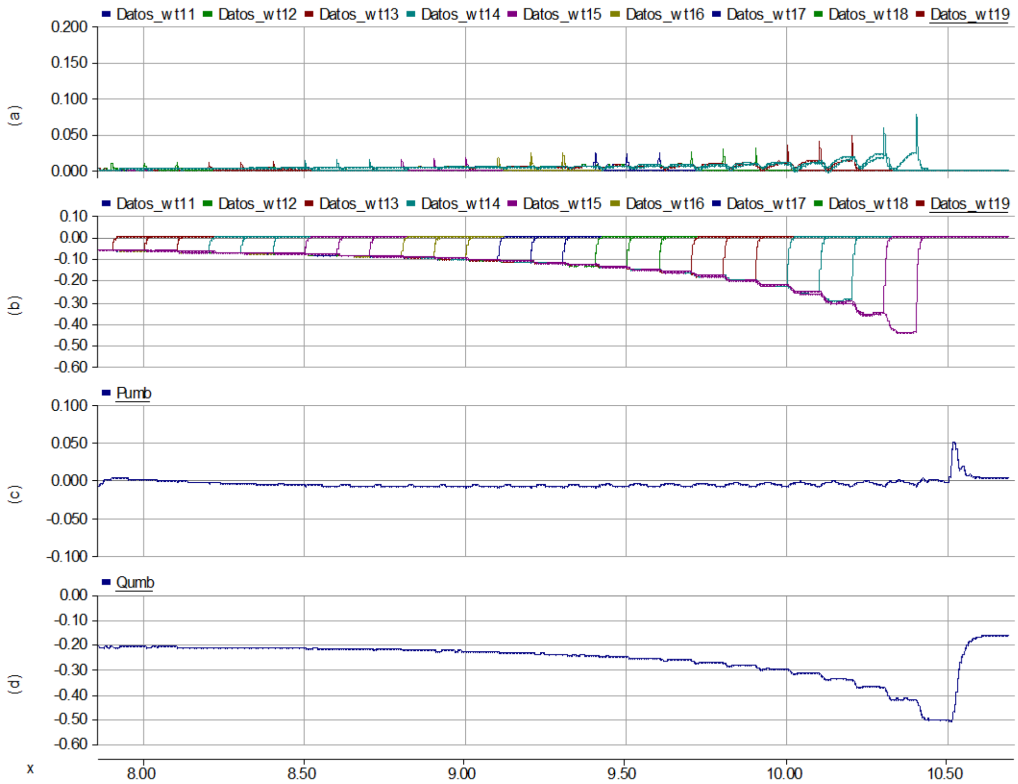

Figure 6-4: WTGs of string 1 in OWF1: (a) active power (pu) of all detailled WTGs (not aggregated); (b) reactive power (pu) of all detailled WTGs (not aggregated) (c) Active power (pu) through the umbilical cable (d) Reactive power through the umbilical cable

6.1.3 INTENTIONAL ISLANDING

Intentional islanding, as defined in D3.2, is composed of two test cases. The first one consists of the transition from DR to ISL configuration (DR → ISL). Second test case deals of the transition from ISL to SAC (ISL → SAC) i.e. re-synchronise to the umbilical cable.

6.1.3.1 INTENTIONAL ISLANDING

The intentional islanding test case begins with the system completely energised and transmitting power via the HVDC Link (DR mode of operation). From this state, a command is sent to the WTGs to reduce the active power transmission through the DRUs from 1.0 pu to 0.2 pu. Then the DRU filters are disconnected sequentially. The next step consists of reducing the active power transmission through the DRUs to 0. From this point, the off-shore ac-grid voltage control is activated and the voltage is conducted to 0.9 pu to ensure that the DRUs stops transmitting power.

Additionally, this test case validates the following requirements:

- 3.3.2 Frequency ranges.
- 3.3.3 Voltage ranges.
- 3.4.5 Minimum production limit. Island support (no HVDC or ac connection)

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- 4.2.7 Rate of change of frequency (ROCOF) limits.
- 4.3.1 Voltage envelope.

Test case	4.2.3.A. INTENTIONAL ISLANDING		
Simulation detail	WT	Level 4: Perfect DC link control is assumed	
	OWF	Level 4: One detailed string and aggregated strings…	
	On-shore MMC	Level 2: Averaged model	
	On-shore grid	Level 3: Thevenin equivalent	
	Configuration (connected strings)	Compliance	Comments
Simulations (sensitivity analysis)	6 Strings + 6 Strings + 6 Strings	pass	P_{TOT}= 1200 MW; Max U^-/U^+ = 0.012; Max Δf = 0.07 Hz; Max df = 0.9 Hz/s
	6 Strings + 3 Strings + 1 String	pass	P_{TOT}= 680 MW; Max U^-/U^+ = 0.013; Max Δf = 0.07 Hz; Max df = 0.9 Hz/s
	6 Strings + 1 String + 1 String	pass	P_{TOT}= 544 MW; Max U^-/U^+ = 0.015; Max Δf = 0.07 Hz; Max df = 0.9 Hz/s
	3 Strings + 3 Strings + 3 Strings	pass	P_{TOT}= 624 MW; Max U^-/U^+ = 0.014; Max Δf = 0.07 Hz; Max df = 0.9 Hz/s
	3 Strings + 3 Strings + 1 String	pass	P_{TOT}= 488 MW; Max U^-/U^+ = 0.015; Max Δf = 0.07 Hz; Max df = 0.9 Hz/s
	3 Strings + 1 String + 1 String	pass	P_{TOT}= 352 MW; Max U^-/U^+ = 0.016; Max Δf = 0.07 Hz; Max df = 0.9 Hz/s
	1 String + 1 String + 1 String	pass	P_{TOT}= 260 MW; Max U^-/U^+ = 0.016; Max Δf = 0.07 Hz; Max df = 0.9 Hz/s
Comments	The results show that changes in active power reference works as expected. In addition, the disconnection of the DRU filters does not produce substantial overvoltage. Moreover, the sample result shows that the change from active power control to voltage control works properly.		

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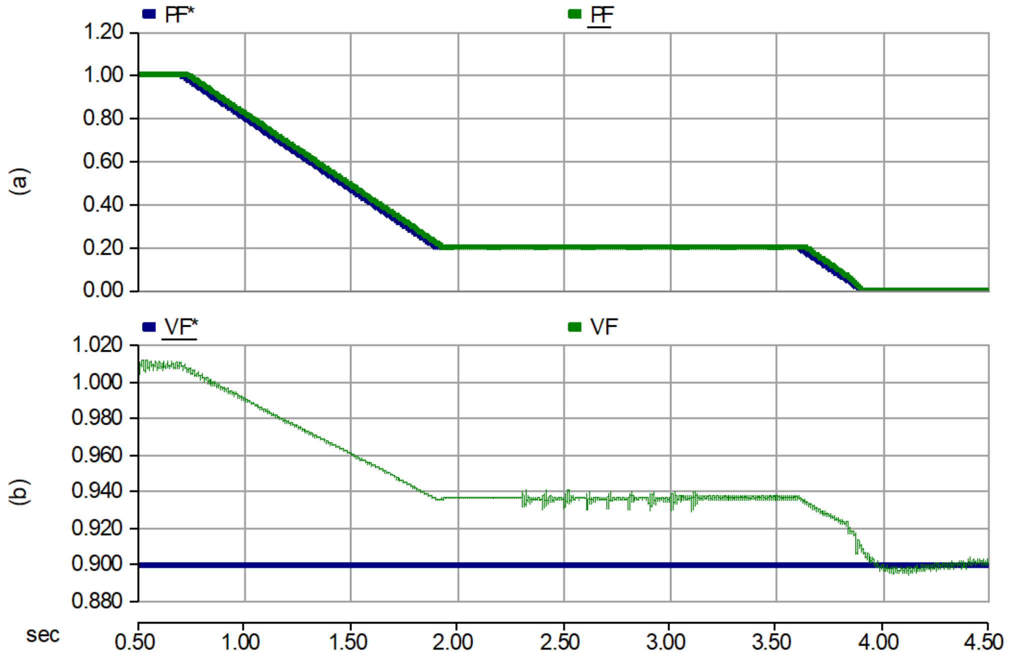
Sample result	 Figure 6-5: (a) Total active power reference (pu); (b) Off-shore ac grid voltage (pu) and its reference (pu).

6.1.3.2 RE-SYNCHRONISATION TO EXTERNAL AC FROM ISL MODE

The re-synchronisation to an external ac grid is carried out when the WPP is working in ILS mode. In this case, the connection is to the umbilical cable, although the same procedure can be used to synchronise to any other ac grid. During the synchronisation procedure the voltage level and the frequency can change slightly, so is important that the WPP is not connected to the DRU since voltage changes could cause power flowing through the DRU.

Additionally, this test case validates the following requirements:

- 3.3.2 Frequency ranges.
- 3.3.3 Voltage ranges.
- 3.4.5 Minimum production limit. Island support (no HVDC or ac connection)
- 4.2.7 Rate of change of frequency (ROCOF) limits.
- 4.3.1 Voltage envelope.

Test case	4.2.3. B. RE-SYNCHRONISATION TO EXTERNAL AC FROM ISL MODE		
Simulation detail	WT	Level 4: Perfect DC link control is assumed	
	OWF	Level 4: One detailed string and aggregated strings…	
	On-shore MMC	Level 2: Averaged model	
	On-shore grid	Level 3: Thevenin equivalent	
	Configuration (connected strings)	Compliance	Comments

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691714.

Simulations (sensitivity analysis)	6 Strings + 6 Strings + 6 Strings	pass	P_{TOT}= 1200 MW; Max U^-/U^+ = 0.012; Max Δf = 0. 065 Hz; Max df = 1.5 Hz/s
	6 Strings + 3 Strings + 1 String	pass	P_{TOT}= 680 MW; Max U^-/U^+ = 0.013; Max Δf = 0.065 Hz; Max df = 1.5 Hz/s
	6 Strings + 1 String + 1 String	pass	P_{TOT}= 544 MW; Max U^-/U^+ = 0.015; Max Δf = 0.06 Hz; Max df = 1.5 Hz/s
	3 Strings + 3 Strings + 3 Strings	pass	P_{TOT}= 624 MW; Max U^-/U^+ = 0.014; Max Δf = 0.06 Hz; Max df = 1.5 Hz/s
	3 Strings + 3 Strings + 1 String	pass	P_{TOT}= 488 MW; Max U^-/U^+ = 0.015; Max Δf = 0.06 Hz; Max df = 1.5 Hz/s
	3 Strings + 1 String + 1 String	pass	P_{TOT}= 352 MW; Max U^-/U^+ = 0.016; Max Δf = 0.055 Hz; Max df = 1.5 Hz/s
	1 String + 1 String + 1 String	pass	P_{TOT}= 260 MW; Max U^-/U^+ = 0.016; Max Δf = 0.055 Hz; Max df = 1.5 Hz/s

Comments

This test case checks the synchronisation of the off-shore ac grid to any external ac grid (in this case , the umbilical cable). As the sample result shows, the WPP is able to set the voltage and the phase of the off-shore ac grid equal to the voltage and phase of the external ac grid. When the voltage and the phase of the both grids are similar (difference lower than a given threshold of both voltage vector magnitude and angle) a breaker closes and the active power control through the umbilical cable is activated. Then the voltage control is re-activated and the offshore grid returns to its reference voltage. Additionally, this test case validates the capability of the WPP to change the off-shore ac grid voltage magnitude when the WPP is connected to an external ac grid.

Sample result

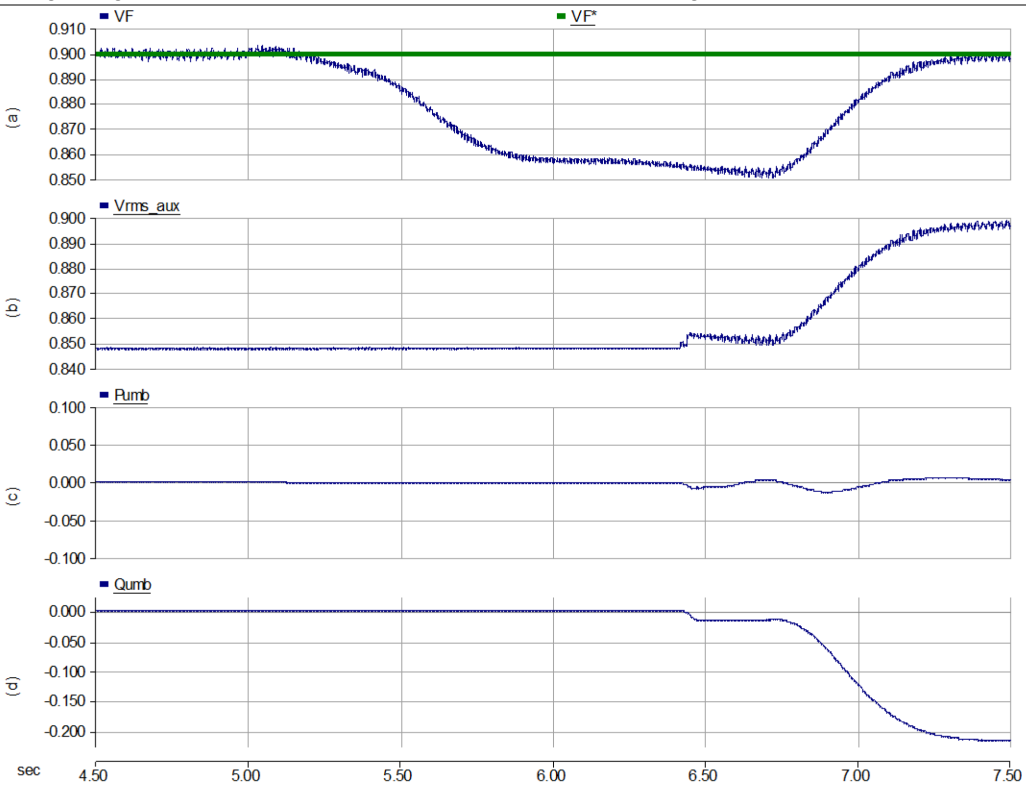


Figure 6-6: (a) offshore voltage (pu) and its reference (pu); (b) umbilical cable voltage (pu); (c) active power (pu) through the umbilical cable; (d) reactive power (pu) through the umbilical cable.

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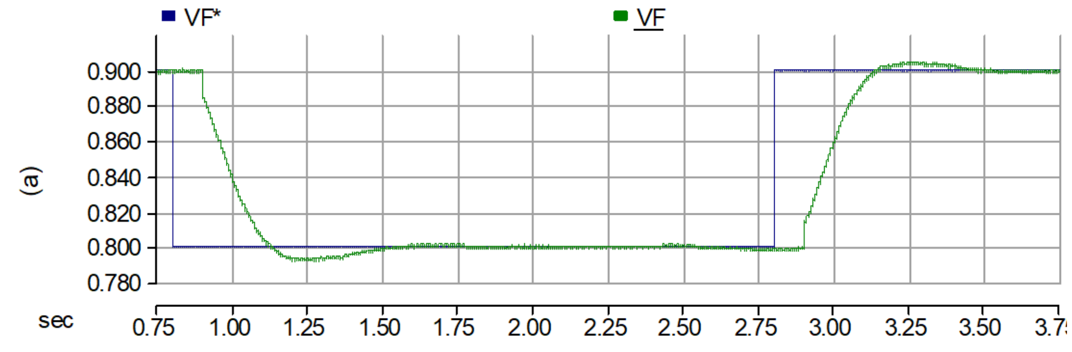
6.1.4 DYNAMIC VOLTAGE CONTROL

This test case validates the capability of the system to control the off-shore ac grid voltage when the WPP is operating in ISL mode.

Additionally, this test case validates the following requirements:

- 4.3.4 Dynamic voltage control.

Test case	4.2.4. DYNAMIC VOLTAGE CONTROL		
Simulation detail	WT	Level 4: Perfect DC link control is assumed	
	OWF	Level 4: One detailed string and aggregated strings…	
	On-shore MMC	Level 2: Averaged model	
	On-shore grid	Level 3: Thevenin equivalent	
	Configuration (connected strings)	Compliance	Comments
Simulations (sensitivity analysis)	6 Strings + 6 Strings + 6 Strings	pass	P_{TOT}= 1200 MW; Max U^-/U^+ = 0.012; Max Δf = 0.2 Hz; Max df = 0.9 Hz/s
	6 Strings + 3 Strings + 1 String	pass	P_{TOT}= 680 MW; Max U^-/U^+ = 0.013; Max Δf = 0.02 Hz; Max df = 0.5 Hz/s
	6 Strings + 1 String + 1 String	pass	P_{TOT}= 544 MW; Max U^-/U^+ = 0.015; Max Δf = 0.02 Hz; Max df = 0.5 Hz/s
	3 Strings + 3 Strings + 3 Strings	pass	P_{TOT}= 624 MW; Max U^-/U^+ = 0.014; Max Δf = 0.02 Hz; Max df = 0.56 Hz/s
	3 Strings + 3 Strings + 1 String	pass	P_{TOT}= 488 MW; Max U^-/U^+ = 0.015; Max Δf = 0.02 Hz; Max df = 0.56 Hz/s
	3 Strings + 1 String + 1 String	pass	P_{TOT}= 352 MW; Max U^-/U^+ = 0.016; Max Δf = 0.02 Hz; Max df = 0.6 Hz/s
	1 String + 1 String + 1 String	pass	P_{TOT}= 260 MW; Max U^-/U^+ = 0.016; Max Δf = 0.02 Hz; Max df = 0.6 Hz/s
Comments	WTG control and OWF control detailed in section 2 of D3.4. This test case validates the capability of the WPP to control the voltage of the offshore grid. For this purpose, the offshore grid voltage reference is changed from 0.9 pu to 0.8 pu, and back again. The WPP voltage controller has a 100ms sampling rate.		
Sample result			

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6.1.5 WIND FARM POWER CONTROL AND POWER TRACKING

This test case validates the capability of the each WTG to follow changes of active power reference. Deliverable D3.6 defines that the wind speed profiles shall follow a Kaimal distribution. However, this option implies extremely large simulation times. As an alternative, 1 Hz active power references of different amplitudes and phases are applied to each WTG. The 1Hz active power references represent a worse case than the Kaimal distribution regarding frequency and amplitude contents.

Additionally, this test case validates the following requirements:

- 3.3.2 Frequency ranges.
- 3.3.3 Voltage ranges.
- 3.4.1 Active power production.
- 3.4.2 Steady state active power control.
- 3.4.3 Dynamic active power control.
- 4.1 Active power control.
- 4.2.1 Frequency envelope.
- 4.2.2 Steady state frequency control.
- 4.2.3 Dynamic frequency control.
- 4.2.7 Rate of change of frequency (ROCOF) limits.

Test case	4.2.5.a. OPTIMAL POWER TRACKING WITH VARYING WIND		
Simulation detail	WT	Level 4: Perfect DC link control is assumed	
	OWF	Level 4: One detailed string and aggregated strings…	
	On-shore MMC	Level 2: Averaged model	
	On-shore grid	Level 3: Thevenin equivalent	
	Configuration (connected strings)	Compliance	Comments
Simulations (sensitivity analysis)	6 Strings + 6 Strings + 6 Strings	pass	P_{TOT}= 1200 MW; Max U^-/U^+ = 0.012; Max Δf = 0.03 Hz; Max df = 0.2 Hz/s
	6 Strings + 3 Strings + 1 String	pass	P_{TOT}= 680 MW; Max U^-/U^+ = 0.013; Max Δf = 0.03 Hz; Max df = 0.2 Hz/s
	6 Strings + 1 String + 1 String	pass	P_{TOT}= 544 MW; Max U^-/U^+ = 0.015; Max Δf = 0. 03 Hz; Max df = 0.2 Hz/s
	3 Strings + 3 Strings + 3 Strings	pass	P_{TOT}= 624 MW; Max U^-/U^+ = 0.014; Max Δf = 0.03 Hz; Max df = 0.2 Hz/s
	3 Strings + 3 Strings + 1 String	pass	P_{TOT}= 488 MW; Max U^-/U^+ = 0.015; Max Δf = 0.03 Hz; Max df = 0.2 Hz/s
	3 Strings + 1 String + 1 String	pass	P_{TOT}= 352 MW; Max U^-/U^+ = 0.016; Max Δf = 0.03 Hz; Max df = 0.2 Hz/s
	1 String + 1 String + 1 String	pass	P_{TOT}= 260 MW; Max U^-/U^+ = 0.016; Max Δf = 0.03 Hz; Max df = 0.2 Hz/s
Comments	The purpose of this test case is to validate the capability of the WTGs to follow active power reference changes. In order to validate that, sinusoidal references of active power at 1 Hz have been introduced to each WTG. The sample result shows that each WTG can follow its reference. Hence, the power tracking capability has been validated.		

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Sample result

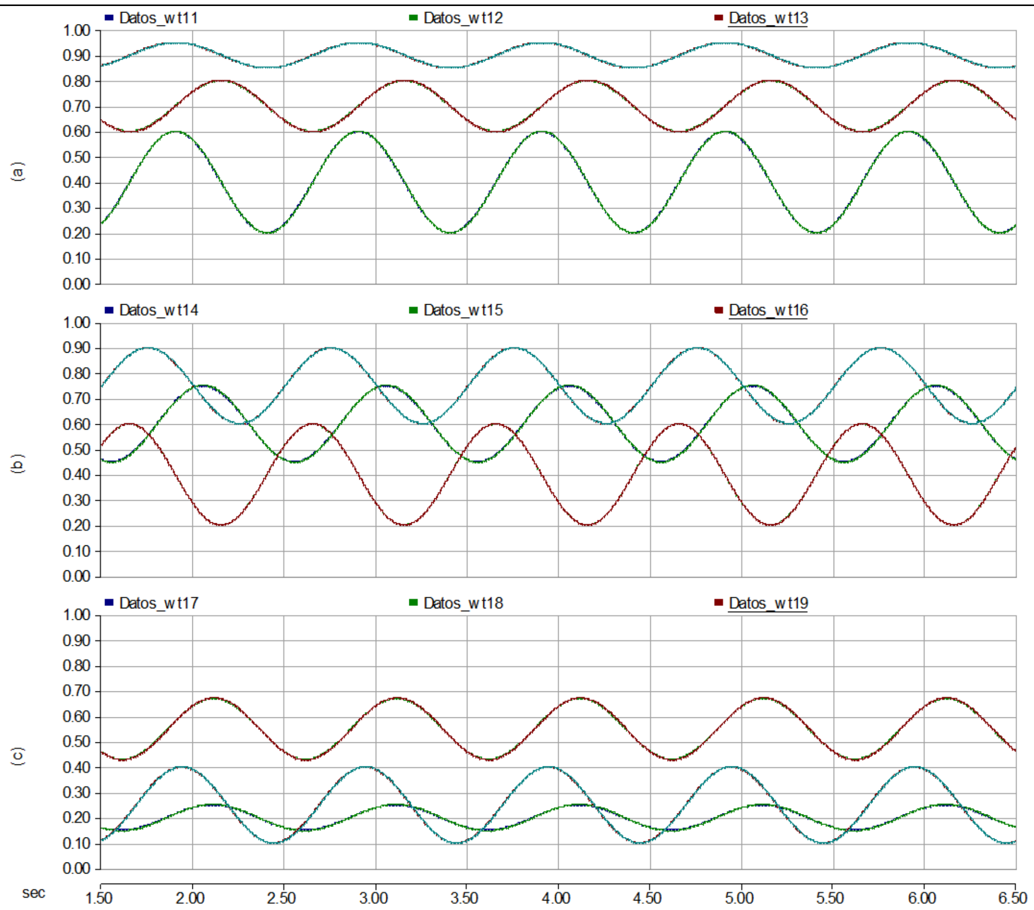


Figure 6-7: Active power (pu) and its reference (pu) of each WTG connected in a string: (a) $WTG_{1\text{-}1}$, $WTG_{1\text{-}2}$ and $WTG_{1\text{-}3}$; (b) $WTG_{1\text{-}4}$, $WTG_{1\text{-}5}$ and $WTG_{1\text{-}6}$; (c) $WTG_{1\text{-}7}$, $WTG_{1\text{-}8}$ and $WTG_{1\text{-}9}$.

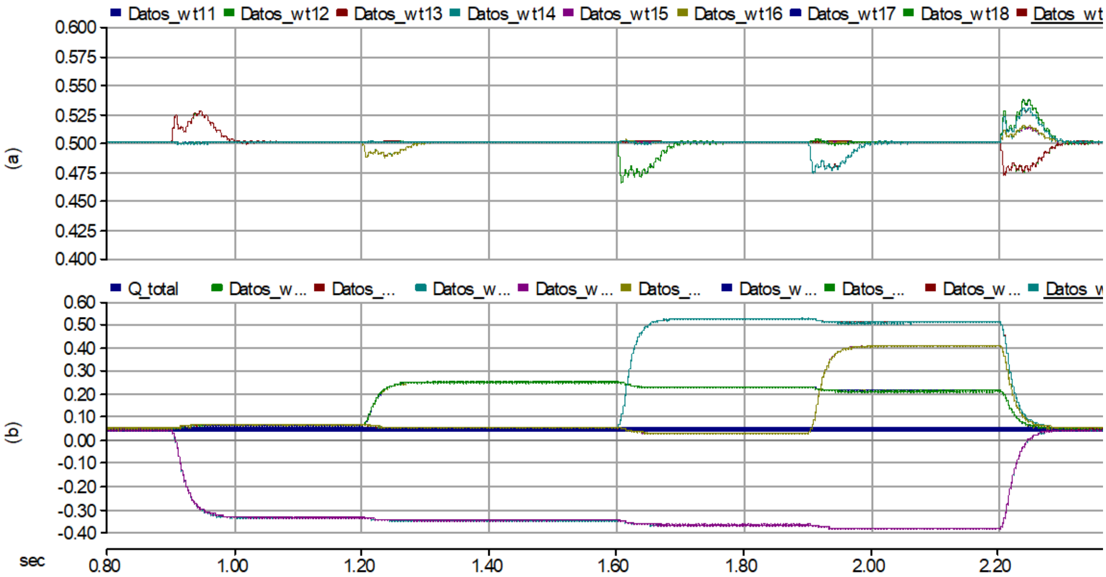
6.1.6 RESPONSE TO CHANGES IN REACTIVE POWER SHARING COMMAND

This test case validates the capability of the WTGs to share the required reactive power of the offshore ac grid. Additionally, this test case validates the following requirements:

- 3.3.2 Frequency ranges.
- 3.3.3 Voltage ranges.
- 4.3.2 Active power control.
- 4.3.2 Steady state voltage/reactive power control.

Test case	4.2.7.a. REACTIVE POWER SHARING COMMAND WITH DR CONFIGURATION		
Simulation detail	WT	Level 4: Perfect DC link control is assumed	
	OWF	Level 4: One detailed string and aggregated strings.	
	On-shore MMC	Level 2: Averaged model	
	On-shore grid	Level 3: Thevenin equivalent	
	Configuration (connected strings)	Compliance	Comments

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691714.

Simulations (sensitivity analysis)	6 Strings + 6 Strings + 6 Strings	pass (see comments)	P_{TOT}= 1200 MW; Max U^-/U^+ = 0.012; Max Δf = 0.08 Hz; Max df = 1.2 Hz/s
	6 Strings + 3 Strings + 1 String	pass	P_{TOT}= 680 MW; Max U^-/U^+ = 0.013; Max Δf = 0.08 Hz; Max df = 1.2 Hz/s
	6 Strings + 1 String + 1 String	pass	P_{TOT}= 544 MW; Max U^-/U^+ = 0.015; Max Δf = 0.08 Hz; Max df = 1.2 Hz/s
	3 Strings + 3 Strings + 3 Strings	pass	P_{TOT}= 624 MW; Max U^-/U^+ = 0.014; Max Δf = 0.08 Hz; Max df = 1.2 Hz/s
	3 Strings + 3 Strings + 1 String	pass	P_{TOT}= 488 MW; Max U^-/U^+ = 0.015; Max Δf = 0.08 Hz; Max df = 1.2 Hz/s
	3 Strings + 1 String + 1 String	pass	P_{TOT}= 352 MW; Max U^-/U^+ = 0.016; Max Δf = 0.08 Hz; Max df = 1.2 Hz/s
	1 String + 1 String + 1 String	pass	P_{TOT}= 260 MW; Max U^-/U^+ = 0.016; Max Δf = 0.08 Hz; Max df = 1.2 Hz/s
Comments	WTG control and OWF control detailed in section 2 of D3.4. The sample result shows the reactive power of the turbines connected within a string. Changes of reactive power references are applied to different WTGs. As the figure shows, reactive power is shared as expected. The total reactive power for the system remains at a constant value in order to maintain the off-shore ac grid conditions. Please note that a wrong setting of the reactive power reference for each WTG might lead to circulating reactive power. However, the objective of this test case was to check that the controls respond to reactive power sharing commands and not how to optimally obtain those commands. During the transients, the overall voltage changes. Voltage changes are always within the specifications, although they produce small changes on the active power delivered through the DRU. Fast reactive power changes can lead to transient active power peaks of up to 0.04pu. However, active power changes can be mitigated by ramping up or down reactive power sharing commands. In any case, operation above 0.96 pu active power is only valid if reactive power reference changes are ramped. Otherwise, both voltage and active power will be outside the operational limits, albeit for a very short period of time.		
Sample result	 Figure 6-8: (a) Active power (pu), Reactive power (pu) of the WTGs within a string.		

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6.1.7 RESPONSE TO ACTIVE POWER REFERENCE COMMANDS WHEN CONNECTED TO EXTERNAL AC

When the WPP is connected to the HVAC umbilical cable (or to any other ac-grid), it is possible to set a power flow through the HVAC cable. This test case validates the capability of the WPP to control the active power flow though the umbilical cable. This result can be extrapolated to any connected ac grid.

Additionally, this test case validates the following requirements:

- 3.3.2 Frequency ranges.
- 3.3.3 Voltage ranges.
- 3.4.2 Steady state active power control.
- 3.4.3 Dynamic active power control.
- 4.1 Active power control.

Test case	4.2.8. RESPONSE TO POWER REFERENCE COMMAND WHEN CONNECTED TO EXTERNAL AC		
Simulation detail	WT	Level 4: Perfect DC link control is assumed	
	OWF	Level 4: One detailed string and aggregated strings…	
	On-shore MMC	Level 2: Averaged model	
	On-shore grid	Level 3: Thevenin equivalent	
	Configuration (connected strings)	Compliance	Comments
Simulations (sensitivity analysis)	6 Strings + 6 Strings + 6 Strings	pass	P_{TOT}= 1200 MW; Max U^-/U^+ = 0.012; Max Δf = 0.15 Hz; Max df = 0.95 Hz/s
	6 Strings + 3 Strings + 1 String	pass	P_{TOT}= 680 MW; Max U^-/U^+ = 0.013; Max Δf = 0.15 Hz; Max df = 0.95 Hz/s
	6 Strings + 1 String + 1 String	pass	P_{TOT}= 544 MW; Max U^-/U^+ = 0.015; Max Δf = 0.15 Hz; Max df = 0.95 Hz/s
	3 Strings + 3 Strings + 3 Strings	pass	P_{TOT}= 624 MW; Max U^-/U^+ = 0.014; Max Δf = 0.15 Hz; Max df = 0.95 Hz/s
	3 Strings + 3 Strings + 1 String	pass	P_{TOT}= 488 MW; Max U^-/U^+ = 0.015; Max Δf = 0.15 Hz; Max df = 0.95 Hz/s
	3 Strings + 1 String + 1 String	pass	P_{TOT}= 352 MW; Max U^-/U^+ = 0.016; Max Δf = 0.15 Hz; Max df = 0.95 Hz/s
	1 String + 1 String + 1 String	pass	P_{TOT}= 260 MW; Max U^-/U^+ = 0.016; Max Δf = 0.15 Hz; Max df = 0.95 Hz/s
Comments	WTG control and OWF control detailed in section 2 of D3.4. The sample results show the active power through umbilical cable and the frequency of the off-shore ac grid. It shows that the active power through the umbilical cable follows its reference while the off-shore ac grid frequency remains within its limits (limits defined in D3.1).		

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Sample result

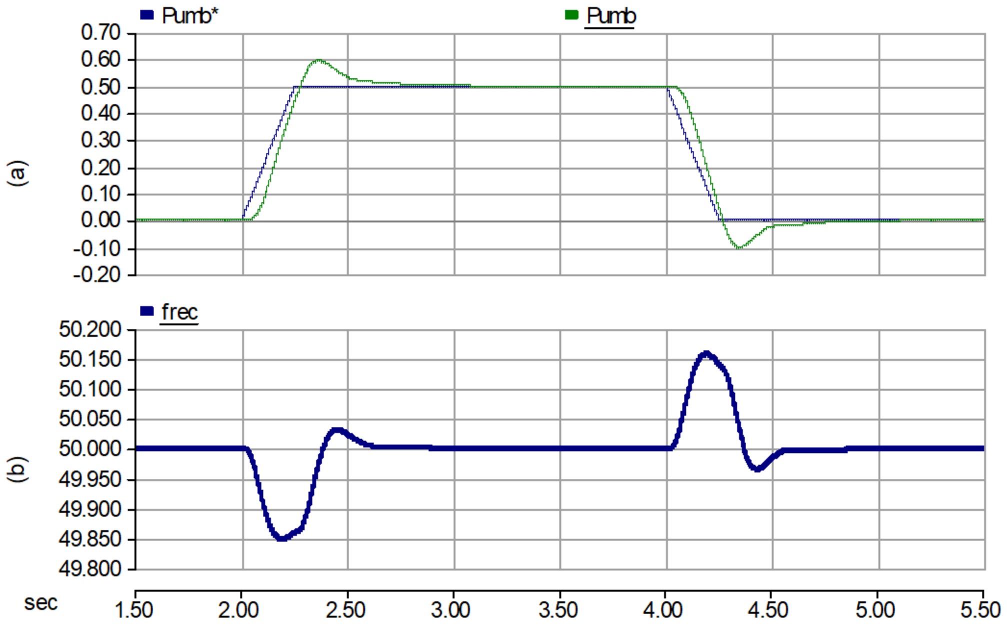

Figure 6-9: (a) Active power (pu) through umbilical cable; (b) frequency (Hz) of the offshore ac grid.

6.1.8 DISCONNECTION / RECONNECTION OF FILTERS

The DRU filters are disconnected or reconnected depending on the power flow though the DRUs in order to minimise the power losses. This test case validates that the WPP remain controlled and within the limits when the filters are disconnected/reconnected. In both cases (disconnection and connection) the connected WTGs are providing 0.2 pu of active power. The total amount of filters in the system is considered (three DRU platforms with three DRU filters each one, nine DRU filters). The connection and the disconnection of the needed DRU filters is carried out sequentially.

Additionally, this test case validates the following requirements:

- 3.3.2 Frequency ranges.
- 3.3.3 Voltage ranges.

6.1.8.1 DISCONNECTION OF FILTERS

Test case	4.2.11.a. DISCONNECTION OF DRU FILTERS		
Simulation detail	WT	Level 4: Perfect DC link control is assumed	
	OWF	Level 4: One detailed string and aggregated strings…	
	On-shore MMC	Level 2: Averaged model	
	On-shore grid	Level 3: Thevenin equivalent	
	Configuration (connected strings)	Compliance	Comments
Sensitivit	6 Strings + 6 Strings + 6 Strings	pass	P_{TOT}= 1200 MW; Max U^-/U^+ = 0.012; Max Δf = 0.2 Hz; Max df = 0.9 Hz/s

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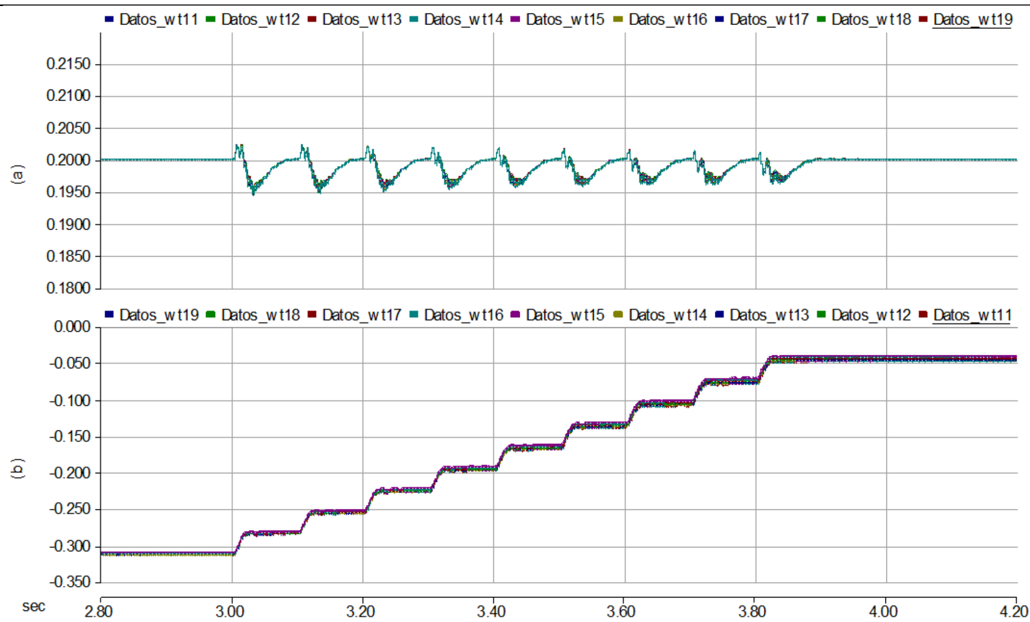
	6 Strings + 3 Strings + 1 String	pass	P_{TOT}= 680 MW; Max U^-/U^+ = 0.013; Max Δf = 0.2 Hz; Max df = 0.9 Hz/s
	6 Strings + 1 String + 1 String	pass	P_{TOT}= 544 MW; Max U^-/U^+ = 0.015; Max Δf = 0.2 Hz; Max df = 0.9 Hz/s
	3 Strings + 3 Strings + 3 Strings	pass	P_{TOT}= 624 MW; Max U^-/U^+ = 0.014; Max Δf = 0.2 Hz; Max df = 0.9 Hz/s
	3 Strings + 3 Strings + 1 String	pass	P_{TOT}= 488 MW; Max U^-/U^+ = 0.015; Max Δf = 0.2 Hz; Max df = 0.9 Hz/s
	3 Strings + 1 String + 1 String	pass	P_{TOT}= 352 MW; Max U^-/U^+ = 0.016; Max Δf = 0.2 Hz; Max df = 0.9 Hz/s
	1 String + 1 String + 1 String	pass	P_{TOT}= 260 MW; Max U^-/U^+ = 0.016; Max Δf = 0.2 Hz; Max df = 0.9 Hz/s
Comments	The connection of the DRU filters reduce the required reactive power of the off-shore ac grid. It reduces the losses of the grid. The result shows the active and the reactive power of the WTGs within a string. It shows that the active power remains at its reference value (power drop lower than 0.5%). Initially, the system has all filters connected and hence, it is over-compensated. As the filters are disconnected, the reactive power absorbed by the WTGs decreases. The opposite is true when the filters are connected.		
Sample result	 Figure 6-10: (a) Active power (pu) of WTGs in string 1 of OWF1; (b) Reactive power (pu) of WTGs in string 1 of OWF1.		

6.1.8.2 RECONNECTION OF FILTERS

Test case	4.2.11.b. CONNECTION OF DRU FILTERS	
Simulation detail	WT	Level 4: Perfect DC link control is assumed
	OWF	Level 4: One detailed string and aggregated strings…
	On-shore MMC	Level 2: Averaged model
	On-shore grid	Level 3: Thevenin equivalent

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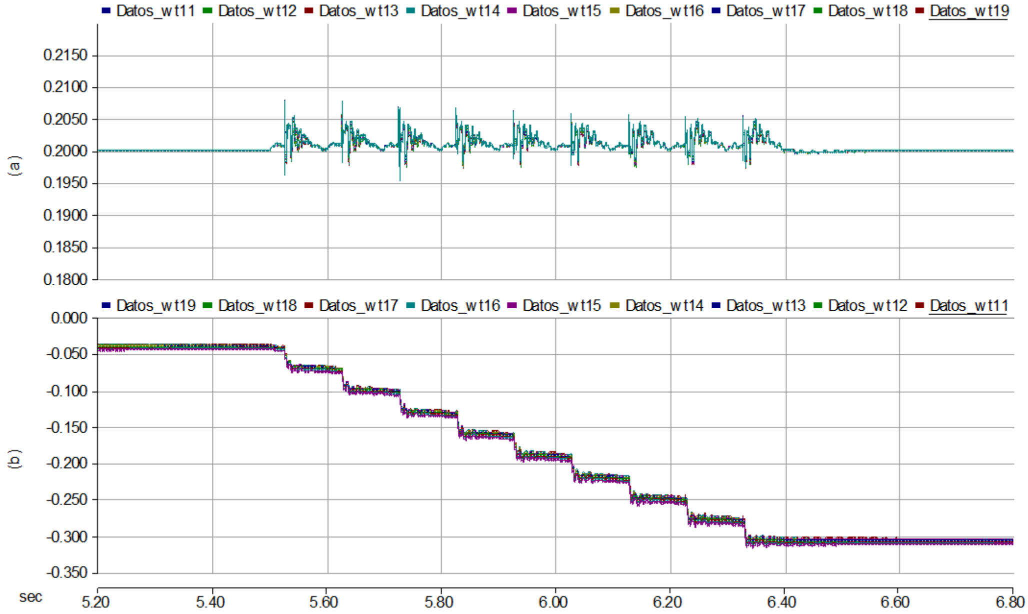
	Configuration (connected strings)	Compliance	Comments
Simulations (sensitivity analysis)	6 Strings + 6 Strings + 6 Strings	pass	P_{TOT}= 1200 MW; Max U^-/U^+ = 0.01; Max Δf = 0.2 Hz; Max df = 1.98 Hz/s
	6 Strings + 3 Strings + 1 String	pass	P_{TOT}= 680 MW; Max U^-/U^+ = 0.013; Max Δf = 0.2 Hz; Max df = 1.98 Hz/s
	6 Strings + 1 String + 1 String	pass	P_{TOT}= 544 MW; Max U^-/U^+ = 0.015; Max Δf = 0.2 Hz; Max df = 1.98 Hz/s
	3 Strings + 3 Strings + 3 Strings	pass	P_{TOT}= 624 MW; Max U^-/U^+ = 0.014; Max Δf = 0.2 Hz; Max df = 1.98 Hz/s
	3 Strings + 3 Strings + 1 String	pass	P_{TOT}= 488 MW; Max U^-/U^+ = 0.015; Max Δf = 0.2 Hz; Max df = 1.98 Hz/s
	3 Strings + 1 String + 1 String	pass	P_{TOT}= 352 MW; Max U^-/U^+ = 0.016; Max Δf = 0.2 Hz; Max df = 1.98 Hz/s
	1 String + 1 String + 1 String	pass	P_{TOT}= 260 MW; Max U^-/U^+ = 0.016; Max Δf = 0.2 Hz; Max df = 1.98 Hz/s
Comments	The sample results show the active and reactive powers. In this case, the filters are connected when the system is generating 0.2pu active power. Note the WTGs begins to absorb reactive power as the DRU filters are been connected, as the system is over compensated. Overcompensation disappears once the DRU is delivering 1pu active power.		
Sample result	 Figure 6-11: (a) Active power (pu) of WTGs in string 1 of OWF1; (b) Reactive power (pu) of WTGs in string 1 of OWF1.		

6.2. FAULT RIDE-THROUGH AND PROTECTION

The compliance evaluation of the DRU-HVDC systems during various faults is carried out in this subsection, including:

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- onshore grid faults
- DC cable faults
- internal DRU faults
- umbilical AC cable faults
- offshore faults.

6.2.1 UNINTENDED TRANSMISSION CAPABILITY LIMITATION

During an event which causes unintended transmission capability limitation, the system should be protected to avoid any damage to equipment and fast recover after fault clearance. The performances of the DRU systems under such conditions are evaluated.

6.2.1.1 ONSHORE GRID FAULTS

The compliance evaluation of the DRU-HVDC systems during onshore grid faults is implemented first, considering both symmetrical and asymmetrical faults.

(A) CLOSE SYMMETRICAL ONSHORE GRID FAULTS

For compliance evaluation, a solid symmetrical AC fault is applied at the transformer grid-side at *t*=0.5 s and cleared at *t*=0.64 s. The simulation results for the systems are shown in Figure 6-12.

Test case	**4.3.1.1.a. CLOSE SYMMETRICAL ONSHORE FAULT**		
Simulation detail	WT	Level 4	
	OWF	Level 6	
	On-shore MMC	Level 2	
	On-shore grid	Level 3	
	Configuration (transmitted power level)	Compliance	Comments
Simulations (sensitivity analysis)	Low power	✓	
	Medium power	✓	
	High power	×	DC voltage increases to 140% of rated value. DC choppers can reduce such DC overvoltage.
Comments	Main criteria for compliance evaluation: DC over voltage, WF power reduction, onshore MMC current limit / limited power transmission capability, power oscillation damping, recovery		

In the event of onshore AC fault, the onshore AC voltage rapidly decreases to 0, as shown in Figure 6-12 (a). Owing to the decrease of the AC grid voltage, the power transmission capability of the onshore MMC decreases to 0, and the maximum active power which can be accepted at the offshore end of the transmission system is less than the available production. The imported energy from the OWF to the HVDC link through the DRUs is

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greater than the maximum power that can be exported by the onshore MMC, so the DC voltage of the HVDC link is charged by the power surplus, leading to an increase in the DC voltage of the HVDC link from 1.0 pu to 1.38 pu in 0.08 s, as shown in Figure 6-12 (b). With the increase of the DC voltage, the offshore AC voltage also increases and reaches the limit (set at 1.1 pu); thus, no active power can be generated and transmitted to DC, as shown in Figure 1 (c) and (d), respectively. The WT converters observe the disturbance at the offshore terminals without need for communication and automatically reduce the generated wind power to alleviate the overvoltage of the DRU-HVDC link and support such unintended limitation of the active power flow.

As shown in Figure 1 (d), the OWF is capable of quickly returning the active power from a limited operating point to the pre-fault active power level. Active Power oscillations are adequately damped and acceptable. The system meets the following compliance requirements defined in D3.6:

(1) The system is protected to avoid any damage to equipment during faults.
(2) OWF is capable of staying connected to the network and continuing to operate stably after the (off-shore) power system has been disturbed by secured faults. That capability is in accordance with the voltage against time profile at the connection point.
(3) Ensure maximum power transmission and fast system recovery.

The OWF is capable of returning the active power from a limited operating point to the pre-event active power level minus 10% (e.g. 100% -10% = 90%) with a ramp rate of 200%/s.

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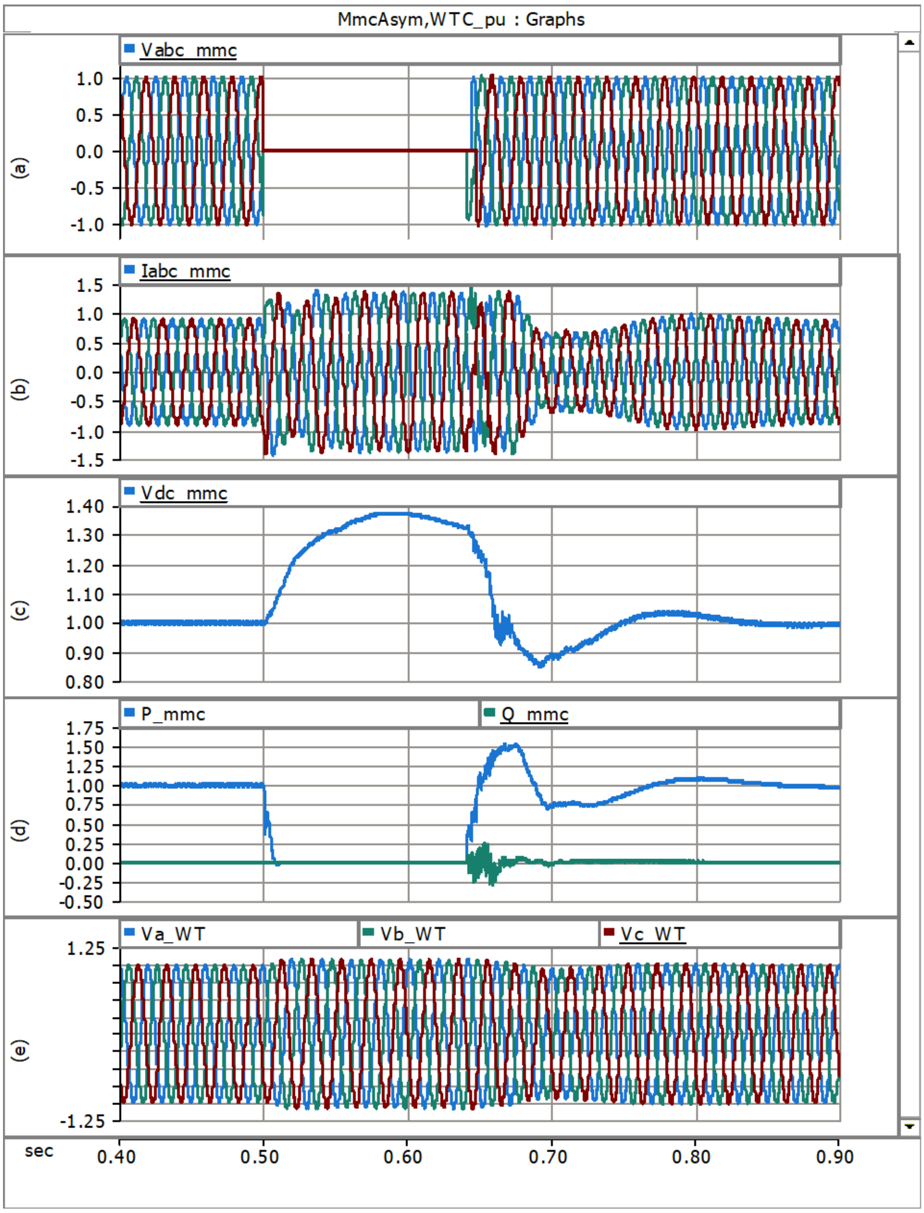

Figure 6-12: Simulation results during close symmetrical onshore AC fault in pu terms: (a) onlshore three-phase AC voltages, (b) MMC three-phase AC currents, (c) DC voltage of DRU-HVDC link, (d) MMC active and reactive powers, and (e) offlshore three-phase AC voltages.

(B) REMOTE SYMMETRICAL ONSHORE GRID FAULTS

For compliance evaluation, a symmetrical solid fault F1 is applied at the transformer grid-side as shown in Figure 6-13 at t=0.5 s and is cleared at t=0.64 s.

Test case	**4.3.1.1.b. REMOTE SYMMETRICAL ONSHORE FAULT**	
Simulation	WT	Level 4

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detail	OWF	Level 6	
	On-shore MMC	Level 2	
	On-shore grid	Level 3	
	Configuration (transmitted power level)	Compliance	Comments
Simulations (sensitivity analysis)	Low power	✓	
	Medium power	✓	
	High power	✓	
Comments	Main criteria for compliance evaluation: DC over voltage, WF power reduction, onshore MMC current limit / limited power transmission capability, power oscillation damping, recovery		

To simulate remote faults, a three-phase fault with fault resistance of 2 Ω occurs at the onshore AC grid at 0.5 s and the onshore AC voltage decreases to 0.4 pu during the fault as shown in Figure 6-13 (a). Different with close solid faults, significant power (around 0.6 pu) can still be transmitted to onshore during remote faults, as shown in Figure 6-13 (d). The onshore MMC station operates on current limiting mode and controls the AC currents at 1.5 pu, Figure 6-13 (b). The WT and DRU station still try to transmit the generated active power and the resultant unbalanced active power leads to the increase of the HVDC-link voltage. As shown in Figure 6-13 (c), the overvoltage of 1.22 pu is lower than that during close faults (1.38 pu). The increase of the DC voltage reduces the power output from the WTs and transmitted to DC by the offshore diode rectifier and the offshore AC voltage is limited by the WT converters (set at 1.1 pu).

At 0.64 s, the fault is cleared and the onshore AC voltage recovers, leading to the increase of onshore transmitted active power. As seen from Figure 6-13 (d), the power transmission is also quickly restored and the active power oscillations are adequately damped and acceptable. The system can still transmit significant wind power to onshore during remote symmetrical onshore AC faults and automatically restore normal operation after fault isolation. The system meets the following compliance requirements defined in D3.6:

(1) The system is protected to avoid any damage to equipment during faults.

(2) OWF is capable of staying connected to the network and continuing to operate stably after the (off-shore) power system has been disturbed by secured faults. That capability is in accordance with the voltage against time profile at the connection point.

(3) Ensure maximum power transmission and fast system recovery.

(4) The offshore wind power could be continuously transferred through the DRU-HVDC but with limited capacity.

(5) The OWF is capable of returning the active power from a limited operating point to the pre-event active power level minus 10% (e.g. 100% -10% = 90%) with a ramp rate of 200%/s.

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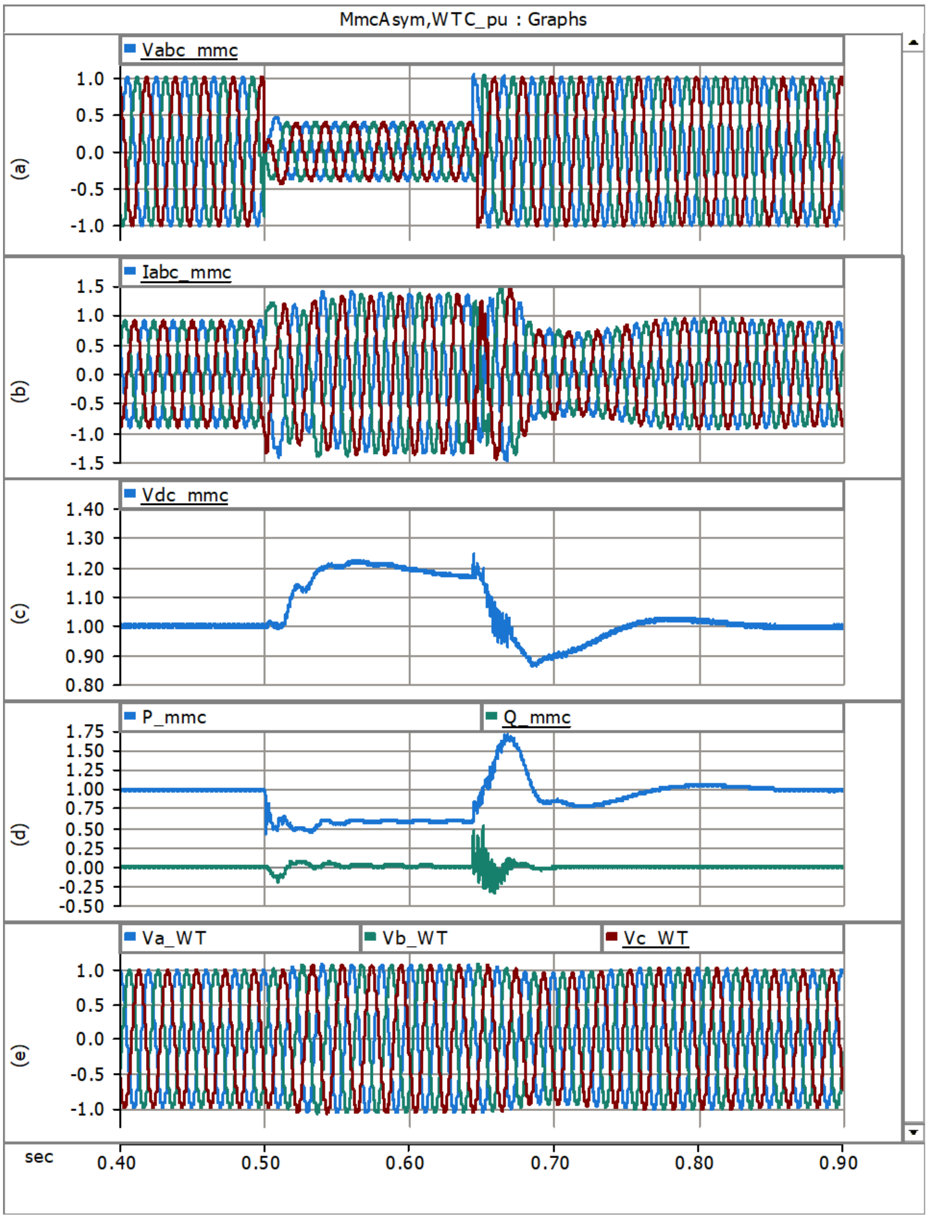

Figure 6-13: Simulation results during remote symmetrical onshore AC fault in pu terms: (a) onlshore three-phase AC voltages, (b) MMC three-phase AC currents, (c) DC voltage of DRU-HVDC link, (d) MMC active and reactive powers, and (e) offlshore three-phase AC voltages.

(C) AYMMETRICAL ONSHORE GRID FAULTS

For compliance evaluation, the performances of the DR-HVDC system during an asymmetrical onshore grid fault is tested in this section. At *t*=0.5 s, a solid ground fault is applied at phase *a* of the onshore grid and is cleared at *t*=0.64 s.

Test case	**4.3.1.1.c. ASYMMETRICAL ONSHORE AC FAULT**	
Simulation	WT	Level 4

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detail	OWF	Level 6	
	On-shore MMC	Level 2	
	On-shore grid	Level 3	
	Configuration (transmitted power level)	Compliance	Comments
Simulations (sensitivity analysis)	Phase-phase (remote and close)	✓	
	Single-phase to ground (remote and close)	✓	
Comments	Main criteria for compliance evaluation: DC over voltage, WF power reduction, onshore MMC current limit / limited power transmission capability, double-frequency power oscillation , recovery		

After the fault occurrence, the voltage of the faulty phase drops to zero, as shown in Figure 6-14 (a). With the negative-sequence current reference set at zero, the three-phase currents of the MMC station are balanced and their peaks during the fault transient are controlled to be lower than the set limit of 1.5 pu, as displayed in Figure 6-14 (b). As shown in Figure 6-14 (d), the active and reactive powers contain second-order harmonic oscillations (i.e. 100 Hz). The DR-HVDC voltage increases to 1.1 pu during faults and then restores to rated value, Figure 6-14 (c).

Due to the increase of the DR-HVDC DC voltage after the fault initiation, the offshore voltage increases to 1.07 pu to remain the power transmission to the onshore grid and then gradually restores to rated value, as seen in Figure 6-14 (e).

During the tested asymmetrical onshore grid fault, the DR-HVDC link does not experience significant overvoltage (1.07 pu) and the system can continue transmitting rated power. The power transmission capability of the onshore MMC will be reduced in the event of a severe onshore gird voltage dip, e.g. during a phase-to-phase fault. Once the generated power of WTs is greater the power transmission capability of the onshore station, the DC voltage of the DR-HVDC link will automatically increase to limit the transmitted power. After fault isolation, the whole system automatically restores normal operation and the active power oscillations are adequately damped and acceptable.

The system meets the following compliance requirements defined in D3.6:

(1) The system is protected to avoid any damage to equipment during faults.
(2) OWF is capable of staying connected to the network and continuing to operate stably after the (off-shore) power system has been disturbed by secured faults. That capability is in accordance with the voltage against time profile at the connection point.
(3) Ensure maximum power transmission and fast system recovery.
(4) The offshore wind power could be continuously transferred through the DRU-HVDC but with limited capacity.
(5) The OWF is capable of returning the active power from a limited operating point to the pre-event active power level minus 10% (e.g. 100% -10% = 90%) with a ramp rate of 200%/s.

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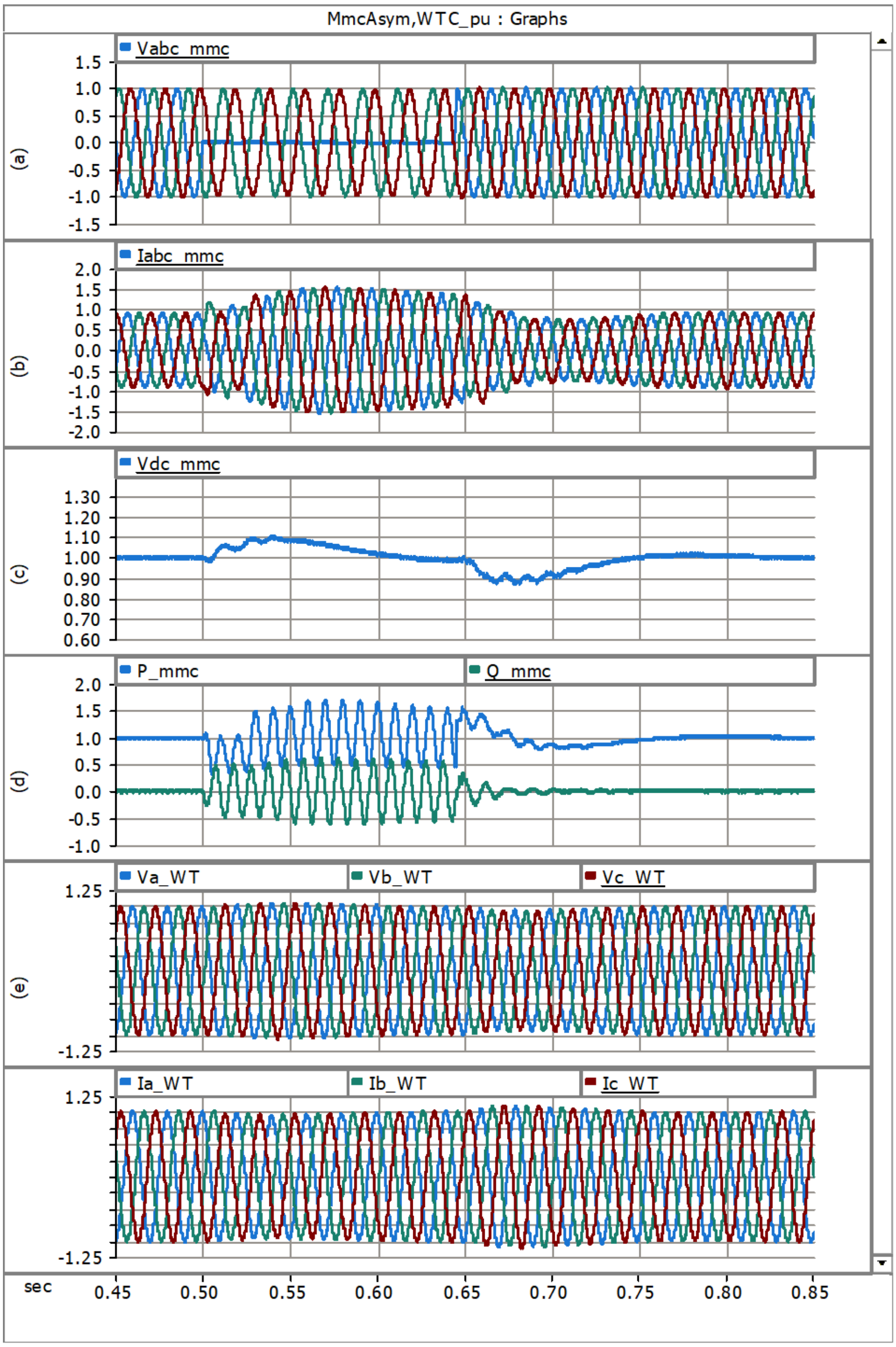

Figure 6-14: Simulation results during asymmetrical onshore AC fault in pu terms: (a) onlshore three-phase AC voltages, (b) MMC three-phase AC currents, (c) DC voltage of DRU-HVDC link, (d) MMC active and reactive powers, (e) offlshore three-phase AC voltages, (f) WT three-phase AC currents.

6.2.1.2 DC CABLE FAULTS

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(A) POLE-TO-POLE DC CABLE FAULTS

For compliance evaluation, a permanent solid pole-to-pole fault is applied at the middle of the DC cable at *t*=0.5 s. Under such a fault, it is impossible to transmit power to onshore grid through DR-HVDC link and thus the WT converters are shut-down after 100 ms from fault initiation, while the onshore MMC station operates on STATCOM mode to support the onshore grid by providing reactive power.

Test case	**4.3.1.2.a. POLE-TO-POLE DC FAULT**		
Simulation detail	WT	Level 4	
	OWF	Level 6	
	On-shore MMC	Level 2	
	On-shore grid	Level 3	
	Configuration (transmitted power level)	Compliance	Comments
Simulations (sensitivity analysis)	Fault at MMC terminal	✓	
	Fault at middle of the DC cable	✓	
	Fault at DRU terminal	✓	
Comments	Main criteria for compliance evaluation: WF fault current, onshore FB-MMC current control and reactive power capability		

The DRU DC voltage drops to zero after the DC fault, as shown in Figure 6-15 (a). WT FECs automatically operate on current limiting mode to provide fault currents, which flow through the offshore grid and the DRU station to feed the fault, as shown in Figure 6-15 (b) and Figure 6-15 (d). This contributes the establishment of the offshore AC voltage to around 0.4 pu as shown in Figure 6-15 (c), even though the system suffers a solid pole-to-pole DC fault. Oscillations are observed in the DC current of the DR-HVDC during fault transients due to the passive *R*, *L*, and *C* components in the offshore AC and DC systems, as shown in Figure 6-15 (b). The generated wind power drops to zero, as seen in Figure 6-15 (e).

As shown in Figure 6-15 (a) and (e), the DC voltage of the DR-HVDC link collapses after the pole-to-pole DC fault and wind power transmission is interrupted. The onshore MMC controls its terminal DC voltage and DC current around zero. The onshore FB-MMC operates on STATCOM mode and continues providing reactive power to the grid. The WT converters provide fault currents during faults in the first 100 ms after the fault initiation, which enables overcurrent protection and contributes the AC voltage control of the offshore network.

The system meets the following compliance requirements defined in D3.6:

(1) The system is protected to avoid any damage to equipment during faults.

(2) OWF is capable of staying connected to the network and continuing to operate stably after the (off-shore) power system has been disturbed by secured faults. That capability is in accordance with the voltage against time profile at the connection point.

(3) OWF is capable of providing fast fault current (start within 20ms after fault detection) at the connection point and delivering additional reactive current supporting voltage retention.

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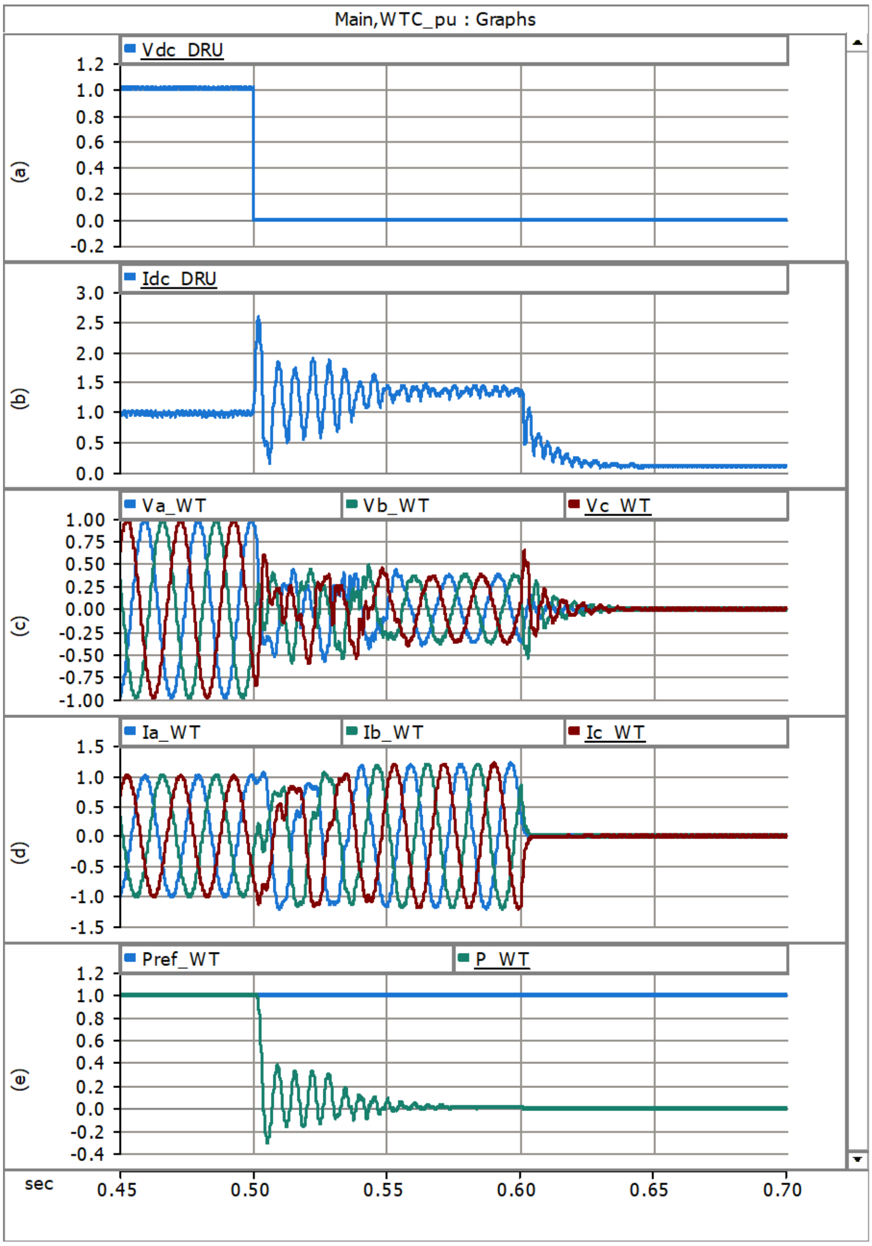

Figure 6-15: Simulation results during pole-to-pole DC cable fault in pu terms: (a) DC voltage of DR-HVDC link, (b) DC current of DR-HVDC link, (c) WT three-phase voltages, (d) WT three-phase currents, and (e) WT active and reactive powers.

(B) POLE-TO-GROUND DC CABLE FAULTS

A positive-pole-to-ground DC fault is applied at the DRU-HVDC link at *t*=0.5 s and detailed response of both the OWF and the DRU HVDC connection is examined to evaluate the compliance of the system.

Test case	**4.3.1.2.b. POLE-TO-GROUND DC CABLE FAULT**	
Simulation detail	WT	Level 4
	OWF	Level 6

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	On-shore MMC	Level 2	
	On-shore grid	Level 3	
	Configuration (transmitted power level)	Compliance	Comments
Simulations (sensitivity analysis)	Fault at MMC terminal	✓	
	Fault at middle of the DC cable	✓	
	Fault at DRU terminal	✓	
Comments	Main criteria for compliance evaluation: DC pole over voltage, reduced power transmission capability, WF current control, onshore FB-MMC current control and reactive power capability		

After fault occurrence, the positive-pole DC voltage drops to zero. For the adopted symmetrical monopole configuration, the onshore full-bridge submodule MMC station continues controlling the healthy negative-pole DC voltage around the rated value during such an asymmetrical DC cable fault with the enhanced independent pole control proposed in [Xiang 2018], as shown in Figure 6-16 (a). The DR-HVDC link is thus operated at half of the rated DC voltage to avoid overvoltage of the healthy negative pole and continuously transmit power. With reduced DC voltage, the DC current is increased to 1.25 pu and the active power, thereby the onshore MMC AC current, is reduced to 0.625 pu, as shown in Figure 6-16 (b), (c) and (d).

Due to the reduced DR-HVDC link voltage, the output voltage of WT converters decreases to 0.65 pu and thus the active power and voltage control loop saturates and the converter outputs maximum current (1.25 pu), as shown in Figure 6-16 (e) and (f).

Assuming a permanent fault, the DR-HVDC link is operated with half of the rated DC voltage to continuously transmit power through the healthy negative pole and the active power oscillations are adequately damped and acceptable. OWF is capable of detecting DC link faults via observing the disturbance at the offshore AC terminals (without communication use). The system meets the following compliance requirements defined in D3.6:

(1) The system is protected to avoid any damage to equipment during faults.

(2) OWF is capable of staying connected to the network and continuing to operate stably after the (off-shore) power system has been disturbed by secured faults. That capability is in accordance with the voltage against time profile at the connection point.

(3) Limited power can still be transmitted.

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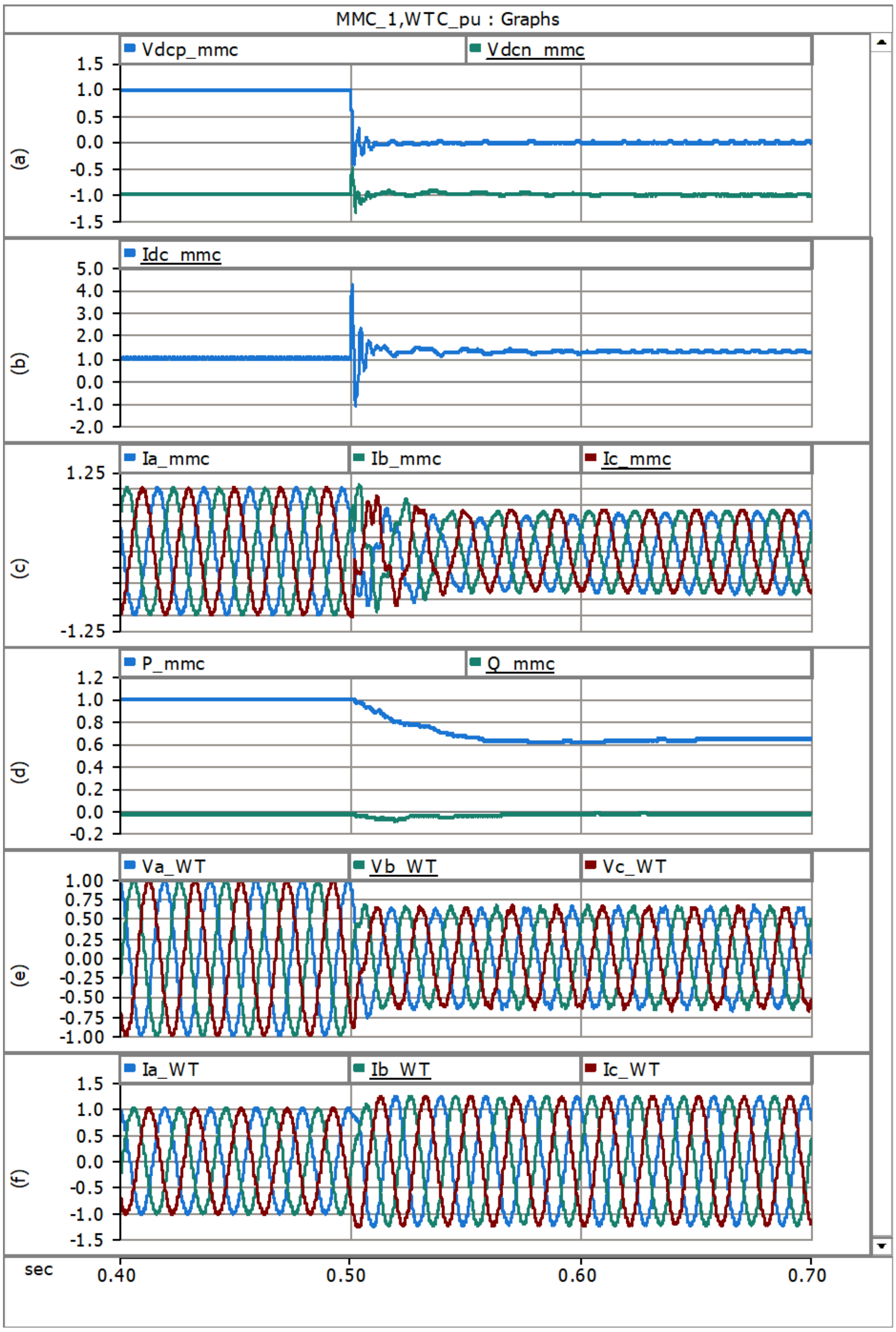

Figure 6-16: Simulation results during positive pole-to-ground DC cable fault in pu terms with full-bridge on-shore MMC station: (a) DC voltage of DR-HVDC link, (b) DC current of DR-HVDC link, (c) three-phase AC currents of onshore MMC, (d) active and reactive powers of WTs, (e) three-phase voltages of WTs, and (f) three-phase currents of WTs.

6.2.1.3 INTERNAL DRU FAULTS

Before the fault, the system operated with 0.6 p.u active power and DRU 1 is suffered an internal fault F3 at *t*=0.5 s, which leads to the short circuit of the DC terminal of DRU 1.

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<table>
<tr><td>Test case</td><td colspan="3">4.3.1.4. INTERNAL DRU FAULT</td></tr>
<tr><td rowspan="4">Simulation detail</td><td>WT</td><td colspan="2">Level 4</td></tr>
<tr><td>OWF</td><td colspan="2">Level 6</td></tr>
<tr><td>On-shore MMC</td><td colspan="2">Level 1</td></tr>
<tr><td>On-shore grid</td><td colspan="2">Level 3</td></tr>
<tr><td></td><td>Configuration (transmitted power level)</td><td>Compliance</td><td>Comments</td></tr>
<tr><td rowspan="2">Simulations (sensitivity analysis)</td><td>WF high power generation</td><td>✓</td><td></td></tr>
<tr><td>WF low power generation</td><td>✓</td><td></td></tr>
<tr><td>Comments</td><td colspan="3">Main criteria for compliance evaluation: Reduced DC voltage and power transmission operation, WF current control</td></tr>
</table>

After the fault initiation, the DC voltage of DRU 1 drops to zero while the DC voltages of the healthy DRUs 2 and 3 remain around the rated value, as shown in Figure 6-17 (a). The DC voltage of the DR-HVDC link is thus reduced to two thirds of the rated DC voltage. Such an internal DRU fault leads to the short circuit of the AC side of the DRU 1 and large currents feed the fault from the WT converters through circuit breaker B_{D1}. B_{D1} experiences overcurrent and thus is opened (assumed at t=0.64 s for illustration) to isolate the fault. However, due to the large fault current and leakage inductance of DRU transformer (0.18 pu), the offshore voltages do not drop significantly during the fault, as seen in Figure 6-17 (c).

After the fault is isolated by B_{D1}, the system is operated with reduced DRUs. The transmitted power autonomously resumes the pre-fault conditions (0.6 pu) and the active power oscillations are adequately damped and acceptable, as shown in Figure 6-17 (e). The WT converters automatically operate on current limiting during the fault and can provide fault currents, which enables the fault detection of breaker B_{D1}. The DRU DC current is slightly over 2 pu as shown in Figure 6-17 (b). however, due to the high overcurrent capability, the DRUs do not suffer overheating problem during the internal DRU faults. The system meets the following compliance requirements defined in D3.6:

(1) The system is protected to avoid any damage to equipment during faults.

(2) OWF is capable of staying connected to the network and continuing to operate stably after the (off-shore) power system has been disturbed by secured faults. That capability is in accordance with the voltage against time profile at the connection point.

(3) Ensure maximum power transmission and fast system recovery.

(4) The offshore wind power could be continuously transferred through the DRU-HVDC but with limited capacity.

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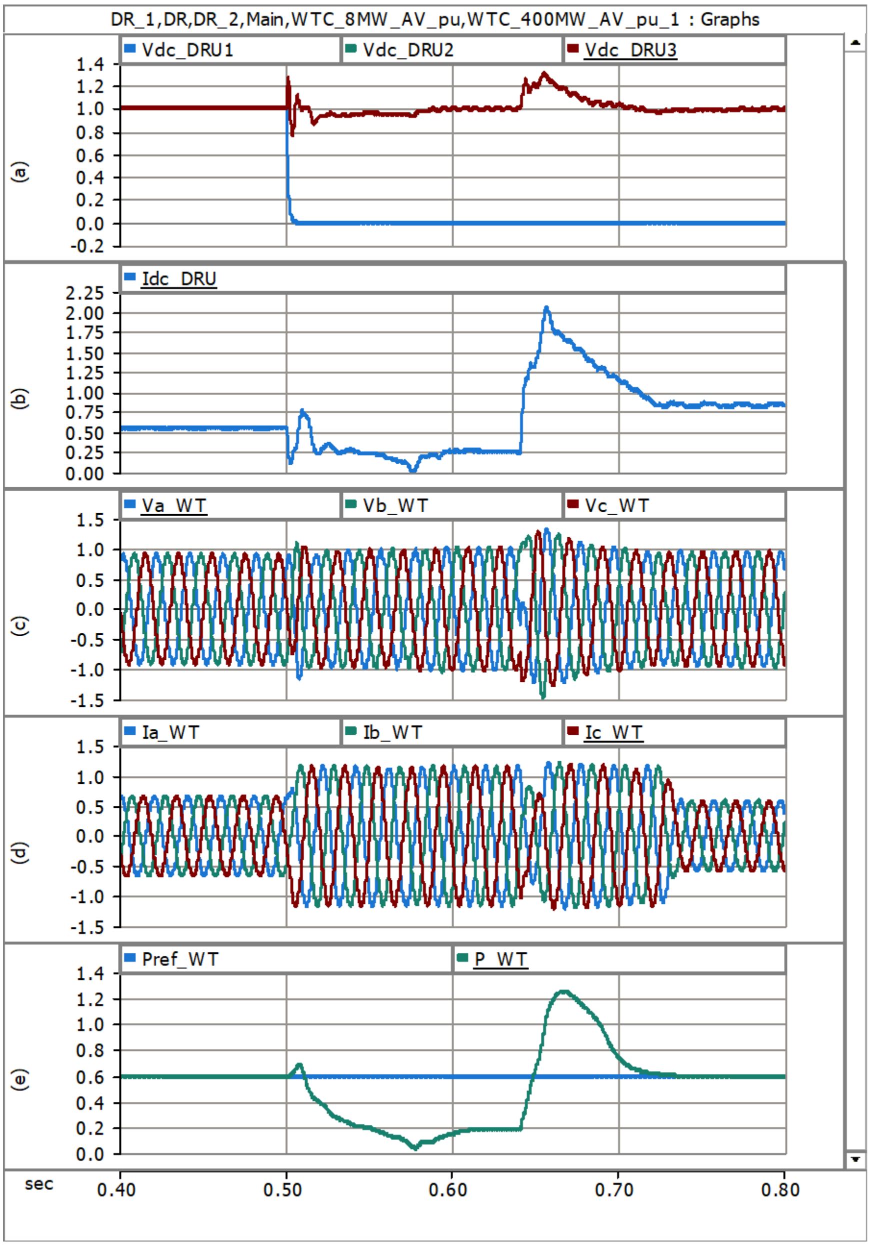

Figure 6-17: Simulation results during internal DRU fault in pu terms: (a) DRU DC terminal voltages, (b) DRU DC current, (c) WT three-phase voltages, (d) WT three-phase currents, and (e) WT active power.

6.2.2 UMBILICAL AC CABLE FAULTS

Compliance evaluation of OWF connected with DRU-HVDC link and umbilical AC cable is conducted by means of simulations based on models of all relevant components as previously described. Symmetrical 3-phase fault are applied at the umbilical AC cable at t=0.2 s and is isolated by breakers B_{umb1} and B_{umb2} at t=0.34 s.

Test case	**4.3.2. UMBILICL AC CABLE FAULT**	
Simulation	WT	Level 4

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detail	OWF	Level 6	
	On-shore MMC	Level 2	
	On-shore grid	Level 3	
	Configuration (transmitted power level)	Compliance	Comments
Simulations (sensitivity analysis)	Fault at onshore terminal	✓	
	Fault at middle of the umbilical AC cable	✓	
	Fault at offshore termial	✓	
Comments	Main criteria for compliance evaluation: WF fault current control, fault protection and isolation, recovery		

Detailed response of the system is examined to evaluate the compliance of the system. After the fault occurs at 0.2 s, the umbilical AC cable voltage drops to 0, as shown in Figure 6-18 (a). Both the fault currents from the WT side (i_{umb1}) and onshore grid side (i_{umb2}) start to increase, as shown in Figure 6-18 (b), (c).

After the fault, the fault currents provided by the WT converters and onshore grid feed to the fault through the circuit breakers B_{Umb1} and B_{Umb2}. By fault detection, breakers B_{Umb1} and B_{Umb2} are assumed to be opened at t=0.34 s to isolate the fault. After 0.34 s, umbilical AC cable transmitted active power and reactive power decrease to 0.

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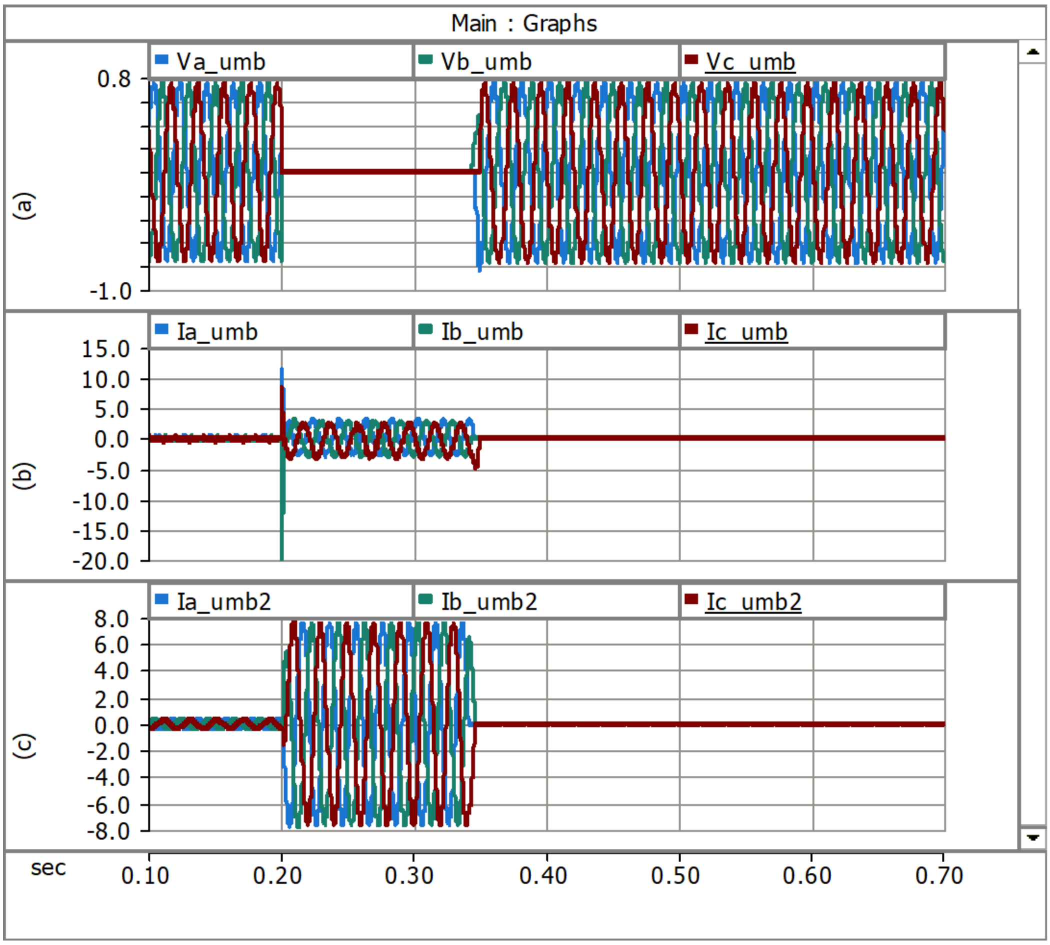

Figure 6-18. Simulation results of WT converter during umbilical AC cable fault in pu terms: (a) three-phase AC voltages, (b) offshore three-phase currents, and (c) onshore three-phase currents,.

The umbilical AC fault also leads to the decrease of the WT AC voltage to around 0.1p.u, as shown in Figure 6-19 (a). Meanwhile, WTs lose the ability to transmit rated power, as the active power control and voltage control saturates, as shown in Figure 6-19 (c). After the fault, WT converters increase the *q*-axis current to provide fault currents whereas the *d*-axis current reduces to avoid overcurrent, as shown in Figure 6-19 (b).

When the umbilical AC cable fault is cleared at 0.34 s, the reactive current starts to decrease with the increase of the active current. Then the active power and AC voltage control start to work again, as shown in Figure 6-19 (a) and (c). The wind power is transmitted to onshore by the DR-HVDC system without the connection of the umbilical AC cable.

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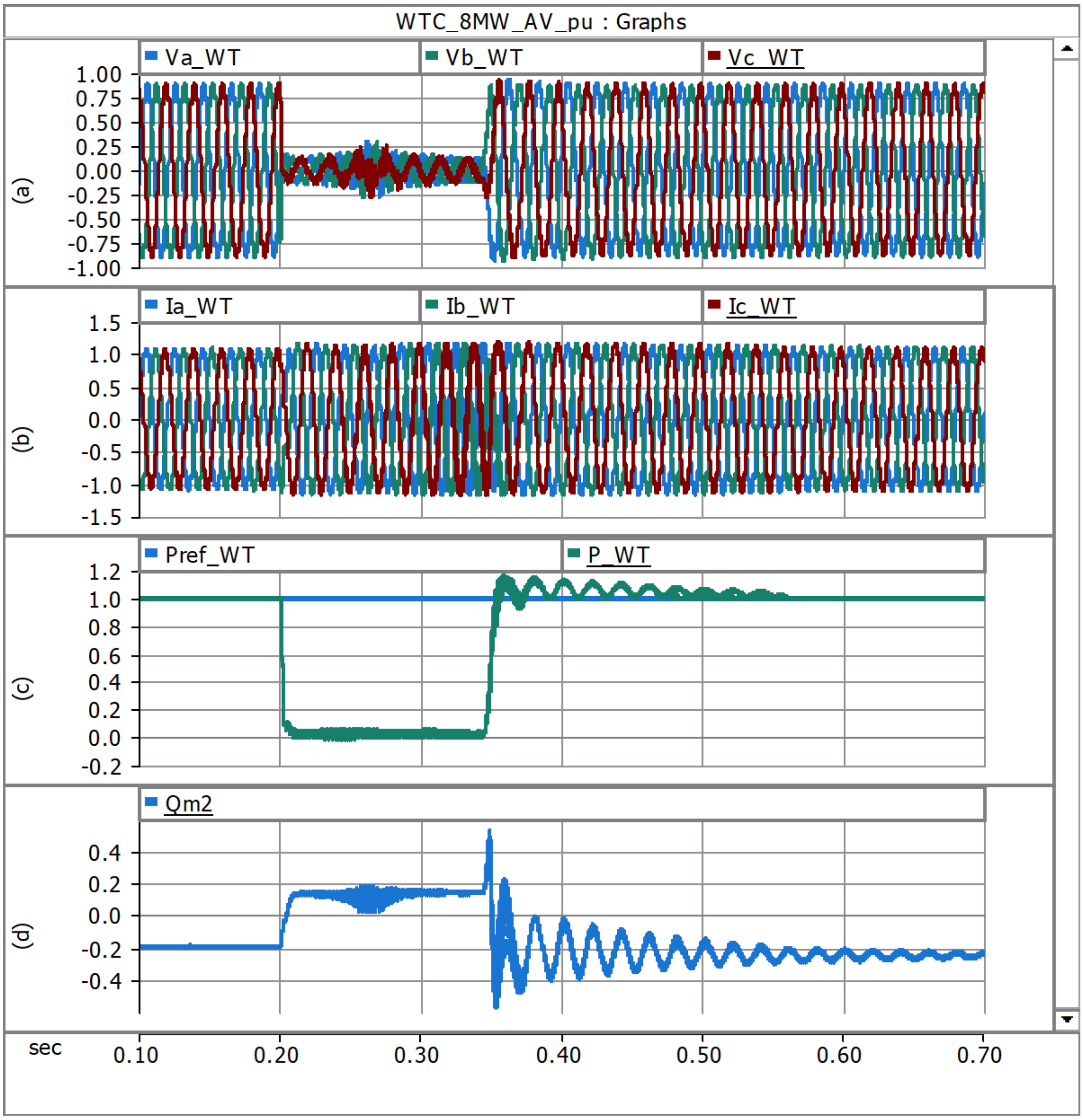

Figure 6-19. Simulation results of WT converter during umbilical AC cable fault in pu terms: (a) three-phase AC voltages, (b) three-phase currents, (c) active power, and (d) reactive power.

As the onshore grid is strong (the impedance of the umbilical AC cable and umbilical cable transformer is much larger than that of the onshore grid), the umbilical AC fault F4 does not have a large impact on the onshore grid voltage, as shown in Figure 6-20 (a). The DC voltage and reactive power is still under control, as shown in Figure 6-20 (c) and (d). The onshore AC current experiences a slight increase during the umbilical AC cable fault, as shown in Figure 6-20 (b). During the fault period, no wind power can be transmitted to the onshore MMC.

When the umbilical AC fault is cleared, the offshore wind power is restored and transmitted through the DR-HVDC, as can be seen from the Figure 6-20 (c).

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The system is robust to the umbilical AC cable fault and then can automatically restore power transmission through the DRU-HVDC, once the faulty umbilical AC cable is isolated. The system meets the following compliance requirements defined in D3.6:

(1) The system is protected to avoid any damage to equipment during faults.
(2) OWF is capable of staying connected to the network and continuing to operate stably after the (off-shore) power system has been disturbed by secured faults. That capability is in accordance with the voltage against time profile at the connection point.
(3) Ensure maximum power transmission and fast system recovery.
(4) The offshore wind power could be continuously transferred through the DRU-HVDC but with limited capacity.
(5) The OWF is capable of returning the active power from a limited operating point to the pre-event active power level minus 10% (e.g. 100% -10% = 90%) with a ramp rate of 200%/s.
(6) OWF is capable of providing fast fault current (start within 20ms after fault detection) at the connection point and delivering additional reactive current supporting voltage retention.

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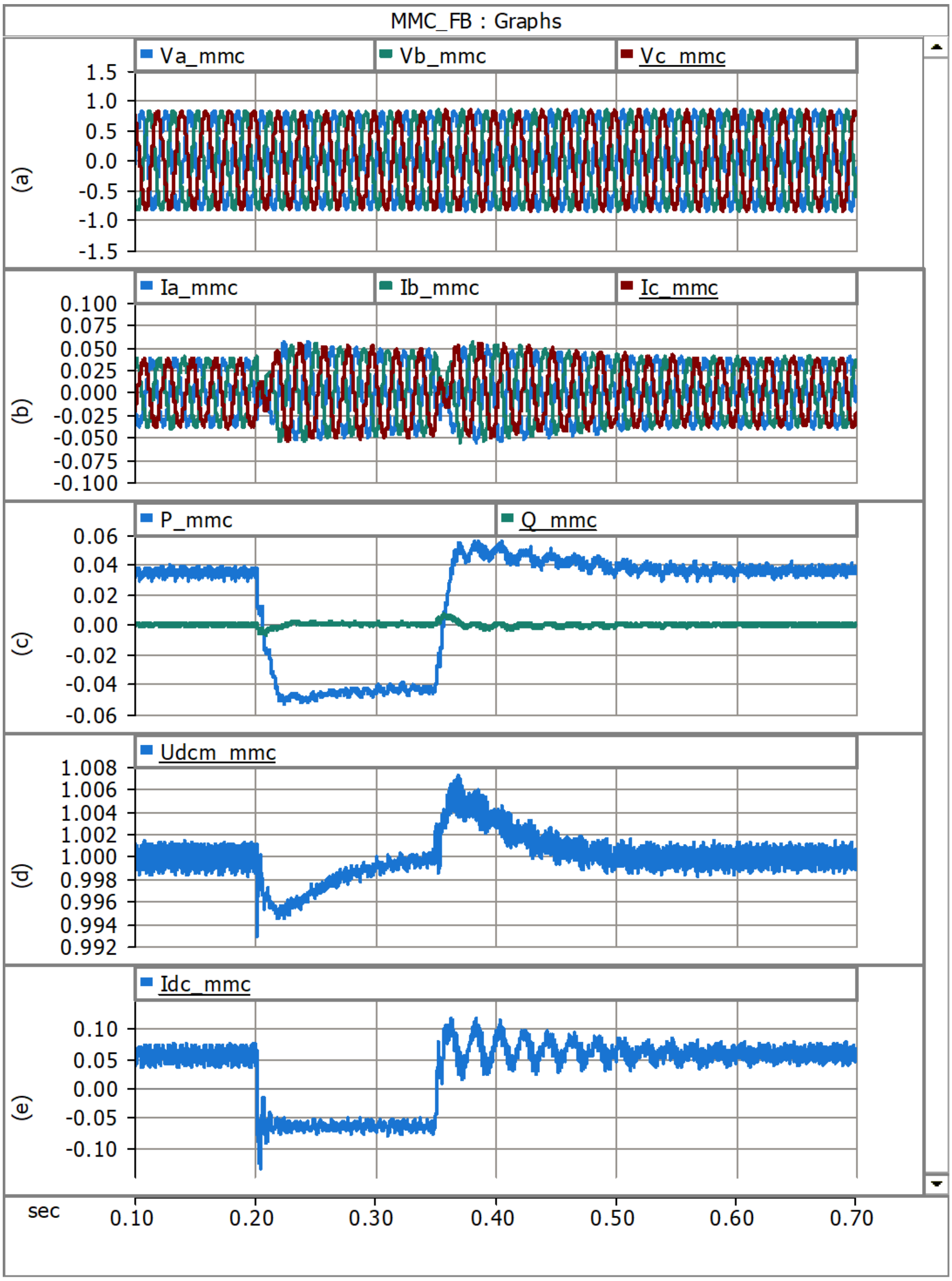

Figure 6-20. Simulation results of onshore MMC during umbilical AC cable fault in pu terms: (a) three-phase AC voltage, (b) three-phase AC currents, (c) active and reactive powers, (d) DC voltage, and (e) DC current.

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6.2.3 OFFSHORE AC FAULTS

6.2.3.1 SYMMETRICAL OFFSHORE AC FAULTS

Compliance evaluation of OWF is conducted by means of simulations based on models of all relevant components as previously described. A symmetrical 3-phase fault is applied in the offshore AC network at t=0.5 s and is isolated by breakers B_{B13} and B_{B31} at t=0.64 s.

Test case	**4.3.3.a. SYMMETRICAL OFFSHORE AC FAULT**		
Simulation detail	WT	Level 4	
	OWF	Level 3	
	On-shore MMC	Level 2	
	On-shore grid	Level 3	
	Configuration (transmitted power level)	Compliance	Comments
Simulations (sensitivity analysis)	WT string fault	✓	
	WT cluster ring cable fault	✓	
	DRU AC busbar fault	✓	
Comments	Main criteria for compliance evaluation: WF fault current control, fault protection and isolation, recovery, DC voltage control		

Detailed response of both the OWF and the DRU HVDC connection is examined to evaluate the compliance of the system. After fault occurrence, the WT converters reduce the active currents while increase the reactive currents to provide fast fault currents, which enable overcurrent fault detection and support the offshore AC voltage [Li 2019], as shown in Figure 6-21 (b) and (a), respectively. The WT converters operate in current-limiting mode and do not experience overcurrent, thus, the OWF is capable of staying connected to the network and continuing to operate stably during the fault.

AC circuit breakers B_{B13} and B_{B31} open at t=0.64 s to isolate the fault and then the offshore voltage quickly restores and the voltage profile is shown in Figure 6-21 (a). As there is no connection to the onshore AC (i.e. DR state), the voltage profile depends on the response of the WTGs and the offshore voltage quickly resumes, as shown in Figure 6-21 (a), much faster than that outlined in Figure 1. As showed in Figure 6-21 (c), the OWF is capable of quickly returning the active power from the limited operating point to the pre-fault active power level. Active Power oscillations is adequately damped and acceptable. The system meets the following compliance requirements defined in D3.6:

(1) The system is protected to avoid any damage to equipment during faults.

(2) OWF is capable of staying connected to the network and continuing to operate stably after the (off-shore) power system has been disturbed by secured faults. That capability is in accordance with the voltage against time profile at the connection point.

(3) Ensure maximum power transmission and fast system recovery.

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(4) The offshore wind power could be continuously transferred through the DRU-HVDC but with limited capacity.

(5) The OWF is capable of returning the active power from a limited operating point to the pre-event active power level minus 10% (e.g. 100% -10% = 90%) with a ramp rate of 200%/s.

(6) OWF is capable of providing fast fault current (start within 20ms after fault detection) at the connection point and delivering additional reactive current supporting voltage retention.

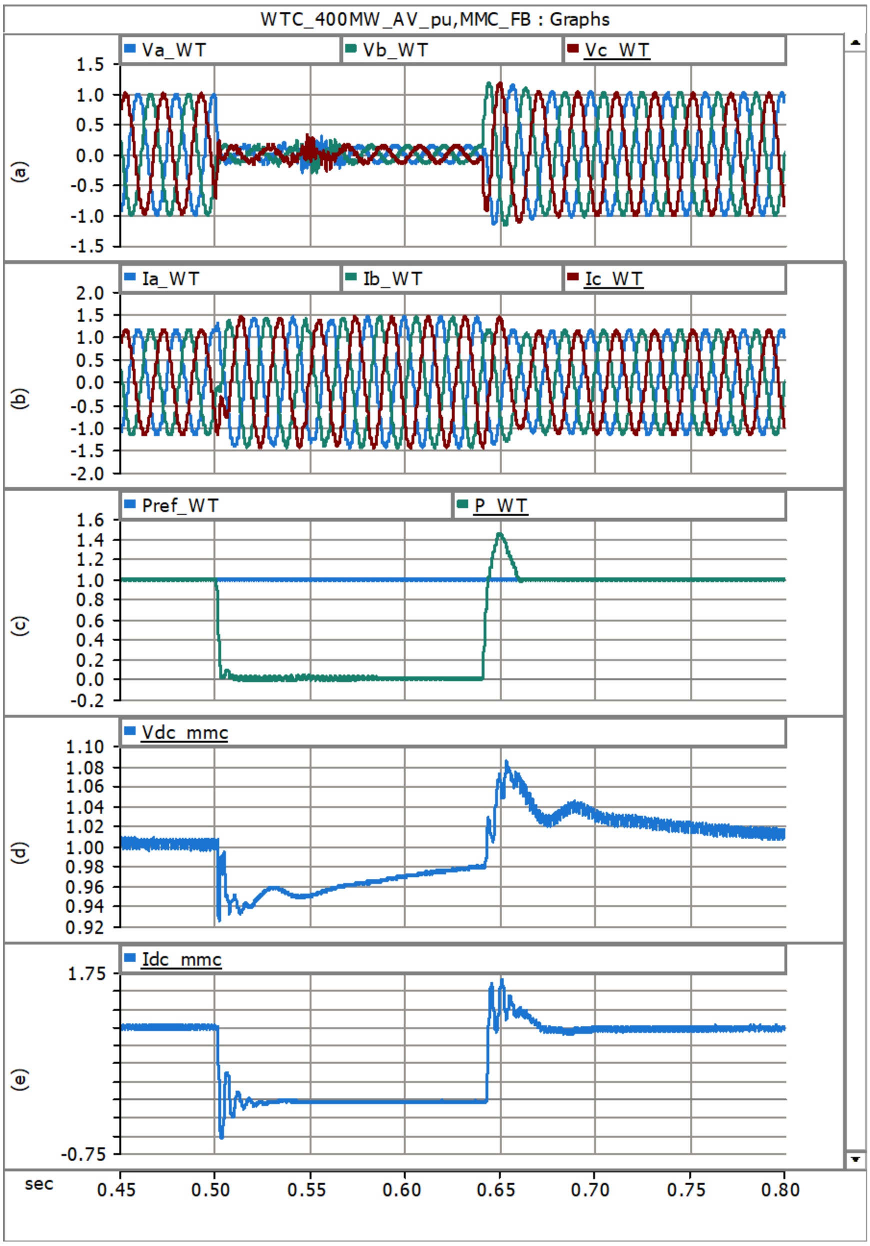

Figure 6-21: Simulation results during symmetrical offshore AC fault at cluster interconnection cable in pu terms: (a) WT three-phase voltages, (b) WT three-phase currents, (c) WT active power, (d) DC voltage of DRU-HVDC link, and (e) DC current of DRU-HVDC link.

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6.2.3.2 ASYMMETRICAL OFFSHORE AC FAULTS

To evaluate the compliance of the DR-HVDC system in the event of an offshore asymmetrical AC fault, a solid ground fault is applied at phase *a* of the cluster interconnection cable at t=0.5 s and is isolated by breakers B_{B13} and B_{B31} at t=0.64 s. An additional negative-sequence current controller is developed to suppress the active power ripple.

Test case	**4.3.3.b. ASYMMETRICAL OFFSHORE AC FAULT**		
Simulation detail	WT	Level 4	
	OWF	Level 3	
	On-shore MMC	Level 2	
	On-shore grid	Level 3	
	Configuration (transmitted power level)	Compliance	Comments
Simulations (sensitivity analysis)	WT string fault –single phase	✓	
	WT string fault –phase to phase	✓	
	WT cluster ring cable fault – single phase	✓	
	WT cluster ring cable fault – phase to phase	✓	
	DRU AC busbar fault – single phase	✓	
	DRU AC busbar fault – phase to phase	✓	
Comments	Main criteria for compliance evaluation: WF fault current control, negative sequence current control, reduced power generation, fault protection and isolation, recovery, DC voltage control		

After the fault, the offshore grid side voltages of the faulty phase drop to zero while Figure 6-22 (a) shows the WT converter side voltages, which exhibit different fault behaviour with grid side voltages. The peaks of the three-phase currents of the WT converters are around 1.5 pu, as displayed in Figure 6-22 (b). As shown in Figure 6-22 (c), the second-order oscillation of the active power is effectively suppressed by the negative-sequence controller.

During the tested asymmetrical offshore fault, the WT FECs do not experience significant overvoltage and overcurrents (1.2 pu and 1.5 pu respectively). The whole system automatically restores normal operation after fault isolation and the active power oscillations are adequately damped and acceptable. The system meets the following compliance requirements defined in D3.6:

(1) The system is protected to avoid any damage to equipment during faults.
(2) OWF is capable of staying connected to the network and continuing to operate stably after the (off-shore) power system has been disturbed by secured faults. That capability is in accordance with the voltage against time profile at the connection point.
(3) Ensure maximum power transmission and fast system recovery.

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(4) The offshore wind power could be continuously transferred through the DRU-HVDC but with limited capacity.
(5) The OWF is capable of returning the active power from a limited operating point to the pre-event active power level minus 10% (e.g. 100% -10% = 90%) with a ramp rate of 200%/s.
(6) OWF is capable of providing fast fault current (start within 20ms after fault detection) at the connection point and delivering additional reactive current supporting voltage retention.

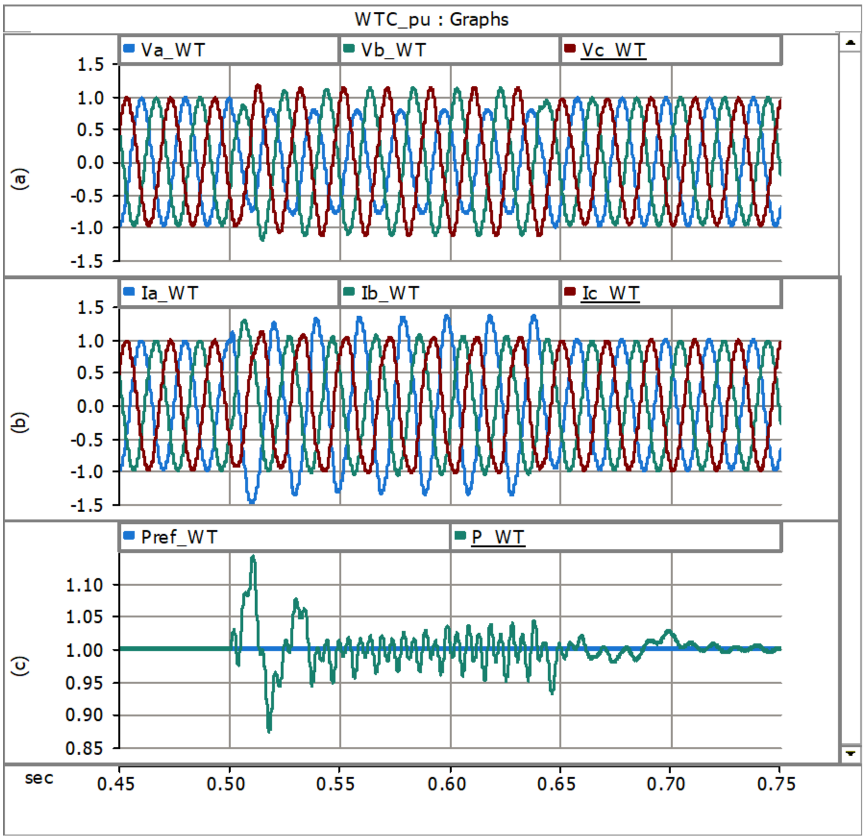

Figure 6-22: Simulation results during asymmetrical offshore AC fault at cluster interconnection cable in pu terms: (a) WT three-phase voltages, (b) WT three-phase currents, (c) WT active power.

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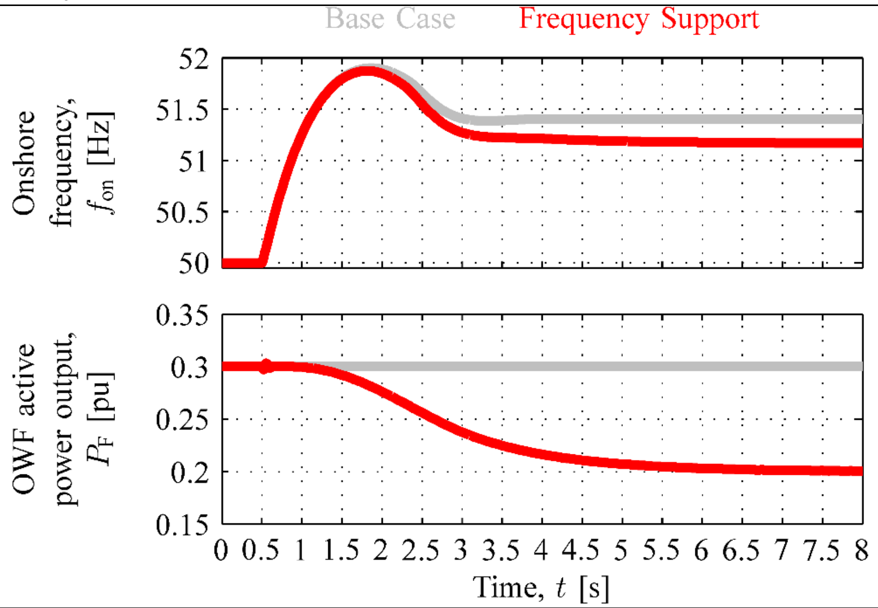
6.3. ANCILLARY SERVICES

6.3.1 ONSHORE FREQUENCY SUPPORT

6.3.1.1 ONSHORE OVERFREQUENCY EVENT

Test case	ONSHORE OVERFREQUENCY EVENT		
Simulation detail	WT	Level 4	
	OWF	Level 6	
	Onshore MMC	Level 2	
	Onshore grid	Level 3	
	Configuration (available power)	Compliance	Comments
Simulations (sensitivity analysis)	100%	✓	
	70%	✓	
	40%	✓	
Comments	Closed-loop tests; 10% of the nominal active power reserved by curtailed operation; onshore frequency, f_{on}, communicated to the OWF with a delay of 100 ms		
Sample results			

The sample results (red traces) show that the OWF is able to support the onshore ac network during an onshore overfrequency event at low wind speed (i.e. 40% of the nominal power available). Base case results (grey traces) with no support from the OWF are included for comparison.

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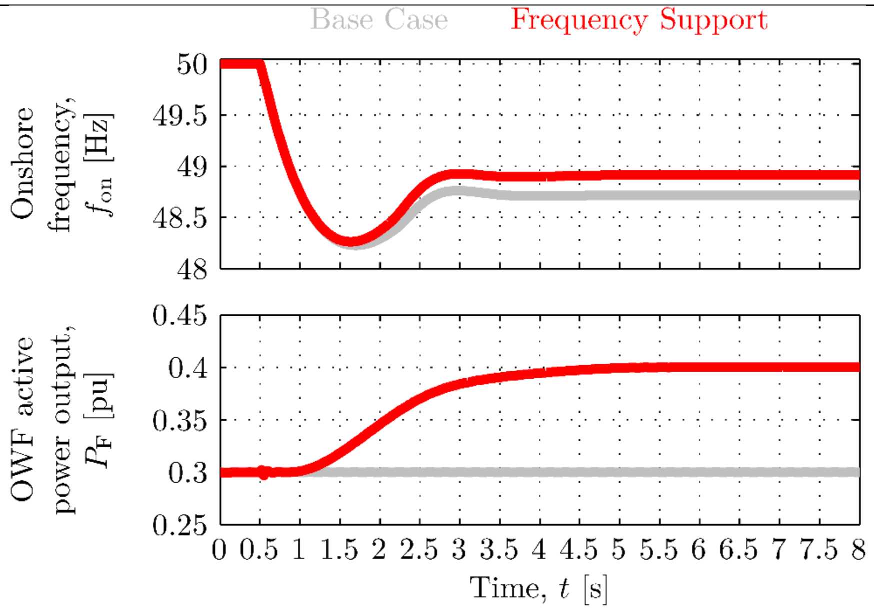
6.3.1.2 ONSHORE UNDERFREQUENCY EVENT

Test case	ONSHORE UNDERFREQUENCY EVENT		
Simulation detail	WT	Level 4	
	OWF	Level 6	
	Onshore MMC	Level 2	
	Onshore grid	Level 3	
	Configuration (available power)	Compliance	Comments
Simulations (sensitivity analysis)	100%	✓	
	70%	✓	
	40%	✓	
Comments	Closed-loop tests; 10% of the nominal active power reserved by curtailed operation; onshore frequency, f_{on}, communicated to the OWF with a delay of 100 ms		
Sample results			

The sample results (red traces) show that the OWF is able to support the onshore ac network during an onshore underfrequency event at low wind speed (i.e. 40% of the nominal power available). Base case results (grey traces) with no support from the OWF are included for comparison.

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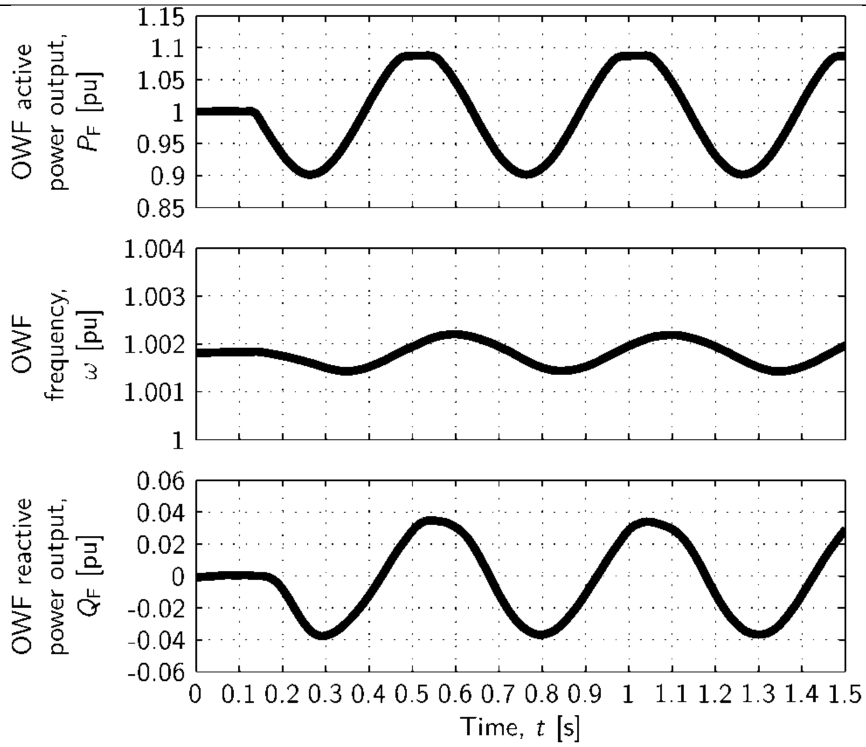
6.4. ONSHORE POWER OSCILLATION DAMPING

Test case	ONSHORE POWER OSCILLATION DAMPING			
Simulation detail	WT		Level 4	
	OWF		Level 6	
	Onshore MMC		Level 2	
	Onshore grid		Level 3	
	Configuration		Compliance	Comments
	Available power	Modulating frequency		
Simulations (sensitivity analysis)	100%	0.3 Hz	×	OWF active power output saturates below 110% when the WT front-end converter output currents hit their 110% limit
		1 Hz	×	
		2 Hz	×	
	60%	0.3 Hz	✓	
		1 Hz	✓	
		2 Hz	✓	
	40%	0.3 Hz	✓	
		1 Hz	✓	
		2 Hz	✓	
	12.5%	0.3 Hz	✓	OWF active power output saturates above 0 when the DRs stop conducting
		1 Hz	✓	
		2 Hz	✓	
Comments	Open-loop tests; 0% of the nominal active power reserved by curtailed operation; sinusoidal active power *modulating* signal with a magnitude of 10% of the nominal active power and fixed frequency			

Sample results



The sample results show the OWF active power output at high wind speed (i.e. 100% of the nominal power available) oscillating with a *modulating* frequency of 2 Hz and saturating below 110% when the WT front-end converter output currents hit their 110% limit.

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7. DRU CONTROLLER DISCUSSION AND CONCLUSIONS

The detailed validation of the DRU-enabled WTG and WPP controllers has been carried out in this part, considering the functional requirements stated in deliverable D3.1, the scenarios defined in deliverable D3.2 and the controllers included in deliverable D3.4.

The performance of the considered controllers has been validated during normal operation (umbilical start-up, islanded, DRU-connected, power transients, etc) and during faults (off-shore, on-shore, HVDC cable, etc). The operation of a DRU-connected WPP when providing ancillary services has also been shown (frequency support, power oscillation damping).

Therefore, these detailed simulation studies represent the first phases for a full DRU-enabled WTG controller validation.

The results presented here will be extended in WP16 where real-time CHiL validation will be carried out.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691714.

8. BIBLIOGRAPHY

PROMOTioN H2020 Project Deliverable 3.1 *"Detailed functional requirements to WPPs".* Dec 2016. https://www.promotion-offshore.net/fileadmin/PDFs/ D3.1_PROMOTioN_Deliverable_3.1_Detailed_functional_requirements_to_WPPs.pdf

PROMOTioN H2020 Project Deliverable 3.2 *"Specifications of the control strategies and the simulation test cases".* April 2017. https://www.promotion-offshore.net/fileadmin/PDFs/ D3.2_Specifications_Control_strategies_and_simulation_test_cases.pdf

PROMOTioN H2020 Project Deliverable 3.4 *"Results on control strategies of WPPs connected to DR-HVDC"* Jan 2018. https://www.promotion-offshore.net/fileadmin/PDFs/ D3.4_PROMOTioN_Results_on_control_strategies_of_WPPs_connected_to_DR-HVDC.pdf

PROMOTioN H2020 Project Deliverable 3.5 *"Performance of ancillary services provision from WFs connected to DR-HVDC"*. Jan 2018. https://www.promotion-offshore.net/fileadmin/PDFs/ D3.5_PROMOTioN_Performance_of_ancillary_services_pro-vision_from_WFs_connected_to_DR-HVDC.pdf

PROMOTioN H2020 Project Deliverable 3.6 *"Report with the compliance test procedures for DR and VSC connected WPPs"*. Dec 2018. https://www.promotion-offshore.net/fileadmin/PDFs/ D3.6_Report_with_the_compliance_test_procedures_for_DR_and_VSC_connected_WPPs.pdf

[Li 2019] R. Li, L. Yu, and L. Xu, 'Offshore AC Fault Protection of Diode Rectifier Unit-Based HVdc System for Wind Energy Transmission', *IEEE Transactions on Industrial Electronics*, vol. 66, no. 7, pp. 5289–5299, Jul. 2019.

[Martinez-Turegano 2018] J. Martinez-Turegano, S. Añó-Villalba, S. Bernal-Pérez, R. Peña, and R. Blasco-Gimenez, 'Mixed Grid Forming and Grid Following Wind Power Plants for Black Start Operation', in *17th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants*, Stockholm, 2018.

[Sakamuri 2019] J. N. Sakamuri, Ö. Göksu, A. Bidadfar, O. Saborío-Romano, A. Jain, and N. A. Cutululis, "Black Start by HVdc-connected Offshore Wind Power Plants," in *IECON 2019 - 45th Annual Conference of the IEEE Industrial Electronics Society*, 2019.

[Xiang 2018] W. Xiang, W. Lin, L. Xu, and J. Wen, 'Enhanced Independent Pole Control of Hybrid MMC-HVdc System', *IEEE Transactions on Power Delivery*, vol. 33, no. 2, pp. 861–872, Apr. 2018,

[Yu 2018] L. Yu, R. Li, and L. Xu, "Distributed PLL-based Control of Offshore Wind Turbine Connected with Diode-Rectifier based HVDC Systems," *IEEE Trans. Power Deliv.*, vol. 33, no. 3, pp. 1328–1336, 2018.

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APPENDIX

HVAC CONNECTED WIND FARM SIMULATION MODEL PARAMETERS FOR BLACK START STUDIES

This section includes a list of model parameters of the OWPP connected via a HVAC export cable. In addition, the simulation model parameters described in Deliverable 3.1 and 3.2 should be considered.

HVAC CABLE

The HVAC cable connects the OWPP with the on-shore grid.

Table 1: Cable parameters.

Parameters	Value
Power	400 MW
Frequency	50 Hz
Rated voltage	220 kV
Maximum admissible voltage	245 kV
Conductor cross-section	1000 mm^2
Conductor material	Copper
Insulation material	XLPE
Armour material	Steel
Diameter of conductor	37.9 mm
Insulation thickness	23.0 mm
Diameter over insulation	87.3 mm
Lead sheath thickness	3.1 mm
Outer diameter of the cable	241.0 mm
Capacitance	0.19 µF/km
Charging current per phase at 50 Hz	7.4 A/km
Inductance	0.38 mH/km
Distance	75 km

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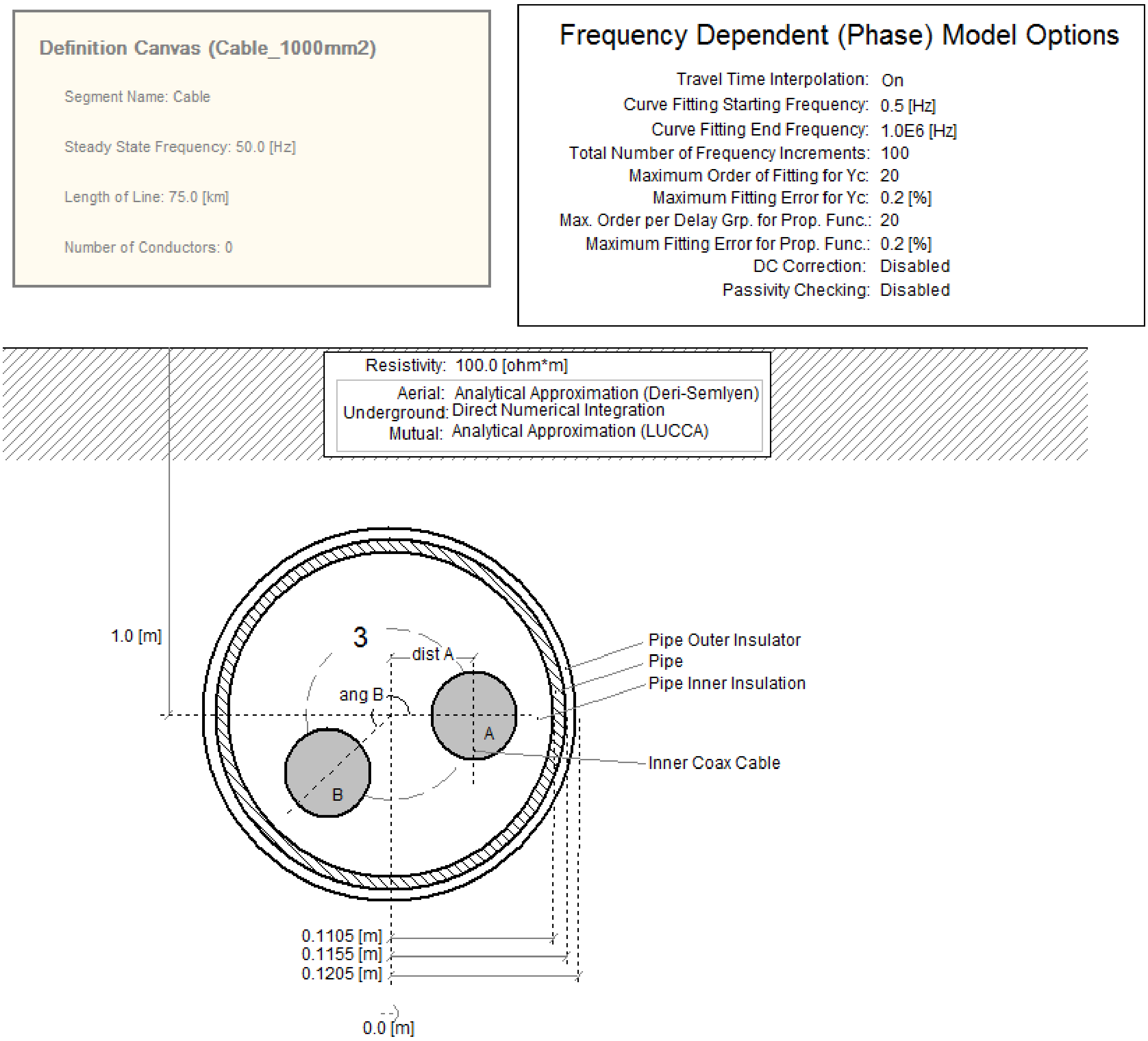

Figure 0-1: model of cable used to power transmission.

SHUNT REACTORS

Shunt reactors are connected at both ends of the HVAC cable. Each shunt reactor compensates 40 % of the reactive power of the HVAC cable. The parameters are listed below.

Table 2: Shunt reactors parameters.

Parameters	Value
Apparent Power	80 MVA
Voltage	220 kV
Reactance	1.92 H
Resistance	-

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TRANSFORMERS

The parameters of the WT transformer, and the off-shore and on-shore transformers that are connected to the HVAC cable are listed below.

Table 3: WT transformer parameters.

Parameters	Value
Apparent Power	9.2 MVA
Winding 1	0.69 kV
Winding 2	66 kV
Transformer ratio N	66/0.69
Frequency	50 Hz
Leakage reactance	0.1 %
No load losses	0.03 %
Copper losses	0.4 %
Magnetising current	0.2 %
Inrush decay time constant	2 s

Table 4: Off-shore transformer parameters.

Parameters	Value
Apparent Power	460 MVA
Winding 1	66 kV
Winding 2	220 kV
Transformer ratio N	220/66
Frequency	50 Hz
Leakage reactance	0.1 %
No load losses	0.03 %
Copper losses	0.4 %
Magnetising current	0.2 %
Inrush decay time constant	5 s

Table 5: On-shore transformer parameters.

Parameters	Value
Apparent Power	460 MVA

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Winding 1	220 kV
Winding 2	400 kV
Transformer ratio N	400/220
Frequency	50 Hz
Leakage reactance	0.1 %
No load losses	0.03 %
Copper losses	0.4 %
Magnetising current	0.2 %
Inrush decay time constant	5 s

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