COMPOSITE TESTING OF HVDC-CONNECTED OFFSHORE WIND FARMS

Report prepared by RTE international

For The National HVDC Centre

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EXECUTIVE SUMMARY

It is expected that offshore wind farms could generate enough electricity to power every home in the UK by 2030. This follows the UK Government's ambition to achieve a four-fold increase in installed offshore wind capacity 40GW by 2030 up from 10GW in 2020, and rising to 80GW by 2050.

Integrated High Voltage Direct Current (HVDC) and High Voltage Alternating Current (HVAC) electricity connections that are technically efficient, coordinated and interoperable will be required to link the offshore wind generation to onshore grids. However, composite testing of the transmission and generation equipment supplied by different manufacturers will be needed to de-risk the integration of complex connections into the existing electricity infrastructure.

To start to address these technical challenges the HVDC Centre, with the support of the ESO connections team, commissioned the COMPOSITE project with RTE international (RTE-I) to identify practical guidelines and best practices for composite testing and compliance of complex electricity connections, leveraging the experience we share across multi-vendor and multi-device testing we have delivered.

The **key findings** from the COMPOSITE project are:

- HVDC systems are becoming more complex, with more variation in controls, protection, and co-ordination performance across more devices;
    - This means that the potential for control interaction and protective action that can occurs when these controls conflict increases with the layers of devices and functions asked of the overall system. Individual tests of individual devices cannot capture the operating states of the other contributing devices prior to and following disturbances that define the overall system performance. Perfectly compliant individual devices may perform inappropriately when combined with other equally compliant devices, driving specific control damping solutions.
    - Compliance is currently defined as an onshore interface measure, however within designs involving multiple projects offshore, the role each one plays in a given function is important; as such it is important for this function to be defined, and also for the expected performance expectations offshore to be made clear- this is an area where offshore Grid codes may become increasingly important.
- Simulation and Tests of this nature are becoming increasingly important, using a range of off-line and real-time tools and analytical techniques;
    - Hosted environments can support this whether off-line or physical, and need to capture the extent of relevant devices and their relevant functions that describe their performance for a given type of event or service such as frequency response- it can be the case different models are needed to be combined to test different behaviours- there is not a "one-size fits all" the models used depend on the situation being studied
- These system studies and technical de-risking activities should be done across a range of potential operating points, and at key points in the design and commissioning of projects; and
- Each simulation tool has pros and cons; different tools are appropriate to study different phenomena at the various stages of a project's development cycle, to effectively de-risk project interoperability.
    - Control systems have different characteristics and priorities at different operating points

To enable composite testing on a complex (i.e. multi-vendor and/or multi-device) project, the following **key recommendations** are made:

- **Developing approaches for managing the exchange of confidential models:** to facilitate the testing of complex connections comprising representation of equipment control and protection systems, electricity network data and wide area supervisory/monitoring schemes;
- **Demonstration-at-scale of different composite testing arrangements:** that are flexible, re-configurable and portable would enable efficient testing of multi-device connections across all project stages from inception to operation;
- **Establishing offshore network technical requirements and codes:** with mechanisms on interoperability testing and demonstration would ensure transmission and generation equipment/components supplied by different manufacturers work together across project lifecycle; and
- **Co-creating operational simulators:** based on real-time arrangements capable of replaying day in a life expected or encountered operation, would facilitate control room operator training, enable refinement of operation and control approaches for complex connections, and support diagnosis of network events.

The technical analysis underpinning the key findings and recommendations from this COMPOSITE project are described in this report.

GLOSSARY

Code	Description
C&P	Control and Protection
DC	Direct Current
EMT	ElectroMagnetic Transient
HV	High Voltage
HVDC	High Voltage Direct Current
HIL	Hardware In the Loop
Hz	Hertz
IP	Intellectual Property
MMC	Modular Multilevel Converter
OWF	Offshore Wind Farm
R&D	Research & Development
SM	Sub-module
TSO	Transmission System Operator
VSC	Voltage Source Converter

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1. INTRODUCTION

Offshore transmission solutions will need to increase significantly in Great Britain (GB) to meet the government targets for achieving up to 40 GW installed offshore wind capacity by 2030, and beyond 75GW by 2050 [1]-[2]. Transmission connections to offshore wind generation typically consist of multiple technologies supplied by different manufacturers with each tested at the factory, but there is no composite modelling and testing capability currently available in GB, for complex designs and combined solutions.

The National HVDC Centre has been requested to support follow on work between National Grid Electricity System Operator and SHE Transmission, with an activity focusing on composite testing of HVDC-connected offshore generation.

RTE-I, in collaboration with HVDC Centre, has been requested to undertake studies as part of this activity. Based on RTE/RTE-i experience, recommendations for EMT studies at each project stage and list of dynamic studies that should be performed are provided. The report illustrates dynamic phenomena and HVDC system performances. The report provides a methodology to conduct EMT studies over the lifetime of a project based on Cigré recommendations.

Chapter 2 provides an overview on the main power circuit equipment for HVDC-OWF system. In Chapter 3 an overview on the different dynamic tools commonly used for each study in HVDC-OWF project application is provided. Chapter 4 describes Electromagnetic Transient (EMT) modelling types that are commonly used for dynamic studies of HVDC installation. Chapter 5 illustrates the type of studies to be performed in EMT tools at each project phase and the associated input data and modelling tools required to support the analysis. In Chapter 6 generic system study of a HVDC-OWF is provided that highlight the general performance and sensitivity of model parameters on HVDC performances. The last Chapter 7 provides a description of EMT studies based on RTE/RTE-I real project at different stage of an HVDC project.

2. OVERVIEW ON HVDC-OWF SYSTEM

2.1. Introduction

This chapter provides an overview on the HVDC-OWF system for dynamic studies. It introduces the voltage-sourced converter (VSC) based on the Modular-Multilevel Converter (MMC) for high-voltage DC transmission (VSC-HVDC) system, with emphasis on the VSC-HVDC link configuration for integration of the offshore wind power plant (WPP) in the onshore AC power grid and describes the main equipment of the VSC-HVDC link in the context of HVDC-OWF system.

2.2. HVDC-OWF configuration

Up to now, the installed HVDC-OWF systems are all based on point-to-point with symmetrical monopolar configuration, as illustrated in Figure 2-1.

Several HVDC-OWF system configurations can exist, such as bipolar configuration, multi-infeed connection or multiterminal DC grid. Several investigations and feasibility studies are currently undertaken by TSOs to evaluate, upgrade and or built such different types of configuration. It should be noted that several DC grids based on VSC technology, are in operation such as Zhoushan Project and Nan'ao Island or under-construction such as Ultranet Project.

This work will focus on the most common HVDC configuration. Nevertheless, the expected outcome from this work is also valid for other configurations.

VSC based on Modular Multilevel Converter (MMC) topology has become the most attractive solution, mainly due to their higher performances and lower cost. This work will focus on the MMC topology with half-bridge sub-modules that is the most common topology used for rated power higher than 500 MW and for the upcoming projects.

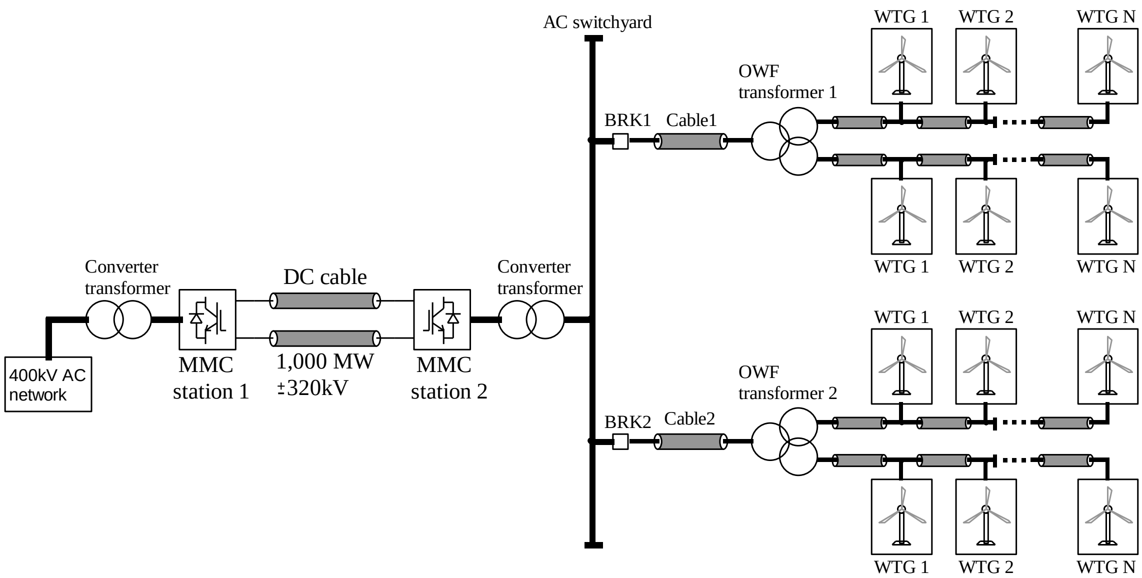


Figure 2-1 : Overview of HVDC-OWF system

2.3. Main electrical component overview

The following sections provide a general description of the main HV equipment that constitutes the HVDC-OWF system.

2.3.1. MMC station (onshore and offshore)

A converter station includes several HV equipment that should be considers for dynamic studies [1]. The typical symmetrical monopolar converter with a half-bridge MMC type is illustrated in Figure 2-2. The main components of a MMC station are presented as well. Depending on project specification and manufacturers, some of the components may be different and/or found at different locations, such as pre-insertion resistor, high impedance grounding, etc.

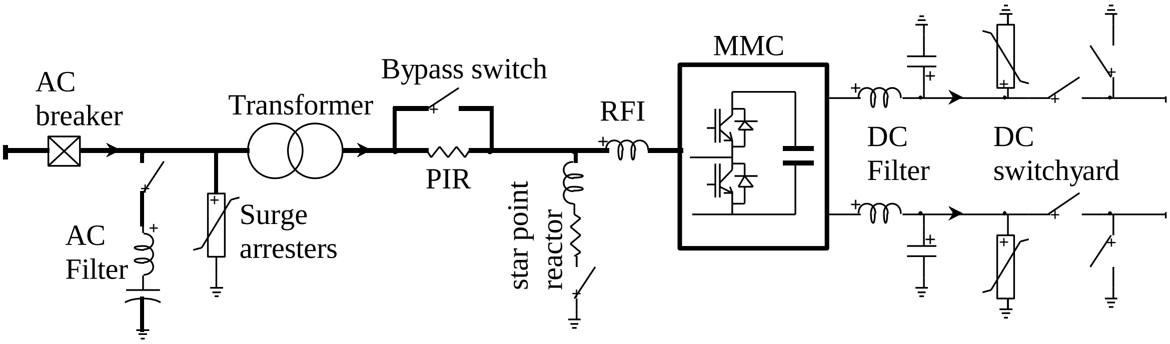


Figure 2-2 : Converter station layout

Each converter station is mainly composed of:

- Main AC breaker that allows connecting and disconnecting the converter station to the ac grid or offshore wind farm. Synchronizing switching controllers can be used to limit inrush currents when converter transformers are energized.
- Power transformer connected in YD or in YYd (with surge arresters in the neutral of the secondary winding side). The transformer converts the AC system voltage to the voltage of the converter. The transformers are typically three single-phase two-winding transformers. A tertiary winding may also be included to provide auxiliary power to the converter station from the AC system.
- Pre-insertion resistance (PIR) in parallel with a bypass switch installed between the converter and the transformer or at the transformer primary side at onshore station. The insertion resistance is used during start-up sequence to prevent inrush current during capacitor charging of the converter. During normal operation, this resistance is bypassed by the bypass switch.
- A star point reactor composed of high impedance of inductances and resistances to get a reference to ground. Depending on manufacturer and project specifications, this reference to ground is replaced by a reactor in the neutral of secondary side of the transformer.
- AC/DC converter using the MMC technology with half bridge power module.
- Several surge arresters are installed at AC and DC sides to meet the insulation coordination requirements.
- Depending on manufacturer and project specifications, AC and DC filters can be included to meet harmonic requirements.
- To prevent high frequency (HF) harmonics in the converter valves spreading to the switchyard and the connected AC network, a radio frequency interference (RFI) filter can be introduced on the AC side as close as possible to the valve area. The RFI filter may consist of a low-LC filter (inductance capacitor) connected between the AC bus and earth and an AC line filter reactor. Radio frequency filters are not needed on the DC side if the transmission consists of a shielded DC cable.
- AC and DC disconnectors and earthing switches are usually installed at each electrical HV nodes to earth the system for maintenance safety. It is also possible to install a

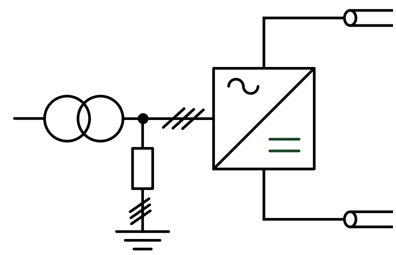
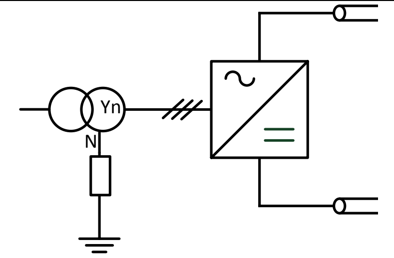
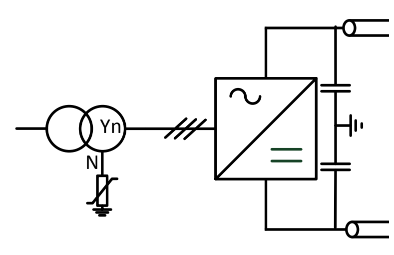
resistance in series with the DC disconnector to discharge DC cable by avoiding voltage polarity reversal and reduce transient cable stresses.

- For OWF application, a DC chopper at onshore station is installed to limit DC overvoltage during onshore events.
- It should be highlighted that several measurement devices such as CT and VT are installed in the converter station to provide monitoring/feedback for Control and Protection (C&P) system.

2.3.1.1. HVDC grounding system

In a HVDC symmetrical monopolar configuration, AC and DC converter side does not have a reference to ground, therefore a specific HVDC grounding system is required. Depending on project specifications and manufacturers, different grounding system are commonly used. In Table 2-1, the three main configurations are presented. It should be noted that a fourth solution including a zig-zag transformer at converter AC side is technically possible. Nevertheless, such configuration is not yet used in current VSC installations due to higher cost.

Table 2-1 : HVDC grounding system configurations

a) 3-phase start point reactor	b) 1-phase start point reactor	c) DC capacitors and AC surge arresters
		

2.3.1.2. MMC overview

Figure 2-3 shows the three-phase configuration of the MMC topology. The MMC is comprised of *N* submodules (SMs) per arm (or valve) which results into a line-to-neutral voltage waveform of (*N+1*) levels. The number of SM to be installed are project dependent and mainly relies on: DC Voltage rating, Reactive Power Requirements and Dynamic Performance Requirements. The inductor L_{arm} is added to each converter arm to limit arm-current harmonics, di/dt during faults and for phase decoupling. These reactors can be located either at the transformer side of the valves or at the DC side of the valves. Each submodule (SM) is a half-bridge converter as depicted in Figure 2-4 and includes mainly a capacitor *C* and two IGBTs with antiparallel diodes (S1 and S2).

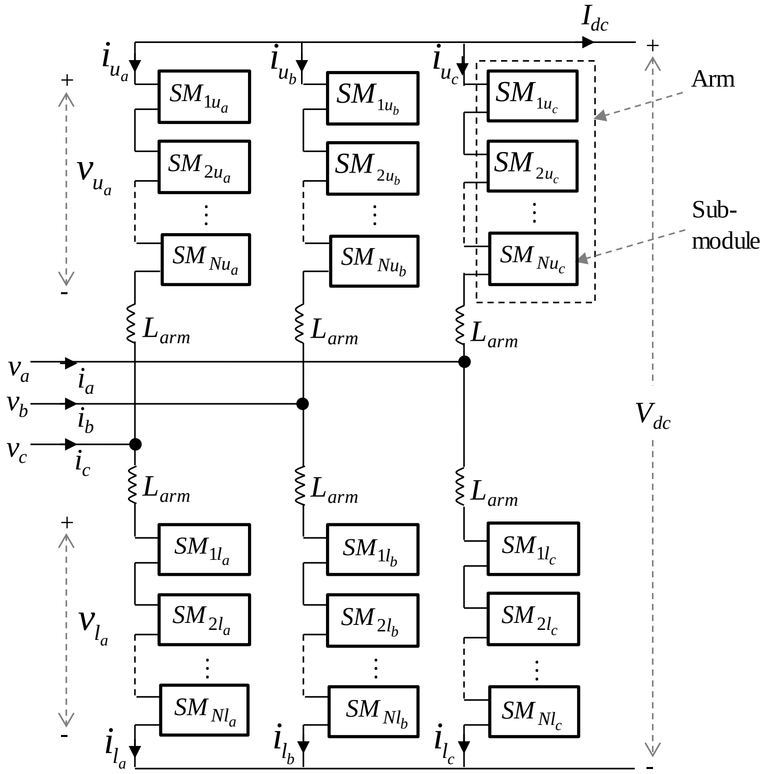
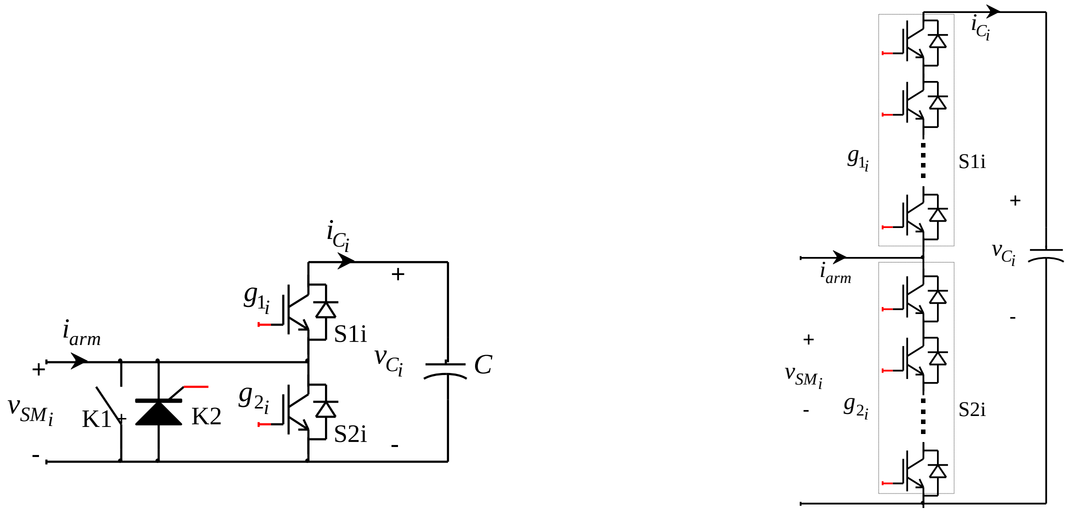


Figure 2-3 : Typical MMC topology

2.3.1.3. Sub-module Operation

Since the IGBT device is controllable, through gate signals g_{1_i} and g_{2_i}, the SM can have three different states. In the ON state: g_{1_i} is on, g_{2_i} is off and the SM voltage v_{SM_i} is equal to the capacitor voltage v_{C_i}. In the OFF state: g_{1_i} is off, is g_{2_i} is on and $v_{SM_i} = 0$. Figure 2-5 illustrates the normal operation of one sub-module. In the Blocked state: g_{1_i} is off, g_{2_i} is off and v_{SM_i} depends on the arm current (i_{arm}) direction. The capacitor may charge through S1 and cannot discharge actively.



a) SM configuration #1 b) SM configuration #2

Figure 2-4 : Half-bridge SM circuit for the ith SM

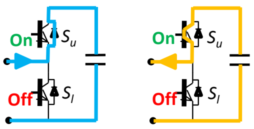
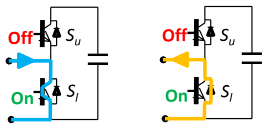
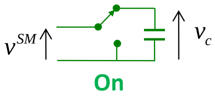
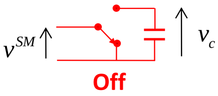
	g_u=1 et g_l=0 -> *ON state*	g_u=1 et g_l=0 –> OFF state
Normal operation modes		
Ideal submodule and equations	 $S=1$ $v^{SM}=v_c$	 $S=0$ $v^{SM}=0$ $C\frac{dv_c}{dt}=i_c=0 \Rightarrow v_c=cst$

Figure 2-5 : Steady state operation of SM

Depending on the IGBT technology used in such a converter, the high-speed bypass switch K1 (Figure 2-4 -a) is required to increase safety and reliability in case of SM failure, and the thyristor K2 (Figure 2-4 -a) is fired to protect the IGBTs against high fault currents. For the configuration depicted in Figure 2-4-b, IGBT's technology is different, during high fault current, the IGBT is designed to melt and become short-circuited. Therefore, for such configuration #2 protection devices such as Thyristor and is not needed. Also, in configuration #2, several IGBTs are connected in series, therefore the SM rated voltage is higher than configuration #1, which reduces *N* SM in each arm.

2.3.1.4. Control and protection overview

HVDC C&P system is used for controlling, monitoring and protecting the main HV equipment such as circuit breakers, valves, transformers, reactors, etc. The controls of VSC-HVDC systems are comprised of three main levels: The dispatch control setpoints, the upper-level control and the lower-level control TB604 [4]. The combination of lower and upper-level controls is located at converter station control. Figure 2-6 shows these three levels of controls. Lower-level controls are specific to valve topology and manufacturers and their scope is the management of each valves separately. Upper-level controls mainly manage the inner current control, energy and power control of the MMC. The control strategies differ based on manufacturer and/or project specifications. For onshore station, the PQ mode is used to regulate the DC voltage and voltage/reactive power. For offshore station, the UF mode (or grid forming) is used to regulate AC voltage and frequency.

Dispatch control setpoints originate from an offsite system operator or coordinator who will provide the upper-level dispatch inputs necessary to operate the grid.

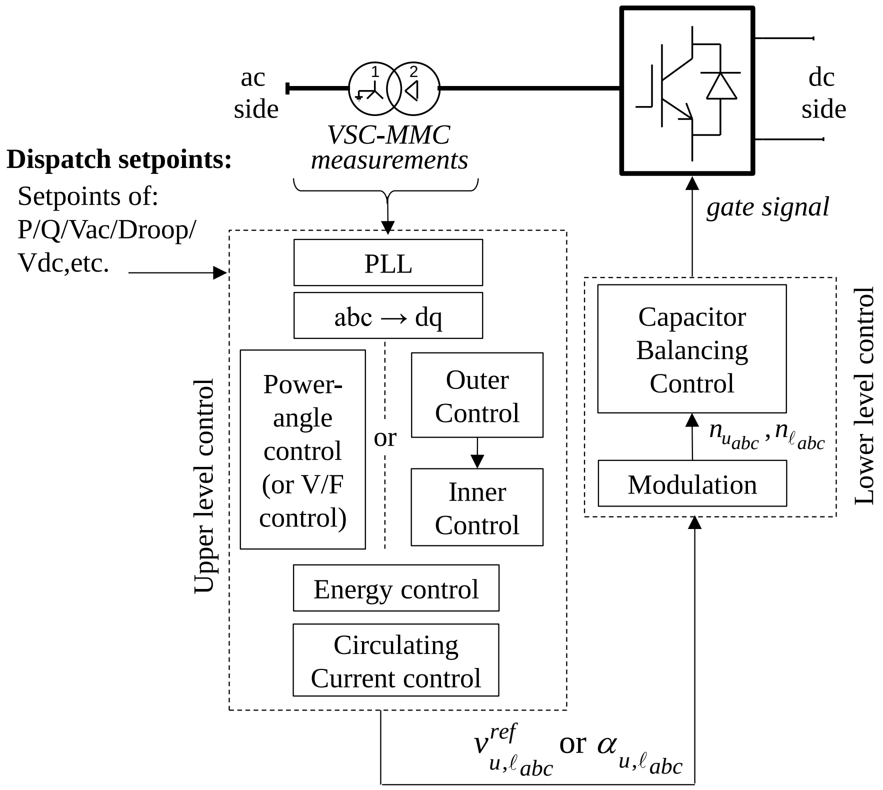


Figure 2-6 : MMC station generic control structure

The converter protection system is subdivided into the zones as provided in Figure 2-7. This later is provided as an illustrative example. Real systems can differ to some extent. The following zones can be identified:

- AC system protection zone (1)
- Converter transformer protection zone (2)
- Converter busbar protection zone (3)
- Converter protection zone (4)
- Positive DC busbar protection zone (5)
- Negative DC busbar protection zone (6)
- Positive DC cable protection zone (7)
- Negative DC cable protection zone (8)
- Auxiliary power protection zone (9)
- Transformer connection protection zone (10)

Depending on dynamic tool used and the conducted study, relevant protection should be included in the model to analysis and investigates risk of HVDC blocking and/or tripping for the relevant system studies (faults, energizations, etc.). For instance, for external AC faults, not only zone (1) should be included in the model but also several other protections that may triggers the blocking of the converter such as zone (4) and (5).

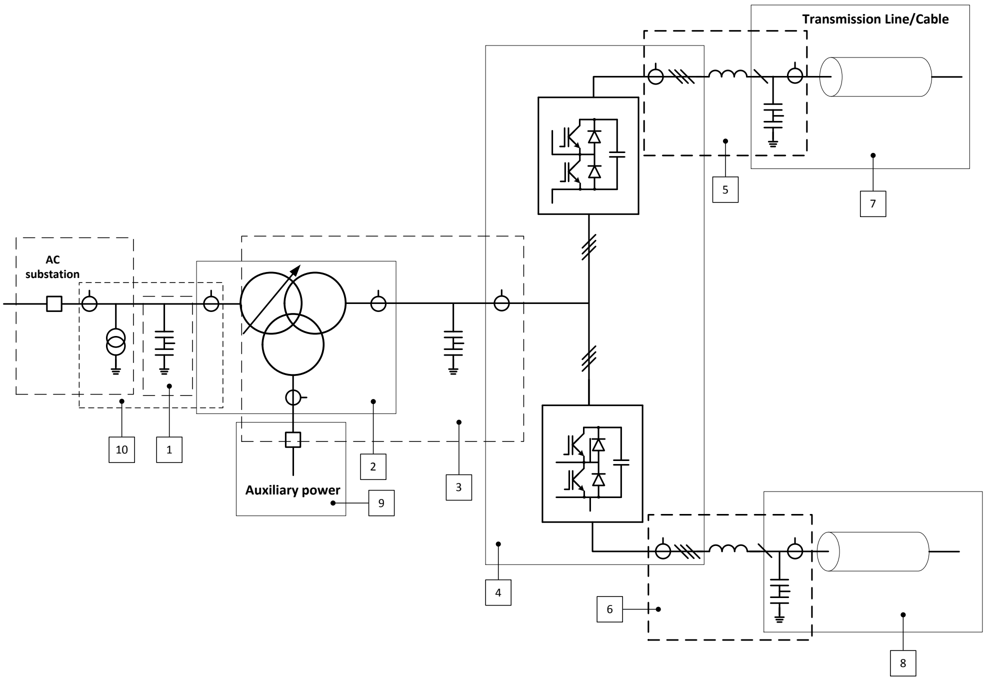


Figure 2-7 General overview of VSC protection zones [29]

2.3.2. DC chopper

2.3.2.1. Configuration

The injected power from the wind farm cannot be reduced by the offshore side converter during onshore events (such as ac faults) and this causes a fast increase in DC overvoltage that may harm the DC cable. This can be avoided by using a DC chopper to dissipate energy in breaking resistors and OWF will take no notice of short onshore grid interruptions. HVDC DC chopper is installed at the onshore converter station between AC/DC converter and DC cable terminals.

Figure 2-8 depicts a typical configuration that can be found; it consists of IGBTs in series with resistance for each DC poles and a surge arrester at neutral pole to limit any DC poles unbalances during major events. It should be highlighted that other circuit configurations exist depending on project specifications and manufacturers, such as a series connected half bridge circuits including resistances.

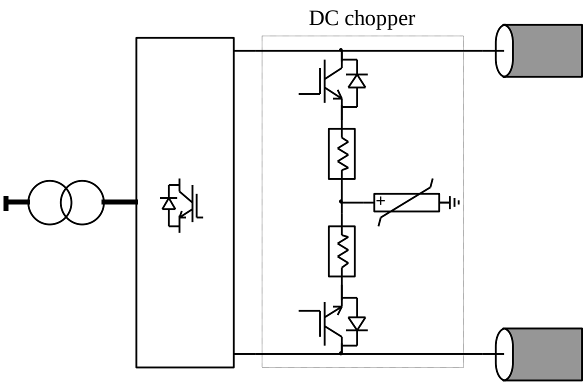


Figure 2-8 : DC chopper overview

To illustrate the impact and the main role of the DC chopper, HVDC-OWF link behavior is compared between DC chopper activated and deactivated during a three-phase onshore fault at t=1 sec. Figure 2-9 shows a comparison of the behaviour during AC fault with and without DC chopper. The following variables are plotted: onshore AC voltage, onshore/offshore active power, DC chopper activation and DC pole-to-pole voltage. Red curves represent the results when the DC chopper is absent or deactivated and the blue curve represent this behavior when the DC chopper is properly activated. It can be noticed, that when AC fault occurs, active power produced by offshore wind farm cannot be reduced, therefore, offshore active power is maintained at around a constant value. This leads to a fast increase of DC voltage when DC chopper is not activated (1.7 pu for a fault duration of 160 ms). When DC chopper is properly design and activated, DC overvoltage is limited in the range of 1.15 pu during fault.

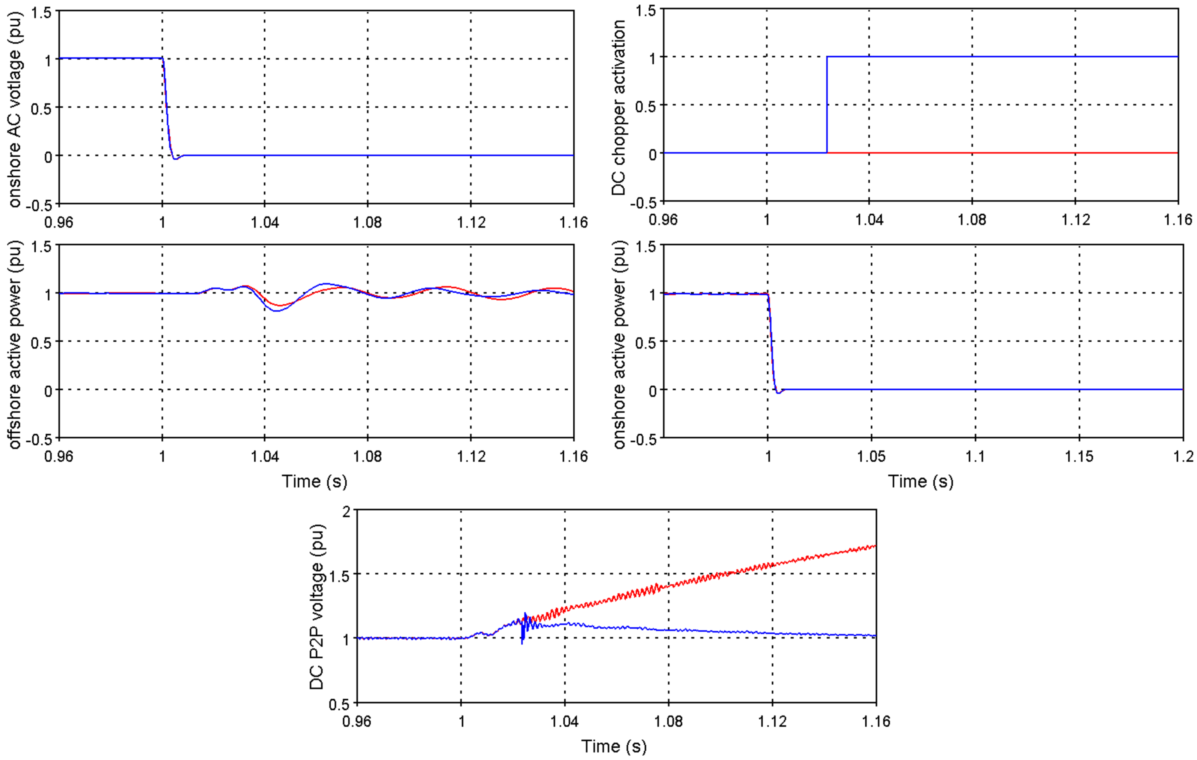


Figure 2-9 : DC chopper behavior

To limit DC overvoltage, the DC chopper resistance dissipates major part of the energy produced by the OWF. Therefore, the resistance should be properly designed to allow an onshore fault ride through based on the specification.

2.3.3. DC Cable

Most common HVDC OWF link installations include a long DC cable length in the range of hundred of km and high rated power (i.e. > 200 MW). This is mainly because of technical-economic reasons, the break-even distance between AC and DC cable installation should be exceeded to justify a HVDC OWF project. For such long cable length and high rated power, cable system (including cable production, installation, cable joints, fibre optics, etc.) has the highest cost in the overall HVDC link CAPEX. DC cable usually includes a minor section installed underground but the major cable will be a submarine cable.

2.3.4. Wind Turbine Generator (WTG)

Wind turbine generators (WTG) installed for offshore applications consist of Type 3 -DFIG or Type 4 Full converter topologies. However, Type 4 represent the predominant technology.

2.3.4.1. Configuration

Type III - DFIG

The typical configuration of a Type III WTG is shown in Figure 2-10. The stator of the doubly fed induction generator (DFIG) is directly connected to the grid and the wound rotor is connected to the grid through a VSC back-to-back (B2B) converter system. The B2B converter system consists of two, three-phase pulse-width modulated (PWM) converters (Rotor-Side Converter (RSC) and Grid-Side Converter (GSC)) connected by a dc bus. A line inductor and an ac filter are used at the GSC to improve the power quality. A crowbar is used to protect the rotor-side converter (RSC) against over-currents and the dc capacitors against over-voltages. During crowbar ignition, the RSC is blocked and the machine consumes reactive power. Therefore, the dc resistive chopper is widely used to limit the dc voltage and avoid the crowbar ignition during ac faults.

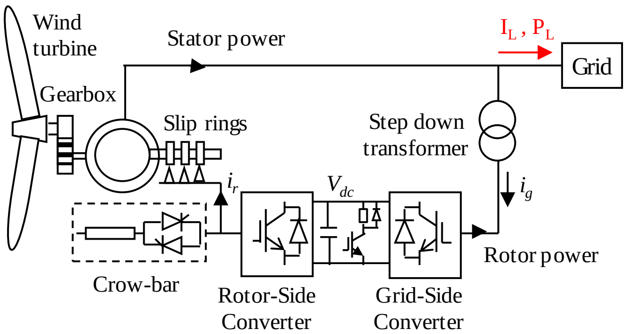


Figure 2-10 : DFIG Type III WTG configuration

Type IV- FC model

The Type IV, i.e. the full converter (FC) WTG concept uses, generally, a permanent–magnet synchronous generator (PMSG) or a synchronous generator with an external excitor connected to the grid through a B2B link. Depending on the size of the wind turbine, the PMSG side converter (MSC) can be either a diode rectifier or a voltage-sourced converter (VSC). On the other hand, the Grid Side Converter (GSC) is typically a VSC. Typical type IV circuit overview is presented in Figure 2-11.

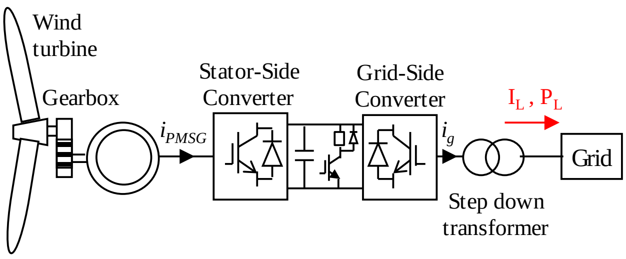


Figure 2-11 : FC Type IV WTG configuration [9]

2.3.4.2. C&P overview

The control of the DFIG is achieved by controlling the RSC and GSC through vector control techniques. Vector control allows decoupled control of both real and reactive powers. The RSC controls the active power delivered to the grid and ac voltage and follows a tracking characteristic to adjust the generator speed for optimal power generation depending on wind speed. On the other hand, the GSC is used to maintain the dc bus voltage and to support the grid with reactive power during faults. Details on DFIG wind turbines control are given in [7].

The simplified control diagram of the DFIG model is shown in Figure 2-12. In addition to the dc resistive chopper and crowbar controls, the protection system block in Figure 2-12 includes at least:

- undervoltage and overvoltage protection,
- overcurrent protection for GSC and RSC which temporary blocks the converter that is subjected to overcurrent,
- A deep voltage sag detector which temporary blocks the GSC and RSC in order to restrict the fault ride-through (FRT) operation to the faults that occur outside the wind park.

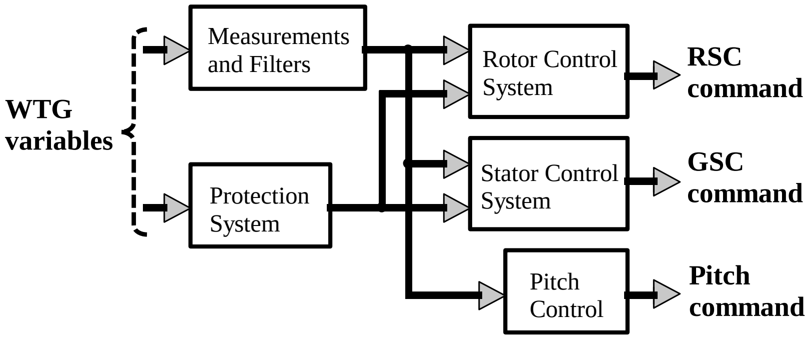


Figure 2-12 : Control and protection system [8]

The control of the FC is achieved by controlling the MSC and GSC using vector control techniques [7]. The MSC controls the active power delivered by the PMSG and follows a tracking characteristic to adjust the PMSG speed for optimal power generation depending on wind speed. The function of GSC is maintaining the dc bus voltage, i.e. transmitting the active power delivered to the dc link by the MSC. It is also used to control the ac voltage and reactive power delivered to the grid Figure 2-13.

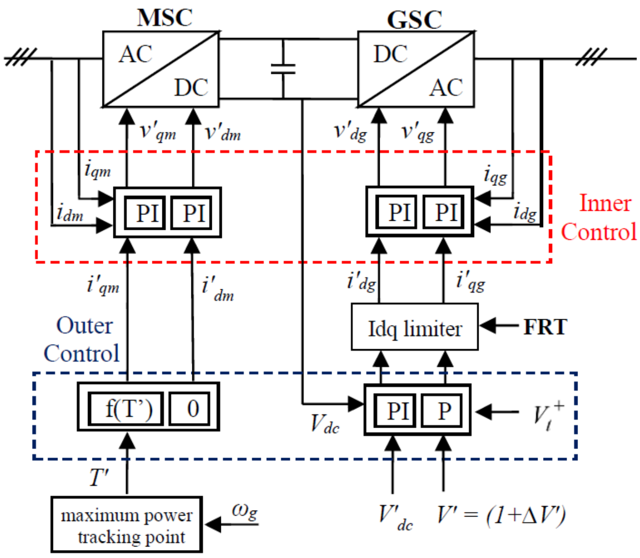


Figure 2-13 : Schematic diagram of FC control system [9]

2.3.5. Offshore wind farm

2.3.5.1. Configuration

The topology of the wind farm layout is usually a radial configuration consisting of several feeders connected into the offshore collector substation (or AC switchyard) see Figure 2-14.

For some specific cases, for improving reliability or ensuring the supply of auxiliary devices for WTGs, the radial configuration can be extended into a ring configuration, however this may significantly increase the cost and footprint, which makes such configuration less attractive for offshore projects [4].

Also HVDC-OWF system with transform-less configuration is recently adopted to reduce the overall cost as illustrated in Figure 2-15.

The number of offshore feeders and OWF transformer configurations will vary depending on project specification.

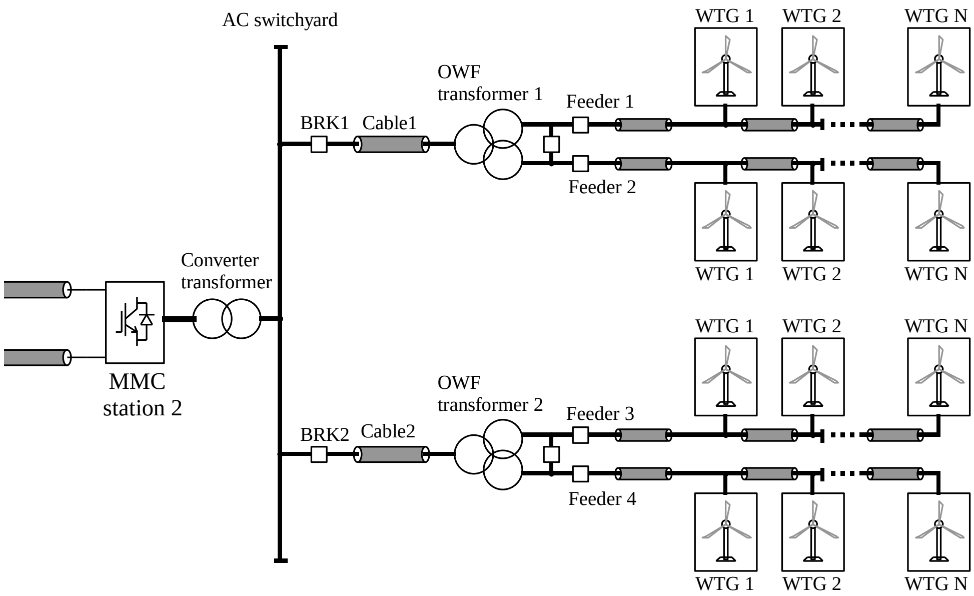


Figure 2-14 : Offshore wind farm layout – radial configuration

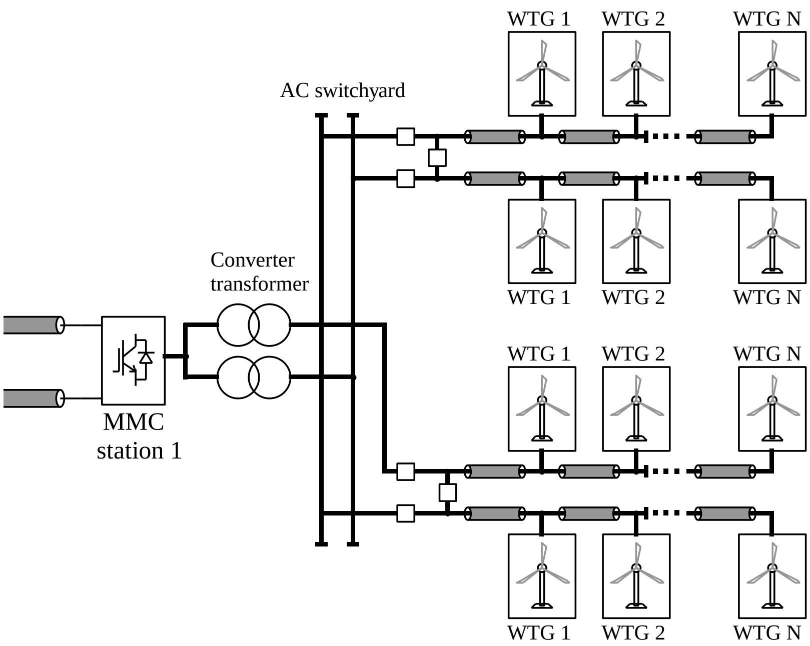


Figure 2-15 : Offshore wind farm layout – transform-less

Several other HV equipment are installed in the wind farm offshore platform that are not represented in Figure 2-14 such as:

- Auxiliary devices (control systems, communications, life support, navigation lights, etc.)
- Diesel generator to supply to the platform's auxiliary equipment, if the HVDC link is not in operation (due to outages or maintenances)
- If applicable shunt reactors to compensate AC inter-area cable reactive power
- Zig-zag transformer to provide a reference to ground at feeder sides.
- Surge arresters at each electrical node to protect cables/transforms and other HV equipment.

2.3.5.2. Control and protection overview

Wind farm includes a wind power plant (WPP) control unit to communicate with each WTG. The main purpose of the WPP is to provide a secondary regulation of active and reactive power to maintain the requested output of the plant as close as possible to the required active and reactive power setpoints. In the case that the WTG controllers are using voltage instead of reactive power setpoints, voltage setpoints is sent. Other functions are also included in the WPP, such as measurements (active power/reactive power/AC voltage/Frequency), power limits, frequency control (if requested), dispatcher, operation modes, etc.

Telecommunication overview between grid operator, WPP control, WTGs and HVDC link is presented in Figure 2-16.

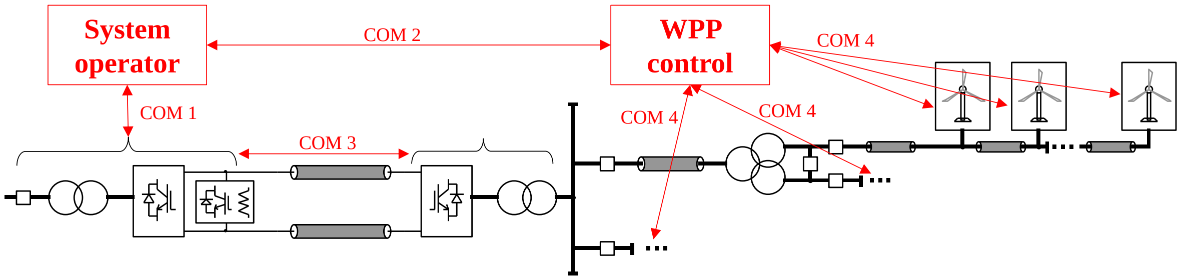


Figure 2-16 : Offshore wind farm control overview

COM1: onshore AC voltage (or reactive) setpoints, offshore AC voltage and Frequency setpoints, onshore frequency measurements

COM2: includes information shared between grid operator and the WPP control. Typical information are active power setpoints, onshore frequency measurements, emergency shutdown, etc.

COM3: includes several internal converter manufacturer variables (measurements and commands) it may also include other signals exchanged from offshore to onshore.

COM4: consists of several telecommunications between WPP and each WTG. It includes AC voltage or reactive power setpoints, active power setpoints, emergency shutdowns, etc.

2.3.6. Ownership and main parties involved

Offshore system's ownership is different in each country. In Great Britain, the framework for offshore connections is designed to allow for competition in the ownership of the offshore transmission network, with a separate Offshore Transmission Operators (OFTO) owning the transmission assets from the onshore transmission network to the offshore connection point where WTG connects. The System Operator Transmission Owner Code (STC) defines the relationships between the System Operator (SO) and Transmission owner (TO) and requires the OFTO to provide certain technical performance criteria at the onshore interface point. The Grid Code then also requires the generator to be able to meet certain technical performance criteria.

An important point to capture is the responsibility of different and several involved parties from planning to commissioning stage and ensure it is compliant sits with the generator/developer. These assets are divested around 18 months after commissioning and adopted by OFTO. This makes it challenging and different respect to other country in Europe.

Figure 2-17 illustrates the ownership regime for the market in Great Britain. Important interface points and the requirements that apply are briefly described.

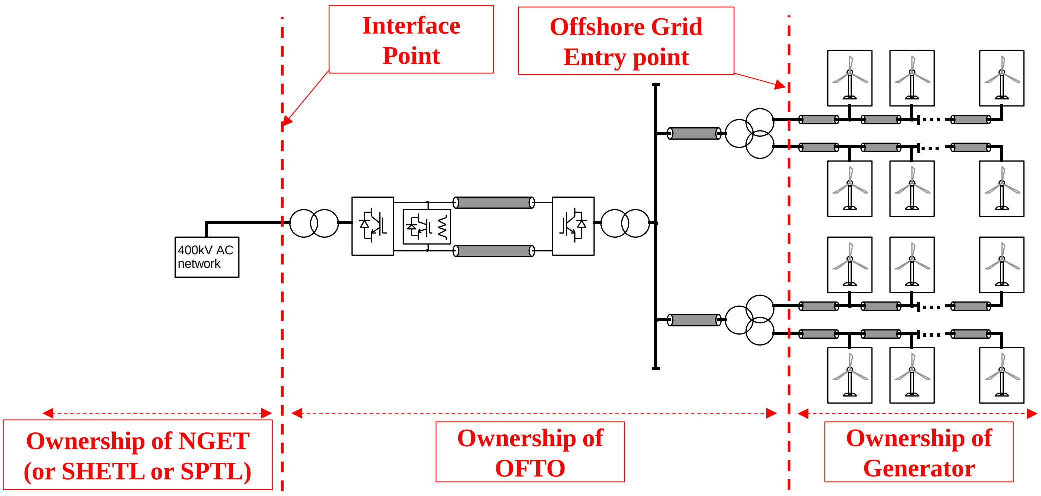


Figure 2-17 : Ownership and Interface points in Great Britain [10]

Offshore Grid Entry Point

This is the point where the offshore WTG connects to the offshore transmission system. It is an ownership boundary.

Offshore Transmission System (OFTO)

This can be built by the WPP or the OFTO but must be owned and operated by the OFTO post construction. It can either be an AC or DC transmission system.

Interface Point

This is the point at which the offshore transmission system connects to the onshore transmission system and this is an ownership and control boundary. It is at this point that all the onshore grid code requirements apply. National Electricity Transmission System Security and Quality of Supply Standard (SQSS) defines the interface point depending on ownership of the first onshore substation.

3. TYPE OF TOOLS FOR HVDC DYNAMIC STUDIES

With regards to HVDC studies, several dynamic tools are used depending on the phenomena to be investigated. This section provides a general overview of the common practice and the adequate tools that are used for different studies. Figure 3-1 provides a general overview of software tools that are commonly used in each frequency range for HVDC applications.

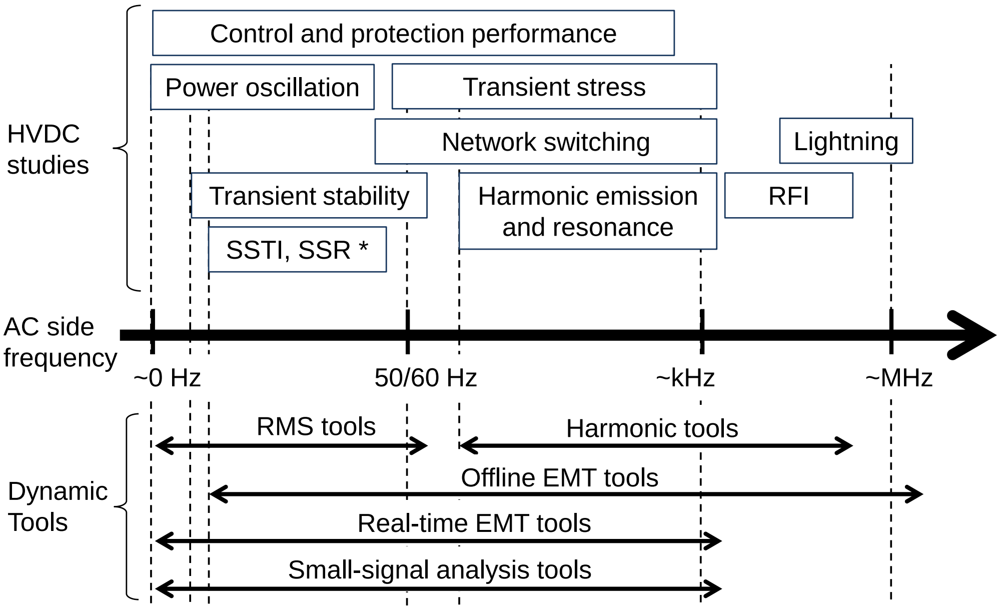


Figure 3-1 HVDC studies and tools overview[1]

HVDC studies that are illustrated in Figure 3-1 are categorized as follow:

- Control and protection performance deals with HVDC performances. It includes (but not limited) reference step-change, ramp-up ramp-down functions, interloking tests, start-up/shut-down sequence, black-start operation, islanded performances, AC fault performance, protection performance when HVDC is subject to AC or DC faults, etc.
- Power oscillation include the study of inter-area oscillation that can occur between two synchronous or asynchronous network areas.
- Transient stability studies : These studies are performed to assess the transient stability of the AC system including generator under the influence of the HVDC and vice-versa. The scope of the transient stability study is to ensure the stability of the whole HVDC system inside the AC network area. In addition, system stability between OWF and HVDC is also within the scope of this study.
- SSTI, SSR: The objective of this study is to investigate sub-synchronous phenomena such as torsional interaction (SSTI) with neighbouring generators on the AC network and/or resonance (SSR) with serie compensators in the network.

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* Even though SSTI and SSR are within the bandwidth of RMS tools, such phenomena cannot be studied by this later.

- Transient stress studies are related to insulation coordination, equipement design i.e. current and voltage stress. Typically, such studies are performed during the design stage and during refurbishment.
- Network switching studies deal with transient event on the network area where HVDC is installed. It includes (but not limited) line switching, transformer saturation phenomena, switching shunt reactors or capacitor banks, load shedding, Transient Recovery Voltage (TRV) analysis for Circuit Breakers, etc.
- Harmonic emissions and resonances : Harmonic emissions deals with harmonic generated by power electronic switching devices and therefore continuously transmitted by the system which may affect the quality of the wave. Harmonic resonance (or Harmonic stability) are related with control instability in the range of harmonic frequency. Usually, harmonic resonance leads to the trip of the HVDC, therefore, they are not continousily transmitted in steady state but rather during few second or few minutes.
- RFI (Radio frequency interference) study is to evaluate the high frequency interferences generated by converters and to establish a radio frequency screening.
- Lightning studies are performed during design stage and refurbishement for insulation coordination and clearance distances.

In Figure 3-1, for HVDC applications the following software tools are commonly used :

- RMS tools: PSSE, DigSilent PowerFactory, Eurostag and Netomac
- Offline EMT tools: ATP, EMTP, PSCAD, SimPowerSystem (Matlab) and DigSilent PowerFactory
- Real time EMT simulation: RTDS, Hypersim and RT-Lab (Opal-RT)
- Harmonic tools: DigSilent PowerFactory, EMTP and several inhouse manufacturer tools
- Small-signal analysis tools: as defined in [30], small-signal stability is the ability of the power system to maintain stability when subjected to small disturbances. In this context, a disturbance is considered to be small if the equations that describe the resulting response of the system may be linearized for the purpose of analysis. Thus, modal analysis and impedance based appraoch can be used. The tools dedicated for such small-signal analysis are usually developped with Matlab packages or dedicated programs incorporated in the EMT and RMS tools to derive such results.

As can be seen in Figure 3-1, RMS tools cover frequency range related to power oscillation up to transient stability studies. It should be noted that even though SSTI/SSR phenomena are in the range of frequency covered by the RMS tool, thus studies are performed only with EMT tools due to several simplification in RMS that does not allow representing such phenomena.

Transient stability studies are usually covered by RMS tool when network is large to reduce simulation time, however in some cases when network is small or for islanded network, EMT tools is used to ensure higher accuracy and reliable results. It should be noted that EMT tools might also includes RMS solver and vice-versa.

Real-time simulation can cover lower frequency range than offline EMT tool because of faster simulation time and no simplification in control and protection system (when connected to physical cubicles) used in the offline EMT tool. For such lower frequency range, it is common to use RMS tool for system studies and real-time tool to validate HVDC behavior and benchmark the RMS HVDC model. Phenomena higher than kHz, is usually covered by Harmonic tools and/or offline EMT tool. Up-to-now, real-time simulations are not common for phenomena in the range of frequency higher than tens of kHz, because real-time execution constraints impose a big challenging for the use of highly detailed power circuit model with a very small-time step in the range of hundreds of *ns*; i.e. theoretically this is possible but for HVDC applications, this is not applicable, indeed for such high frequencies EMT offline tool are more adequate.

Finally, it should be highlighted, that each tool has his pros and cons; for each studied phenomenon adequate tool should be used and it is common to use several tools to perform relevant studies to validate models, improve confidence by reaching consistency between simulation outputs, analyse results to derive accurate conclusions.

The selection of the tool is based on the type of simulation to be performed, taking into account the adequate representation which required to capture the dynamic behaviours of interest. Some of the considerations when deciding upon the most suitable modelling tool include, but not limited to: requirement for representation of individual phases rather than RMS, resolution (time step) driven by type of modelling, dynamic phenomena to be simulated, purpose of the study and level of accuracy that is acceptable (initial screening to inform more detailed assessment) etc.

Therefore, all dynamic tools should be considered as complementary rather than a predominance of one over the other.

4. EMT MODELING OF HVDC-OWF SYSTEM

Numerical simulation tools such as Load low, RMS and EMT tools are used by power system engineers and researchers to conduct various dynamic studies. The increase installations of power electronic devices (PED) on the transmission system implies the use of more and more EMT tools. The main reasons are because PEDs have faster dynamic and more complex behavior that cannot by captured or properly analysed with RMS approach tools.

Figure 4-1 provides an overview of thus three main simulation tools that are commonly used. It shows, that the load flow tools covers a single "snapshot" on a time domain scale, whereas the RMS provides slow dynamic in the range of few seconds and the EMT provided transients dynamics within the microseconds or milliseconds time scale.

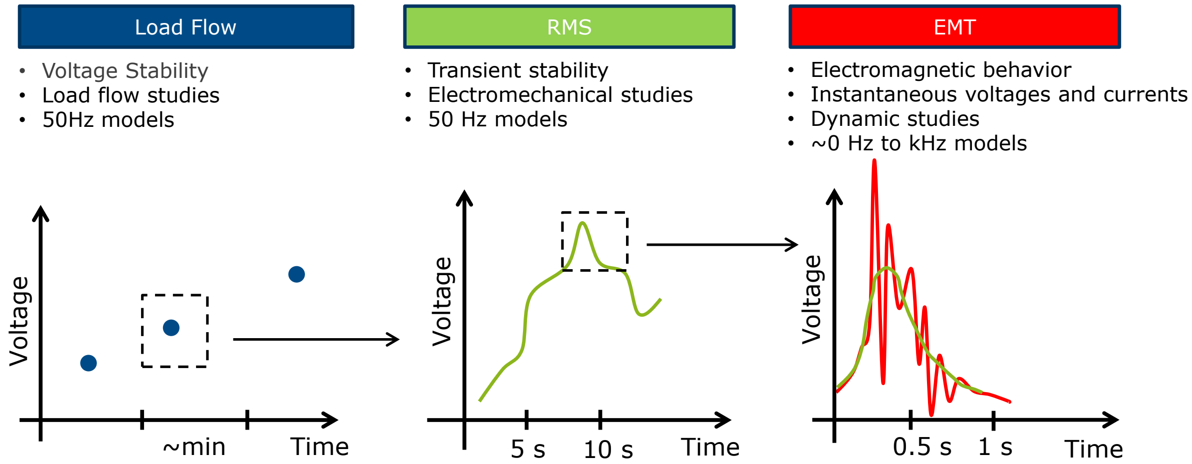


Figure 4-1: Overview on type of simulation tools for HVDC applications

EMT simulations apply to a wide range of frequencies and therefore require a very detailed representation of each components (i.e. HV equipment, C&P systems, converters, etc.). The simulation is performed in time domain and the objective is to compute the instantaneous waveforms of state variables at an arbitrary point in the simulated network. EMT programs are used to accurately represent fast transients, therefore, they are well suited to simulate devices such as PEDs. In comparison to RMS tools, the main drawback is the computation time which is longer than RMS tools because device modeling are much more detailed and simulation time step is smaller. Several software developments are ongoing to reduce the simulation time, such as combination of RMS and EMT tools, solver optimization, parallel processing, etc.

EMT real time simulation offers a complementary solution respect to the offline EMT and RMS simulation, because the computation time of the simulation is lower than the real-time. The main advantages are, therefore, to achieve faster EMT simulation and the possibility to connect physical external devices to perform hardware-in-the-loop (HIL) or power-in-the-loop simulation (PHIL) as will be described in this chapter. To cope with such faster computation and connection of physical devices, simplifications in the EMT model and dedicated simulator with bigger processor are needed. This is usually performed by acquiring and the installation of a dedicated simulation platform rather than performing offline simulation on the classical PC.

4.1. EMT basics

The common approach in EMT-type software consists of using a system of nodal analysis equations [5]:

$$\mathbf{Y}_n \mathbf{v}_n = \mathbf{i}_n \tag{1}$$

The matrix $\mathbf{Y}_n$ represents the nodal admittance matrix, $\mathbf{v}_n$ is the vector of node voltages, and $\mathbf{i}_n$ is the vector of the sum of the node currents. Since, in an electrical network, known voltage sources exist, it is therefore necessary to classify them at the end of the vector and perform the following partition (1) :

$$\begin{bmatrix} \mathbf{Y}_{n11} & \mathbf{Y}_{n12} \\ \mathbf{Y}_{n21} & \mathbf{Y}_{n22} \end{bmatrix} \begin{bmatrix} \mathbf{v}_{n1} \\ \mathbf{v}_{n2} \end{bmatrix} = \begin{bmatrix} \mathbf{i}_{n1} \\ \mathbf{i}_{n2} \end{bmatrix} \tag{2}$$

The voltage vector $\mathbf{v}_{n2}$ is known, which makes it possible to reduce the previous system to the following solution:

$$\mathbf{Y}_{n11} \mathbf{v}_{n1} = \mathbf{i}_{n1} - \mathbf{Y}_{n12} \mathbf{v}_{n2} \tag{3}$$

Where $\mathbf{Y}_{n11}$ is related only to the voltages of unknown nodes $\mathbf{v}_{n1}$, $\mathbf{i}_{n1}$ is the sum of the currents of the incoming nodes and $\mathbf{Y}_{n12}$ is related to the voltages of known nodes $\mathbf{v}_{n2}$.

Despite the effectiveness of this formulation, solution (3) has several limitations for the representation of electrical components. The main drawbacks of this formulation are:

- The inability to represent voltage sources with floating neutrals. In other words, the voltage sources must have a connection to the earth.
- It assumes that all network components can be represented by such a matrix, while some components, like the ideal transformer, use a relationship function between two or more branches.
- An ideal switch cannot be represented under this formulation.

An approach to eliminate these limitations, an improved technique called MANA (Modified-Augmented-Nodal-Analysis) [11] was developed. In the MANA formulation, equation (1) is augmented to include additional generic equations, to give:

$$\mathbf{A}_n \mathbf{x}_n = \mathbf{b}_n \tag{4}$$

$\mathbf{x}_n$ contains the unknown voltage and current variables, $\mathbf{b}_n$ includes known voltages and currents and $\mathbf{A}_n$ is the augmented matrix which includes not only the $\mathbf{Y}_n$ admittance matrix but the specific sub-matrices for voltage sources with floating neutrals, for transformers, other dependency functions and ideal switches.

4.2. HVDC-OWF system modeling

This section covers the modeling of each HVDC-OWF devices.

4.2.1. Converter station onshore/offshore: MMC, transformer, surge arresters, etc.

For EMT studies, converter station modeling should consider all the electrical components highlighted in section 2.3.1 and as recommended in [4] and [15]. Based on the electrical datasheet of each HV equipment depicted in Figure 2-2, offline and real-time model can be implemented. The major computation burden resides in the MMC model, because it includes a large number of semiconductors. Detailed MMC models include the representation of thousands of IGBTs switches and must use small time steps to accurately represent fast and multiple simultaneous switching events. The computational burden introduced by such models highlights the need to develop more efficient models. This becomes particularly more complex for performing real-time simulations where simplifications are required to achieve hardware-in-the-loop (HIL) simulations.

4.2.1.1. MMC modelling

Four types of MMC models can be derived [12]. These models can be used according to the type of study and required accuracy. MMC model evolution in decreasing complexity is depicted in Figure 4-2. Black boxes represent simplifications for each model. It is expected that computational performance can be increased by decreasing model complexity. The model descriptions are presented in the next subsections. Model 1 is the most detailed. Model 2 uses a simplified power switch circuit model. Model 3 makes a simplified arm circuit equivalent. In Model 4, the complete MMC structure is reduced to an equivalent system. Model details are presented in the following subsections.

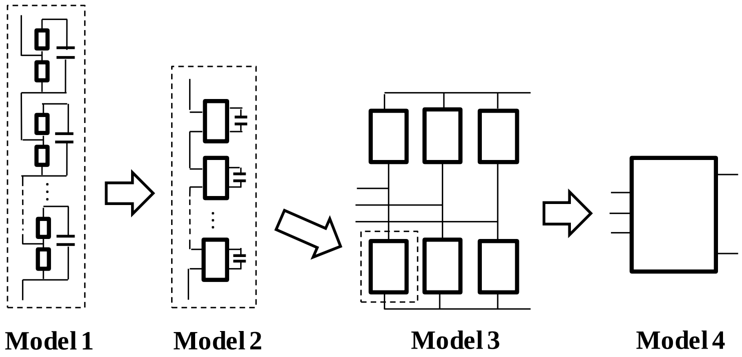


Figure 4-2 MMC model evolution in decreasing complexity order [12]

Model 1 – Full Detailed

This model is based on nonlinear IGBT/diode representation. The IGBT/diode circuit shown in Figure 4-3 is modeled using an ideal controlled switch, two non-ideal (series and anti-parallel) diodes and a snubber circuit. The non-ideal diodes are modeled with nonlinear resistances using the classical V-I curve of a diode. The nonlinear characteristic can be adjusted according to manufacturer data. It is the most accurate model for EMT-type programs and can account for every conduction mode of the MMC.

This model type [12] offers several advantages due to its increased accuracy in the modeling of IGBTs. It replicates the nonlinear behavior of switching events (through diodes) allowing to account for conduction losses. It also allows simulating specific conditions, such as blocked states, SM details, converter startup procedures, internal converter faults and different SM circuit topologies.

The introduction of thousands of components (i.e. for 401-level MMC we have 4,800 ideal switches and 9,600 non-ideal diodes) involves a high computational effort and therefore, except for specific cases mentioned above, this modelling approach should be mainly used as an accuracy reference for validating and tuning simplified MMC models. Up-to-now, such type of model is not possible in real-time simulation because of such large number of non-linear elements.

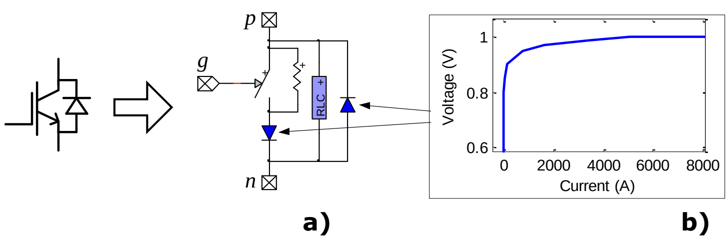


Figure 4-3 Model 1: (a) nonlinear IGBT valve; (b) Diode V-I characteristic.

Model 2 - Detailed Equivalent

In this model the SM power switches are replaced by variable ON/OFF resistors: R_{ON} (small value in mΩ) and R_{OFF} (large value in MΩ). This approach allows performing an arm circuit reduction for eliminating internal electrical nodes in the software and allowing the creation of a Norton equivalent for each MMC arm.

Figure 4-4 shows the representation of each SM. The derivation of the Norton equivalent is briefly explained as follows. With the trapezoidal integration rule, each SM capacitor is replaced by an equivalent current history source $i^h_{C_i}(t-\Delta t)$ in series with a resistance $R_C = \Delta t/(2C)$. The resistance is found from the discretization of the capacitor and Δt is the numerical integration time-step.

The *i*th SM equation is given by

$$v_{SM_i}(t) = i_{arm}(t) R_{SM_i}(t) + v^h_{SM_i}(t-\Delta t) \tag{5}$$

Where

$$R_{\mathrm{SM}_i}(t) = \frac{R_{2_i}\left(R_{1_i} + R_C\right)}{R_{2_i} + R_{1_i} + R_C} \tag{6}$$

$$v^h_{\mathrm{SM}_i}(t-\Delta t) = R_{\mathrm{SM}_i}(t)\left(\frac{R_C}{R_C + R_{1_i}}\right) i^h_{C_i}(t-\Delta t) \tag{7}$$

The Thevenin resistance R_{SM_i} is time-dependent, since the resistances R_{1_i} and R_{2_i} are time-dependent. The equivalent circuit of the SM is shown in Figure 4-4. The arm current is the same in all arm SMs. Thus, each arm can be replaced by an equivalent circuit composed of the Norton resistance and current source given by

$$Y_{arm}(t) = 1/\left(\sum_{i=1}^{N} R_{\mathrm{SM}_i}(t)\right) \tag{8}$$

$$i^h_{arm}(t-\Delta t) = -\sum_{i=1}^{N} v^h_{\mathrm{SM}_i}(t-\Delta t).Y_{arm}(t) \tag{9}$$

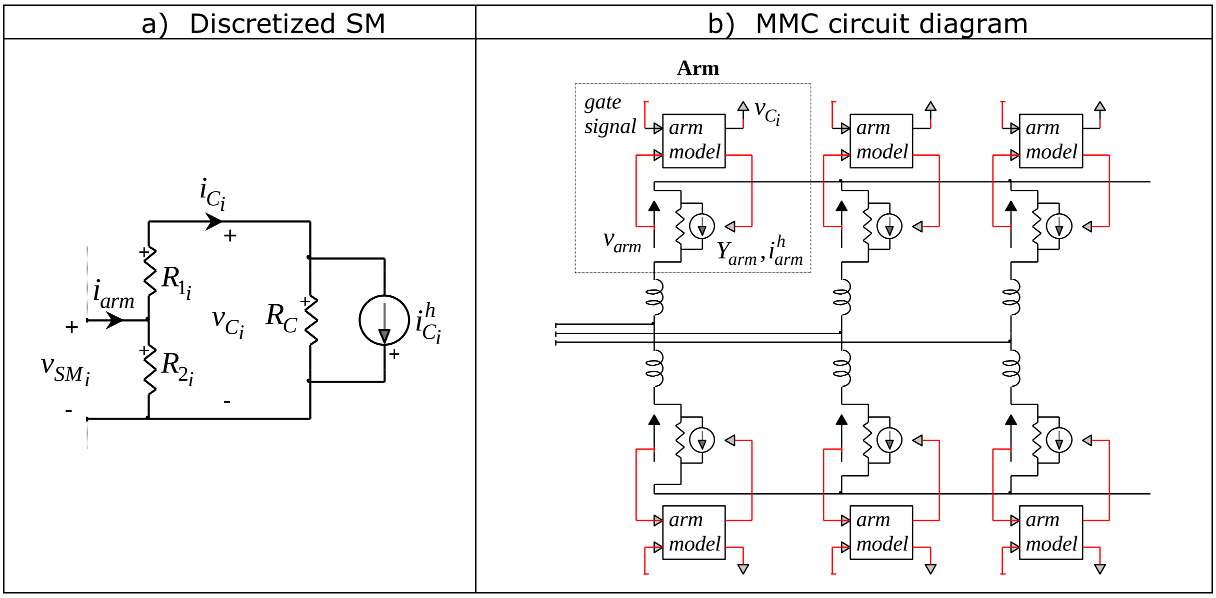


Figure 4-4 Model 2 main circuit diagram.

Advantages:

As can be seen from Figure 4-4, the main advantage of Model 2 is the significant reduction in the number of electrical nodes in the main system of network equations. The algorithm still considers each SM separately and maintains a record for individual capacitor voltages and currents. It is applicable to any number of SMs per arm. This reduces the computation burden respect to Model 1. Balancing controls of capacitor voltages in each arm can be studied using this approach.

Inconvenient:

The model is hard coded in the software, hence the user has no more access to SM circuits. Also, the V-I curve of IGBT/diode is not modelled.

Model 2 is applicable for offline and real-time simulation and is the most common model used during the design stage of a HVDC project.

Model 3 - Switching Function of MMC Arm

In this model, each MMC arm is averaged using the switching function concept of a half-bridge converter. Let S_i be the switching function which takes the zero value when the state of SM is OFF and 1 when it is ON. For each SM

$$\begin{aligned} v_{SM_i} &= S_i \, v_{C\,i} \\ i_{C_i} &= S_i \, i_{arm} \end{aligned} \tag{10}$$

Assuming that capacitor voltages of each arm are balanced, the average values of capacitor voltages are equal. In addition, by neglecting the voltage differences between capacitors, the following assumption can be made:

$$v_{C_1} = v_{C_2} = \ldots = v_{C_i} = \frac{v_{C_{tot}}}{N} \tag{11}$$

where $v_{C_{tot}}$ represents the sum of all capacitor voltages of an arm. The accuracy of assumption (11) increases when the number of SMs per arm is increased and/or when the fluctuation amplitudes of capacitor voltages are decreased. This assumption allows deducing an equivalent capacitance $C_{arm} = C/N$ for each arm.

By defining the switching functions of an arm as follows:

$$\frac{1}{N}\sum_{i=1}^{N} S_i = s_n \tag{12}$$

and including the linear conductivity losses (R_{ON}) for each SM, the following switching functions can be derived for each arm when the SMs are in ON/OFF states:

$$\begin{aligned} v_{arm} &= s_n \, v_{C_{tot}} + \left(NR_{ON}\right) i_{arm} \\ i_{C_{tot}} &= s_n \, i_{arm} \end{aligned} \tag{13}$$

where v_{arm} and i_{arm} are the arm voltage and current respectively.

There are mainly two main approach to implement MMC Model 3; hard-coded in the specific EMT software or using generic EMT blocks. Both approaches are illustrated in Figure 4-5.

Half-bridge converters are non-reversible in voltage. In order to avoid negative voltages, a diode D is added in parallel with the equivalent capacitor (Figure 4-5.i.a).When all SMs are in the Blocked state, each MMC arm can be simply represented by an equivalent half-bridge diode connected to the equivalent capacitor (Figure 4-5.ii.b).

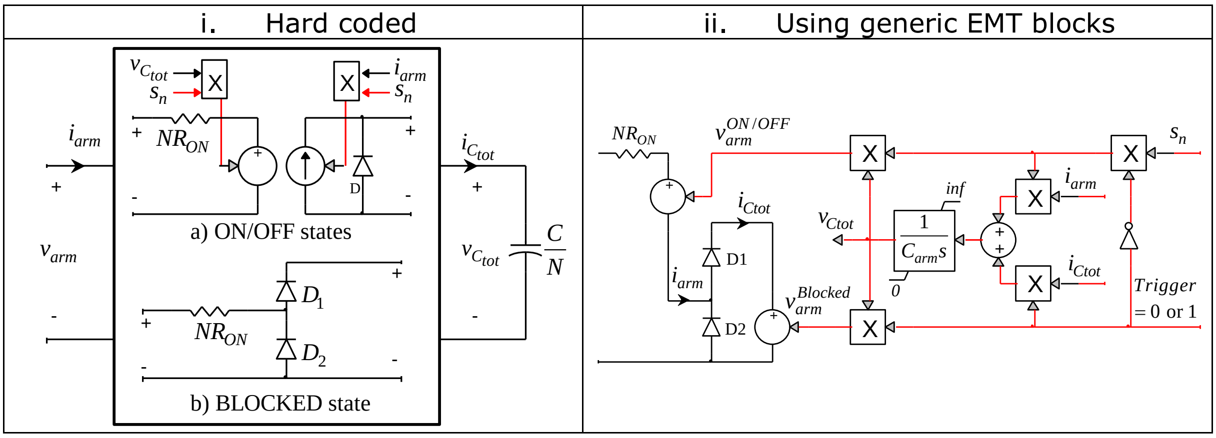


Figure 4-5 Model 3 implementation: hard coded or using generic EMT blocs.

<u>Advantages:</u>

By reducing each arm to an equivalent switching function, computation time is reduced further respect to Model 2. Circulating currents and the linear conduction losses can be represented. Also, the energy transferred from ac and dc sides into each arm of the MMC is considered.

<u>Inconvenient:</u>

SMs are no longer represented. This means that the balancing controls of capacitor voltages in each arm cannot be studied using this approach. Should be used with care when dealing with MMC having < 51 Level as depicted in [23]

Model 3 is applicable for offline and real-time simulation and is generally used during planning/early design stage and system studies.

Model 4 - AVM Based on Power Frequency

In the average value model (AVM) [24], the IGBTs and their diodes are not explicitly represented and the MMC behavior is modeled using controlled voltage and current sources. The classical AVM approach developed for 2 and 3 level VSCs in [25] is extended to MMCs in [18]. It is used by assuming that the internal variables of the MMC are perfectly controlled, i.e. all SM capacitor voltages are perfectly balanced and second harmonic circulating currents in each phase are suppressed. The following equation can be derived from Figure 2-3 for each phase $j = a,b,c$

$$v_{conv\,j}^{ac} = \frac{L_{arm}}{2}\frac{di_j}{dt} - v_j \tag{14}$$

Assuming that the total number of inserted SMs in each phase is constant and since the circulating current is assumed to be zero

$$v_{conv\,j}^{ac} = \frac{L_{arm}}{2}\frac{di_j}{dt} - v_j \tag{15}$$

With the above equations (14) and (15), the MMC can be represented as a classical VSC (2 and 3 level topologies). Thus, using an approach like [25], the controlled voltage sources become:

$$v_{conv\,j}^{ac} = v_{ref\,j}\frac{V_{dc}}{2} \tag{16}$$

where v_{ref_j} are the voltage references generated from the inner controller. The ac side representation of this model is shown in Figure 4-6.a.

The dc side model (Figure 4-6.b) is derived using the principle of power balance, thus it assumes that no energy is stored inside the MMC converter:

$$V_{dc}I_{dc} = \sum_{j=a,b,c} v^{ac}_{conv_j}\, i_j \tag{17}$$

The dc current function is derived from (17) and (16):

$$I_{dc} = \frac{1}{2}\sum_{j=a,b,c} v_{ref_j} i_j \tag{18}$$

The equivalent capacitor C_{dc} is calculated using the energy conservation principle and neglecting the energy stored in arm inductances:

$$C_{dc} = \frac{6C}{N} \tag{19}$$

Unlike the classical VSC model, an inductance is included in each arm of the MMC, thus an equivalent inductance should be also added on the dc side. Since one-third of the dc current flows in each arm and the same dc current flows in upper and lower arms of each phase, the equivalent inductance is given by $L_{arm_{dc}} = (2/3)L_{arm}$. The total conduction losses of the MMC can be found using $R_{loss} = (2/3)N\, R_{ON}$.

During a dc fault, all SMs in the MMC are blocked, thus transforming the MMC into a 6-pulse bridge diode converter (see Figure 4-6). However, since only the equivalent tree-phase MMC is represented, the Blocked state behavior cannot be accurately modeled. In order to mimic this behavior, the equivalent capacitor C_{dc} is disconnected and the current source control is short-circuited.

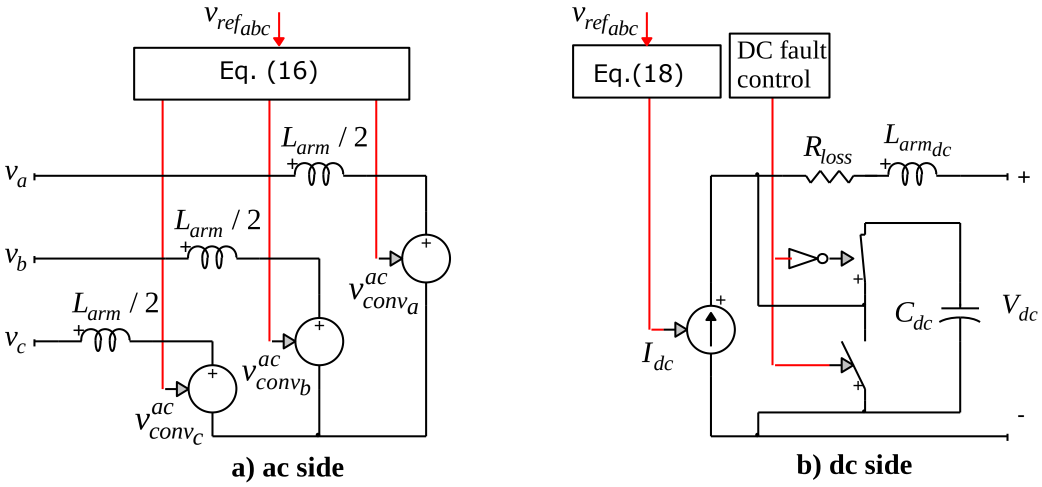
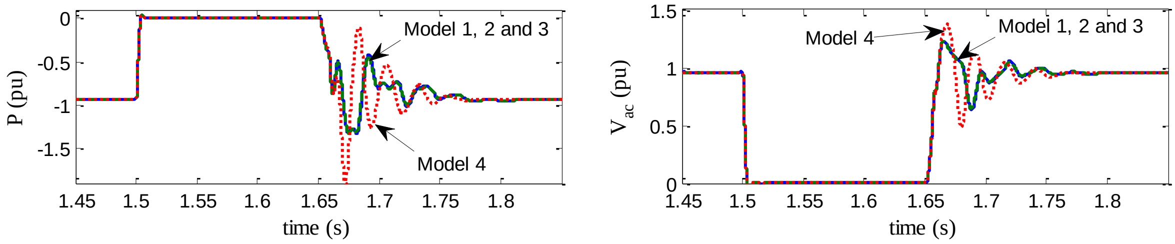


Figure 4-6 Model 4: (a) ac side and (b) dc side.

Model 4 is mainly used for wide area network electromechanical studies in RMS tools. However, since the computation burden of model 4 and model 3 are close, it is preferable to use model 3, in the EMT tools, because the model is more accurate.

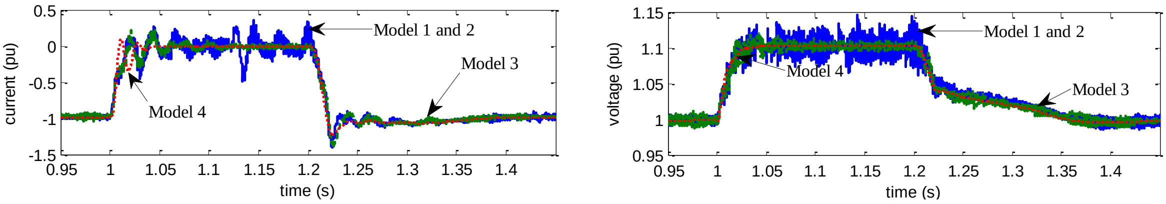
Model comparison

Figure 4-7 and Figure 4-8 show results comparison between the four MMC models. In both test case, an AC three-phase solid fault is applied at PCC of the HVDC. Results provided in Figure 4-7, illustrates the differences that can occurs between Model 4 and the remaining one when weak network is considered. It shows that in such case, model 4 is not sufficiently accurate to investigate precisely HVDC performances. In Figure 4-8, a MMC 51 Levels is considered. For such low number of MMC levels, one can notice that Model 3 and 4 cannot reproduce the non-linear fluctuation behavior that appears in Model 1 and 2. Therefore, it is recommended that when MMC levels is low, Model 2 is more appropriate than Model 3.



a) MMC-1 Active power at PCC b) MMC-1 ac voltage at PCC

Figure 4-7 : MMC model comparison - AC fault during weak network [23]



a) MMC-2 dc current I_{dc} b) MMC-2 dc voltage V_{dc}

Figure 4-8 : MMC model comparison – AC fault wit MMC 51 levels [12]

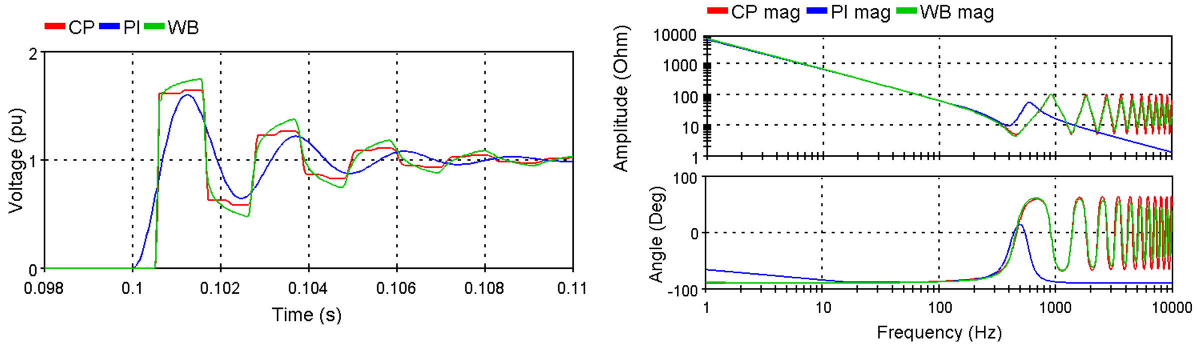
4.2.2. DC cable

In HVDC system, DC cable are subject to fast transients. Such transients may have an impact on cable design, aging and/or lifecycle. There are mainly three types of cable models in EMT tools:

- PI model: this is a simplified PI circuit that can reproduce the main frequency resonance of a cable. This model is not suitable for HVDC EMT studies since it is not accurate enough and does not cover the wide range of frequency that should be covered. Hence, the results may not be accurate.
- CP model: the constant parameter model (or Bergeron) model can reproduce the frequency of resonance in range of frequency needed for EMT tool, when it is well tuned. However, because the RLC parameter are constant in full range of frequency, the damping (and the sometimes the frequency resonance) are not sufficiently accurate. This model can provide realistic behavior; however, results may be too conservative or not sufficiently accurate for deep analysis on cable design, for harmonics studies, etc.
- WB model: this wideband (or frequency dependant) model is the most accurate one because cable parameters are frequency dependant. This allows accurately representing the transients and high harmonic frequency for EMT studies. This model should be used to avoid any miss-interpretation and provide results close to reality: such as realistic overvoltages and voltage reversal during faults.

Other models such as multiple PI sections can be used [13] and can provides sufficient accurate results. Nevertheless, it is worth validating such models by performing comparison with the reference one that is the frequency dependant model.

In Figure 4-9, an illustrative comparison between these three type of model are presented: Figure 4-9.i provides the time domain behavior after voltage step change on a DC cable and Figure 4-9.ii provides the frequency response comparisons. As can be seen, the PI model can reproduce the main frequency oscillation, the CP is close to the reference WB model, however at high frequency the cable damping is not sufficiently accurate.



i. Time domain ii. Frequency scan

Figure 4-9 : Illustrative comparison between cable models

To show the importance of cable model, comparison between onsite measurement and EMT cable model is presented here after. On the 20th November 2016, a DC pole-to-ground fault occurred on the IFA2000 HVDC link, after that a boat anchor has hooked the cables (Figure 4-10). Figure 4-11 shows DC voltage results comparison between onsite measurement (Blue curve), frequency dependant model (Red curve) and Bergeron model (Green curve). It can be noticed that the frequency cable model results are close to onsite measurements. Whereas, when Bergeron cable model is used, the damping and frequency oscillation of DC voltage is different which may lead to different interpretation or false conclusions.

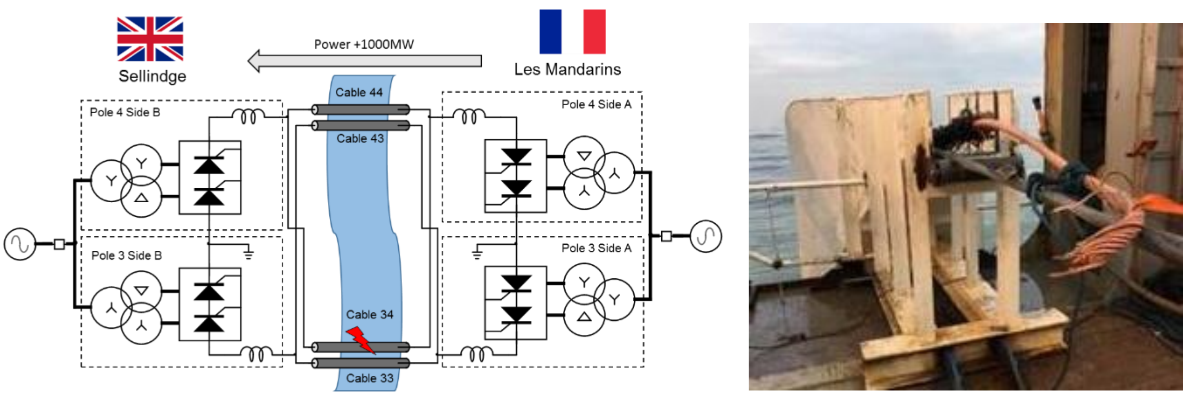


Figure 4-10: DC pole-to-ground fault incident (left) cable damage after incident (right) [37]

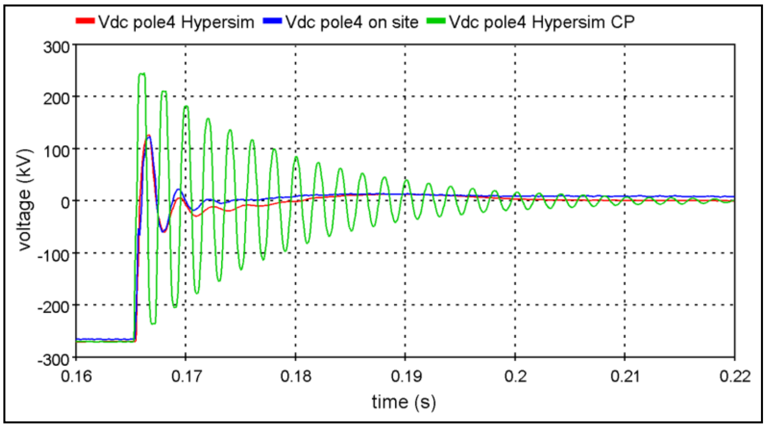


Figure 4-11 Comparisons between onsite measurement and EMT cable models [37]

4.2.3. Onshore grid

AC side grid modelling depends on project specificities and can vary depending on the conducted study. Network modeling recommendation for EMT tools can be found in [15] and [16]. For HVDC project, in general, two types of EMT model are used:

- Simple representation using Thevenin equivalent where the short-circuit levels (for balanced and unbalanced events) is covered. For HVDC systems, it is recommended that the Thevenin equivalent consist of an R//RL equivalent as shown in Figure 4-12. The L_s is computed based on the three-phase short-circuit level of the grid and the L_{spp} is based on the single-phase short-circuit level. To limit the inductive impedance at high frequencies, parallel resistances R_{spp} and R_p are included.
  Such simple approach is practical and efficient for the analysis of the converter station performance during early design stages of a project.

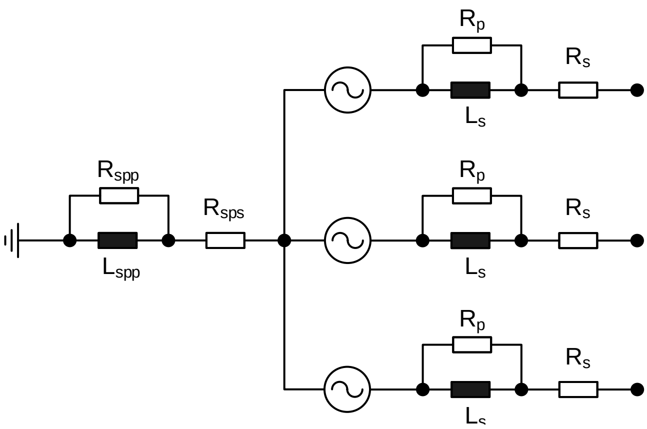


Figure 4-12 AC Thevenin equivalent system [14]

- Detailed representation including AC grid equipment: lines, transformers, loads, generators, compensators, etc. Such model is intended for the analysis of the converter dynamic behaviour within the network and to cover higher transients. Specific and realistic network behaviour can be reproduced to analyse the impact of converter station on the network and vice-versa. Also, such detail representation is necessary to account for interaction studies between HVDC system and AC equipment. The single line diagram example illustrated in Figure 4-13 includes:
    - Transformers with impedances and saturation characteristics

- Lines and cables with geometrical and electrical characteristics to generate frequency-dependant line/cable models
- Min/max short-circuit power for each Thevenin source connected to the reduced grid
- Min/max P/Q load at each substation
- Busbar configuration, especially in the substation where the converter station is connected
- Generators and associated controls
- Wind farm connected in proximity

Modelling the AC network in such greater detail becomes necessary during design stage, before commissioning and during operation stage.

The development of the AC network details to be included depends on the studied phenomena.

In order to provide a more accurate representation of the AC system, and especially the harmonic impedance, some Thevenin sources can be replaced with a Frequency Dependant Network Equivalent (FDNE) as described in [17].

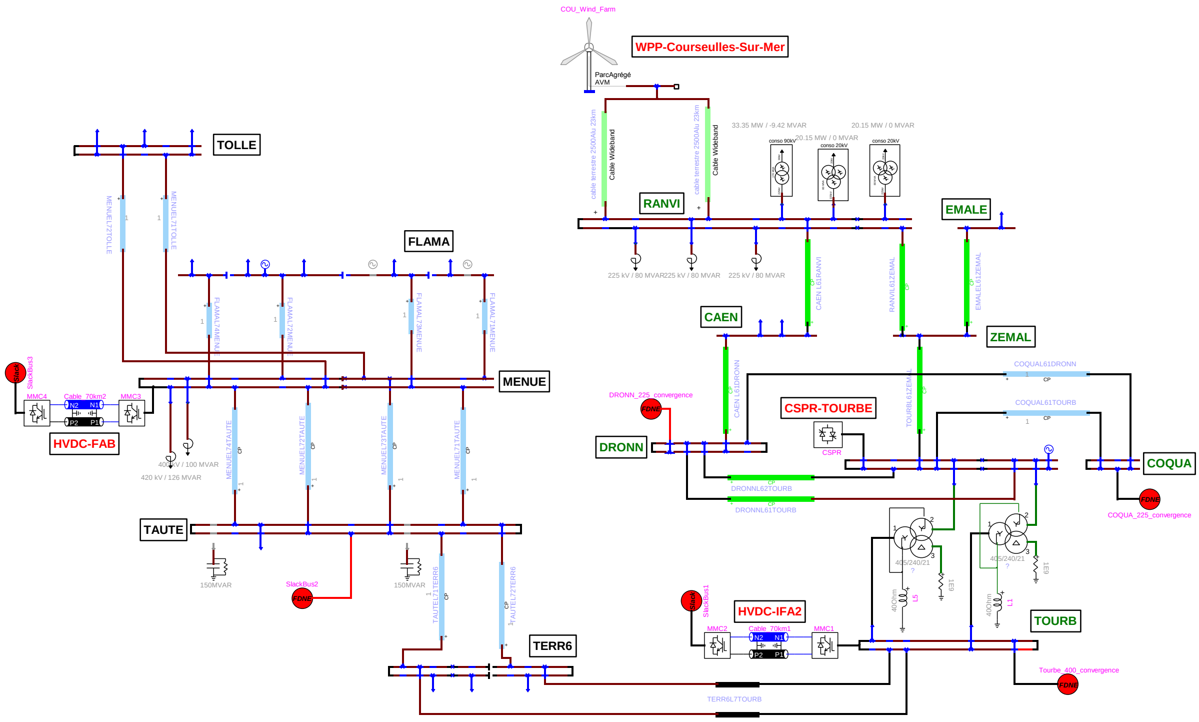


Figure 4-13 Detailed representation of AC network

4.2.1. Wind Turbine Generator (WTG)

WTG models should consider all the electrical components mentioned in section 2.3.4. The wind turbine model considers a gearbox for the rotating blade and a two-mass model for the mechanical shaft. For specific studies, such as sub-synchronous torsional oscillation inside the WTG, the shaft model should be detailed to account for torsional modes. The back-to-back converter can be either modeled using a detailed IGBT model representation (such as in Figure 4-3) either by means of average value model (AVM) approach [18]-[22]. The later replaces the converters power switches with equivalent controlled sources that replicate the converter behavior and decreases computational burden.

The detailed VSC uses PWM technique at high frequency (in the range of kHz) forcing the use of a small time-step during time-domain simulations. While being more accurate, the detailed representation of the VSCs using IGBT switches will make the simulation slow when modeling large amount of wind generation. For this reason, the AVM with voltage-and current-controlled sources is commonly used as illustrated in Figure 4-14. The simulation time-step can be increase (for instant around 50us). In the AVM approach, the voltage reference signals v_j^{ref} can include harmonic content to reproduce ideal harmonic emissions produced by the PWM, in such case simulation time should be reduced or only include the fundamental frequency content which allows increasing the time step of simulation.

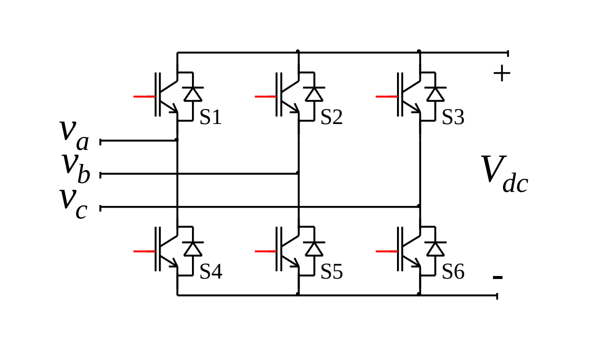
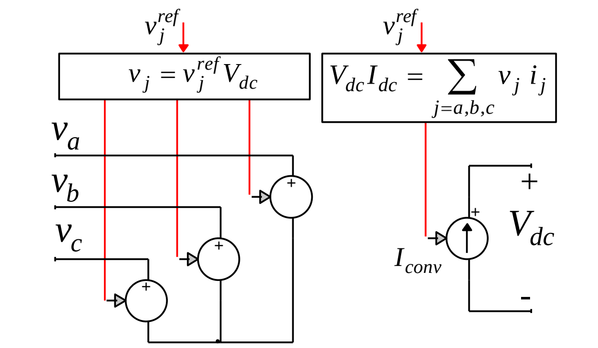
a) Detailed model (DM)	b) Average value model (AVM)
	

Figure 4-14 VSC back-to-back modeling approaches

4.2.2. Offshore grid

Offshore wind farm is usually composed of tens to hundreds of WTG connected to the offshore converter station through a collector network of subsea cables, power transformers, etc. (Figure 2-14). A full representation of each WTG and OWF can be achieved in EMT software by modeling individually each component. Simulating a detailed system is possible but require a long simulation time. To reduce such simulation time, one common approach, is to aggregate a group of WTG.

For EMT studies, we can therefore, define three types of OWF model:

- Full detailed presented in Figure 4-15. Such model is usually used as a reference model to validate the two other reduced ones. It is also used for harmonic studies and to reproduce onsite offshore events to accurately account for each equipment.
- Semi-aggregated OWF model illustrated in Figure 2-13.a. In such approach each feeder is grouped in one WTG. Such model will be used to investigate ac onshore and offshore events (such as AC faults at PCC, HVDC converter faults, etc.).
- Full aggregated model depicted in Figure 2-13.b stands for one WTG representing all OWF system. This model is mainly valid for some event studies on the AC onshore network.

It should be noted that a combination between detailed and aggregated feeders is possible, i.e. one detailed feeder with an aggregation of the other feeders. Such combination is useful for event studies inside the OWF system.

The Full detailed model is usually used to validate the two simplified aggregated model, for harmonic and high frequency resonance studies. The Semi-aggregated model is generally used for dynamic performance studies and the aggregated model can be sufficient for system level study for onshore network studies. The exact list of study where the aggregated model are valid is project dependent. Based on the validation process that will performed, the use of aggregated OWF maybe extended accordingly.

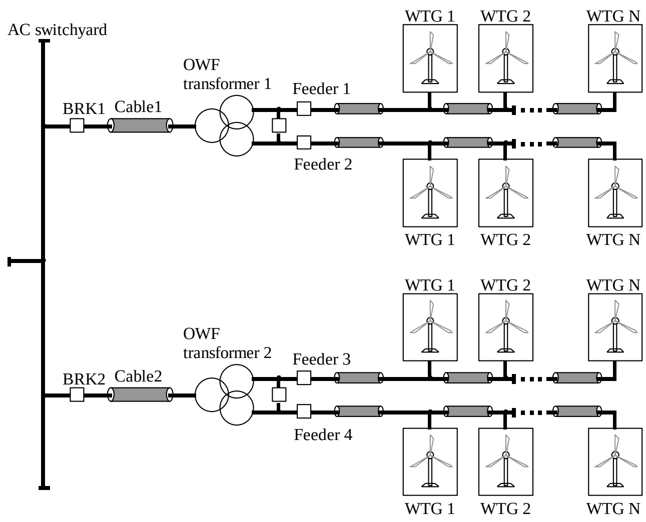
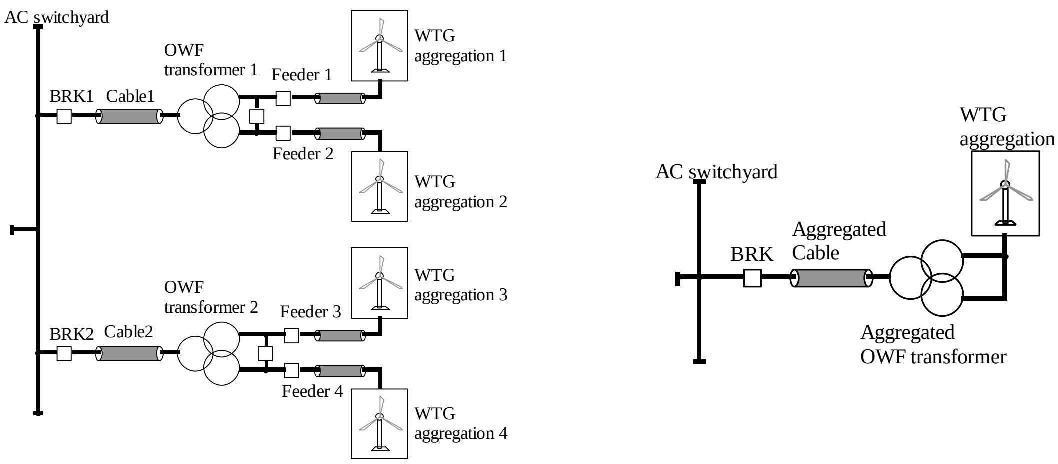


Figure 4-15: Detail representation of the OWF



a) Semi-aggregated OWF b) Fully aggregated OWF

Figure 4-16 OWF aggregated model types

4.2.2.1. Aggregation method

The aggregation of a group of WTG in one feeder (or string) or in the entire OWF are based on the following assumptions:

- Voltages and currents at PCC of each WTG are identical.
- Electrical equipment as well as control and protection output are the identical
- Mechanical equipment such as blade, shaft, gearbox, etc are identical

<u>WTGs aggregation:</u>

One WTG can represent a group of *n* number of WTGs. Two main approaches are commonly used;

- Performing *n* scaling of each WTG equipment. In this approach, the machine parameters, AC filters, DC chopper, DC capacitors, VSC devices, should be scaled. Such approach becomes less common because it requires several modifications inside the WTG model that need to be validated.

- Multiplying the output current at PCC of the WTG by a *n*. This approach is simpler and more common because the WTG equipment and control models are not modified. Only an artificial current multiplication with a factor of *n* at PCC output is added at the output of the WTG model.

<u>Cable layout aggregation:</u>

Several approaches exist to aggregate the OWF cables (or the collector grid) [26] and [27]. The general concept assumes that OWF cables lengths are sufficiently short for the frequency range considered for EMT studies and that the current injected by each WTG is identical. Based on such valid assumption, an aggregated PI model cable can be derived [26], where the shunt capacitance of the aggregated cable account for the reactive power generated by the entire cable layout and the series impedance $R+Xj$ is computed to reproduce the predominant oscillation mode of the cable layout.

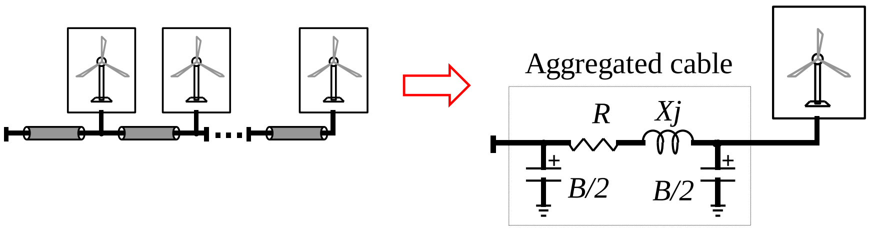


Figure 4-17: Aggregation appraoch

To illustrate the differences between all three types of detailed and aggregation approaches, a frequency response comparison, based on a real OWF project, is provided in Figure 4-18. It can be noticed that the semi-aggregated OWF, when properly tuned, is close to the detailed model for the frequency range relevant for EMT studies. However, in this example, the fully OWF aggregation is valid up to the first frequency resonance value that is around 2.2 kHz. Above this frequency the impedance response become different than the detailed OWF model.

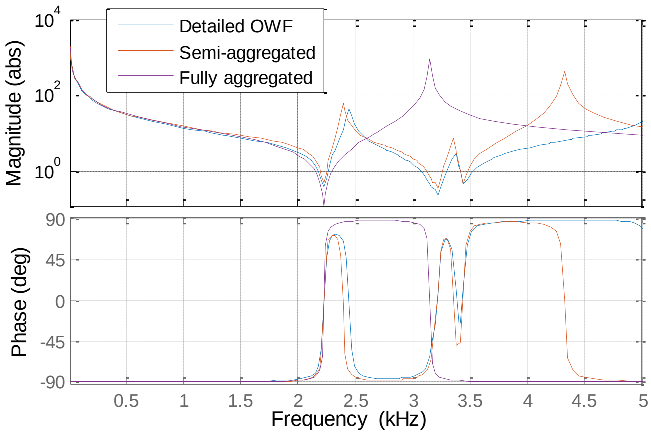


Figure 4-18 : Frequency response : comparison between full and aggregated OWF

Figure 4-19 shows a second illustrative example of comparison between fully detailed and aggregated OWF model. In this test case, an AC fault (at 1 sec during 150 ms) is performed at point of common connection of OWF, and AC voltages at different WTGs connection level is plotted. As can be seen from Figure 4-19, because the aggregated model includes only one aggregated WTG, voltage dips differences, due to different cable lengths, that will appear inside the wind park cannot be reproduced. In a detailed model, such different voltage dips can lead to the tripping or not of each individual WTGs. Thus this individual WTG behavior cannot be reproduced in the aggregated model.

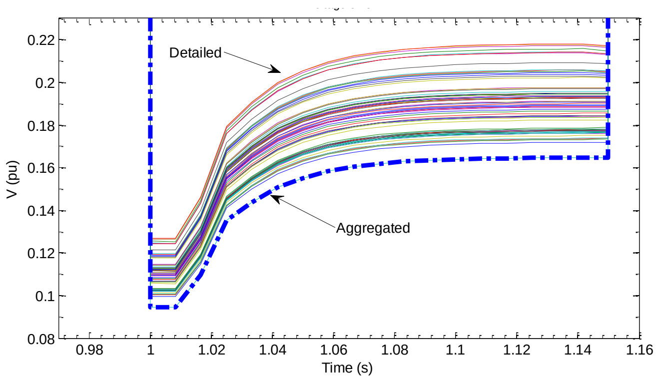


Figure 4-19: Time domain comparison between full and aggregated OWF – AC fault [21]

4.3. PED type of model

The previous sub-section has highlighted different types of model that can be used to develop each PED model for EMT simulations. Such model development is made by different stakeholders. For clarity, the definition of model includes the entirety of relevant control, protection and performance required in the study including any necessary scripting, referenced power system elements. The model requires to interface, necessary measurement, filtering and any external code associated with accurate model performance for the purposes intended.

At a system level, the model of the PEDs should be suitable for dynamic performance studies with appropriate representation of control and protection (C&P) performance. PED models could typically be implemented as:

- Full software schemes – comprising measurement elements, control loops, protection algorithms, and switching devices based on:
    - offline simulation tools with either black-box or open-access C&P system; or
    - real-time simulation models with either black-box or open-access C&P system;
- Hybrid schemes comprising hardware replica of C&P system and software model of switching devices implemented using real-time simulation tools

It should be noted that laboratory-scale prototype (or power-HIL setup) of actual equipment with C&P systems, which could be connected through power amplifiers with AC grids modelled using real-time simulators, is also a valuable test bench to perform validation for innovative HVDC project application. Nevertheless, as the focus of this section is on HVDC and OWF models for project application such approach is not considered as a model.

During project phases, utilities usually conduct several PED integrations studies to assess, anticipate or analyse issues. There are several types of PED models that can be used depending on each project phases and utilities. Such different types of PED model can be categorized in mainly three types: Generic model, manufacturer's model, and C&P cubicles with real-time simulation. These types of models are described in the following subsections.

4.3.1. Generic models

A generic model is defined as a model that is developed based on a general concept. A generic model can be re-used for a wide range of different projects with relatively minor reconfiguration or modification but must be sufficiently complete in form to describe the studied area or performance - for example fast front waveform responses of the control system would only be relevant if the generic model included associated measurement elements in a realistic way on top of the relevant control loops, multiple fault ride-through analysis would only be relevant if the model included both fast and slow acting protections etc.

For HVDC-OWF systems, five types of generic model can be listed: model based on standards/pre-standards, models from software library, in-house generic model, academic model and manufacturer's generic model.

Generic models can reproduce some dynamic performances and small perturbations but can be limited to cover a wider range of phenomena mainly when non-linear transients or high disturbances occur.

Generic models can be either black-boxed, open-boxed or semi-black-boxed. However, several parameters are usually accessible for the end-user to tune and understand the general PED structure. A generic model usually includes only the main part of the C&P functions that is relevant for the considered study and does not necessary represents the same power circuit configuration/element than the real project.

4.3.1.1. Model based on standards/pre-standards

Models based on standards/pre-standards are developed by international working groups (WGs) that often include experts from industries, academics, consultancies, and utilities. Therefore, such generic models are generally accepted by the international community and all data/information provided are publicly available. It, also, facilitates the sharing of information (or models) and understanding between different stakeholders.

For WTG, the IEC 61400-27 [28] is generally used in industry. It is usually sufficiently detailed for RMS tools but not the case for EMT tools. For this latter, IEC standard is yet to published, nevertheless, several WGs such as IEEE Task Force as in [9] has started to provide some useful EMT WTG models.

Regarding HVDC model, the Cigré TB604 [4] provides an EMT generic model that is also useful for RMS tools. Additional information on C&P system is provided in Cigré B4-70 [29]. It should be also noted that other WGs such as JWG B4-82 are ongoing to provide improved EMT generic models.

Such models are good for network focussed studies to provide expected HVDC or OWF performance, but their application beyond this scope may provide limited accuracy

4.3.1.2. Open-access model

Because power electronic devices are complex, several universities and research institutions developed generic open-access models based on theoretical background. Therefore, such models help engineers to better understand the theoretical phenomena that can occur and give an insight on some practical issues. There are several articles and universities that develop such generic models; for instance, the model developed by Strathclyde University in collaboration with HVDC Centre [32] and EU funded R&D projects BESTPATH [31] developed by a group of academics together with industry partners.

4.3.1.3. Model from software library

Generic models are also available in different commercial software packages; HVDC and WTG generic models are available in most EMT commercial tools (EMTP, PSCAD, Simulink, etc.). Depending on commercial software and versions, such models are usually developed based on available standards/pre-standardization and/or academic collaborations and/or industrial collaborations. It is useful to conduct some EMT planning studies. Such models are useful for exploring areas where standards may be required or features where no standard currently cover the intended areas of analysis.

4.3.1.4. In-house generic model based on specification

Some utilities, consultancies and converter manufacturers have capability and knowledge to develop their own in-house generic model. The advantage of such approach is that the model can be easily customized based on their own need to conduct a study. However, such approach requires expert engineers and human resources to develop an in-house generic model and to maintain the model during the life cycle of the project.

Such model is based on experience and may capture in more detail anticipated behaviours or represent a simplification/ translation of a vendor model/ set of vendor models supplied. It may provide limited insight in new vendor technology or new phenomenon not previously a focus of the models' validation.

4.3.1.5. Manufacturer's model from previous project

Manufacturer's model based on previous project can be used for an upcoming project development. This is a common practice used by converter manufacturers at the early stage of an upcoming project. It is also possible for utilities and consultancies to use a manufacturer's model from a previous project when the legal framework allows to do so.

The accuracy of such a generic model depends on project specifications and PED versions. Obviously, when the specifications of an upcoming project and PED version are the same (or close) than the previous one, such model is expected to provide results close to the real project. In such situation, this generic model can be considered as the most accurate compared to all previous generic models described in previous subsections. On the other hand, when specifications of an upcoming project and/or PED version are different, such generic models are still valuable, however results should be carefully analysed similarly to all previous generic models.

4.3.2. Manufacturer's black-boxed model

Unlike a generic model, the manufacturer's black-boxed model is referred to a specific model for a specific project. To protect Intellectual Property (IP), a black-boxed model (i.e. not fully accessible) is usually provided by the manufacturer to the utilities for the considered project. Such model includes the exact data of power circuit and configuration of the real project and the exact C&P system relevant for offline EMT simulations. Some simplifications in the C&P system are usually performed; for instance, some functions as start-up/shut-down sequences are simplified and/or accelerated to reduce the simulation time. In RMS tool, the manufacturer's black-boxed model includes only the relevant C&P systems for network stability studies since not all C&P functions (specially the fast control loops) can be implemented in RMS tools. For EMT tool, the manufacturer's black-boxed model includes an exact copy (or similar) of all C&P functions that are relevant for offline EMT simulation. However, slow control functions such as Run-back functions, AC emulation, POD, etc. are simplified. Relevant protection functions are also included in the EMT model.

4.3.2.1. Model requirement for black box

There are two types of black-boxed models distinguished:

A complete black-boxed (or encrypted) model

The end-user has only access to the main control parameters such as references of active power, reactive power, AC voltage, frequency, etc. as well as droop values and upper/lower limits. No further detailed information on C&P systems and the HV equipment (or power circuit structure) are available and accessible. Such types of complete black-bloxed models are usually provided by default by the manufacturers when no detailed model requirements are explicitly specified in the project.

Customized black-boxed model

Depending on project needs and utility specifications, another type of black-boxed model can be required; where the power circuit Figure 2-2 (transformer, cables, generators, filters, converter, etc.) is accessible and only sensitive IP aspects (such as internal control and protection systems) are black-boxed. This customized black-box model is possible, for example, when the utility owns the PED system, in such case the HV equipment data are already available and, therefore, power circuit can be fully accessible also in the software. In such customized black-boxed model, C&P system can be fully black-boxed or partially black-boxed depending on project needs and agreement/discussion between manufacturers and utilities. For MMC-HVDC system, the interface between the encrypted and open-data is at the level of the MMC valves; either all valve information (each SM capacitor voltage/current) are accessible as per Model 2 in Figure 4-2 or the valve is black boxed as in Model 3 in Figure 4-2.

- HV equipment requirements: All the HV component characteristics (transformers, cables, compensation systems and/or filters, synchronous units, converters using power electronics, surge arresters, etc.) shall be described in a document in a generic format. This document shall also include the location, the direction, the type and the transformer ratio of voltage and current sensors. These characteristics shall be identified in a single line diagram of the facility so that detailed EMT models of the HVDC link can be created in any EMT simulation tool.
- C&P system requirements: The C&P model must be suitable for EMT studies. This usually means that all control functions from the upper-level controls, corresponding to the functional operation of the system, and the lower-level controls, corresponding to the control of the valves (including the pulse generation) are provided in the digital model. Similarly, all protection functions required to capture the realistic behaviour of the station for AC, DC and internal faults are implemented in the model. This ranges from slow protection systems (hundreds of ms), such as Low Voltage Ride Through (LVRT) to fast protection systems (few ms), such as overcurrent protection systems.
  The controls and protections, relevant for EMT studies, compatible with the digital model can be provided by the manufacturer as a dynamic library, directly generated from the tool used to design the control and protection software. This solution is especially important to ensure a better accuracy of the model. Moreover, this black-box solution provides effective protection against data disclosure on control and protection.
  In addition to the digital model, a description of the control system may be provided in the form of block diagrams. These block diagrams allow the main functionalities of the system to be understood. Every protection function that interacts with the control system should be described as well. These descriptions are quite useful during the analysis of the results provided by the EMT model.
  The parameters available in the HMI should also be available in the control system model.

Model Maintenance and Upgrade

The EMT model is used throughout the life of the HVDC system. During this period, some HV equipment will be replaced, the C&P system will be adapted and, therefore the model has to be designed to be easily updated according to the changes in the real system.

Moreover, prospective studies on fine-tuning of available control functions or on new controllers (for instance, frequency-sensitive active power reference modulation controller) can be performed. For this purpose, the black-boxed model provided by the manufacturer should be interactive enough that new features or solutions linked to the upper-level controls can be investigated.

4.3.3. C&P cubicles with real-time simulation

Unlike the two previous types of PED models (i.e. generic and black-boxed models), this approach is performed with real-time simulator.

4.3.3.1. HIL setup

Hardware-in-the-loop (HIL) setup is a method that is used to test and develop complex physical C&P systems. A HIL setup includes:

- Real-time simulator to emulate the power system network
- Physical C&P system cubicles

- IO interfaces between the plant simulation and the C&P system under test

Because the physical C&P cubicles are represented, this approach is the reference model for C&P functions validation. These physical C&P cubicles can be either the real cubicles that are installed on site or the replicas that are described in the next sub-sections.

4.3.3.2. Real cubicles

During design stage of an HVDC project, the HIL setup is used to test the real physical C&P cubicles before onsite shipment and commissioning. This real-time simulation tests are, usually, performed by the manufacturers in their real time laboratory. The aim of such HIL setup and tests are multiple: validate performance requirements, ensure compliance with grid code, perform additional EMT tests (that are not possible in offline EMT simulation), achieve the factory acceptance test (FAT) with customers, validate/test the remote-control interface between HVDC and dispatcher, ensure that the protection system is well coordinated, ensure that transient behaviors are in compliance with offline EMT studies, to prepare onsite commissioning test.

4.3.3.3. Replicas

A replica is a copy of the actual C&P system installed on site. Figure 4-20 provides an overview of a HIL setup with replicas. Replicas are usually acquired by utilities to de-risk the HVDC project. Two types of replicas are available depending on project specifics.

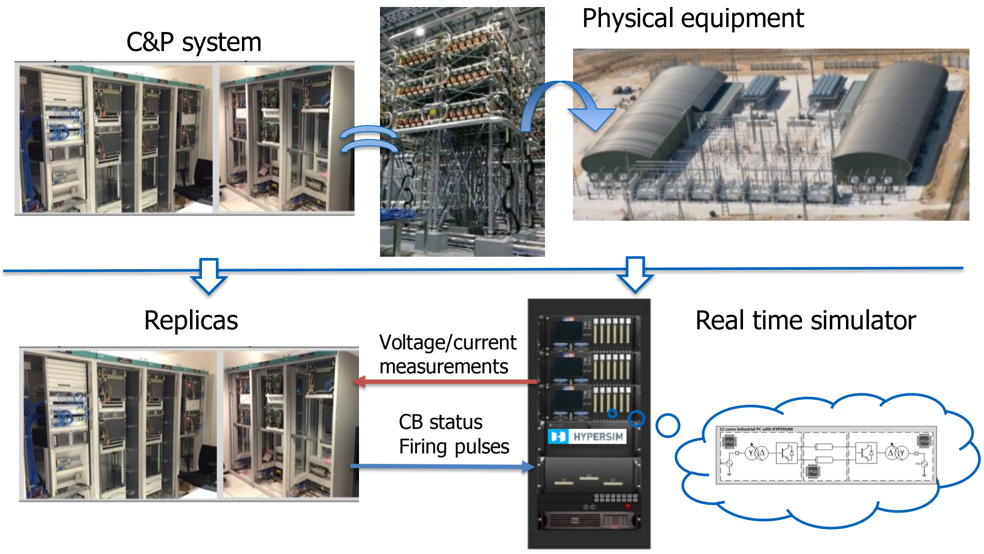


Figure 4-20 : HIL setup overview

Study replica

The study replica is dedicated to functional verification, dynamic system performance and protection studies. The Study replica is provided only with equipment relevant to network studies and redundancy is not included. The number of cubicles is lower compared to the Maintenance replica (described in the following section).

Modeling of detailed C&P systems for EMT offline studies is a quite complex task because actual controls may run on multiples platforms (CPU, DSP, FPGA…) and as a consequence simulation on a single CPU require long computation times. Moreover, the HVDC controls are based on algorithms that are protected by manufacturers due to IP rights. Therefore, replicas are useful to perform network studies without any simplifications or assumptions in control systems. Off-line C&P system models can be also validated with replicas.

In addition, some transient studies cannot be performed on offline software due to a large simulation time (several minutes) and some functions of the real system may not be included in the offline model (i.e. the real procedures of the start-up, shut-down and black-start sequences, etc.). In such cases, the replica becomes a complementary tool to validate dynamic studies.

Maintenance replica

The maintenance replica is intended to help the preparation of on-site maintenance operations and operator training. The preparation of maintenance operations includes testing and validation of the upgraded system version before field implementation during the life cycle of the project. In order to perform preparations for maintenance, validation of upgraded control system, fault diagnostics and training of operators, the Maintenance replica includes a set of control and protection cubicles identical to the original cubicles in the converter substations with the same interfaces, including any redundant equipment implemented in the converter cubicles. In comparison to Study replica, the number of cubicles is higher and is close to the number of cubicles that are installed onsite. Since the maintenance replica includes everything represented in the Study replica; the maintenance replica can be also used for all activities listed in Study replicas section.

It is expected that maintenance replica will have higher cost than the Study replica because of higher number of cubicles. Therefore, depending on project specificities, the technical-economical aspects should be analysed to decide whether a study and/or a maintenance replica are necessary. Also exchange/discussion with the relevant stakeholders is needed to find the optimal solution.

Reconfigurable Replicas

Reconfigurable Replicas (RR) concept represent a hardware solution where different power electronic device firmware from an equipment manufacturer may be uploaded into a common hardware foundation across different devices allowing hardware to be pooled and used flexibly across multiple projects. The concept could enable the underlying performance of power electronic devices in the Factory Acceptance Testing to be flattened into a smaller hardware footprint without loss of the critical functionalities, which would impact the performance of the overall solution within an onshore AC network. Further active engagement with vendors and industry surrounding the development of the concept of reconfigurable replicas is required to allow hardware to be pooled across projects. The RR concept enable an appropriate class of replica hardware to support the HIL testing requirements of different PEDs or project applications, which would act to minimise the overall costs of delivering the de-risking activities for complex electricity connections.

4.3.4. Pros and cons between PED type of models

In section 4.3, three main types of PED models have been presented: Generic models, manufacturer's black-boxed model and C&P cubicles with real-time simulation. Depending on project specificities, stakeholders and project phases, all these models are recommended to be used because they are complementarity and each one has his own pros and cons.

Generic models

Pros:

- Because generic model is usually less complex system than a manufacturer's black boxed model, therefore computation time is faster.
- Usually, in the generic model, the end-user has access to much more information in the internal structure and parameters than the manufacturer's black-boxed model. This makes the generic model more accessible, more flexible, and easier to manipulate.

Cons:

- Because the generic model does not represent the real system, the model is less accurate, and the precision of the results should be carefully interpreted. The end-user needs to have a deep technical knowledge and experience in the system to correctly analyse and investigate the results before deriving any conclusion.

Manufacturer's black-boxed model

Pros:

- Such model is provided by the manufacturer who builds the system. Thus, the results and accuracy of the model should be close to reality and the end-user has more confidence in the results.
- With respect to the generic model, in the manufacturer's black-boxed model, the end-user has less information and parameters to be configured and manipulated. Therefore, the end-user does not need to have a deep technical knowledge in the system to manage the model.

Cons:

- The model is slower than generic models because it includes much more components.
- Because the model is less accessible, the model is less flexible: for instance, the model can depend on software version and becomes more complicated to manage at long-term. Also, only few fixed time step can be guaranteed for the operation of the model. In such cases, interaction studies with the different PED becomes more difficult.
- During the lifetime of a project, the C&P systems are continuously updated onsite. However, generally speaking, offline model is not updated accordingly. Therefore, at long term, manufacturer's black-boxed models become less accurate and reliable than a real-time simulation with replicas.
- The model is mainly valid for specific studies that are advised by manufacturer and that are requested in the specification of the project. Investigation should be performed to insure that the model is also valid for extend system studies that were not foreseen during design stage.

C&P cubicles with real-time simulation

Pros:

- In this approach the C&P is identical (or similar) then onsite. The HVDC C&P behavior, in the frequency range of concerns (see Figure 3-1), will reproduce the most accurate results.
- C&P functions are more accessible than the manufacturer's black-boxed model. The end-user can have more information and deeper insight to analyse the behavior.
- At long-term, the maintenance of the C&P cubicles is much more manageable than the manufacturer's black-boxed model.
- Simulation time is faster than manufacturer's black-box model because it runs in real-time.
- Such HIL platform can also host other hardware such as: DC protections, AC protections and Wide area control devices to validates and perform coordination study among thus multi-vendors devices.

Cons:

- In comparison to the previous two models, such approach is more costly and requires additional investment in human resources and facilities, but solution such as Reconfigurable Replica concept could help to minimise costs.
- Unlike C&P cubicles, the power circuit model is usually less accurate than offline model due to real-time simulation constraints. Therefore, transients' behavior above several kHz is usually less accurate than the offline model.

5. EMT STUDIES DURING PROJECT PHASES

Dynamic simulations are conducted at different stages of an HVDC project. Dynamic studies can be divided into four main groups: feasibility studies, specification studies, implementation studies and operating studies. Figure 5-1 gives a typical flow chart of the studies needed for each stage of the HVDC project lifecycle. All information provided in this section is based on Cigré WG B4-70 [29].

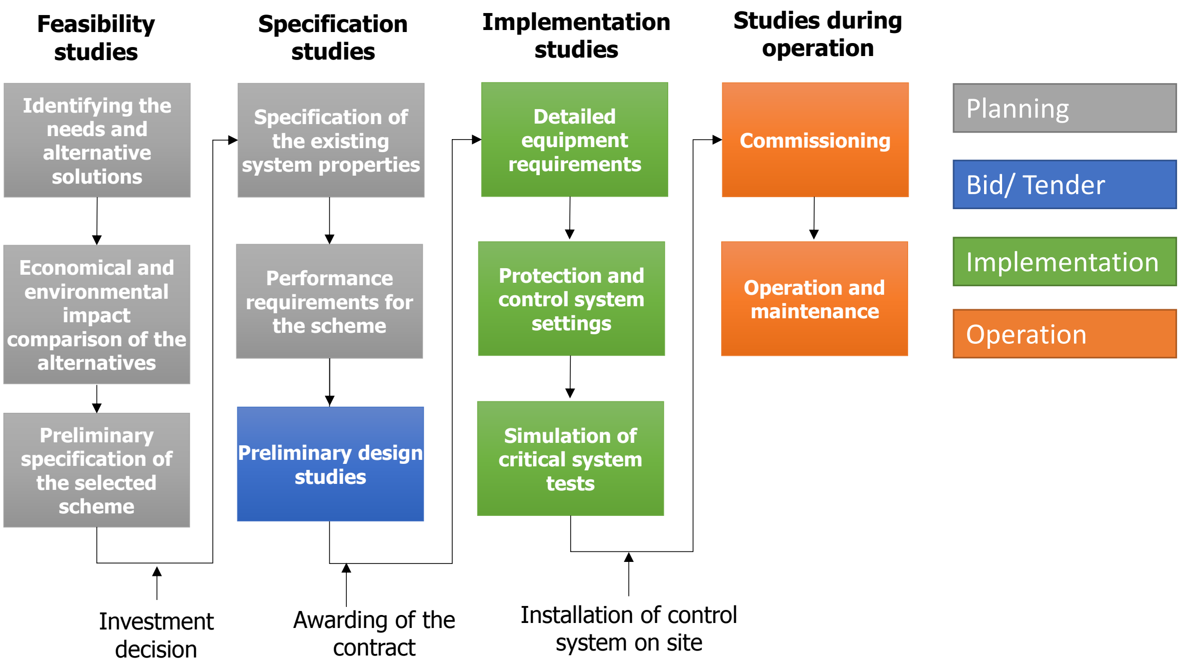


Figure 5-1: General overview of studies over an HVDC link life cycle from Cigré WG B4-70 [29]

5.1. Planning stage

During the planning and development stage of HVDC projects the project owner and/or the involved grid operator is recommended to perform feasibility studies as well as specification studies. These studies include evaluation of general project needs, analysis of configurational/topological alternatives and determination of important aspects to be covered in the specification.

5.1.1. EMT studies to be conducted

Usually, the studies performed during the planning stage focus mainly on load flow and stability simulations. However, for VSC-HVDC projects, it is beneficial for the project owner or utilities to perform EMT studies as well. This is the case if the project has an innovative character due to special needs or if the technologies being considered may have only recently been introduced or the impact of the HVDC link on the network is considerably high. Studies that may be conducted by means of EMT simulations at this stage are listed hereafter.

Preliminary fault performance

The HVDC system's response to various fault scenarios can only be evaluated in detail utilizing EMT simulations. The expected fault clearance times, availability/quality of reactive power/current injection during faults and loss-of-power strongly depend on the configuration and topology of the HVDC system and may be the outcomes of this study.

Analysis of the DC cable transients overcurrents and overvoltages

Such studies provide inputs parameters for DC cable design and rating.

Analysis of AC temporary overvoltage

At the stage of the project, the project owner or utility should identify the AC TOV limits that should be considered for the project. This can be assessed by EMT simulations to analyse AC voltage recovery after fault, load shedding and other events that lead to TOV on the network.

Analysis of different configurations and technologies regarding grid code requirements

Even though the fulfilment of grid code requirements will be the responsibility of the manufacturer, EMT studies may support the project owner to define the desired configuration and understand the general behavior.

Determination of AC system equivalent

Based on the location of the HVDC converter stations the characteristics of the AC system may have a significant influence on the required HVDC system performance. Preliminary studies can help to understand the size of the AC network that should be considered when performing the studies.

Analysis of AC overvoltages and overcurrents

Overcurrent stresses and insulation coordination studies are performed by the converter manufacturer during the design phase. However, by using typical insulation coordination concepts and estimated arrester's I-V characteristics it is possible to perform a preliminary evaluation of the amount of energy absorption capability of the arresters required for the project.

Analysis of ancillary services that can be foreseen

Ancillary services such as: Voltage control strategy, frequency control strategy, inertia and voltage stability support, blackstart, etc. are usually required in the project. Such EMT preliminary studies can provide an input on the parameter values and limits that should be accessible to the operator.

First evaluation of interaction risks

Perform preliminary investigation based on analytical simple approach such as SCL, MIIF, UIF, etc. Also, the purpose is to identify the network area that should be modeled in detail and relevant for interaction studies.

The outcome of these EMT studies may either directly or indirectly be used for the preparation of the technical specification. Additionally, the results obtained may also support the project owner in preparation for the assessment of proposals in the bid process.

5.1.2. EMT model to be used

At planning stage, no detailed manufacturer models are available, therefore, HVDC generic models are sufficient to cover the relevant question.

Onshore and offshore network model is developed in EMT and RMS tools based on the available information.

Usually, the detailed onshore network model is used at this stage and network reduction are performed for the purpose of the project. If interaction risks are identified, the network area of concern is also developed and prepared for the next stage of the project.

5.2. Tender phase

During the bid/tender stage a preliminary design of the HVDC transmission is prepared by the HVDC supplier. The correct, but still simple modelling of the system, into which the HVDC system shall be incorporated, is of high importance. The input for the models used in this task is a combination of customer information and converter manufacturer models.

5.2.1. EMT studies to be conducted

Tender phase period is usually short in time. Thus, the focus is mainly to highlight to the manufacturers the main issues that were identified during the planning stage. During this stage, it is usually the manufacturers that conducts the EMT simulation based on the data/information provided by the costumer.

Temporary Overvoltage and Undervoltage Profiles

For the design of the VSC converter the voltage fluctuations during normal operation and faults are of importance. Consequentially an exact definition of the over- and undervoltage-profile - including the expectations of the HVDC system behaviour during such events - is beneficial for customer as well as the manufacturer. The TOV and TUV definitions have a significant impact on the converter design and consequentially on investment as well as operating cost (losses) of the system.

Preliminary Transient Stresses Study

Investigation of internal converter or DC cable faults which will cause the converter to trip. Determine the worst case for equipment and verify the arrester configuration for the protection of the converter.

Preliminary Dynamic Performance Study

This study is based on preliminary control parameters. Verification of a reduced set of non-steady-state events on the AC and DC sides at which the HVDC system remains in operation. For offshore connection, costumer can provide to the suppliers a generic WTG model to perform such preliminary performance study.

Required data and models

To identify offshore and onshore parameters that are required to conduct the design studies. The main C&P parameters that may have an impact on the considered project.

5.2.2. EMT model to be used

A desirable approach during the tender stage would be for the customer to prepare an EMT model of the system excluding the converter stations itself. This model shall be used for the rating or performance simulation in the offer process.

If the DC cable is not within the scope of the converter supplier, an appropriate representation of the cable can be part of this model. If there is an AC cable/ AC line between the point of interconnection and the converter station, which is not in the scope of the converter supplier, a representation of the cable/ line should form part of this model. For convenience of the customer also the measurement points and signal naming can be provided (this will reduce the risk of misinterpretations of the results of the tender studies).

The HVDC link is usually represented and modelled by the converter manufacturers during the performance of the tender studies. The data provided by the customer in the technical specification is used for such purposes.

Similar to the AC network models, it might be advantageous for the costumer to deliver along with the tender specifications, an EMT model of the HVDC link and the WTG generic model. This ensures that all the manufacturers base their studies on comparable representations of the HVDC link. It also has the potential for speeding up the tender studies stage by reducing the need for further clarifications.

Typical information from the customer includes:

- AC network Thevenin source parameters
- AC network operation parameters: P/Q/U/F
- DC cable parameters (if DC cable is not in scope of supply of the converter supplier)
- Profiles for overvoltage and undervoltage
- Harmonic data and limits for onshore and offshore

5.3. Implementation stage

Design studies are used to determine the electrical parameters of the HVDC converter and its components. They provide the basis for component specifications and consequentially for the layout. The scope of the studies can vary depending on the project specifics.

For offshore network, additional AC overvoltage studies are performed with EMT programs. A detailed representation of the windfarm and its controllers are necessary.

5.3.1. Dynamic studies to be conducted

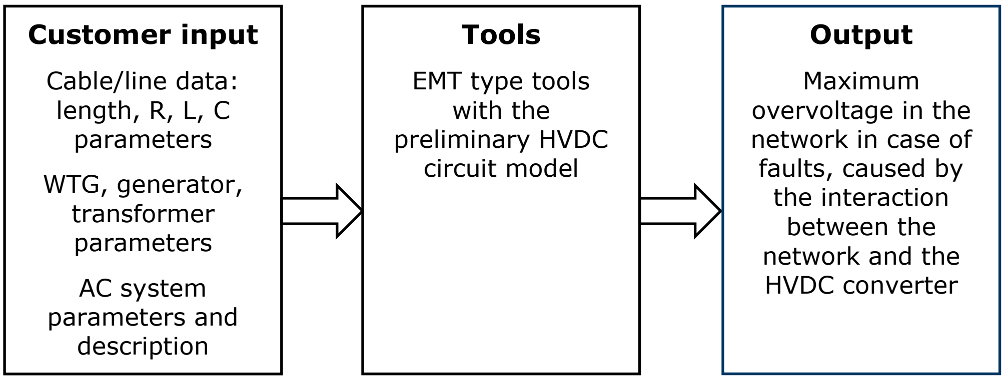
During implementation stage, the supplier conducts EMT studies based on costumer inputs/data. Therefore, it should be highlighted, that the quality of the HVDC design depends highly on costumer's inputs and data. When such information is not available, suppliers will take assumptions that can lead either to misunderstanding or undesired outcomes.

AC Overvoltage Study

Study objective:

- Calculation of AC overvoltage onshore and offshore
- The controls and configuration of the offshore layout and converters is to be considered

Input/Tools/Output:

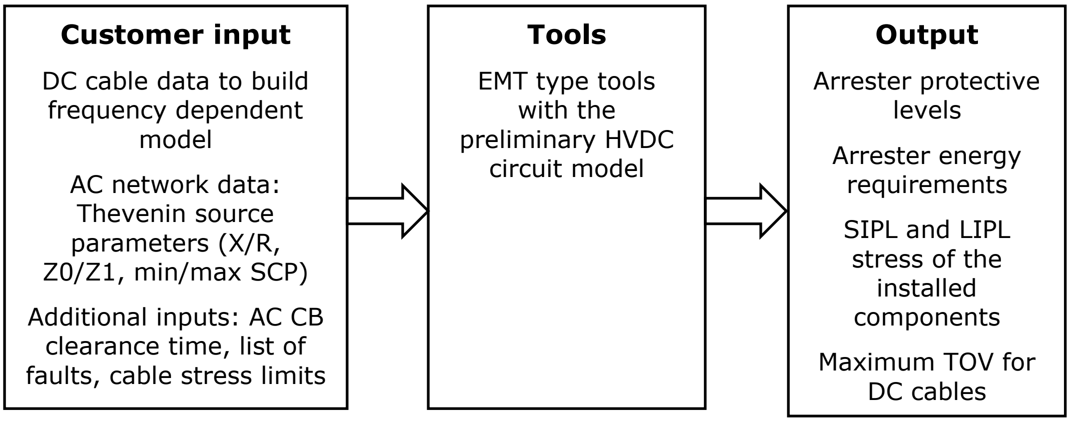


Transient Stresses/Insulation Coordination

Study objective:

- Investigation of internal converter or DC cable faults which cause the converter to trip
- Establish the worst-case stresses for equipment and verify the arrester configuration for the protection of the converter

Input/Tools/Output:



AC Circuit Breaker Study

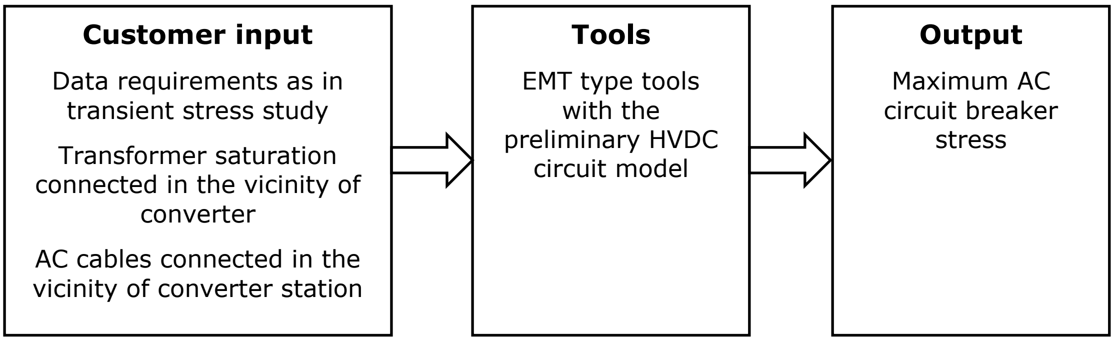
This study is considered optional as the switching task for a converter AC circuit breaker is similar or even the same for any substation circuit breaker.

This situation might change, if for example, AC filters are switched or there is a special configuration such as a long AC cable. In this case, a study can be useful.

Study objective:

- Examine the technical requirements for AC circuit breakers with the aim of specifying the breaker

Input/Tools/Output:

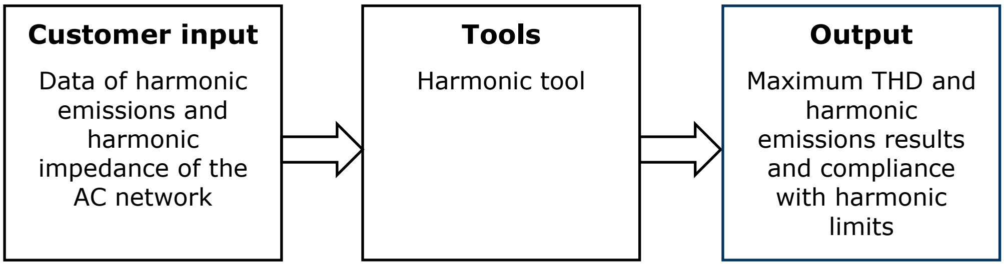


Harmonic emission studies

Study objective:

- Verification of harmonic limits and compliance with the grid code
- Design of AC and/or DC filters in case required

Input/Tools/Output/:

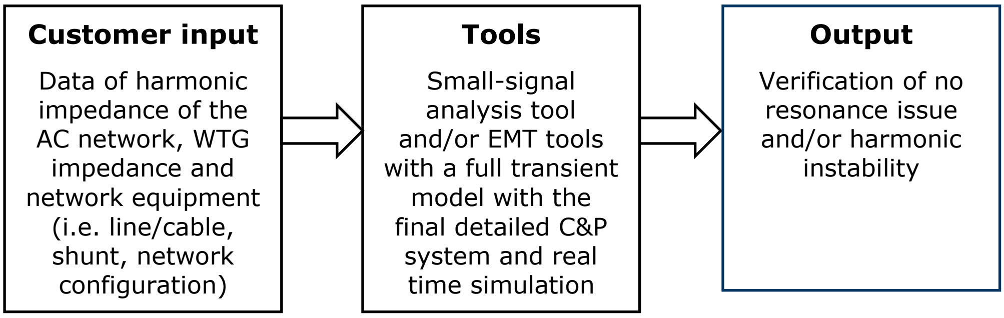


Harmonic stability

Study objective:

- This study computes the phase margin of the control system within the surrounding network and with offshore WTG
- Verification of no resonance issue due to control behaviour in the harmonic frequency range.

Input/Tools/Output:

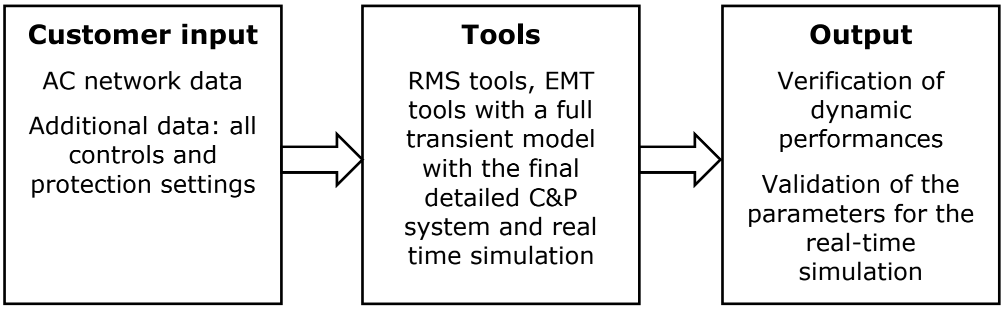


Dynamic Performance Study/Dynamic Performance Test

Study objective:

- Dynamic performance are studies which are used to determine the behaviour of the HVDC converter and to demonstrate compliance with the specified performance and grid code.
- Verification of all non-steady-state events of AC and DC sides at which the HVDC system remains in operation, such as: Reference step change, transformer energizations, fault performance, start-up and shut-down sequences, etc.

Input/Tools/Output/:



System Restoration and Black-start Study

For the verification of the black-start and system restoration performance, two possible solutions are described:

1. System restoration/black-start test (generic representation of the connected network)
2. System restoration/black-start study (specific network restoration scenarios)

Both approaches are described hereunder.

1. System Restoration and Black-Start Test

Study objective:

- Verification of capacities during black-start and system restoration conditions
- Different switching events and faults are simulated in a generic network representation

Input/Tools/Output:

Customer input	**Tools**	**Output**
AC network data Performance requirements during system recovery	EMT type tools with a full transient HVDC model with the final detailed control and protection system <u>Generic</u> representation of the connected system	Prove that the HVDC system can support the network restoration without violating the specified performance requirements Indication of capacity that the HVDC can provide (maximum size of switched elements) Performance of the HVDC system during network disturbances during system restoration

Comments:

- The study can be performed with a real-time simulator and/or in an offline simulation tool.

The test is performed with a simplified network representation. This network representation typically comprises of one local bus and one remote bus connected by cable or line. Each bus is equipped with different types of equipment and loads.

2. System Restoration and Black-Start Study

Study objective:

- Detailed verification of system behaviour during specific black-start and system restoration sequences
- Switching events and faults are simulated in a specific network representation for a specific restoration scenario

Input/Tools/Output:

Customer input	**Tools**	**Output**
Detailed AC network data of all the equipment involved (including generator data) Switching sequence for system recovery. Performance requirements during system recovery	EMT type tools with a full transient HVDC model with the final detailed control and protection system Detailed representation of the system part involved in the restoration scenario.	Prove that the HVDC system can support the network restoration for specific restoration scenarios without violating the specified performance requirements Performance of the HVDC system during network disturbances during system restoration

Comments:

- The study can be performed with a real time simulator and/or in an offline simulation tool
- All data required for the detailed model and the initial restoration plan shall be provided by the customer.

Sub-Synchronous Torsional Interaction (SSTI) Study (if applicable)

This study is typically divided into two stages:

1. Pre-examination of the system
2. Detailed study in case part 1 highlights generators that could interact

Both approaches are described hereunder.

1. SSTI Pre-Examination

Study objective:

- Evaluate the possibility of SSTI between HVDC and generators in the given AC system
- Identify the generators that are to be studied in detail in part 2 of the study

Input/Tools/Output:

Customer input		Tools		Output
Full network model suitable for short-circuit calculations for a given number of load flows (typically 2 to 4)	⇨	Analytic calculation	⇨	Unit interaction factor for generators in the vicinity. Decision, which generators must be considered in part 2 of the study.

2. SSTI Detailed Study

Study objective:

- Detailed evaluation of SSTI for the generators identified in part 1 of the study

Input/Tools/Output:

Customer input		Tools		Output
Technical data of the generating unit(s) and transformers Exciter, governor, and PSS models of the generator(s) Reduced shaft system models (typically 5 to 8 masses)	⇨	EMT type tools with a full transient HVDC model with the final detailed control and protection system	⇨	SSTI vulnerability of the generators Verification of positive electrical damping of the VSC converter controls in the sub-synchronous range

Comments:

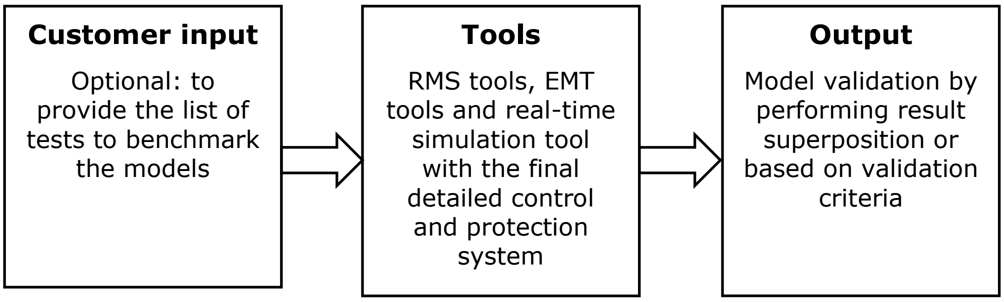
- The study can be performed with EMT offline simulation and small signal analysis to derive the electrical damping.
- SSTI study should be considered for onshore and offshore network

Model validation test/benchmarking

Study objective:

- The objective is to validate the three main models that are used during the implementation stage: RMS, offline EMT and C&P cubicles with real-time simulation.
- To ensure that power circuit data and C&P functions are similar

Input/Tools/Output/:



Comments:

- For slow dynamic studies, RMS tools can only be validated with the real-time simulation
- For fast dynamic studies, offline EMT tools can only be validated with the real-time simulation

5.3.2. EMT model to be used

For EMT studies in which the AC system shall be represented, the customer can provide a detailed description of the equipment connected in close vicinity to the converter stations. A reduced network example is provided in Figure 4-13 for the installation of a VSC converter station. It includes the main equipment connected to three (or more) substations away from the converter station.

This data provides the manufacturer with a clear description of the environment where the converter station will be connected. They display some specific equipment or configuration of the grid that can have an impact on the converter station design and control tuning. For instance:

- Energization of the two largest power transformers connected at the same busbar as the HVDC. These transformers generate inrush currents that can enable some converter protection.
- HVDC interconnector that can be connected to 2 different busbars in the event of a split bus in the substation. This information is important for the coordination of control and protection systems in the converter station. This configuration shall be tested during the dynamic performance tests.

5.4. Studies during operation

After HVDC commissioning, it is generally the utilities that conduct EMT studies to assess system operation. When needed, HVDC supplier perform also studies and/or support for utilities.

5.4.1. EMT studies to be conducted

The utility is responsible for the stability of its own network, and therefore shall perform studies to evaluate the impact of the HVDC system on the network. For this reason, accurate models of the HVDC system shall be used. The list of potential situations for which EMT studies are required can be long, however, a non-exhaustive list is provided for illustration purpose:

- Post-incident analyses
- Impact and interaction with classical AC protection studies

- Development of the grid topology close to the HVDC
- Dynamic behaviour studies (lead to operational limitation, e.g. ramp rate)
- Transient studies on temporary or permanent AC, DC faults and internal faults
- Interaction studies with other power electronic devices and renewable sources
- Harmonics and resonance studies
- Black-start studies
- Sub-synchronous interaction studies
- Line energisation studies
- Transformer magnetization studies
- Control coordination with other equipment studies
- Extension of the HVDC system
- Refurbishment of high voltage equipment studies or modification of the converter station topology (new filter, change of transformer, new DC cable)
- Refurbishment of the control and protection system
- New control function assessment

5.4.2. EMT Model validation

Validation of the EMT model is a substantial part of the model delivery. Some solutions to validate the model are presented below:

- Comparisons with the Dynamic Performance Tests results performed with another EMT model and/or the real cubicles connected to a real-time simulator.
- Comparisons with onsite measurements and especially during site commissioning. The digital recordings provided by Transient Fault Recorder (TFR) are quite useful to support this validation process.
- Comparisons with real-time EMT simulation connected to control and protection replicas. These replicas can be provided in the scope of the project. This solution provides a valuable solution to validate the EMT model. The differences between the offline EMT model and this reference is not restricted to only the control and protection system because the HV equipment models running in real-time may include simplifications and/or adaptations required to meet the real-time constraint. This is why special attention shall be paid when offline EMT simulation is compared against real-time simulation with control and protection replicas.
- Comparison with measurements during on-site events. For events involving the HVDC system, the incident can be reproduced with the EMT model to understand the phenomenon and suggest remedial action.

5.4.3. EMT model to be used

During operation, all three type of tools are used: RMS, Offline and real-time simulation. The application will depend on the studied scope. It is common to use two different tools to perform a study in order to validate and to cross-check the results. For instance, when performing RMS studies for slow dynamics (such as POD), the real-time simulation is also used as a complementary tool to validate HVDC model behavior and the provided mitigation solution. In some cases, generic models are also used, this helps to understand a specific behavior and to acquire deeper knowledge in the system.

6. GENERIC CASE STUDY - PARAMETER SENSITIVITY ON SYSTEM PERFORMANCE

The scope of this chapter is to provides illustrative example of HVDC-OWF system dynamic operation using generic model in EMT software. Therefore, several simulations such as AC faults, load rejection and step change are analysed. In addition, impact of parameters is also analysed to show the sensitivity of different control tuning and EMT modeling on the dynamic performance of the overall system.

The considered case study is based on the Cigré TB604 benchmark model [4]: a MMC based HVDC link in symmetrical configuration with a rated power of 1GW, rated DC voltage of ±320 kV and DC cable length of 200 km. The cable is modeled using the frequency dependent model (section 4.2.2). Since generic system studies is of concern, the MMC Model #3 is used and considered sufficient. Submodules capacitor stored energy is 33 kJ/MVA, arm reactors is 15% and transformer reactor is 18%. The remaining electrical parameters of the converter station can be found in Cigré TB604. All simulations are done using EMTP-rv software [6].

The generic onshore and offshore converter control structures is RTE's in-house generic model based on specification (as defined in section 4.3.1.4) : The onshore converter station is operating in PQ mode to control DC voltage and the offshore converter station is in VF mode (to regulate offshore frequency and AC voltage) see section 2.3.1.4. The generic VF control structure details can be found in [34] and the PQ mode including the negative sequence current control for unbalance AC fault is detailed in [35].

The OWF system is represented as an aggregated park. Regarding WTG model, four types of models are used in order to study the impact of WTG on HVDC performance:

- WTG Generic 1: One RTE's in-house generic model based on specification (as defined in section 4.3.1.4). This model is used as the base case and three others are only used to analyse the impact of WTG model on HVDC performance.
- WTG Vendor A, vendor B1 and vendor B2 : Three manufacturer's black-boxed model from previous projects. Regarding vendor B1 and B2, differences are only on reactive current support strategy during AC fault; in vendor B1, WTG does not provide current injection during AC fault whereas in vendor B2 the WTG provides current injection. A power plant controller is used to set the reactive power reference of OWF to zero.

It should be noted that all four WTGs models are compliant with RTE's onshore grid code. The following simulation will show that such onshore Grid Code compliance is not sufficient to guarantee the same compliance for offshore network.

Regarding onshore 400 kV network two equivalent simplified network are considered with a short-circuit level of 10 GVA:

- Equivalent synchronous generator including its governor/turbine IEEEG3 and its exciter SEXS. This is the base case and the second one is used only to identify the impact of the AC network on HVDC performance.
- Equivalent Thevenin source with a short circuit level equal to the SM (i.e. 10 GVA).

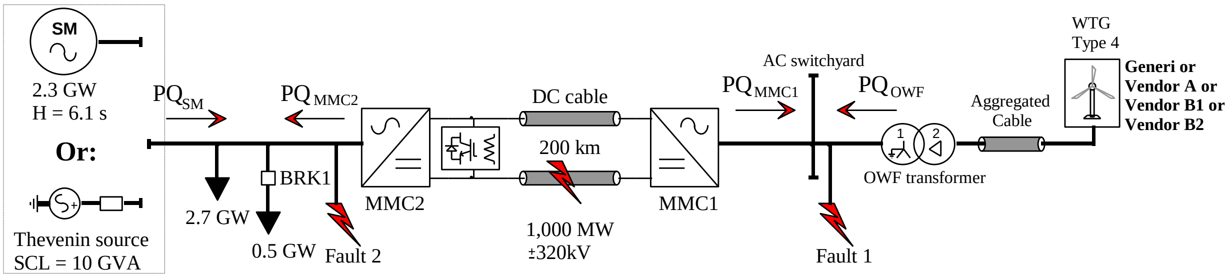


Figure 6-1: Unifilar schema of HVDC-OWF system

6.1. Offshore AC voltage step change

Step change of 5% is applied on the ac voltage reference at Offshore station MMC1. The test is to show the good performance of the considered generic model and the overall expected behavior of the offshore system.

Active/reactive power and AC voltage measurement and references results are plotted in Figure 6-2. It can be noticed that the system remains stable and that AC voltage step change applies a change on reactive power, whereas active power and frequency are not affected.

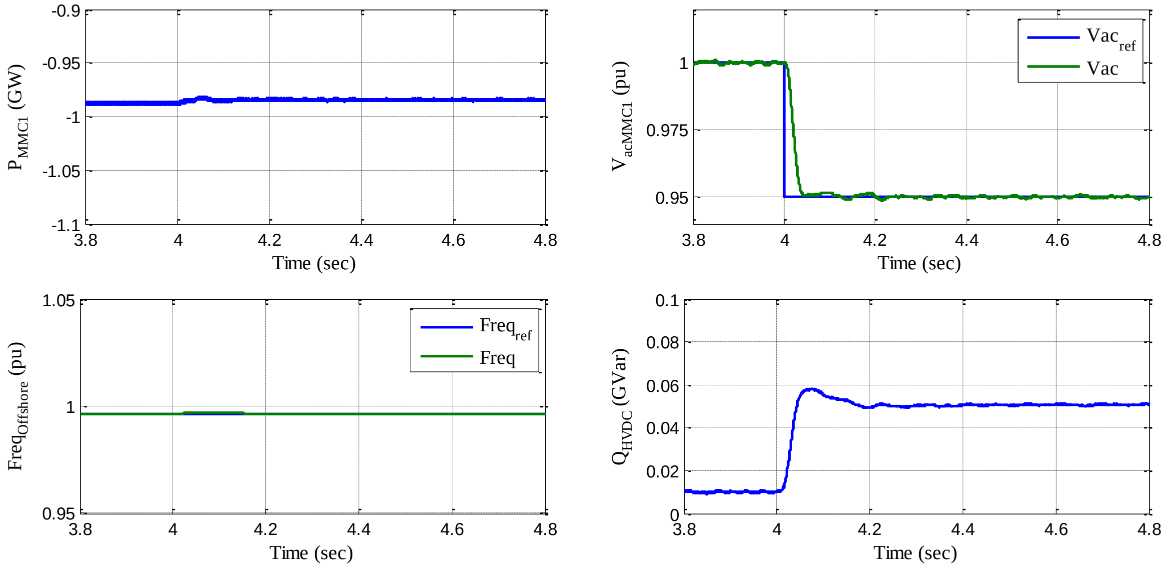


Figure 6-2 : Vac offshore step change – with WTG Generic 1

Impact of WTG model on HVDC performance

The same test is now applied using the three WTG vendors model (i.e. Vendor A, Vendor B1 and Vendor B2). Comparison results are provided in Figure 6-3. It is noted that Vendor B1 and B2 remain stable during the step change, and thanks to the power plant controller, after voltage step change applied, the reactive power of OWF goes back to zero. However, results with Vendor A shoes an undamped 15 Hz oscillation after ac voltage step change is applied. Such oscillation is noticed mainly on the reactive power as well as on the active power results.

In a real project, the performance of HVDC link with WTG Vendor A would be unacceptable, both or either HVDC or WTG control should be improved to reach a stable operation.

This example shows the importance of control coordination between OWF and HVDC to ensure stable performance. It shows that during design stage, accurate model should be used for each component level in the offshore system and control dynamics should be specified and checked at early stage of the design phase.

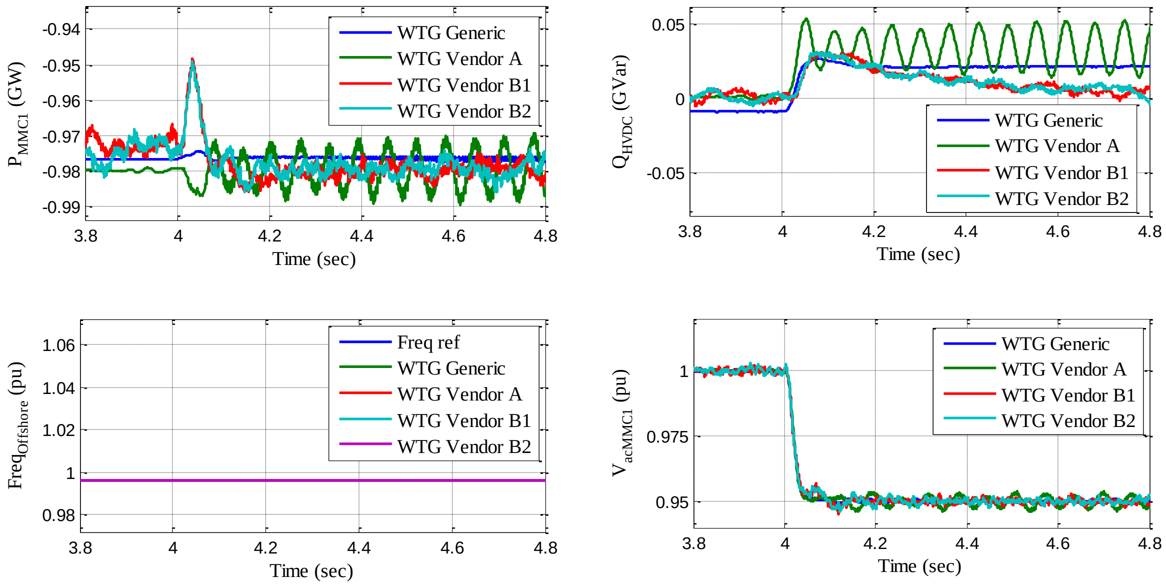


Figure 6-3 : Vac offshore step change – impact of WTG model on HVDC performance

6.2. Offshore frequency step change

Impact of WTG model on HVDC performance

Step change of 0.4 Hz is applied on the frequency reference at Offshore station MMC1. Offshore Active/reactive power, AC voltage and frequency results are plotted in Figure 6-4. All four WTG models are compared. It can be noticed that system remains stable and that the frequency step change applies slight perturbation on active and reactive power within an acceptable margin. However, active and reactive power dynamic response behave differently depending on the WTG model used: for instance, reactive power's first reaction (just after the step change is applied) is different for all vendors (note that vendor B2 have similar behavior than WTG generic but is different than vendor B1). In this test case, the four WTG models does not have a major impact on HVDC performance.

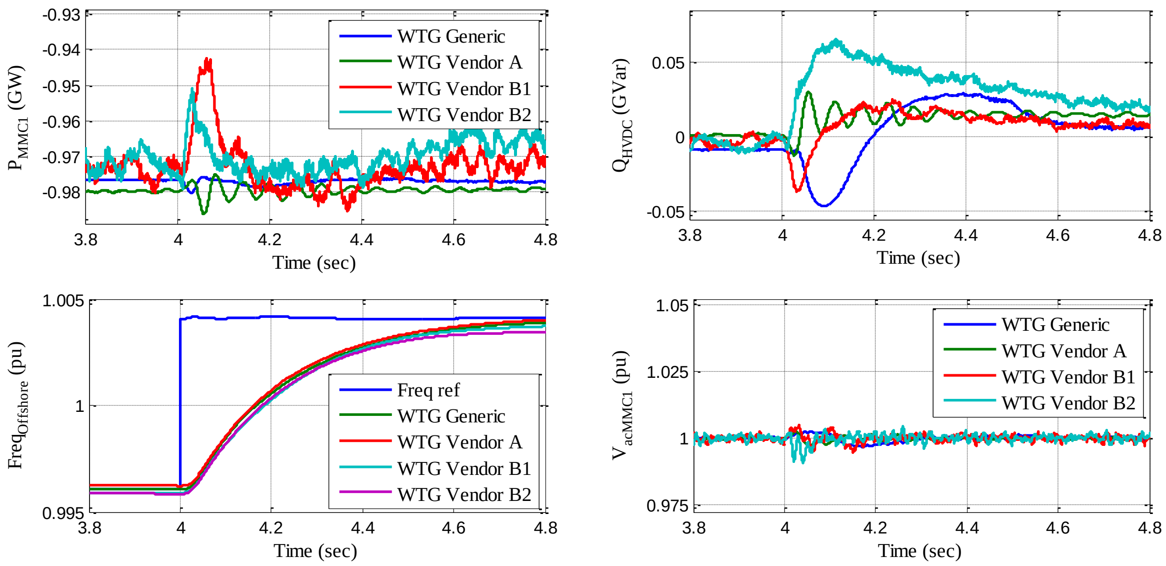


Figure 6-4 : Offshore Frequency step change

6.3. Offshore AC fault

A three-phase AC offshore with 5% voltage residual, during 200 ms, is applied at AC switchyard (Fault 1 see Figure 6-1). Offshore results of MMC1 are depicted in Figure 6-5.

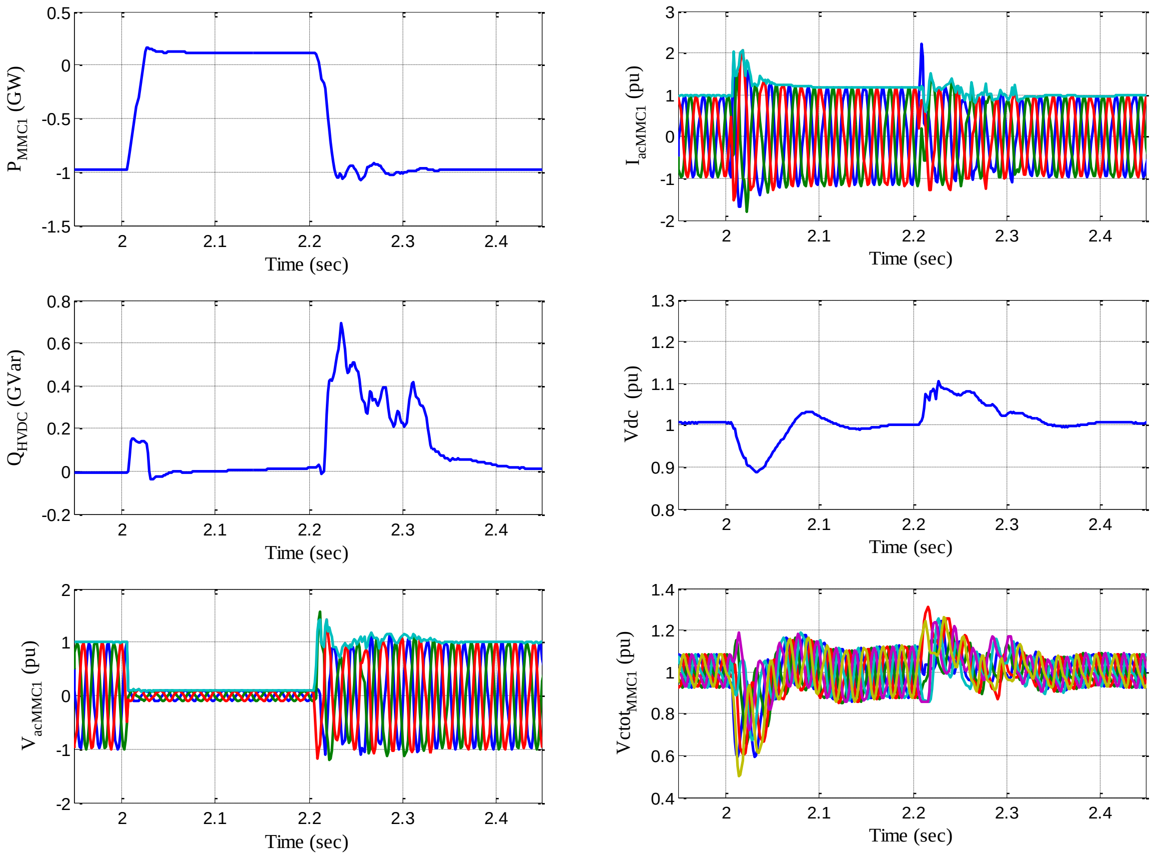


Figure 6-5 : Offshore AC fault – with WTG Generic 1

During AC fault, converter station provides the full current rating that reaches a peak value of 2 pu and a steady state short-circuit value of 1.27pu (to support AC voltage). When fault occurs, instantaneous energy is provided by the MMC capacitors, therefore, Vctot (capacitor voltages) decreases and reaches 0.6 pu value. Such value might be problematic if the converter is not properly designed for such undervoltage. In such case, it is possible to tune the control to limit MMC capacitor discharging. On the other hand, DC voltage is affected with a fluctuation in the range of ±10%, such variations are usually not problematic for DC cable design.

After fault recovery, we notice that AC overvoltage can reach a peak value of 1.6 pu. The converter should be designed to withstand such value, alternatively a better control tuning with better coordination between HVDC and WTG control systems should be performed to reduce such temporary overvoltage. Furthermore, during AC voltage recovery period, offshore transformer saturates, therefore a high reactive power surge is injected in the offshore network during this period.

Impact of WTG model on HVDC performance

The same AC fault test is now applied using the three WTG vendors model (i.e. Vendor A, Vendor B1 and Vendor B2). Comparison results are provided in Figure 6-6. It can be noticed that active power recovery period is affected depending on vendor's model; in vendor A, the performance looks like the RTE's inhouse generic model, however with vendor B1, the active power is ramped and recovered in 400 ms, and with vendor B2, the WTG trips due to overvoltage protection.

It is interesting to note that HVDC-OWF performance results are different for small perturbances (i.e. step change) and high disturbances (i.e. as AC fault). Indeed, when comparing AC step change results (Figure 6-3) and AC fault results (Figure 6-6), the different WTGs have inconsistent performance, WTG that trips during the fault isn't the one that oscillated during step change test : for AC step change, vendor A leads to oscillation and for AC fault it is vendor B2 that leads to the tripping. This because it is not the same control functions that are interacting between HVDC and OWF and shows the sensitivity and highly non-linearity of the overall system. Therefore, functional specification HVDC/WTG controls should be defined and designed to ensure stable operation across a wide range of system events, e.g. step change, AC faults, energization, etc.

On the other hand, the tripping of WTG Vendor B1 implies that such WTG may not comply with the Grid Code. However, it should be recalled that all 4 WTG models considered, are compliant with RTE's onshore Grid Code which means that Vendor B1 does not trip for such type of fault when connected to an AC network grid (or equivalent Thevenin source). Therefore, this case shows that, from one side, common onshore gride code may not be sufficient for offshore WTG connection and, from the other side, that C&P of WTG and HVDC are expected to be more sensitive, hence C&P tuning of HVDC and WTGs should be closely coordinated.

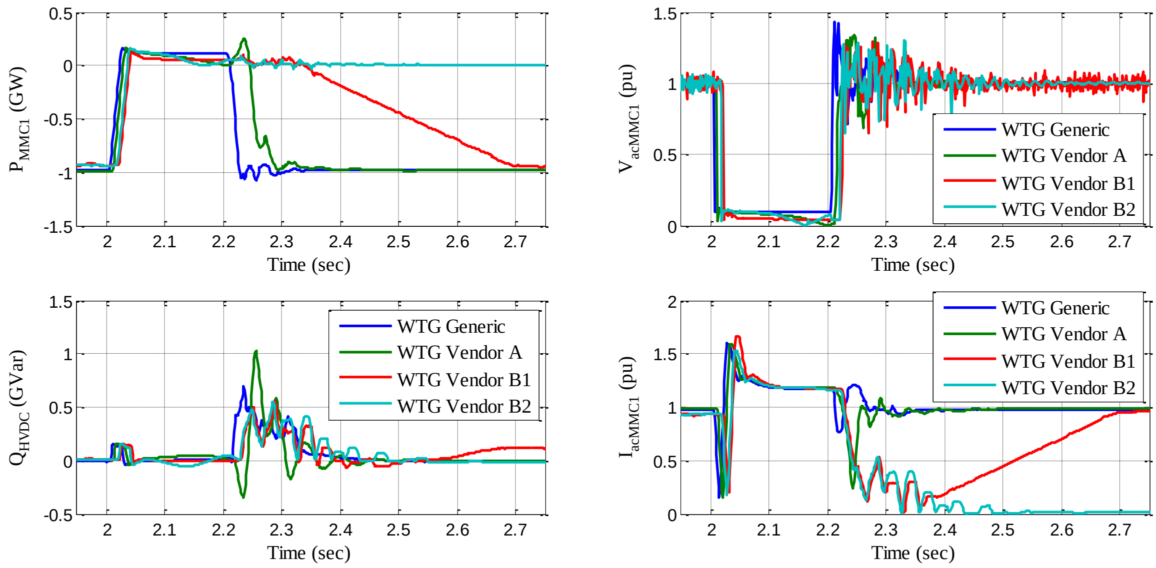


Figure 6-6 : Offshore AC fault - impact of WTG model on HVDC performance

6.4. DC pole-to-ground fault

In this section, a permanent DC pole-to-ground fault is applied at the middle of the negative pole cable as illustrated in Figure 6-7. Results of the HVDC-OWF system base case are provided in Figure 6-8. Just after fault ignition (t=3sec) MMC blocks in less than one millisecond and AC breaker open after 2 cycles. This leads to temporary AC overvoltage (1.53 pu) with a peak value of 2.44 pu and temporary DC overvoltage on the healthy DC cable (1.65 pu) until AC breaker opening instant. The energy of the DC pole-to-ground arrester in converter station reaches 23 MJ. Such transient has, obviously, an impact on DC cable design as well as on the converter station and OWF system.

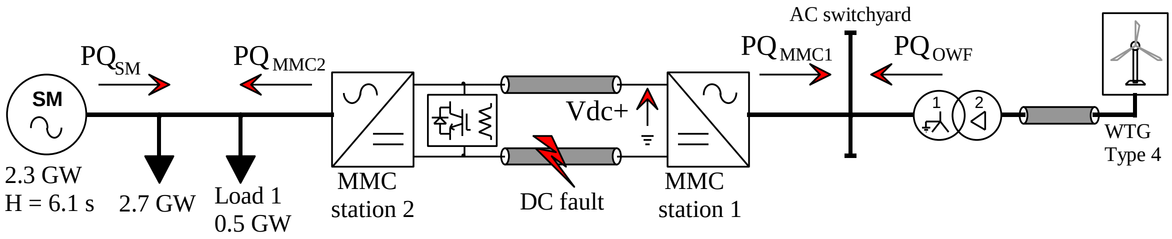


Figure 6-7 : DC fault location on the generic HVDC-OWF system

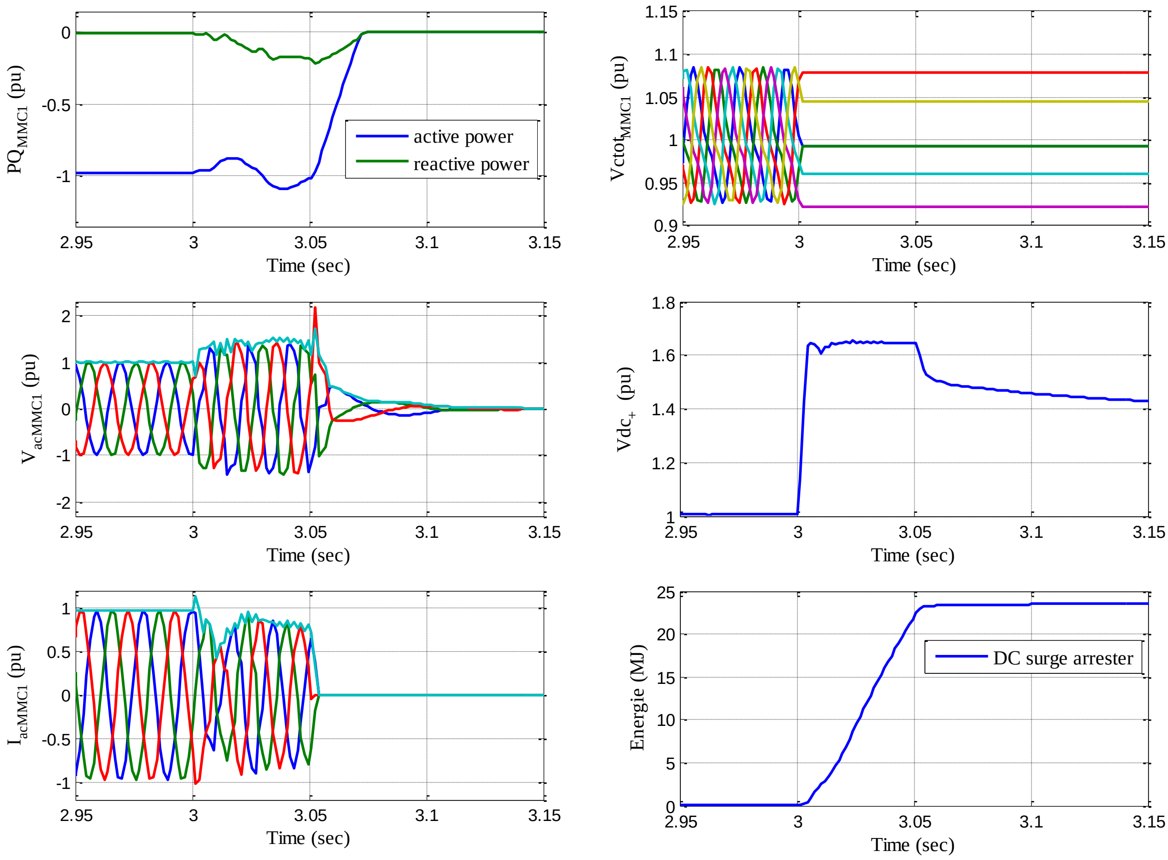


Figure 6-8 : DC pole-to-ground fault - with WTG Generic 1

Impact of WTG model on HVDC performance

The same DC fault test is now applied using the three WTG vendors model (i.e. Vendor A, Vendor B1 and Vendor B2). Comparison results are provided in Figure 6-9: AC and DC voltages, AC current as well as the DC arrester's energy. Regarding AC voltage, after DC fault, Vendor B1 and Vendor B2 have similar results during the first 50ms, then AC voltage in vendor B1 reduces to zero, however in vendor B2 some resonances appear at the AC switchyard. On the other hand, for vendor A, a temporary AC overvoltage reaches 1.27 pu and stays during 200 ms after fault inception. Regarding the DC overvoltage, the WTG generic model has the longest overvoltage when compared to Vendor's models. Regarding, DC energy absorbed by the surge arrester, results with WTG generic model has the highest and worst-case when compared to the three results with vendor's model. These results show that HVDC converter equipment design can be impacted by the OWF control system, therefore, for transient stress studies during design phase, accurate WTG model should be carefully considered. Also, in this test case, Vendor B2 behavior is not acceptable and therefore, should be, from one side, stated in the specification and, from the other side, corrected if it was in a real project.

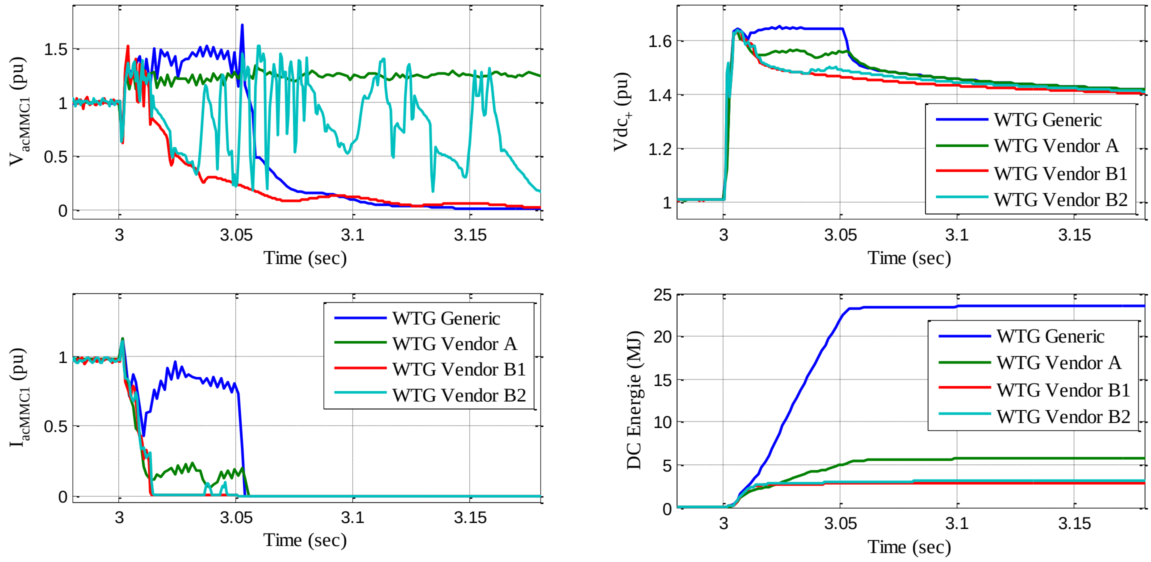
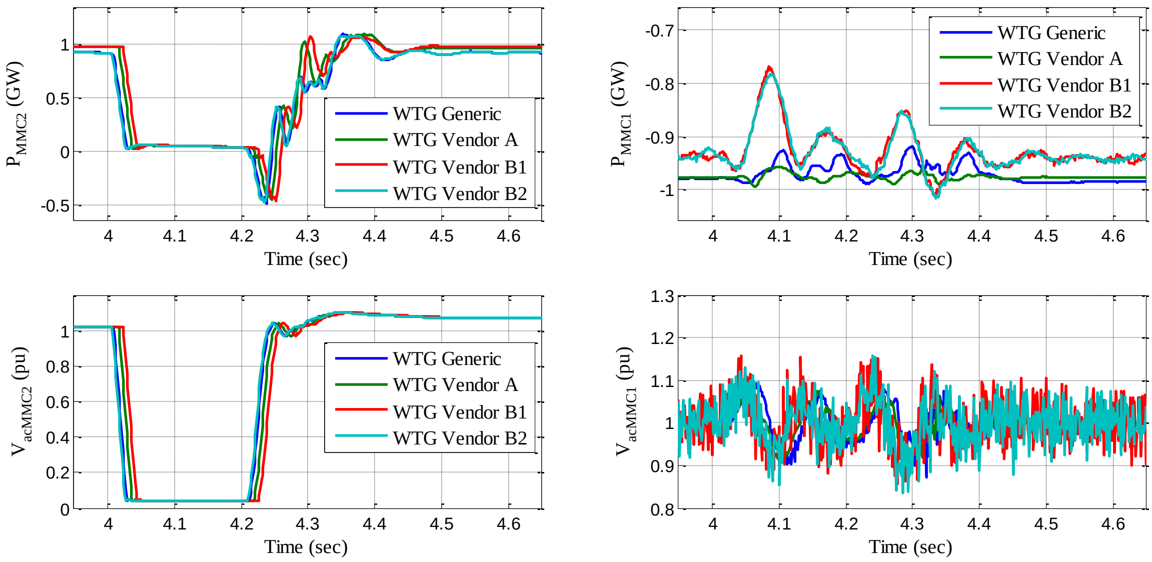


Figure 6-9: DC pole-to-ground fault- Impact of WTG models on HVDC performance

6.5. Onshore AC fault

Impact of WTG model on HVDC performance

A three-phase AC onshore with 5% voltage residual, during 200 ms, is applied at PCC (Fault 2 see Figure 6-1). To analyse the impact of OWF model on HVDC performance, HVDC results are depicted in Figure 6-10 with all fours WTG models: Active power onshore and offshore, AC voltage onshore and offshore and DC voltage variables are compared. It appears that offshore WTG model does not have a major impact on onshore fault performance, this is because DC chopper operates to maintain the DC voltage within an acceptable range, therefore the onshore converter station performance becomes similar. However, at active power and AC voltage offshore station, slight differences are noted which may lead in some cases to different behavior, and therefore should be carefully validated.



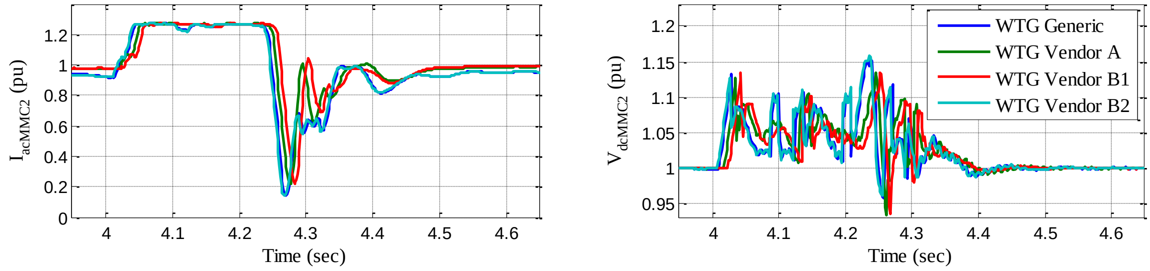


Figure 6-10 : AC onshore fault – impact of WTG model on HVDC performance

Impact of onshore network on HVDC performance

In this test case, comparisons are made between the onshore Synchronous machine model and the Thevenin equivalents (see Figure 6-1). Active power, AC and DC voltages are compared in Figure 6-11. By comparison the results are observed to be close, this is because the three-phase short circuit levels are identical and because no onshore frequency control is investigated in this test case.

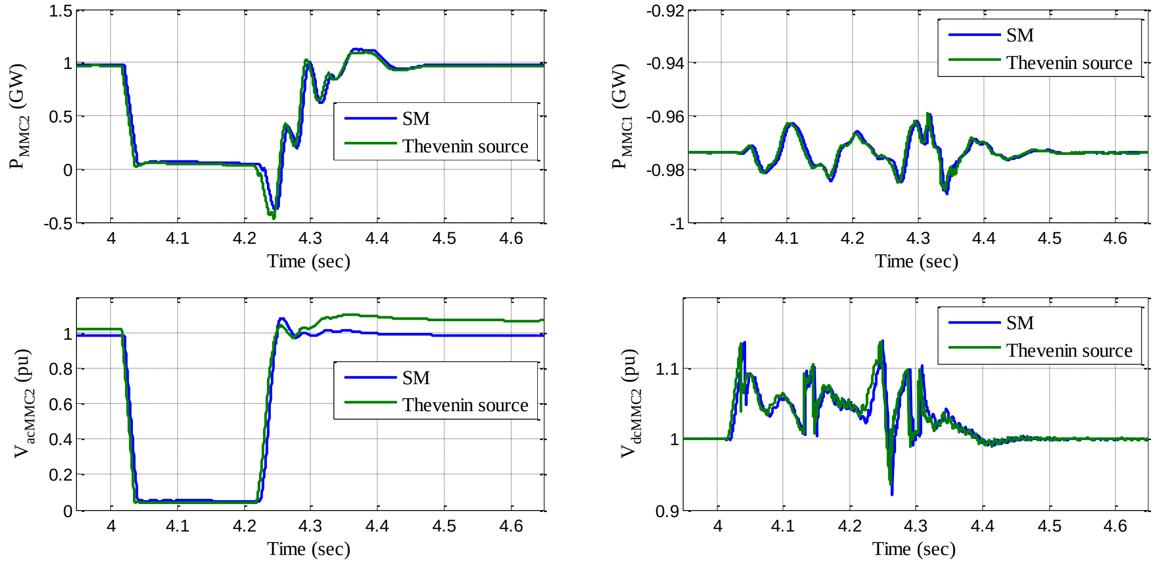


Figure 6-11: AC onshore fault – impact of onshore network on HVDC performance

6.6. Frequency response

The required frequency control during over-frequencies can be achieved by active power control of the WTGs (i.e., converter and pitch control of the turbine blades), or through shutting down a portion of the WPP. To provide frequency control during under-frequency events, a possible approach is to intentionally operate the WPP at reduced level to provide system frequency response according to a governor droop and automatic generation control (AGC) by adjusting the WPP active power set point.

6.6.1. Comparison between two main approaches

During onshore frequency variations, the active power from the WPP may have to be changed according to the grid code requirements. In this case there are two main approaches:

- Frequency control #1: direct communication is sent from the system operator to the OWF WPP control. The WPP control dispatches power references (ΔP_{ref}) to each WTG. This approach is shown in Figure 6-12.
- Frequency control #2: communication is sent from the onshore converter station to the offshore converter station that acts on offshore grid frequency to mimic the onshore grid frequency. The WTG react accordingly modifying the active power injected. This approach is shown in Figure 6-13.

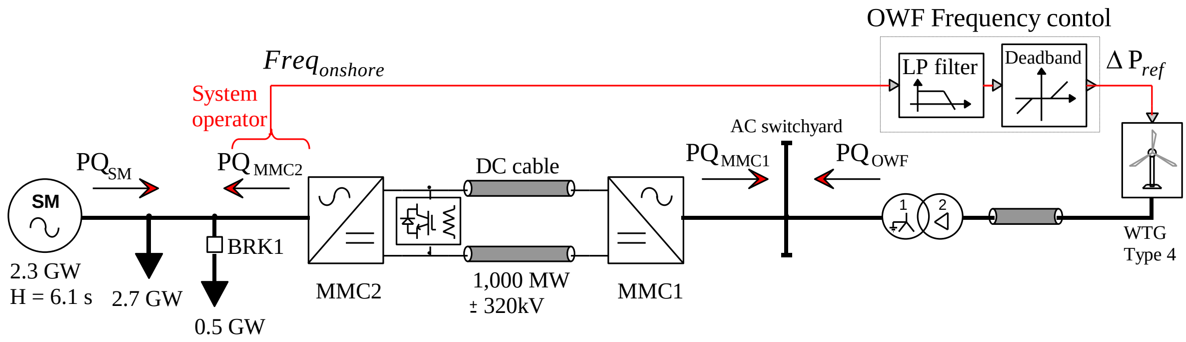


Figure 6-12 : Frequency control #1 structure

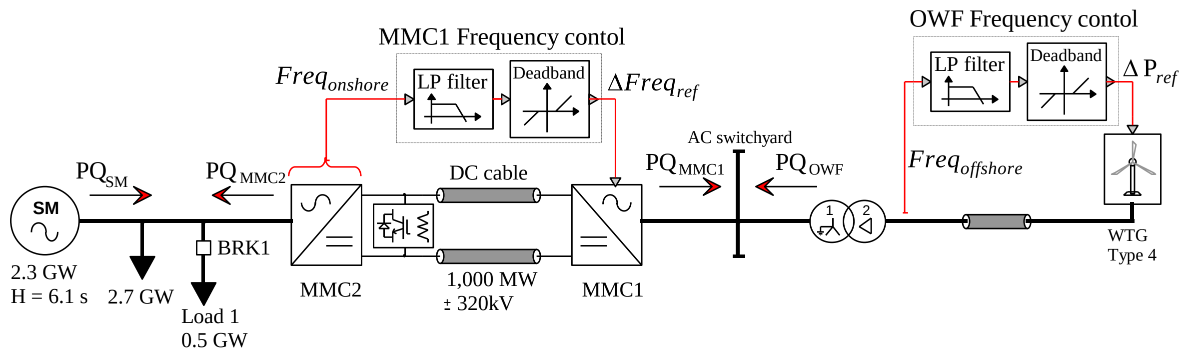


Figure 6-13 : Frequency control #2 structure

For the considered test case, in frequency control #1 approach, communication delay between system operator and OWF is set at *200 ms* and, in frequency control #2 communication delay between onshore and offshore converter station is set to *20 ms*. Low-pass filter time constants, that are depicted in Figure 6-12 and Figure 6-13, are set to *500 ms* and the deadland thresholds to ± *0.5 Hz*. Obviously, the onshore network considered is the equivalent synchronous machine (SM) because the Thevenin equivalent model cannot be used in such study to reproduce the mechanical inertia dynamics. To illustrate the operation of the frequency control, a loss of load (*500 MW*) at onshore network is simulated by opening breaker BRK1 at *t=10 sec*.

Result comparison between the two frequency control approaches and without frequency control are illustrated in Figure 6-14. The following variables are presented:

- Active power of SM and MMC2: P_{SM}, P_{MMC2}
- Onshore and Offshore frequencies: $Freq_{onshore}, Freq_{offshore}$
- AC and DC voltages: V_{MMC2}, V_{dc}

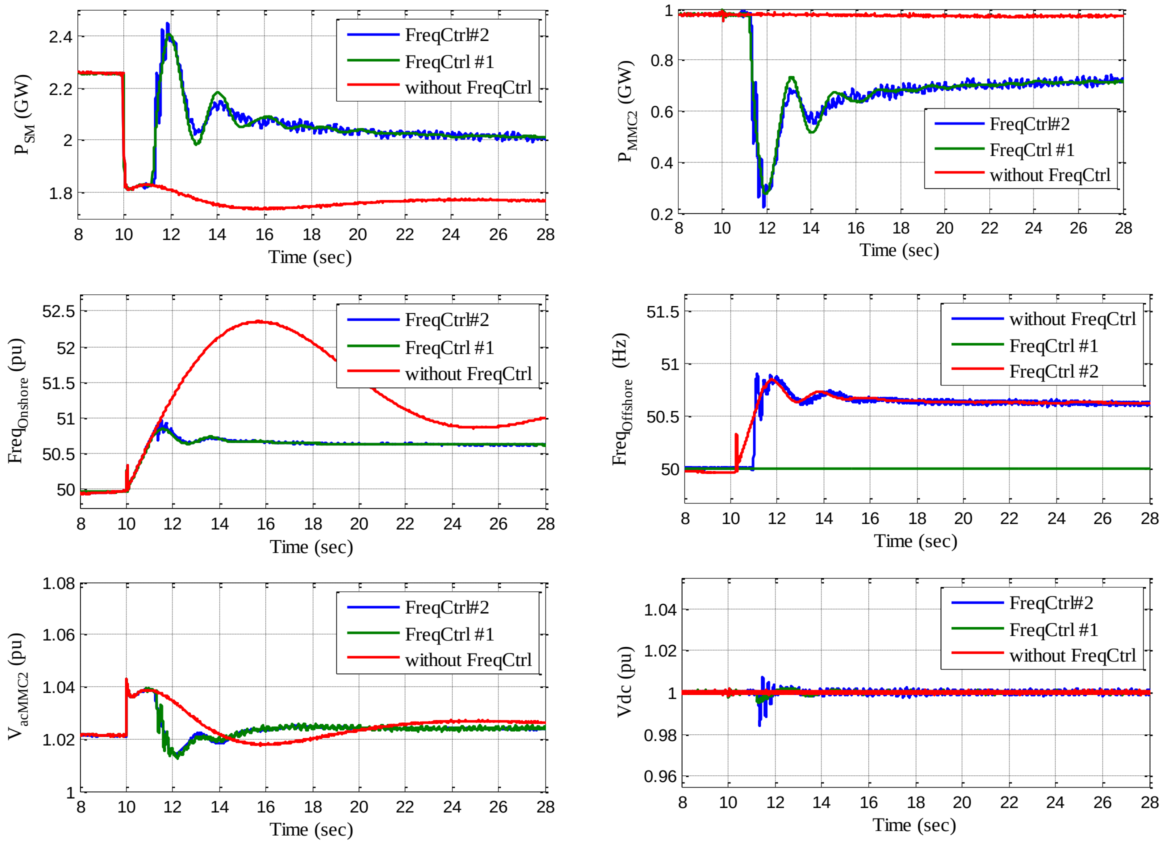


Figure 6-14: Frequency control approaches - load outage case

After the load rejection, when no frequency control is present, the HVDC-OWF active power is kept constant, however when the freqency control is implemented, the HVDC-OWF active power leads to an automatic decrease of the active power to improve network stability.

Without frequency control implemented, onshore frequency increases (due to power unbalance) and reaches an over-frequency around 52.4 Hz whereas when frequency control is implemented (and appropriately tuned) the frequency overshoot is limited to 50.9 Hz for both frequency control approaches. During the entire loss of load event, one can notice that AC and DC voltages are not affected and are kept stable.

When freqeuncy control is implemented, a damped frequency oscillation in the range of 0.44 Hz is noticed on frequency and power results. Such oscillation involves SM and HVDC-OWF system dynamics and is well damped because the overall system was considered (i.e. AC network, HVDC and OWF system). Therefore, this case shows the importance of accurate representation of each relevant system component; from AC network dynamic, to HVDC links up to OWF WTGs dynamics.

To illustrate the importance of control coordination for the overall system stability, the following example considers the Frequency control #2 with slight control modification on the low pass filter's time constant. Considering that no accurate models and proper coordination has be performed between all involved parties on HVDC-OWF system design the 4 following parameters set are used and compared:

- Tuning #1 : MMC1 freqency control Time constant : 500 ms and OWF frequency control Time constant : 500 ms -> initial condition
- Tuning #2 : MMC1 freqency control Time constant : 100 ms and OWF frequency control Time constant : 500 ms

- Tuning #3 : MMC1 freqency control Time constant : 100 ms and OWF frequency control Time constant : 300 ms

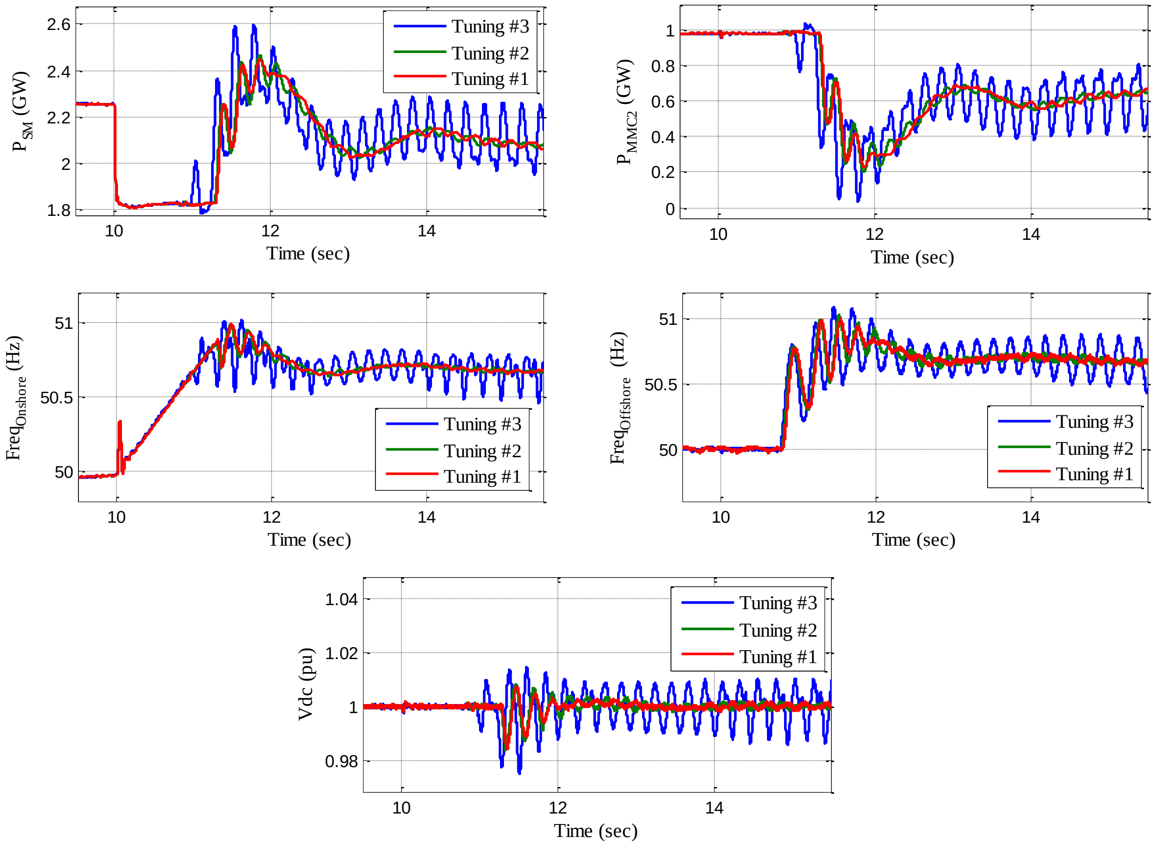


Figure 6-15 : Impact of Frequency control tuning

From results depicted in Figure 6-15, in the considered test case, when both time constants are decreased (Tuning #3), an undamped oscillation of around 3.4 Hz appears at onshore as well as at offshore frequency/powers variables. Such frequency range oscillation is a systemic issue that is within the bandwidth of several C&P systems in HVDC as well as in WTGs. In addition, such oscillation might be also present in the onshore network area that may lead to inter-area oscillation in the network. Therefore, for proper tuning of each HVDC-OWF system component, appropriate tools and models is of importance; EMT offline and real-time simulation including accurate C&P systems becomes crucial.

7. CASE STUDY OVER PROJECT LIFECYCLE - LESSONS LEARNED BASED ON REAL PROJECTS

In this chapter, RTE/RTE-I ’s experiences based on real HVDC projects are provided. Several examples form planning to operation stage studies are provided. The outcome and lesson learned of each illustrated example is also provided.

7.1. AC Temporary Overvoltage after voltage recovery – planning stage study

In this section the connection of a new HVDC-MMC project link at the same busbar as an existing HVDC-LCC link is investigated (Figure 7-1). This configuration is similar to the ELECLINK HVDC link that is planned to be commissioned in 2021 close to the IFA2000 link. For such planning stage study, the generic inhouse HVDC-MMC link model is used and the IFA2000 link is based on the manufacturer EMT model. IFA2000 is an interconnection between Les Mandarins (France) and Sellindge (UK). It is a 2,000MW interconnection composed of 2*1,000MW HVDC LCC links in bipolar configuration. For this study, only one link of 1,000MW is considered.

For all this parametric study, a short-circuit power of 5 GVA and three-phase faults are considered. In order to study the impact of an HVDC-LCC link next to an HVDC-MMC link, parameter variations were carried out and summarized in

Table 7-1. The total number of simulations carried out are 120. ELECLINK and IFA2000 converter stations are connected in close vicinity in France and in UK. To simplify the analysis of this situation, converter stations have been decoupled on UK side as shown in Figure 7-1.

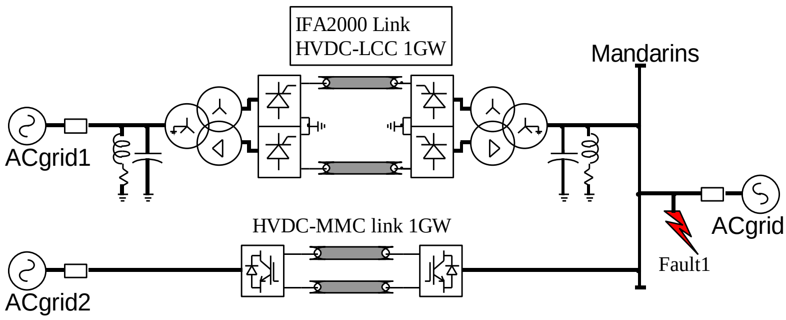


Figure 7-1: Circuit configuration of HVDC-LCC link connected next to an HVDC-MMC link

Table 7-1 Parameter Variations In The Presence Of HVDC-LCC Link

Parameters	Number of configurations
Impact of HVDC-LCC link	HVDC-LCC link included with active power transits of ± 1000 MW HVDC-LCC link excluded
P/Q setpoints of the HVDC-VSC link	± 1000 MW, ± 800 MW, 0 MW -300 MVar
Fault resistance	0, 10, 30 and 50 Ω
Settling time of the VSC Inner control	7 and 10 ms

RMS phase-to-phase overvoltage results at PCC are shown in Figure 7-2 and Figure 7-3. In Figure 7-2, the waveforms of the 120 simulated cases are shown. The black bold curves represent the overvoltages without the HVDC-LCC link and the remaining thin curves represent the results with the HVDC-LCC link. Note that in the presence of the HVDC-LCC link, oscillations are less damped and overvoltages duration are longer. In Figure 7-3, maximum RMS peak recorded for each of the 120 simulations are presented; the first 80 simulations are related with cases including the HVDC-LCC link and the last 40 simulations are thus without the HVDC-LCC link. For some configurations, maximum TOV are higher when the HVDC-LCC link is included: maximum peak voltage with the HVDC-LCC link is 1.53 pu and without this link is around 1.34 pu.

We can therefore conclude that the impact of an HVDC-LCC link on a new HVDC-MMC link increases the TOV peak and also increases the duration of the overvoltages. This is due to mainly three aspects: reduction of the short-circuit ratio, the increase in reactive power support during fault instant and control interaction between these two HVDC links.

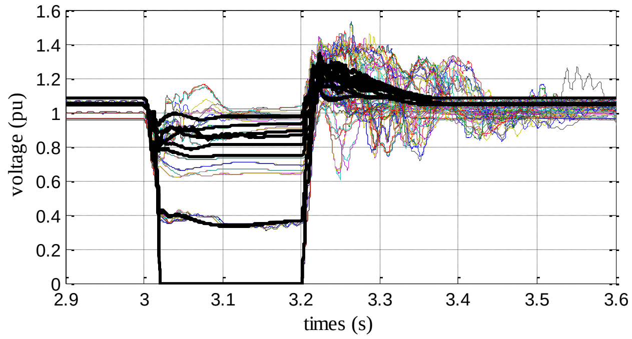


Figure 7-2: RMSLL AC overvoltage at PCC results - impact of HVDC-LCC link

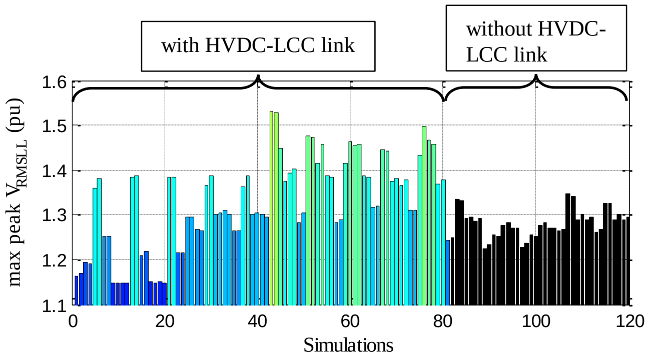


Figure 7-3 : Maximum TOV peak - impact of HVDC-LCC link

7.1.1. Outcome

Such planning stage studies reveals the importance of conducting dynamic studies to estimate the temporary overvoltage that can occur on a new HVDC link connected in proximity of another existing one. The outcome of such study has an impact on TOV waveshape that should be specified and also on the risk of interaction between both HVDC links.

7.2. Offshore harmonic instability – Planning stage study

The test case considered is the planning stage study performed for the FAB link project. The planned project consists of 2 symmetrical monopoles HVDC-MMC links, between France and UK, with a total rated power of 2*700 MW and a DC voltage of ±320 kV. On one of the two links, a tee connection is planned to host a third converter station at Alderney Island. This offshore station is planned to connect tidal farm power plant at a rated power up to 600 MW. For this preliminary EMT study, since the tidal farm is composed of a VSC back-to-back converter similar to a wind power plant (WPP) Type 4 technology, a black-box manufacturer model of a WPP Type 4 is, therefore, used (section 4.3.1.5). For this planning study this assumption is sufficiently valid because the dynamic performance is similar. The offshore converter station is a generic in-house MMC model using the U/F control system.

In Figure 7-4, the circuit configuration of the offshore network is illustrated. Seven feeders are connected to the main converter transformers. Each feeder is rated at 100 MW and a cable connection with length of 5 km is assumed between the transformer and the wind farm. For this planning stage study, the semi-aggregated park model is sufficient.

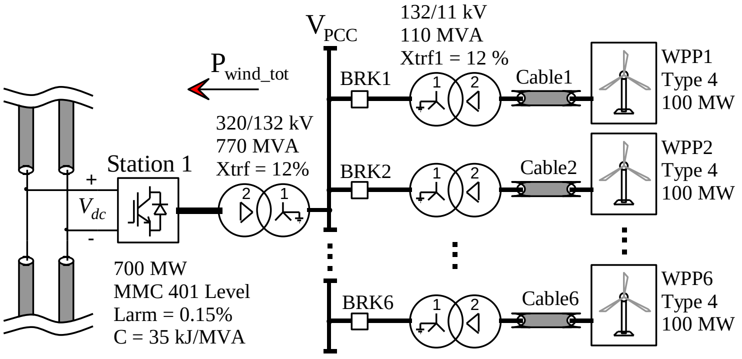


Figure 7-4 : Circuit configuration of the offshore station [38]

7.2.1. Time domain simulation

Time domain simulation are presented in this section. The considered test case is the wind farm feeders' disconnection (100 MW) one by one with a time delay of 0.5 s. Total active power and AC voltage at PCC are depicted in Figure 7-5.

At 3.5 s, the opening of BRK3 circuit breaker leads to a high frequency resonance phenomenon. In the zoomed waveform ac voltage are depicted during the opening of this circuit breaker. Frequency resonance around 830 Hz appears.

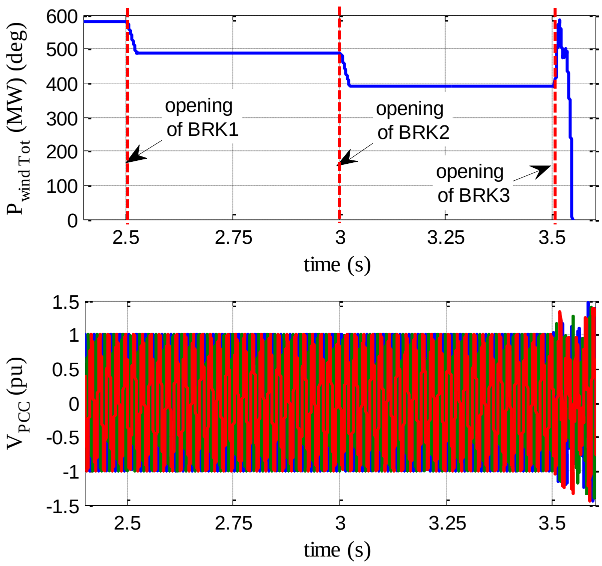


Figure 7-5 : Time domain waveform of wind farm feeders disconnections

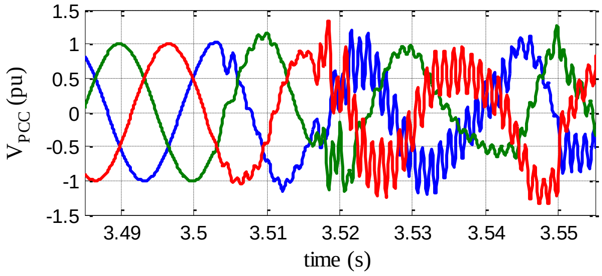


Figure 7-6 : Zoomed waveform of AC voltage (V_{PCC})

7.2.2. Small-signal stability analysis

The small-signal stability tool by means of impedance-based approach is used to analyse this harmonic resonance. The impedance of the converter station $Z_{HVDC}(s)$ and the wind farm $Z_{WPP}(s)$ are plotted in frequency domain Figure 7-8. To deduce these frequency responses, the current injection method with a frequency scanning is used in the EMT-type simulation as illustrated in Figure 7-7.

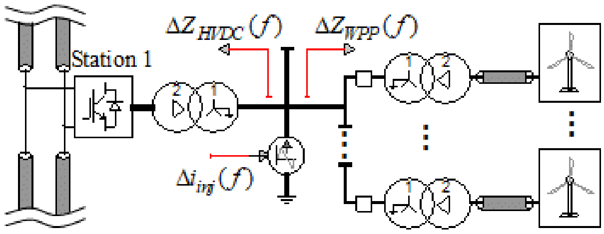


Figure 7-7 : Circuit diagram of the offshore station

In order to analyse this resonance, in Figure 7-8, the following three frequency responses are plotted: $Z_{HVDC}(f)$ and WPP impedance before and after the BRK3 disconnection. The intersection between $Z_{HVDC}(f)$ and $Z_{WPP}(f)$ amplitude curves determines the frequency value at which the phase margin is computed [36]. Before the closing of the BRK3, one intersection is noticed between $Z_{HVDC}(f)$ and $Z_{WPP}(f)$ that is around 800 Hz with a phase margin close to 180^0. However, After BRK3 opening, there are two intersections around 520 and 833 Hz. The phase margin of both frequencies becomes higher than 180^0, which explains the resonance phenomena seen in Figure 7-6. In addition, it is noticed that $Z_{WPP}(f)$ has a negative resistance (< -90^0) in this frequency range area, whereas the angle of $Z_{HVDC}(f)$ does not exhibit any negative resistance in the considered frequency range. Therefore, it can be concluded that the main system that is causing this instability is the WPP controllers rather than the converter station's control loop. This frequency approach allows to identify the main root of instability in a power system.

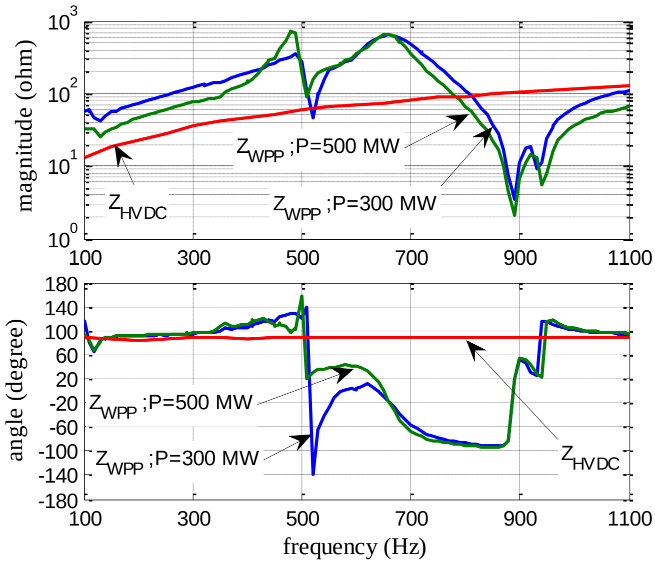


Figure 7-8 : Frequency response of converter station and WPP

7.2.3. Outcome of such planning stage study

Such planning stage studies allow to highlight the importance of wind turbine model for system stability. It shows that WTG EMT model as well as harmonic impedances data should be provided at the early phase of the HVDC project design stage to anticipate and solve such potential issue.

7.3. Harmonic instability study – study during operation

This case refers to a resonance phenomenon that has led to the tripping of the INELFE link. Figure 7-9 (left figures) shows the registered onsite measurement occurred on the 22nd of September 2015 [37]. As it can be observed, a high frequency oscillation (around 1.7 kHz) at PCC was recorded with an overvoltage that reached 1.7 pu during few seconds until the tripping of the HVDC link leading to a sudden loss of the exchanged power.

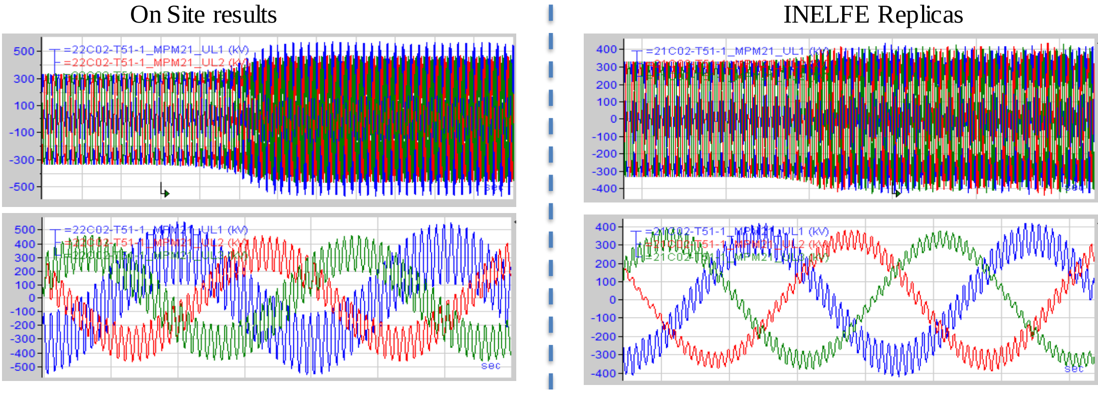


Figure 7-9 : INELFE AC voltage at PCC - high frequency oscillation issue

To investigate such event, initially, both offline EMT studies and real-time simulation using the replicas have been used. It was not possible to reproduce this incident with the offline manufacturer black-boxed model because of C&P system simplification and version update of the offline model. Therefore, only the real-time simulation with replicas has been able to capture such event as illustrated in Figure 7-9 (where a comparison between replicas and onsite measurements are depicted).

After reproducing the event by means of real-time simulation, studies have been conducted: to investigate network topologies that lead to such event, to understand the root cause and potential solutions. In addition, discussion with HVDC manufacturer has been conducted and software update to solve such issue has been proposed by the HVDC manufacturer. This proposed update software has been tested on the real-time simulator, it was concluded that such new updates will effectively solve the resonance issue but, on the other hand, dynamic performance of the link is reduced and does not comply anymore with specification.

To preserve the intellectual property of the HVDC manufacturer, in the following section a generic in-house EMT model is used to illustrates and understand the root cause of such resonance.

The circuit configuration is depicted in Figure 7-10, where a MMC-based HVDC link is connected to an AC network. Network 1 in Figure 7-10 includes two overhead lines in parallel, the AC breaker "BRK", a shunt compensator and a Thevenin equivalent source with short-circuit power of 20 GVA. A power of 1,000 MW is transmitted from Grid 1 to Grid 2. At simulation time 0.5 seconds, the AC breaker "BRK" is opened to disconnect one of the overhead lines from Station 1. This disconnection modifies the impedance characteristic of the network, which produces undesired interactions when the converter impedance of Station 1 has a negative resistance in a certain frequency range.

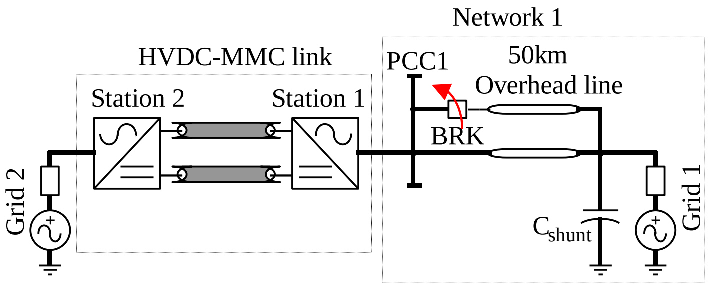


Figure 7-10 : Circuit configuration of the negative resistance test case

Figure 7-11 shows the frequency responses of the converter impedance Z(f), and Network 1 impedance at PCC1 before and after the disconnection of the overhead transmission line. Figure 7-12 shows the phase angles of the frequency responses from Figure 7-10 zoomed in the y-axis. From these figures, we notice that the converter impedance presents a negative resistance in the frequency range of 1.3 to 3.4 kHz. The intersection between the Z(f) and Network 1 impedance amplitude curves determine the frequency value at which the phase difference is computed. When only one overhead transmission line is connected to Station 1, the intersection between the magnitudes of Network 1 and the converter impedance varies, hence the phase margin is affected as well. If the phase difference becomes greater than 180 degrees, the system becomes unstable in this specific frequency range. It may be seen that the phase difference between the Network 1 impedance with one AC line and converter impedance is greater than 180 degrees for a frequency of around 1.7 kHz which explains this resonance.

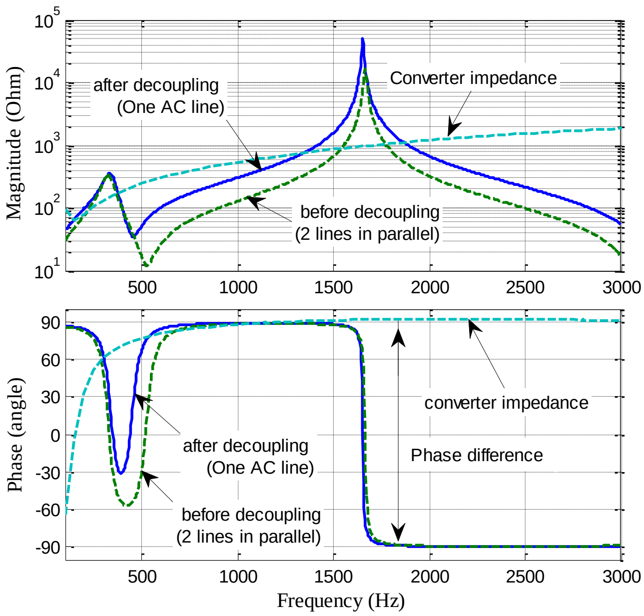


Figure 7-11 : Frequency response of Network 1 and the converter station

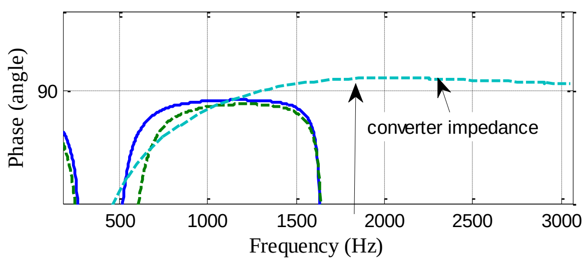


Figure 7-12 : Phase angle from Figure 7-11zoomed in the y axis.

The frequency domain analysis performed previously is validated through time domain simulations. Voltage waveforms at PCC 1 are presented in Figure 7-13 where a resonance frequency of 1.7 kHz is observed after the opening of the breaker BRK.

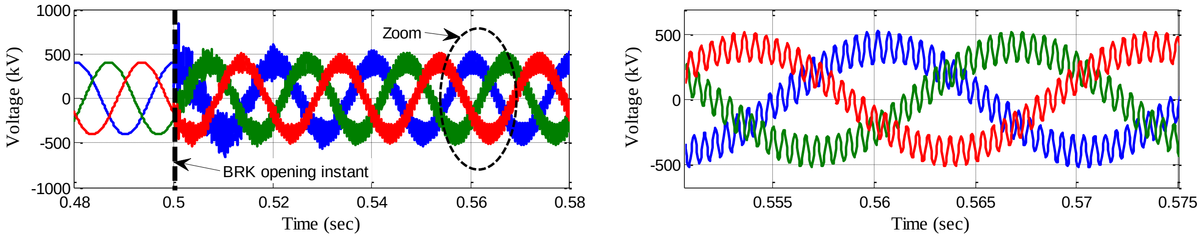


Figure 7-13 : AC voltage at PCC1 and zoomed extract

7.3.1. Lessons learned

The event was due to the interaction between the HVDC link and the surrounding AC network due to non-passivity of converter impedance (or negative resistance). Detailed study of such control instability can be found in [39].

The main lessons learned from these investigations are:

- For such high frequency, accurate EMT representation of AC grids are required (mainly the frequency dependant model for overhead line and surrounding HV equipment).
- These high frequency resonances depend on several network parameters: AC line, Short-circuit level, AC configuration, etc. It shows the importance of computing and providing to the manufacturer the network harmonic impedance during implementation stage.
- Unlike previous example, such event has occurred with a relatively strong short circuit level (rather in a weak network). This highlights the need to perform such study also for onshore connection.
- The actual controls are required to get the exact behavior of controls. It was not possible to replicate this incident with the offline model provided by the manufacturer because of control simplification and/or control version update. Measurement delays and filter processing have a major impact on this event see [39].
- To avoid or anticipate such issue for future project, specification has been improved.

7.4. Inter-area oscillation (INELFE)

The considered test case is based on the East-Centre-West inter-area oscillation event occurred on 1st December 2016 [40]. The Iberian Peninsula and Turkey oscillated against the centre of the system (Germany, Poland, etc.), following the mode shape illustrated in Figure 7-14.

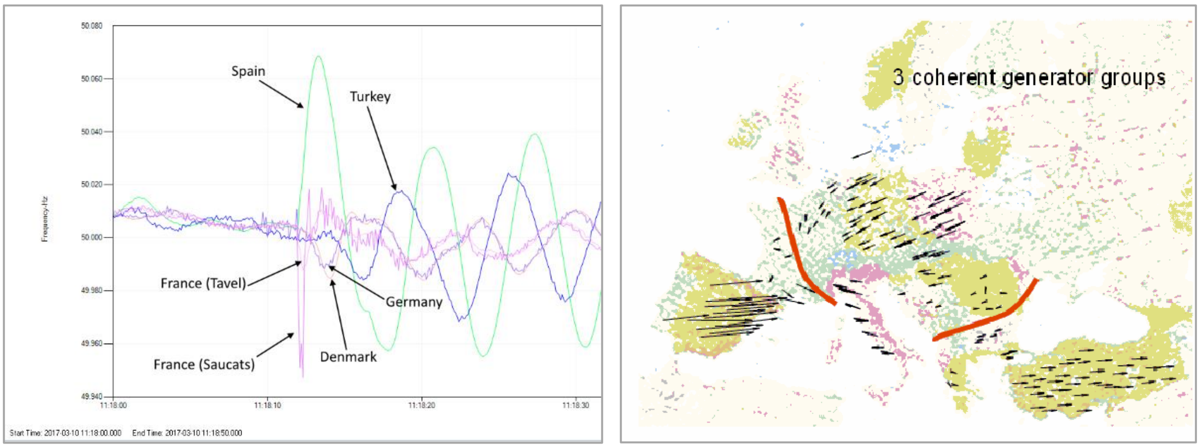


Figure 7-14 : Frequencies in different locations of CE and mode shape. Oscillatory event [40]

The Spain and French network are connected by only 3 overhead lines (400 and 225 kV) in parallel with the 2GW INELFE HVDC link. Dynamic studies were performed jointly by REE and RTE using RMS tools to reproduce this event and to find the possible mitigation measures. To support such RMS studies, the real-time simulation with replicas was used:

- to validate and improve the RMS INELFE model
- to validate and test the mitigation solution that has be proposed
- to identify in the C&P software the exact parameters that should be modified onsite
- to write the procedure that should be used by the operator for onsite modification
- to develop a test benchmark for future tests for future software updates during lifecycle operation.

Therefore, a test bench was developed in the RT simulator, in order to reproduce an inter-area oscillations event. This configuration is therefore not intended to model a detailed and realistically network but only to mimic the phenomenon; that is the inter-area oscillation around 0.155 Hz and the sequence of events.

Based on the sequence of events reported in [40], one can represent the equivalent network as in Figure 7-15. Zline1 and Zline2 are the equivalent AC line between France and Spain. Two generic synchronous machines (H1 and H2) are modeled to reproduce the inter-area oscillation mode. The INELFE link is operating in AC Line Emulation [41].

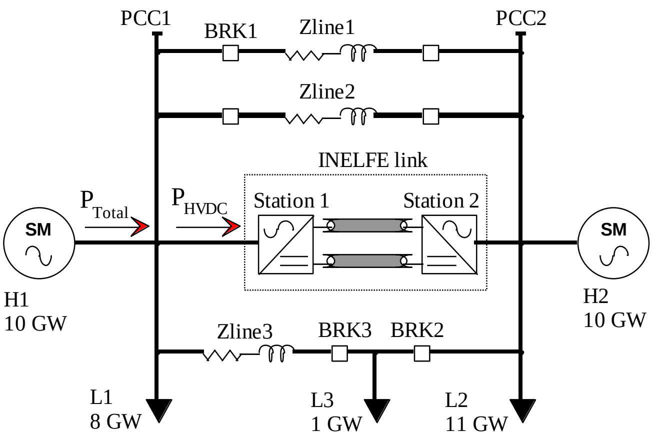


Figure 7-15 : Equivalent grid around the HVDC-INELFE link

To mimic the inter-area oscillation event, the following sequence of events are simulated (see Figure 7-15):

- Stage #1, t < 5s: all circuit breakers are closed except the BRK3 which is open. A 2 GW exchange takes place between PCC1 and PCC2
- Stage #2, 5s < t < 55s: Opening of the BRK1. This results in an oscillation around 0.155 Hz between PCC1 and PCC2
- Stage #3, t > 55s: Load transfer; opening of BRK2 and closing of BRK3. This leads to increased damping of the oscillations.

The results obtained using the INELFE replicas connected to the RT simulator are shown in Figure 7-16. The power transfer through the HVDC link and the angle difference are plotted. Two different control tunings are illustrated; the red (tuning #1) and the blue (tuning #2) curves stand for two different control gains tuning of the AC emulation control system. One can notice that the new control tuning increases the damping of the oscillations. This behavior was validated with RMS model adding more confidence on the mitigation solution proposed. Once validated, the new control tuning has been successfully implemented onsite without the need of manufacturer involvement.

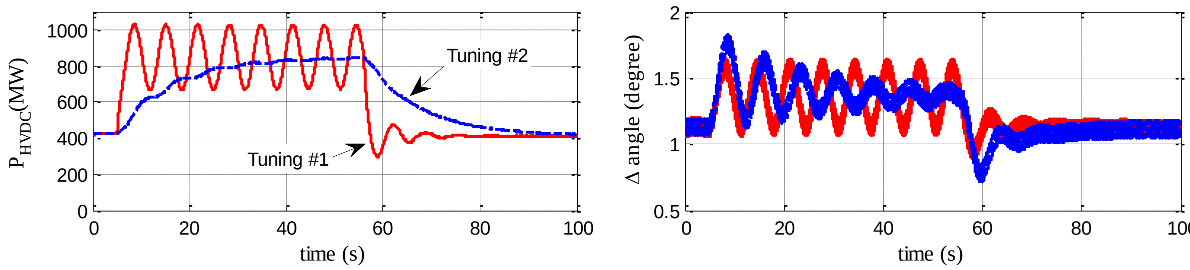


Figure 7-16: INELFE - Interarea oscillations

7.5. INELFE AC fault performance – study during operation

The national control center of RTE, regularly sets up a list of different grid contingencies scenario that might impact INELFE performance, to explore and investigate to foresee network stability. The goal is to increase network reliability including INELFE operation and investigate some specific or critical situations in the grid. For some scenario such as in weak network, the RMS model does not provide accurate behavior. Therefore, the real-time simulation with replicas has been used to compliment the RMS study and provide accurate and more realistic performance.

For the considered system study, the equivalent AC network, illustrated in Figure 7-17, was modeled in RT simulator. This AC network model has been considered sufficiently conservative to perform AC fault studies near the INELFE link.

The RTE AC side is composed of a Thévenin source representing the 400 kV AC station of Gaudière that is linked via an AC overhead lines to the 400 kV AC station of Baixas. The Gaudière substation represents the major SCL (Short Circuit Level) for the HVDC station. Two other Thévenin sources representing the 225kV and 63kV are also linked to the 400 kV Baixas station via power transformers. Near the INELFE link, an AC interconnection connects Baixas to the Spanish 400 kV AC station Vic. The Spanish grid is based on the design given by ENTSOE at 02/13/2019 and REE information provided to RTE. We can notice that Vic is linked to the AC side of the station Santa Llogaia trough the 400kV AC station Bescano.

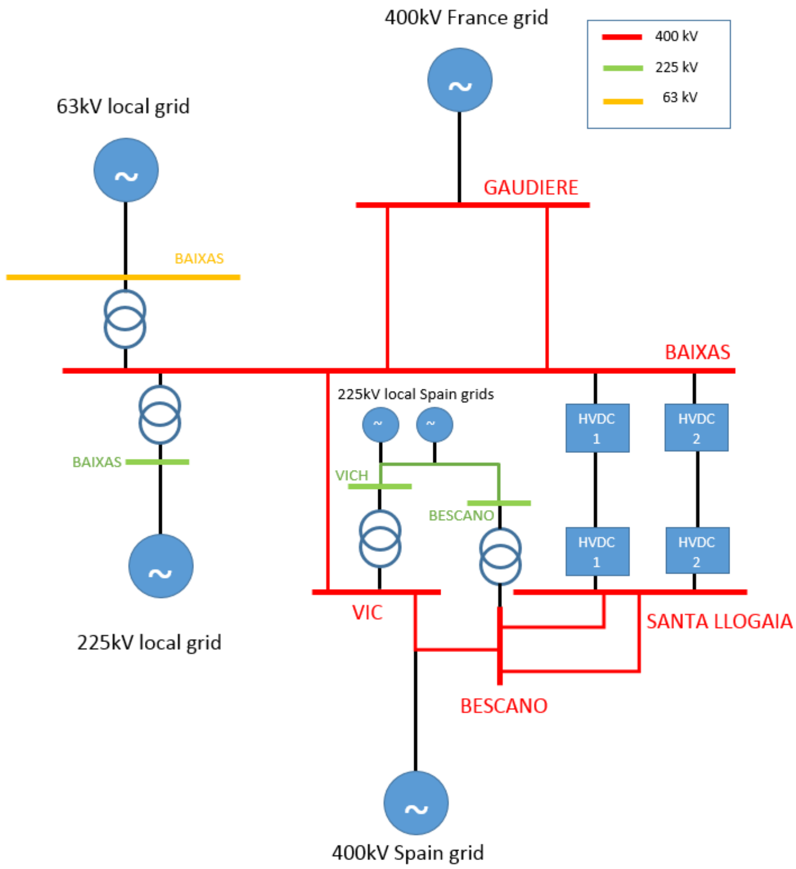


Figure 7-17 : INELFE and the surrounding HV network in Hypersim Simulator

Several fault scenarios, that were not possible to be performed with RMS model, have been conducted to support the dispatcher center in their decision making, such as:

- Faults on Baixas-Vic line in weak network situation
- Faults on the double circuit of Baixas-Gaudière with Baixas-Vic out of service
- Faults in Baixas AC substation in weak network situation

More details can be found in [42]. For instance, results comparison with and without reactive power injection activation is illustrated in Figure 7-18. This example, where the network situation is out of the requested initial specification, shows that the deactivation of current injection function avoids the tripping of the link.

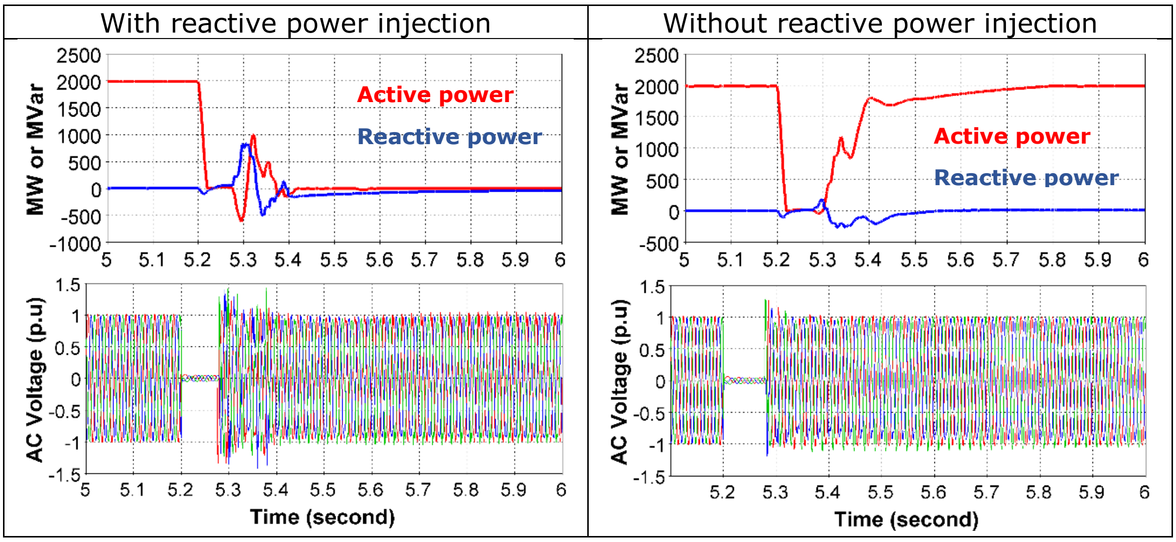


Figure 7-18 : Comparison for case P=2000MW; three-phase-to-ground fault located at Baixas

7.5.1. Outcomes

The outcome of the ac fault studies has provided a deep insight in the HVDC performance for extreme scenario. We can underline the importance of HVDC active power flow, and the station's operation mode (inverter or rectifier) which is a great factor regarding the risk of tripping. Also, it appears that the right control of the reactive power injected or absorbed during a fault event is essential to limit this risk. So, regarding the current topology, the available short circuit level, the dispatcher team was able to take decision regarding the INELFE control to reach a balance between the tripping risk and grid stability.

7.6. Johan Sverdrup Interaction study – Implementation stage study

The Johan Sverdrup O&G field located at the Norwegian continental shelf is under construction. Several offshore Oil and Gas platforms in the area will be supplied by two symmetric monopole HVDC links, connected in parallel at onshore and offshore grid: Phase-1 is under commissioning and consists of a 100 MW 2-level VSC-HVDC link manufactured by ABB and, a couple of years later, the Phase-2 will include the installation of an additional 200 MW, MMC-HVDC link supplied by Siemens. Both HVDC links will utilize DC cables of approximately 200 km length. Further details can be found in [43].

The Johan Sverdrup (JS) project will be the first application of two HVDC links (from different manufacturers) supplying an islanded offshore AC power system in grid-forming mode. Control structure is different for both links because of different manufacturers. In addition, each HVDC system is developed, by each manufacturer, without any detailed information on the second HVDC system for IP aspects. Therefore, studies are required to ensure secure power supply of Johan Sverdrup and neighbouring offshore platforms and consumers under all operational conditions. This is why detailed EMT simulations are performed to analyse interactions at onshore and offshore grid. Through this parallel operation studies, interoperability, and interactions between the two HVDC links under steady-state, dynamic and transient operation conditions have been identified. RTE-i as third party oversees performing the offline and real-time parallel operation studies with data supplied by both HVDC vendors.

For offshore grid, a SCADA system, designed by Aibel, includes a master controller called Power Management System (PMS) unit for secondary control of active and reactive power during parallel operation of HVDC links. In addition, fast load shedding strategy called FALS when faults occur in the system and synchronization process for start-up and shutdown sequences are implemented.

During the design stage of Phase-2, offline simulation studies are conducted to identify possible interoperability issues when both HVDC converters are operated in parallel. Results from the offline simulations is used to define a set of real-time HIL tests is undertaken before commissioning of the second link. When interactions are detected and/or software updates are delivered, an iterative process has been established to provide an efficient and robust coordination between all stakeholders (see Figure 7-19 Figure 7-21).

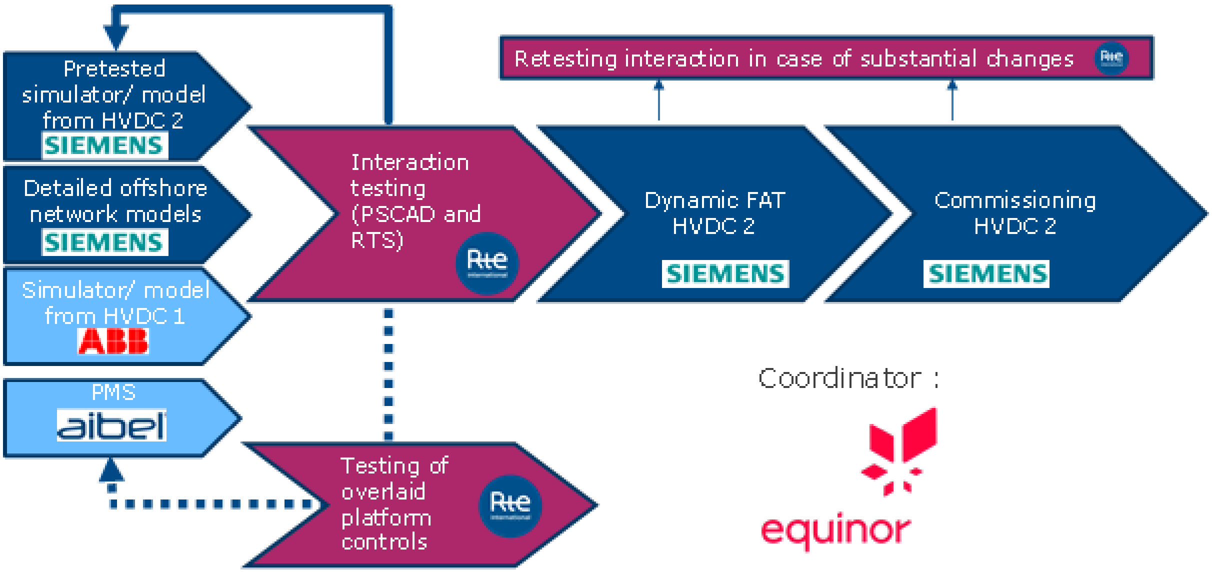


Figure 7-19 : Process for parallel operation studies and coordination between stakeholders

In this project, the main advantages of C&P replicas are the limitations raised with offline models:

- Computation time of the offline model for parallel operation simulation is high (i.e. average time for each simulated case ~ 4 hours).
- The SCADA and specially the PMS function is not available and cannot be provided in the offline EMT model. Therefore, a generic PMS model has been developed by RTE-i for offline studies to provide a general functionality.
- Converter models have limited and simplified switching sequence functions e.g. start-up and shut-down sequences are simplified in order to speed up the simulation time.
- C&P system of HVDC Phase-1 project has been updated onsite. It is challenging to ensure that the offline model is updated accordingly.
- C&P replicas offer the opportunity to reproduce conditions of tests similar to the onsite conditions (for instance Human Machine Interface, interlocks, etc.)

However, offline simulations are still used when HIL simulations are performed because they still present the following advantages:

- More detailed and accurate representation of the electrical equipment and especially non-linearities
- Possibility to run several simulations in parallel without any human actions.

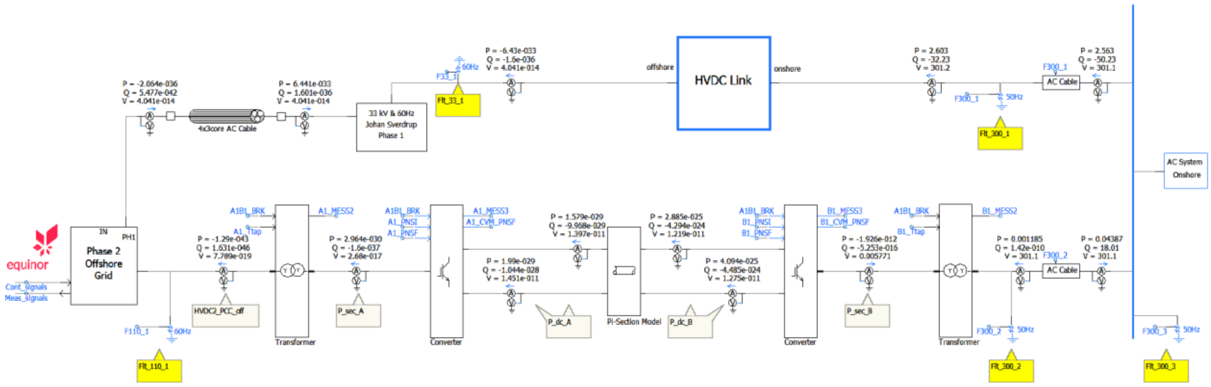


Figure 7-20 : Manufacturer offline EMT model for parallel operation studies [43]

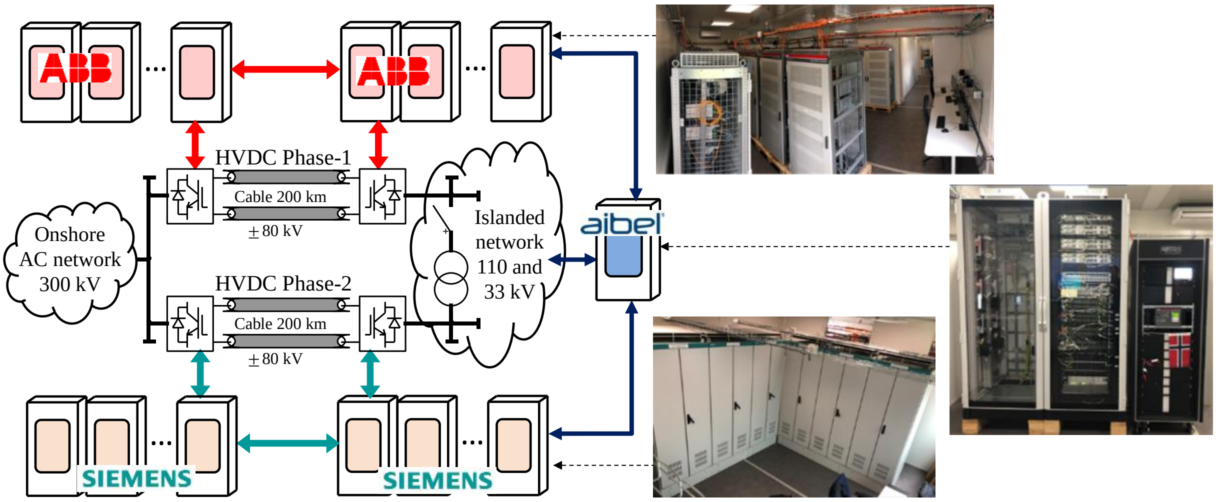


Figure 7-21 : HIL setup with replicas for interaction study of Johan Sverdrup project

In conclusion, both tools (offline and real-time simulation) are used during the full process because they are complementary.

8. CONCLUSION

Numerical simulation tools such as RMS and EMT tools are used by power system engineers and researchers to conduct various dynamic studies. The increasing installations of power electronic devices (PED) on the transmission system requires the increased use of EMT tools. The main reasons are because PEDs have faster dynamic and more complex behaviour that cannot be captured or properly analysed with RMS approach tools.

EMT real-time simulation offers a complementary solution in comparison to the offline EMT and RMS simulation, because the computation time of the simulation is lower to real time. The real time simulation enables a more complete representation of hardware replica control and protection system than offline EMT models. The report highlights practical examples where real time simulation with replicas are essential to verify the exact behaviour of controls in areas where an offline model provided by the manufacturer is insufficient due to control simplification and/or the tracking of control version update.

The **key findings** from the COMPOSITE project are:

- HVDC systems are becoming more complex, with more variation in controls, protection, and co-ordination performance across more devices;
    - This means that the potential for control interaction and protective action that can occurs when these controls conflict increases with the layers of devices and functions asked of the overall system. Individual tests of individual devices cannot capture the operating states of the other contributing devices prior to and following disturbances that define the overall system performance. Perfectly compliant individual devices may perform inappropriately when combined with other equally compliant devices, driving specific control damping solutions.
    - Compliance is currently defined as an onshore interface measure, however within designs involving multiple projects offshore, the role each one plays in a given function is important; as such it is important for this function to be defined, and also for the expected performance expectations offshore to be made clear- this is an area where offshore Grid codes may become increasingly important.
- Simulation and Tests of this nature are becoming increasingly important, using a range of off-line and real-time tools and analytical techniques;
    - Hosted environments can support this whether off-line or physical, and need to capture the extent of relevant devices and their relevant functions that describe their performance for a given type of event or service such as frequency response- it can be the case different models are needed to be combined to test different behaviours- there is not a "one-size fits all" the models used depend on the situation being studied
- These system studies and technical de-risking activities should be done across a range of potential operating points, and at key points in the design and commissioning of projects; and
- Each simulation tool has pros and cons; different tools are appropriate to study different phenomena at the various stages of a project's development cycle, to effectively de-risk project interoperability.
    - Control systems have different characteristics and priorities at different operating points

To enable composite testing on a complex (i.e. multi-vendor and/or multi-device) project, the following **key recommendations** are made:

- **Developing approaches for managing the exchange of confidential models:** to facilitate the testing of complex connections comprising representation of equipment control and protection systems, electricity network data and wide area supervisory/monitoring schemes;
- **Demonstration-at-scale of different composite testing arrangements:** that are flexible, re-configurable and portable would enable efficient testing of multi-device connections across all project stages from inception to operation;
- **Establishing offshore network technical requirements and codes:** with mechanisms on interoperability testing and demonstration would ensure transmission and generation equipment/components supplied by different manufacturers work together across project lifecycle; and
- **Co-creating operational simulators:** based on real-time arrangements capable of replaying day in a life expected or encountered operation, would facilitate control room operator training, enable refinement of operation and control approaches for complex connections, and support diagnosis of network events.

The work could be extended to investigate future upcoming DC developments such as:

- HVDC-OWF with bipole configuration; analyse the impact of tripping of one pole and how to coordinate with OWF.
- Offshore installation of WTG from different vendors and investigate the interaction that can occur between these different WTG vendors and HVDC converter station.
- DC grid configurations and investigate the strategies and behaviour of the frequency control in such configuration.
- Black start and system restoration from HVDC-connected offshore wind farms with grid forming control capabilities, including the potential for adverse interactions with conventional generation.

9. Q&A

9.1. Q&A: Section 2.3.2

Questions:

1. DC chopper – is there a minimum time required between multiple operation of DC choppers?
2. How is this requirement represented in EMT offline models vs. replica controls?

Answers:

1. For DC chopper, one of the main constraints is the thermal heating of the DC resistance. The dissipation energy in the resistance should be designed accordingly to the specification; if it is designed to account for multiple AC fault onshore it will be able to operate because studies will be performed. If no requirements are available, then manufacturer will decide on the best techno-economic solution, therefore, it will be design depending on vendors' decision. However, generally, it is expected that two consecutive faults should be covered by the design of the DC chopper.
2. Repetitive AC fault cases should be covered in the EMT model and protection of DC chopper should be included in the provided manufacturer's black-boxed model. Temperature model can be considered in EMT models to determine the heating of the resistance during transient events (i.e. AC faults). However, after such transient event, the cooling time of a resistance is in the range of hours and depends on several parameters such as the ambient temperature. Such phenomena cannot be represented in EMT offline model (because it is based on few seconds of phenomena). To cover the full process, the HIL setup using replicas or real cubicles is the most appropriate tool.

9.2. Q&A: Figure 5-1

Questions:

1. Should studies during refurbishment be included?
2. For shared HVDC-links connected up to two or more different wind farms – how would Figure 5-1 be modified for the subsequent connection of windfarms, assuming one wind farm is connected with the HVDC link during the first phase of the project?

Answers:

1. Yes, studies during refurbishment is covered in the phase "studies during operation". For example, the refurbishment of a transformer unit will require to perform some dynamic and harmonic studies to ensure good system performance.
2. If this multiple wind farms are within the same project development, the process does not change (such option should be already covered during planning and design stage). If this new wind farm is added later on in an already existing HVDC project, this will lead to the repetition of the same process as in Figure 5-1 for this "new project" including interaction studies between new an existing wind farms. For example, the Johan-Sverdrup HVDC project, described in section 7.6, consists of two project phases; for the second project phase similar process is performed as in Figure 5-1 and in addition interaction studies are performed in parallel to validate C&P performance and ensure good compliance with the pre-existing first project phase. EMT offline models an real-time simulation including replicas are both used guaranty accuracy and reliable results.

9.3. Q&A: Section 7.2 and Figure 7-8

Questions:

1. Is Z HVDC magnitude and phase angle similar across Pwf = 500 & 300 MW? Is Zwf similar and harmonic impedance trend similar using all six strings at reduced power i.e. Pstring = 83 MW & 50 MW per string?
2. Is WF impedance & angle similar if connected to a generic VSC model or generic voltage source?
3. How best can WF manufacturer obtain & provide harmonic impedance response across early stages of the project e.g. will this be using a simplified AC voltage source?
4. Which mitigation options exist to address negative impedance across the identified frequency range & could the HVDC support adaptive damping of this?
5. What is the effect of such resonant interaction on the energisation study i.e. Pwf = 100MW & 300MW?

Answers:

1. Active power of each individual WTG does not have a predominant impact on the harmonic impedance of each WTG. However, if the wind park layout is different than this lead to differences in the overall harmonic impedance (Z_WPP) seen at HVDC converter connection.
2. Considering the same operation conditions, it is expected that WF impedance/angles will be the same if connected to a generic VSC model or generic voltage source. However, some WTG manufacturers may include adaptive control function that automatically modify control tuning based on short-circuit level of the network. In such cases, WF impedance/angles may differs (at lower harmonic ranges within the bandwidth of the controller) when connected to a generic VSC model or generic voltage source.
3. At early stages of the project, it is sufficient for WF manufacturer to provide the harmonic impedance by connecting the WTG to a simplified Thevenin AC voltage source. However, during project design, such harmonic impedance should be validated using more realistic representation by means of EMT studies.
4. There are several mitigation solutions to deal with such issue: Passive filtering by installation of HV filters, Active damping by adding control function in the C&P system of HVDC and/or WTGs, Optimization between passive and active mitigation which combines both previous solutions. More details can be found in the following in Cigré WG B4-67." AC side harmonics and appropriate harmonic limits for VSC HVDC‟ Cigré Technical Brochure 754, Dec. 2019.
5. Because the wind park layout configuration is causing such resonance, it is expected that start-up sequence will also causes similar resonance issue when going up to 300 MW with the same wind park layout configuration.

9.4. Q&A: Figure 7-9

Questions:

In Figure 7-9 Noted offline EMT could not represent high frequency oscillations – could this have been achieved using post-event retuning of offline model EMT models?

Answers:

Yes, if the EMT offline model includes the same functions and same C&P update version, this phenomenon can be reproduced also with EMT offline model. However, in practice, if such resonance occurs during onsite event, the correction/retuning of the offline EMT model will requires model development by the manufacturer which implies several weeks or months for the provision of the new updated/corrected model. Such long duration delays may be problematic for the availability of the HVDC link. In such practical case, the use of real-time simulation with replicas becomes an essential tool for utilities to reproduce such event without project delays and without being dependent on manufacturer’s time and resource constraints.

9.5. Q&A: Section 7.4

Questions:

1. Figure 7-15 – please clarify meaning of INELFE link running in AC line emulation for the POD study?
2. Please expand on the process used for validation of replica model and RMS model
3. Was the RMS model performance significantly improved – for POD and other studies?
4. which controller layer or parameters in RMS model were the most sensitive (e.g. outer loop or inner loop or PLL etc?)

Answers:

1. In steady state, the INELFE link operates as AC line this means that any angle difference change at both converter station, active power is modified accordingly. More information is presented in the following Figure 9-1 and in the following reference:
   - Dominguez Ferrer, J. M. Argüelles Enjuanes, G. D. Castejón, J. Loncle, et al,"Feedback on INELFE France Spain HVDC Project" CIGRE Conference, Paris, France, Aug. 2016

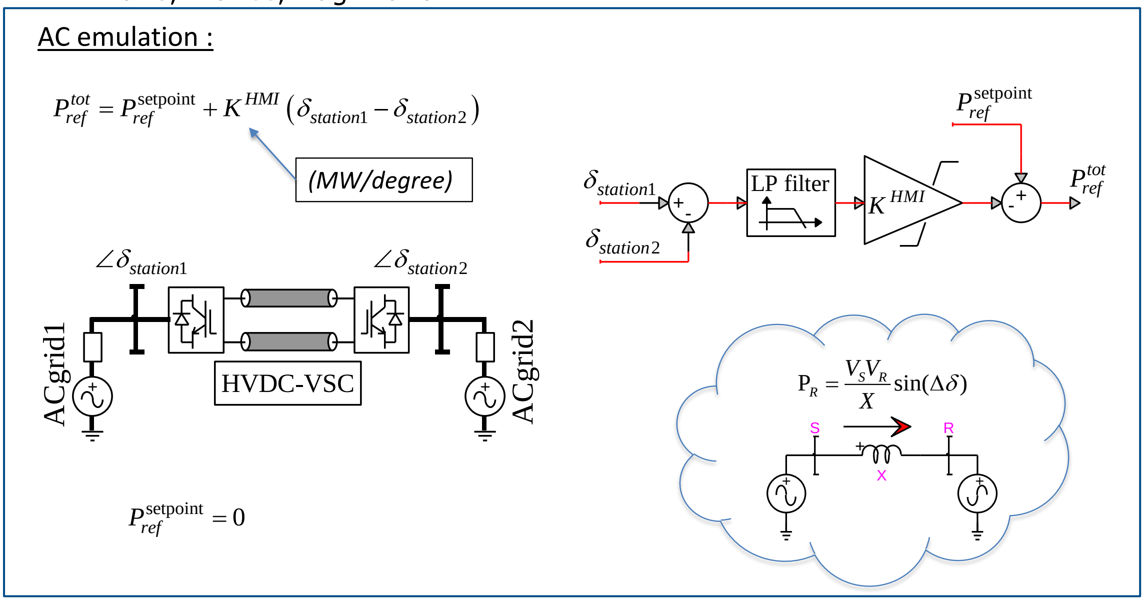


Figure 9-1 : AC emulation mode main principal

2. The general validation process is by performing step change on AC angle differences and to reproduce the same benchmark tests as in Figure 7-15 in both tools.
3. Yes, corrections on time constant and nonlinear functions parameters have been performed during this validation process.
4. The "AC line emulation control" has been the main control that was improved.

9.6. Q&A: Section 7.5

Questions:

1. Figure 7-18: Clarify if HVDC link trip was due to TOV during FRT across weak grid condition or other internal protections?
2. Which operational recommendations informs the decision to disable current injection (e.g. if SCR is below 3 or 5 etc?)
3. How can HVDC Grid code compliance be assured across such conditions?

Answers:

1. The trip of the link is due to TOV that triggers not only OVRT protection but also other protections that are within the HVDC converter station.
1. Decision has been made that during such network configuration, the current injection will be disabled because such network configuration was not defined in the requirement during project design phase.
2. Indeed, the HVDC requirements for the INELFE project does not cover such extreme conditions. The purpose of such Real-time simulation study is mainly to analyse and

REFERENCES

[1] GOV.UK "The ten point plan for a green industrial revolution", 18 Nov. 2020
[2] GOV.UK "Energy white paper: Powering our net zero future", 14 Dec. 2020
[3] IEC TR 62001-3:2016 High-voltage direct current (HVDC) systems - Guidance to the specification and design evaluation of AC filters - Part 3: Modelling, edition 1.0, 2016
[4] Cigré, W.G. B4-57." Guide for the Development of Models for HVDC Converters in a HVDC Grid" Cigré Technical Brochure 604, Dec. 2014.
[5] H. W. Dommel, "Digital computation of electromagnetic transients in single and multi-phase networks," IEEE Trans. Power App. Syst., vol. PAS-88, no. 4, pp. 388–399, Apr. 1969.
[6] http://www.emtp.com/
[7] O. Anaya-Lara, N. Jenkins, J. Ekanayake, P. Cartwright, and M. Hughes, Wind Energy Generation: Modelling and Control, Wiley, 2009, John Wiley & Sons, Ltd.
[8] F. Evangelos, U. Karaagac, H. Saad, and J. Mahseredjian. "Short-circuit current contribution of converter interfaced wind turbines and the impact on system protection." In 2013 IREP Symposium Bulk Power System Dynamics and Control-IX Optimization, Security and Control of the Emerging Power Grid, pp. 1-9. IEEE, 2013.
[9] U. Karaagac et al., "A Generic EMT-Type Model for Wind Parks With Permanent Magnet Synchronous Generator Full Size Converter Wind Turbines," in IEEE Power and Energy Technology Systems Journal, vol. 6, no. 3, pp. 131-141, Sept. 2019
[10] Cigré, W.G. B4-55." HVDC Connection of Offshore WindPower Plants " Cigré Technical Brochure 619, 2015
[11] J. Mahseredjian, S. Dennetière, L. Dubé, B. Khodabakhchian, and L. Gérin-Lajoie, "On a new approach for the simulation of transients in power systems," Electric Power Systems Research, vol. 77, issue 11, pp. 1514-1520, September 2007.
[12] H. Saad, S. Dennetière, Mahseredjian, et al, "Modular Multilevel Converter Models for Electromagnetic Transients," IEEE Transactions on Power Delivery, vol. 29, no. 3, pp. 1481-1489, June 2014.
[13] J. Beerten, S. D'Arco and J. A. Suul, "Cable Model Order Reduction for HVDC Systems Interoperability Analysis," 11th IET International Conference on AC and DC Power Transmission, Birmingham, 2015, pp. 1-10, doi: 10.1049/cp.2015.0039.
[14] Working Group B4-38, "Modelling and Simulation Studies to be performed during the lifecycle of HVDC Systems," CIGRE Technical Brochure, vol. 563, 2013.
[15] IEC TR 60071-4:2004 Insulation co-ordination – Part 4: Computational guide to insulation co-ordination and modelling of electrical networks
[16] Technical Brochure Network Modelling for Harmonic Studies, CIGRE JWG C4/B4.38, www.e-cigre.org
[17] Y. Vernay, B. Gustavsen, "Application of Frequency-Dependent Network Equivalents for EMTP Simulation of Transformer Inrush Current in Large Networks", IPST2013, International Conf. on Power Systems Transients, Vancouver, Canada, July 18-20, 2013
[18] J. Peralta, H. Saad, U. Karaagac, J. Mahseredjian, S. Dennetière and X. Legrand, "Dynamic Modeling of MMC-based MTDC Systems for the Integration of Offshore Wind Generation," CIGRE Canada Conference on Power Systems, Montreal, Quebec, Canada, September 24-26, 2012.
[19] J. Morren, S. W. H. de Haan, P. Bauer, J. Pierik, and J. Bozelie, "Comparison of Complete and Reduced Models of a Wind Turbine with Doubly-fed Induction Generator," in Proc. 10th European Conference on Power Electronics and Applications., Toulouse, France, September 2-4, 2003, pp. 1–10.
[20] J. G. Slootweg, H. Polinder, and W. L. Kling, "Representing Wind Turbine Electrical Generating Systems in Fundamental Frequency Simulations," IEEE Transactions on Energy Conversion., Vol. 18, No. 4, December 2003, pp. 516–524.
[21] U. Karaagac, J. Mahseredjian, H. Gras, H. Saad, J. Peralta, and L.D. Bellomo. "Simulation models for wind parks with variable speed wind turbines in EMTP", 2017
[22] U. Karaagac, H. Saad, J. Mahseredjian, S. Jensen and L. Cai, "OffShore Wind Power Plant Modeling Precision and Efficiency in Electromagnetic Transient Simulation

Programs," in 11th International Workshop on Large-Scale Integration of Wind Power into Power Systems, Lisbon, Portugal, November 13-15, 2012.

[23] H. Saad, S. Dennetière and J. Mahseredjian, "On modelling of MMC in EMT-type program," 2016 IEEE 17th Workshop on Control and Modeling for Power Electronics (COMPEL), Trondheim, 2016, pp. 1-7

[24] S. R. Sanders, J. M. Noworolski, X. Z. Liu, and G. C. Verghese, "Generalized averaging method for power conversion circuits," *IEEE Trans. on Power Electronics*, vol. 6, no. 2, pp. 251-259, Apr. 1991.

[25] H. Ouquelle, L. A. Dessaint, and S. Casoria, "An average value model-based design of a deadbeat controller for VSC-HVDC transmission link," *IEEE Power Energy Soc. Gen. Meeting*, pp. 1-6, Calgary, AB, Canada, July 2009.

[26] E. Muljadi, C. P. Butterfield, et. al., "Equivalencing the Collector System of a Large Wind Power Plant," IEEE Power Engineering Society General Meeting, 2006

[27] J. Brochu, C. Larose and R. Gagnon, "Generic Equivalent Collector System Parameters for Large Wind Power Plants," in IEEE Transactions on Energy Conversion, vol. 26, no. 2, pp. 542-549, June 2011, doi: 10.1109/TEC.2010.2087022.

[28] Turbines—Part W. 27-1: Electrical Simulation Models-Wind Turbines. IEC Standard. 2015;61400-27.

[29] Cigré Working Group B4-70, "Guide for Electromagnetic Transient Studies Involving VSC converters"

[30] P. Kundur. "Power system stability and control." Edited by Neal J. Balu, and Mark G. Lauby 4, no. 2 (1994).

[31] http://www.bestpaths-project.eu/

[32] https://www.hvdccentre.com/open-source-converters/

[33] Cigré Working Group B4-37, "VSC Transmission," CIGRE Technical Brochure, vol. 269, 2005

[34] H. Saad, S. Dennetière and P. Rault, "AC fault dynamic studies of islanded grid including HVDC links operating in VF-control," 15th IET International Conference on AC and DC Power Transmission (ACDC 2019), Coventry, UK, 2019, pp. 1-8.

[35] A. Stepanov, H. Saad, J. Mahseredjian, A. Wataré. "Overview of generic HVDC-MMC control under unbalanced grid conditions." In Proceedings of IPST 2017 Conference, Seoul, Korea. 2017.

[36] J. Sun, "Impedance-Based Stability Criterion for Grid-Connected Inverters," in IEEE Transactions on Power Electronics, vol. 26, no. 11, pp. 3075-3078, Nov. 2011

[37] H. Saad, Y. Vernay, S. Dennetière, P. Rault, B. Clerc "System Dynamic Studies of Power Electronics Devices with Real-Time Simulation -A TSO operational experience" CIGRE Conference, Paris, France, Aug. 2018

[38] H. Saad, A. Schwob, Y. Vernay, " Study of Resonance Issues between HVDC link and Power System Components using EMT Simulations," 2018 Power Systems Computation Conference (PSCC), Dublin, 2018, pp. 1-7

[39] H. Saad, Y. Fillion, S. Deschanvres, Y. Vernayand S. Dennetière, "On Resonances and Harmonics in HVDC-MMC Station Connected to AC Grid," in IEEE Transactions on Power Delivery, vol. 32, no. 3, pp. 1565-1573, June 2017

[40] "Analysis of CE Inter-Area Oscillations of 1st December 2016", ENTSO-E SG SPD Report, 13.07.2017

[41] A. Dominguez Ferrer, J. M. Argüelles Enjuanes, G. D. Castejón, J. Loncle, et al,"Feedback on INELFE France Spain HVDC Project" CIGRE Conference, Paris, France, Aug. 2016

[42] A. Petit, J. Michel, H Saad, G.Torresan, C.Faure-Llorens, Y.Vernay "System Studies on the French Network Including HVDC stations and using the Real time Simulation" CIGRE Conference, Paris, France, Aug. 2020

[43] S. Dennetiere, K. Sharifabadi, J. H. Johansson, N. Krajisnik, P. Rault, H. Saad, Y. Fillion, "Technical solutions to predict and mitigate inadvertent interaction of two parallel connected VSC-HVDC schemes feeding an islanded offshore Oil and Gas grid" CIGRE Conference, Paris, France, Aug. 2020