Expert Group Interaction Studies and Simulation Models (EG ISSM)

REPORT DRAFT 01.10.2021

Table of Contents

Document control

Version	Date	Change Reference
1.0	15th of April 2021	Draft of the report is submitted for consultation in GC ESC
2.0	1st of May	Implementation of comments from GC ESC members
3.0	28th of June	Final clean version submitted to the GC ESC for review
4.0	10th of September	Revised version with changes implemented after the GC ESC review
5.0	27th of September	Revised version with changes in section 5.4 after the changes as agreed in the EG.
6.0	1st of October	Final version submitted to the GC ESC

EXPERT GROUP MEMBERS

	Name	Organisation	Representation at GC ESC
1	Mario Ndreko (chairman)	TenneT Germany	ENTSO-E
2	Ton Geraerds (Vice-chairman)	RWE	VGB
3	Macarena Martín Almenta	REE	ENTSO-E
4	Hani Saad	RTE	ENTSO-E
5	Tobias Hennig	Amprion	ENTSO-E
6	Ioannis Theologitis / Adrian Gonzalez	ENTSO-E	ENTSO-E
7	Jesus Bernal Lopez	Iberdrola	SolarPower Europe
8	Juan-Carlos Perez Campion	Iberdrola	SolarPower Europe
9	Daniel Premm	SMA	SolarPower Europe
10	Musa Shah	Lightsource BP	SolarPower Europe
11	Naomi Chevillard	SolarPower Europe	SolarPower Europe
12	Vasiliki Klonari	WindEurope	WindEurope
13	Patrick Alizon	Vestas	WindEurope
14	Ranjan Sharma	Siemens Gamesa Renewable Energy	WindEurope
15	Pascal Gartmann	Enercon	WindEurope
16	Eric Dekinderen	VGB	VGB
17	Cedric Lehaire	Veolia	COGEN Europe
18	Luvigi Di Raimondo	Solar Turbines	COGEN Europe
19	Alexandra Tudoroiu	COGEN Europe	COGEN Europe
20	Mike Kay	ENA	GEODE
21	Luca Guenzi	Solar Turbines	EUTurbines
22	Kevin Chan	GE	EUTurbines
23	Magdalena Kurz	EUTurbines	EUTurbines
24	Vincenzo Trovato	ACER	ACER
25	Adolfo Anta	AIT	EASE
26	Christian Krieger	Siemens Energy	Orgalime
27	Stanko Jankovic	TenneT Germany	Support to the chairman
28	Robert Dimitrovski	TenneT Germany	Support to the chairman

1. INTRODUCTION

The Grid Connection European Stakeholder Committee (GC ESC) has decided to establish an expert group on interaction studies and simulation models (EG-ISSM) for synchronous power generation modules (SPGM), power park modules (PPM) and high voltage direct current (HVDC) transmission systems. The creation of this EG was proposed by ENTSO-E to elaborate further on connection network code (CNC) issues, which had been raised by stakeholders during the CNC implementation.

The objective of the EG ISSM is to identify simulation methods, simulation models (for example black box or open source) to be exchanged between the stakeholders in grid connection studies (including wide area network studies), with the main focus on the study of interactions between power generating modules (PGMs), HVDC systems (including FACTs) and other grid users. The interaction studies under the scope of this EG refer to dynamic and control interactions. The EG reviews existing developments and proposes simulation model requirements for the purpose of interactions studies. The interaction studies are defined for a wide frequency range (sub-synchronous, near-synchronous and higher orders of harmonics).

2. PURPOSE OF THE EXPERT GROUP

2.1. Terms of reference

Confidentiality of the exchanged models and data as well as the accuracy of simulation models is an issue when performing interaction studies for power generation modules (PGMs) and high voltage direct current (HVDC) transmission systems. In addition, the validation of the simulations model with respect to the accurate representation of the facility is a key requirement. To address these issues the following tasks have been identified for this EG.

With regard to NC HVDC, Article 54 (1), the EG will provide detailed model requirements and if possible suggest the relevant signal interfaces between the control layers in the models (black box, open source) in order to perform accurate, reproducible and validated interaction studies. As specified in NC HVDC, Article 51 and Article 53, HVDC systems have the capability to enable fault recording and monitoring signal of key operation metrics such as voltages (AC, DC), currents (AC, DC) and power. The EG will evaluate how these can be integrated in the validation of the models used in interaction studies. Moreover, NC HVDC, Article 70 requires the assessment of an HVDC system during its lifetime. This article is relevant for interaction studies, as the required modelling accuracy to cover all potential interaction risks is not yet fully known. Furthermore, a consistent representation of power-electronic assets by separating physical hardware and control ensures interoperability in the long term beyond typical manufacturer warranty periods.

With regard to NC RfG, Article 15 (6, c), the EG will provide an overview of different types of dedicated models (black-box, open source, generic), representing the real plant (PGM) behaviour by implementing/embedding in the models the real source code. A particular focus of the EG will be SPGMs in close electrical proximity to HVDC systems (where sub-synchronous torsional interactions become relevant). The EG should define the model layers in black-box models (covering control and physical layers) and the process for model validation (potentially by field tests). The EG should propose well defined model structure interfaces in the simulation models for the control and physical layer that need to be observable/accessible from stakeholders in grid connection and compliance verification studies.

With regard to the NC RfG article 40 and associated sub-articles, the EG will discuss the way to use mathematical models representing the generating unit behaviour to prove compliance to the requirements. The discussions can include the different type of models and their minimum structure. The EG will provide recommendations on model validation and associated process, including eventual field testing. The EG group elaborates what the model shall include (or exclude).

With regard to DCC, Article 21 (3) stakeholders have requested that the dynamic states of the models are precisely defined to represent electromechanical phenomena based on root-mean-square (RMS) or positive sequence models. The phrase “including 50 Hz component” is unclear and suggests that the 50 Hz component is one of many components required in this type of dynamic studies. The content and format shall include "structure and block diagrams" lacks clarity. With regard to DCC, Article 21 (4), it is not clear why simulation models do not consider frequency regulation despite the capability of demand response system frequency control being defined in paragraph 29, or when considering distribution system connected PGMs. The EG shall address the above mentioned issues and provide recommendations.

2.2. Deliverables

Provide a report to the GC ESC with detailed recommendation and solution to the tasks defined above.

3. INTERACTION STUDIES

3.1. Background

The increasing penetration of Power Electronic Devices (PED) in AC networks leads to a higher risk of adverse interactions between PED, the network passive elements and/or conventional synchronous power generating modules (SPGM). In addition to this, the execution of interaction studies in power systems dominated by PEDs is challenging for the following reasons:

- The high complexity of their control and protection system and the importance of their accurate representation.
- The confidentiality and the intellectual property issues related to the control and protection algorithms.
- The use of different software tools, different software versions and compilers.
- The importance of simulation parameters/data in which the model is provided.
- Maintenance of the model through the lifetime of the project.

With their fast controls (which present smaller time constants compared to conventional synchronous generation based power systems), PED can excite a series of expected or unexpected interactions on the grid. Moreover due to their fast switching capabilities, PED can distort the line voltage by injecting additional harmonic voltages/currents into the grid. Furthermore, an increase in performance requirements, such as high gains and very fast responses, increase the risk of suboptimal parametrization. The complete PED installation cannot therefore be considered as a passive system; the control mechanisms are capable of amplifying, rather than attenuating disturbances so that the system becomes locally poorly damped or unstable if PED tuning and interaction assessment is not properly taken into consideration.

These local instabilities could trigger outages of PED (HVDC stations or large PPMs), imposing power imbalances which could jeopardize the global frequency stability. An interaction is a reciprocal action exerted by a system on one or several other systems. Interaction between components is not necessarily harmful to the network and for the system. It is, therefore, important to distinguish interactions with positive repercussions and those inducing negative consequences. Positive interaction leads to the improvement of network stability, whereas a negative or adverse interaction (or negatively damped interaction) causes system performance to deteriorate.

3.2. Interaction assessment

Background

Numerical root mean square (RMS) and electromagnetic transient (EMT) simulation tools are used by power system engineers and researchers to conduct various grid connection and network planning studies. The increased installation of PED connected to the transmission and distribution systems implies an increasing need for the deployment of EMT tools. The reason is the faster dynamic and more complex behaviour of PED that cannot be captured or properly analysed with RMS simulation tools (which are by definition developed for power systems with conventional synchronous generation where the dynamics are much slower, usually up to 3Hz). On the other hand, the use of EMT simulations for large scale dynamic studies is from computation perspective challenging to be integrated in grid planning and dynamic security assessment studies. Compared to RMS tools, the main drawback of EMT simulation models is the computation time which is longer than RMS simulation models because device modelling is much more detailed and the simulation time steps must be much shorter in order to have stable numerical calculations.

EMT simulations apply to a wide range of frequencies and therefore require a very detailed representation of components (for example the high voltage equipment, the control and protection (C&P) systems, converters switching components, etc.). The simulation is performed in the time domain (where instantaneous values of voltage and currents are observed versus time) 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 and therefore they are well suited to simulate devices such as PEDs or grid areas dominated by PEDs.

Real time (RT) simulation offers a complementary solution with respect to offline EMT and RMS simulation. The main advantages lies mainly in achieving faster (in terms of simulation duration) EMT simulation, augmented with the possibility of connecting physical external devices (hardware) to perform hardware-in-the-loop (HIL) simulations if needed. To cope with such faster computation and the connection of physical devices, a dedicated simulator with more powerful processing is needed. This is usually performed by the acquisition and installation of dedicated software in the loop (SIL) or hardware in the loop (HIL) simulation platforms rather than by performing typical classical offline simulations on a desktop computer.

Simulation tools used during various project phases

For each project phase, several studies are performed to detect potential interaction risks and different types of software are used for those phases, as shown in Table 1.

Project planning phase

HVDC and PPMs

During the planning phase of a project, for the case of PEDs (HVDC and PPMs) the analytical investigation provides a simple and rapid approach to determine the network area where there may be potentially interactions with other grid users. However, if the project has an innovative character due to special needs or if the technologies being considered may have only recently been introduced, it is beneficial for the TSO or the relevant system operator to perform additional dynamic studies (i.e. RMS and EMT type simulations) as well.

SPGMs

During the planning phase of a SPGM projects the developer wants to define a location where the grid conditions are appropriate for the project: correct grid capacity (depending on the voltage), acceptable short-circuit current characteristics, correct supply of fuel, correct environmental conditions (noise, cooling water). The primary electrical characteristics depend on the size of the SPGM and shall be communicated to the TSO. As examples: maximum and minimum active power; short-circuit current injection; range of reactive power. For a type C and D PGM the TSO or the relevant system operator will impose LFSM-U and FSM capabilities in line with NC RfG and whether islanding capabilities should be offered. The TSO will determine if black-start capabilities are required. TSOs perform system stability studies (voltage, rotor-angle and frequency), when assessing the connection of new grid users, changes in the network or network conditions. SPGMs are typically represented using RMS models in the planning studies of TSOs.

Table 1. Study phases and simulation tools used for various technologies.

	Project Planning	Project Design	FAT & Commissioning	Operation
HVDC systems	Analytical investigation is performed in order to identify potential interaction risks. This investigation is usually carried out based on the short circuit ratio analysis, impedance based analysis, modal analysis.	RMS and EMT simulation tools are used in the design phase.	These studies are performed with RMS and EMT tools. Real time simulators using control and protection cubicles if applicable may be used during commissioning when other PEDs are connected in close vicinity.	Depending on the interaction phenomena or the incident recorded, RMS or EMT simulations might be used to study the connection of new grid user, foreseen changes in the network, critical network conditions, or to reproduce field faults. The EMT studies may be performed by means of real time simulation platforms using control and protection cubicles, depending on the incident and the relevant study needs of each project.
SPGMs	Simulations are performed in special cases.	RMS simulations are used concerning reactive power, robustness, system stability studies (incl. interarea oscillations). EMT simulations are used in SSTI	Tests are performed in accordance with the NC RfG and validation of simulation models based on the test results.	TSOs perform system stability studies, when assessing the connection of new grid users, changes in the network or network conditions. SPGMs are typically represented using RMS models. New

		studies.		simulations can also be required only in case of substantial modification or after major incidents, which demonstrate that requirements were not fulfilled.
PPMs	Analytical investigation is performed in order to identify potential interaction risks. This investigation is usually based on short circuit ratio analysis, impedance based analysis, modal analysis	RMS and EMT simulations with detailed model representation	Tests in accordance with NC RfG and validation of simulations models based on test results	TSOs perform system stability studies, when assessing the connection of new grid users, changes in the network or network conditions. Depending on the phenomena, PPMs are represented using RMS, EMT or harmonic impedance models. New simulations can also be required only in case of substantial modification or after major incidents, which demonstrate that requirements were not fulfilled.

Project design phase

HVDC and PPMs

During the design phase of PPMs and HVDC systems, RMS and EMT type offline simulation models are used with the vendor's models to investigate the predominant risk of interaction. The scope of the studies can vary depending on the project specificities. Such interaction studies are conducted by the TSO, by the vendors and/or by third parties.

SPGMs

During the design phase of SPGM projects, the items mentioned above shall be confirmed. The requirements imposed by IEC / EN standards have to be respected. Several characteristics have to be confirmed by RMS simulations. By simulation the default values for the automatic voltage regulator (AVR) and the power system stabiliser (PSS) have to be defined for a type D SPGM. Depending on the classification of the SPGM several simulations are required such as:

- LFSM-O; LFSM-U and FSM with respect for full activation time
- Fault Ride Through requirements

- Robustness (small signal disturbances)
- Settings of protection relays
- P-Q alternator diagram with thresholds caused by stator current, under-excitation and over-excitation

The insulation coordination calculations and the short-circuit-currents simulations shall be performed by the TSO. Potential interactions of HVDC convertor station on the SPGM, according to HVDC NC Art. 29 and Art.31 shall be assessed by the TSO, based on studies performed by the HVDC System Owner or the TSO, depending on national regulations.

The majority of the models used for larger PGMs are not certified by an authorized body. For several decades these models have been fully accepted as correct and adequate by all manufacturers and RSOs.

FAT & Commissioning

HVDC and PPMs

During the Factory Acceptance Test (FAT), the control tuning (of the real control system) shall already be set and is, therefore, validated by means of real time (RT) simulations. Additional interaction studies may be conducted with the use of real cubicles to validate the interaction studies performed during the design stage and, when needed, to perform additional simulations with the control and protection cubicles. During the commissioning phase, it might be possible to conduct interaction study assessments to support the commissioning of the PED system which may avoid onsite delays. The latter shall be decided on project specific basis and based on the national regulations.

SPGMs

For smaller SPGM units, factory acceptance tests are required in order to issue compliance certificates. Factory acceptance tests covering all requirements are not common for larger PGMs, thus site acceptance tests are very important. The items defined during the design phase are checked by measurements. Site acceptance tests regarding reactive power capability are in practice limited by the grid voltage. For that reason simulations will be necessary. For all model verifications, a reasonable range of acceptable differences between simulated values and measured values shall be agreed between the involved parties.

During operation

The TSO or where/if applicable the RSO is responsible for the stability and security of its own network, and therefore shall perform studies to evaluate the impact of any new installed grid-user on the network and the impact of any modification of the network. For this reason, accurate models shall be used. The list of potential situations[1] for which studies are required can be long, however, a non-exhaustive list is provided for illustration purpose only:

- Post-incident analyses
- Impact and interaction with classical AC protections
- Development of the AC grid topology
- Dynamic behaviour studies (leading to operational limitations, e.g. ramp rate, partial load rejection, islanding)
- Studies on faults
- Rate of change of frequency (RoCoF) studies to evaluate the need for synthetic inertia to be provided by PPMs
- Interaction studies between grid users
- Harmonics and resonance studies
- System defence and system restoration studies including Black-start studies
- Sub-synchronous interaction studies (including synchronous and/or non-synchronous power generating modules)
- Line and transformer energisation studies
- Transformer magnetization studies including sympathetic inrush current
- Control coordination with other equipment studies
- Extension of any HVDC system
- For HVDC stations: Refurbishment of high voltage equipment or modification of the converter station topology (new filter, change of transformer, new DC cable)
- Refurbishment of the grid control and protection system

HVDC and PPMs

During operation, four types of simulations could be used: RMS, frequency domain impedance analysis, offline EMT and real-time EMT simulations with control and protection cubicles. The application of real time simulations will depend on the studied scope, on project specific basis according to the national regulations. It is common to use different tools to validate and to cross-check the study results. For instance, when performing RMS studies for slower AC network dynamics (such as the tuning of power oscillation damping controllers) a real-time EMT simulation study could be regarded as complementary to validate the HVDC model behaviour and the accuracy and effectiveness of the provided mitigation solution. It should be highlighted that table 1, is rather a recommendation for risk assessment and shall not be regard as a requirement. Moreover, real-time simulation is not a common case for PPMs (wind power plants and Photovoltaic) and this approach is rarely applied. Also only few TSOs use real-time simulations in the operational phase of HVDC systems.

[1] Cigre TB 563 "Modelling and Simulation Studies to be performed during the lifecycle of HVDC Systems" in Section 3.3.2 AC Modelling Requirements something similar is presented.

SPGMs

A new simulation model is required only in case of substantial modification or after major incidents which demonstrate that applicable requirements were not fulfilled. It is mandatory that each operator of a SPGM informs the RSO of all modifications with an impact on the behaviour in order to allow the RSO to update its models.

3.2. AC network models and data

A comprehensive model representation shall include the detailed modelling of the AC grid equipment: transmission/distribution lines and cables, transformers, loads, generators, compensators, etc. Such a model for the purpose of wide frequency interaction studies is usually simulated under EMT model assumptions and is intended to analyse the PED (HVDC and PPMs) dynamic behaviour focusing on the interaction of the control and protection system within the network in transient domain.

Specific and realistic network behaviour shall be reproduced to analyse the impact of PGMs, HVDC converter stations and demand side behaviour on the network and vice-versa. Also, such detailed representation is necessary to account for interaction studies between PED system and AC equipment. The single line diagram example as illustrated in figure 3-1 includes:

- Transformers with impedances and saturation characteristics
- Lines and cables models capable to generate frequency-dependency for the defined frequency range of the relevant interaction study.
- Min/max short-circuit current/power for each Thévenin source connected to the reduced grid
- Min/max active and reactive load at each substation. Here accurate load modelling is important when control interaction studies are performed in a wide frequency range.
- Bus-bar configuration, especially in the substation where the converter station is connected
- Generators and associated controls affecting the relevant phenomena studied
- PED systems connected in proximity (also at demand side)

To perform interaction studies during design stage, before commissioning and during operation stage it is necessary to model the AC network in such detail, as described above. The level of details of the AC network model shall be in line with the phenomena studied (accuracy for the frequency range where the study is applicable).

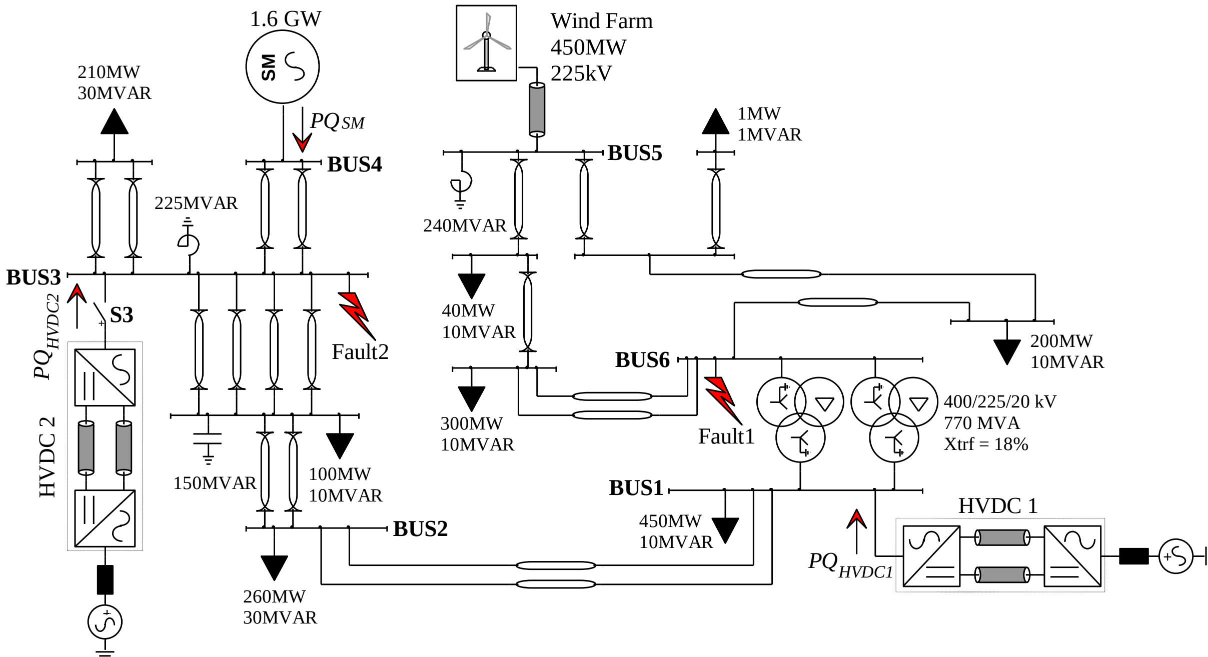


Figure 3-1 An example network with a detailed representation of AC network[2]

In order to provide correct representation of the AC system, and especially when the harmonic impedance is of concern, a Thévenin source can be replaced with a frequency dependent network equivalent (FDNE)[3]. This would allow modelling of higher frequency grid resonances which is not possible to be captured by simple Thévenin sources (voltage source behind impedance). An illustration example from the 400kV frequency dependent impedance is provided in Figure 3.2, which is the impedance as seen at the connection point of an HVDC station.

The latter modelling approach is important for interaction studies concerning HVDC systems and large PPMs, as in high frequency region (up to 2.5 kHz) there is the tendency of the modular multi-level (MMC) converters in HVDC systems to demonstrate negative damping (quite observable from around 1 kHz depending on the manufacturer control systems applied). This negative damping could create undamped high frequency oscillations if coinciding with the AC network resonance. Such excitation could happen as a result of lines switching actions or grid faults. Hence the aggregation of transmission areas with only a simple Thévenin voltage source should be carefully assessed.

2 H. Saad, S. Dennetière and B. Clerc, "Interaction investigations between power electronics devices embedded in HVAC network," 13th IET International Conference on AC and DC Power Transmission (ACDC 2017), Manchester, 2017, pp. 1-7
3 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.

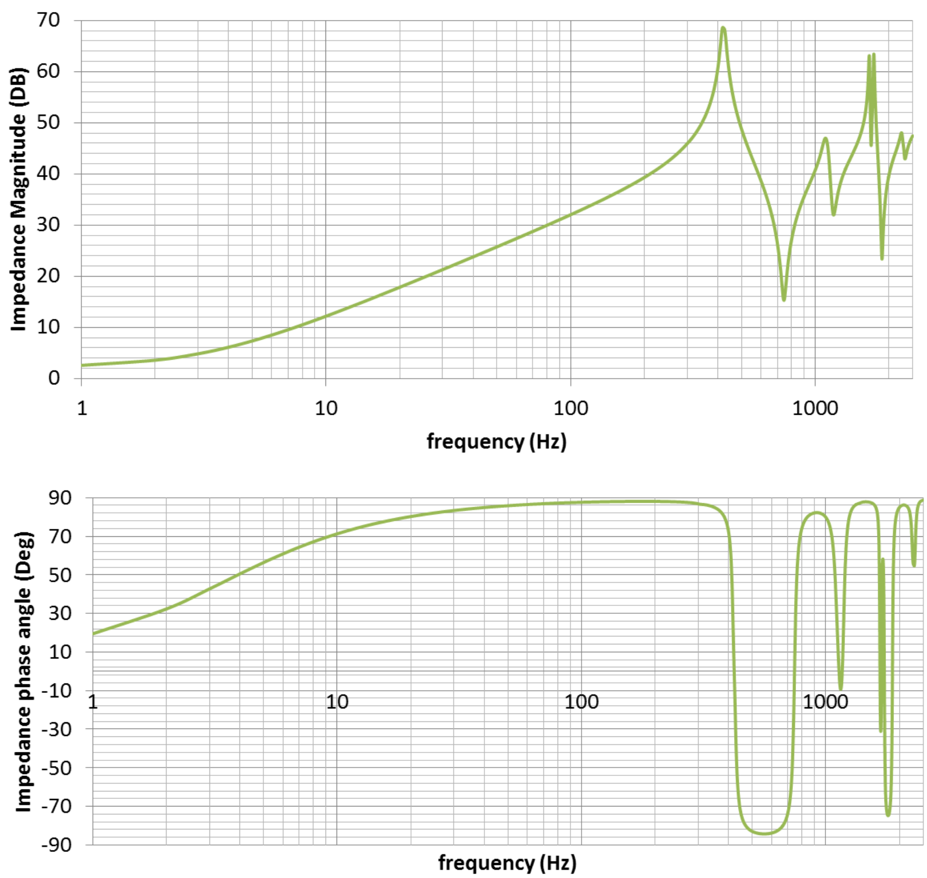


Figure 3-2. Real life example of a frequency dependent positive sequence impedance in the range 1-2500Hz at a 400kV substation bus-bar which is the connection point of an offshore HVDCconverter station.

Along the same lines, the accurate representation of the transmission and distribution system interface (T/D) is also important for interaction studies. For wide frequency interaction studies (range from 5Hz up to 2.5kHz) a distribution grid which hosts a high share of PED and with a T/D being the same sub-station where HVDC systems or large PPMs are connected should be carefully studied. At the T/D interface the frequency dependent behaviour needs to be taken into account as it may have an impact on the resonance stability. Hence, TSOs and DSOs shall cooperate to define such frequency dependent behaviour at the T/D interface in both directions. On the basis, data availability is key issue in order to ensure accuracy in the interaction studies. For transmission system studies, where the effect of control interactions could have more global system effect, the DSO shall cooperate with the TSOs and provide the required data needed at the T/D interface (frequency dependent grid impedance or dynamic equivalent of the distribution grid for RMS type simulations). SOGL Article 48.1.h mandates this already – at least for generation units.

4. INTERACTION PHENOMENA

4.1 List of phenomena

The following table provides a general overview on the interaction phenomena that can occur between at least two main PEDs. In addition, it provides the adequate tools that should be used for different studies. The table is based on the ongoing Cigré WG B4-81 activities and is used as reference for the discussion of this expert group.

Table 2 Categorisation of interaction phenomena[4]

Multi-Infeed and Interaction Study Interaction between : at least two main power electronic devices (HVDC, FACTS, Renewables, etc.)					
Control loop interaction		**Interaction due to non-linear functions**		**Harmonic and Resonance interaction**	
Near steady-state (slow control)	**Dynamic (fast controls)**	**AC fault performance**	**Transient stress and other non-linear interaction**	**Sub-synchronous resonance**	**Harmonic emission and resonance**
• AC filter hunting • Voltage control conflicts • P/V stability	• Power oscillation • Control loop interaction • Sub-synchronous control interaction • Voltage stability	• Commutation failure • Voltage distortion • Phase imbalance • Fault recovery • Protection performance	• Load rejection • Voltage phase shift • Network switching • Transformer saturation • Insulation coordination	• Sub-synchronous torsional interaction	• Resonance effects • Harmonic emission • Harmonic instability • Core saturation instability
• Static analysis • RMS time domain	• RMS time domain • EMT time domain • Small-signal analysis	• RMS time domain • EMT time domain	• EMT time domain	• EMT time domain	• Harmonic analysis • EMT time domain • Small-signal analysis

Control loop interactions

Interactions between control loops are commonly studied for power system stability. The dynamic behaviour of a power electronics component is essentially dictated by the control system. Thus, interactions can take place between the control loops due to the control gain values of a control loop (i.e. PID control, droop control, etc). This type of phenomenon includes two sub-sections; slow and fast control dynamics as highlighted in table 2.

Interaction due to non-linear functions

During high transients (i.e. faults, outage, etc.), the non-linear functions (protections, fault ride through, limiters, transformer saturations, etc.) dictate the behaviour of the PED system. In these cases, EMT transient simulations should be conducted for AC and DC faults, transformers and converters energizations, start-up sequences, connection/ disconnection of large reactive/active loads, etc.

Harmonic and Resonance interactions

Interactions include high frequency harmonics emitted and resonances that can take place between several PEDs, grid or other grid users. The harmonic emissions and resonances are not

[4] Cigré WG B4-81

limited to the voltage level of the connected equipment and can spread through neighbouring networks.

4.2 Review of methodologies for interaction studies

Root-mean square (RMS) simulations

RMS simulations have been used worldwide in the past decades by transmission system operators mainly for large network power system dynamic security assessment. The main hypothesis of accurate RMS studies is based on the fact that the power system time constants are mainly driven by the time constants of the synchronous power generation units and the associated control modules (Turbine Governor, Turbines, AVR and PSS). Hence, RMS simulations ensure a satisfactory level of accuracy for dynamic phenomena in the range from 0.1Hz up to 3 Hz (depending on the quality of the models and the simulation time step).

Compared to SPGMs, the control loops of PED have a broader frequency bandwidth and can trigger interaction phenomena in a much wider frequency range. RMS simulations present a good trade-off between computation burden and accuracy for voltage, frequency and rotor angel stability in a given frequency range but might not be adequate for analysis of power systems with high penetration of PED where the control loops of PED have an important impact. However, as the system strength (short circuit power in conjugation with total system inertia) reaches critical low levels, RMS simulations are not adequate especially for Interaction Studies.

Electromagnetic transient (EMT) Simulations

This analysis method is the most detailed among the various approaches used for the analysis of control interactions. The results obtained from an EMT simulation are traces of physical quantities such as currents, voltages, angles, machine rotational speeds etc. as they can be measured in reality. The execution of control interaction studies by means of EMT simulations is performed by applying disturbances and observing the response of the system. Consequently, a large number of cases under various conditions need to be calculated in order for the system to be properly investigated.

The biggest advantage of this method is its ability to use very detailed and nonlinear models (switching models of power converters), as well as to interface black-box models of controls and protections to other components provided by manufacturers. Namely, the nonlinearities and the delays in the system, which cannot be properly represented in other analysis methods, might play a crucial role in the stability of the system. Considering that EMT simulation has the highest modelling depth, this method can be used for the verification of instabilities found by other methods.

The major drawback of EMT simulations is the exponentially increasing computational burden with the system size.

Impedance-based analysis

The impedance-based analysis[5] emerged originally as a design method for dc-dc input filters and later on it was extended for stability analysis of AC networks. This method is based on dividing the entire system into two subsystems. The first subsystem consists of the connection point of the converter. This is usually selected as the point for splitting the system. Hence, this method predicts the stability locally. The resulting subsystems are then represented as equivalent impedances, which are rearranged to form a feedback loop. Finally, the stability of the system is assessed by applying the Nyquist stability or the generalized Nyquist stability criterion to the system loop. It is worth mentioning that this method can be applied without any prior knowledge of the system, since the equivalent impedances of both systems can be also obtained from measurements. Furthermore, this analysis method could be applied without revealing confidential data in the control and protection system of PED.

Eigenvalue analysis

The eigenvalue (or modal) analysis uses the description of a physical system by first-order differential equations, also known as the state-space representation. Following a linearization around a given operating point, in this method the system is decoupled and isolated modes of oscillation are obtained. The eigenvalue analysis possesses two distinctive features in comparison to other methods – the identification of modes and the use of participation factors. The identification of system modes means that the results obtained from the eigenvalue analysis provide both the frequency of oscillation and the damping of the modes. With this feature it is possible to systematically analyse the dynamics of a given system and also to reveal the rules behind the investigated phenomena. The participation factors on the other hand can pinpoint exactly to the extent that an asset (SPGMs, PPM or HVDC) in the system is responsible for a certain mode of oscillation. In this way, it is possible to directly act on the root-cause of the problem.

Transfer-function-based analysis

The transfer-function-based analysis method is based on the idea of incorporating the grid impedance into the converter's control system. Afterwards the transfer function matrices of the entire system are obtained and the classical approaches from control theory are used to assess the stability of the system. This method supports the use of black-box models and it is suitable to quantify the robustness of the system. However, the root-cause analysis of the detected instabilities is difficult.

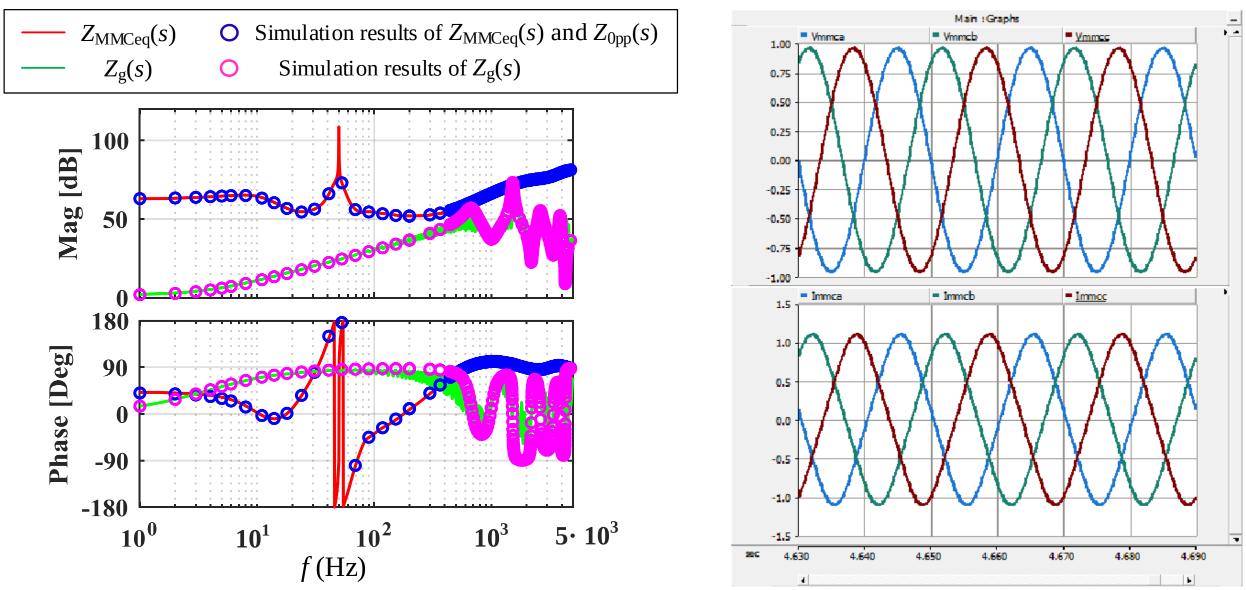
4.3 Example of Impedance-based and EMT simulation used for MMC HVDC system control interaction studies

As pointed out in section 4.2, the stability of grid connected PED can be determined by the impedance based assessment of loop gain Zg(s)/ZMMCeq(s) according to the Nyquist stability

[5] Cigre B4.67 Technical Brochure: AC side harmonics and appropriate harmonic limits for VSC HVDC.

criterion, where Zg(s) is the grid impedance and ZMMCeq(s) the HVDC station impedance in frequency domain.

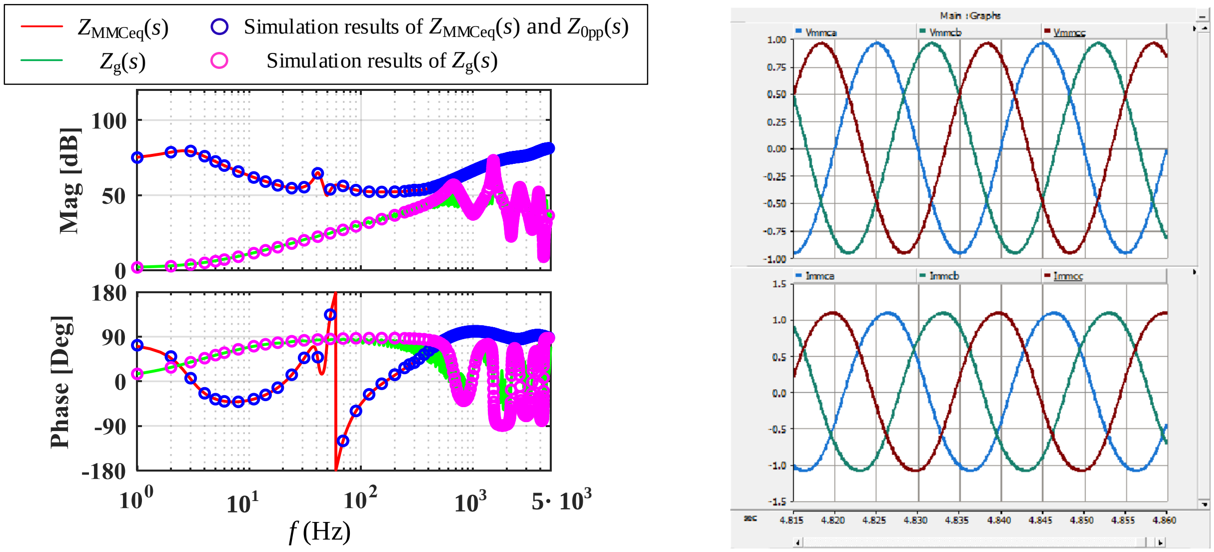
Figure 4.1 and figure 4.2 present an assessment example[6] in frequency and in time domain. More specifically, the frequency dependent impedance profile (Bode diagram) of the MMC HVDC station, here defined as ZMMCeq(s), in conjugation with the frequency dependent grid impedance, Zg(s), of a given transmission system connection point is used. The MMC-HVDC system is operated in the active power control loop (APL) mode and in reactive power control loop (RPL) mode for the example of Figure .4.1, and with the Direct Voltage Control (DVC) mode and AC voltage control (AVC) mode for the case shown in Figure .4.2. It can be seen that ZMMCeq(s) does not intersect Zg(s) in the sub synchronous frequency range, while the phase difference at the magnitude intersection points at the high frequencies is less than 180°. Therefore, the system should be stable, a result which is also verified by the time domain simulation results given by Figures 4.1 (b) and 4.2 (b).



(a) (b)

Figure 4-1. A generic MMC-HVDC system with the active power control loop and reactive power control loop showing a stable case in terms of resonance stability. (a) Bode diagram with the analytical and numerical method. (b) Time-domain EMT simulation validation for the same case.

6 Dongsheng Yang et all, "Automation of Impedance Measurement for Harmonic Stability Assessment of MMC-HVDC Systems", Paper presented at the Wind Integration Workshop, Dublin, 2019.

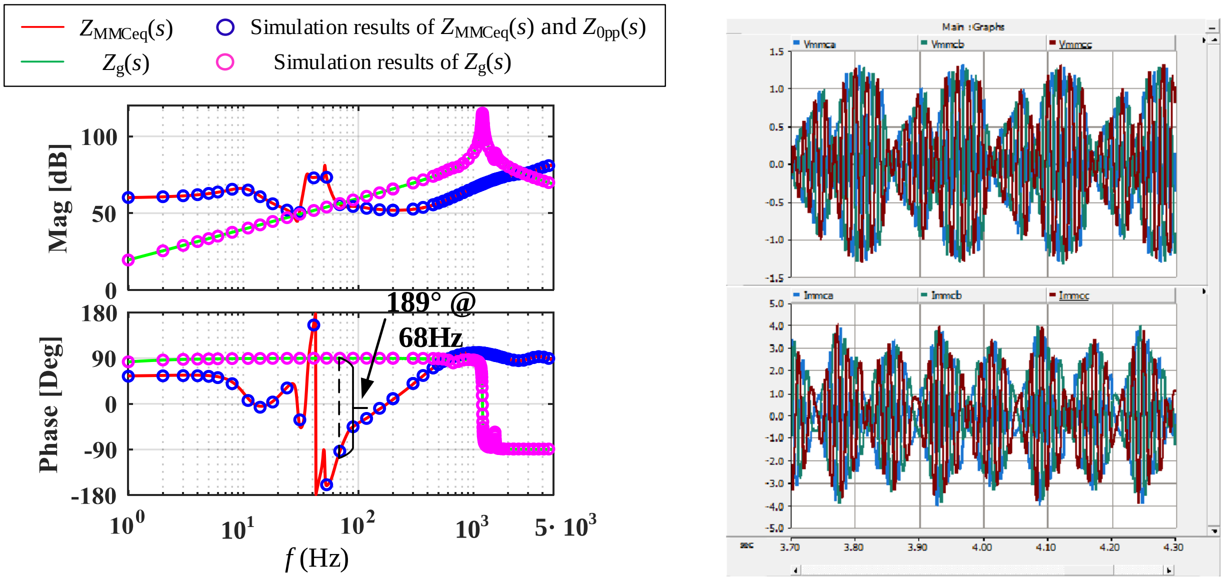


(a) (b)

Figure 4-2. A generic MMC-HVDC system with the direct voltage control and AC voltage control for a stable case in terms of resonance stability. (a) Bode diagram of the analytical and numerical. (b) Time-domain EMT simulation validation for the same case.

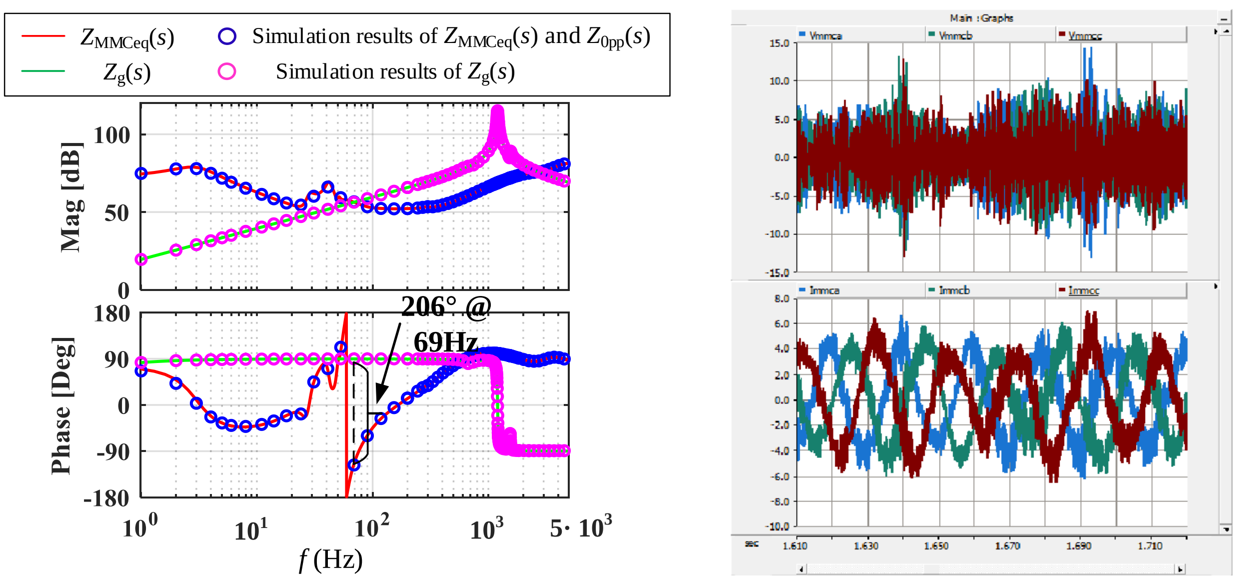
Figures 4.3 and 4.4, present the Bode diagrams ZMMCeq(s) and Zg (s) in the case that the MMC-HVDC converter is connected to a different connection point. For the purpose of this example, a weak connection point with inductive characteristics is selected. The MMC-HVDC system is operated with the APL and RPL in the example of Figure 4.3, and with DVC and AVC in the example of Figure 4.4. It can be seen that ZMMCeq(s) intersects Zg (s) in the near sub synchronous frequency range (at 68Hz), and the phase difference at the impedance magnitude intersection point are larger than 180° (189° in Figure .4.3 (a) and 206° in Figure .4.4 (a)). Moreover, there is a second intersection point which is at 2.5 kHz with phase angle difference of 180°, which justifies the high frequency oscillation seen in the time domain simulation of figure 4.4b. Therefore, the system should be unstable in both scenarios, which are also verified by the time domain EMT simulation results. The presence of resonance around 2.5 kHz in this example justifies the need for some cases to extend control interaction studies up to 9 kHz (including the accuracy of EMT grid and HVDC system model).

These examples aim to present a typical way that the stability of PED is assessed in wide frequency range using an impedance based method verified by EMT simulations. The impedance profiles could be calculated numerically using detailed EMT models or they could be provided by the HVDC manufacturers using analytical approaches for the calculation. Moreover, the impedance based assessment could be applied for various grid configurations, as a pre-assessment or pre-scanning of the cases that need to be assessed with detailed EMT studies.



(a) (b)

Figure 4-3. MMC with the active power control loop and reactive power control loop connected to a weak grid. The system is unstable for this case. (a) Bode diagram of the analytical and measurement results. (b) Time-domain EMT simulation validation for the same case.



(a) (b)

Figure 4-4. MMC-HVDC with the DVC and AVC connected to the weak grid. The system is unstable. (a) Bode diagram of the analytical and measurement results. (b) Time-domain EMT simulation validation for the same case.

5. SIMULATION MODEL REQUIREMENTS FOR INTERACTION STUDIES

5.1 Existing requirements in CNCs with regard to simulation models

The following articles of the Connection Network Codes define the existing modelling requirements:

- **NC RfG Article 15**: General requirements for type C power-generating models (Paragraph (6)(c)) and Title IV describing the compliance provisions for RSOs and PGMs
- **DCC Article 21:** Simulation models (Paragraphs 3 and 4)
- **NC HVDC: Articles 51**, Operation of HVDC systems (Paragraph 2), **Article 52** Parameters and settings, **Article 53** Fault recording and monitoring, **Article 54** Simulation models (Paragraph 1), **Article 70** Tasks of the relevant system operator (Paragraphs 1 and 2).

The national implementation[7] of connection network codes (as monitored per year 2020) is presented in Table 3.

Table 3: Information (Based on 2020 data) of the implementation of RfG Article 15(6)(c)(iii) and DCC Article 21(3)[8]

	AL	AT	BA	BE	BG	CH	CY	CZ	DE	DK	EE	ES	FI	FR	GB	GR	HR	HU
RfG / Article 15(6)(c)(iii)		√		√					√	√	√	√	√	√	√	√		√
DCC / Article 21(3)		√						√	√	√		√	√		√	√	√	√

	IE	NI	IS	IT	LT	LU	LV	ME	MK	NL	NO	PL	PT	RO	RS	SE	SI	SK
RfG / Article 15(6)(c)(iii)	√	√								√		√	√	√				√
DCC / Article 21(3)	√	√		√		√				√[9]	√	√	√	√			√	

5.2 Other examples for model requirements up to date

Table 4 provides information about available EMT modelling guidelines for PPM and SPGMs as requested from several TSOs around the world. It is important to highlight that in several connection codes there is a general clause that says the following: "User(s) with EU Grid Supply Points may be required to provide electromagnetic transient simulations in relation to those EU Grid Supply Points at TSO's reasonable request." By including this sentence in the grid codes, the TSOs have the right to request the EMT model for a particular project, even if they do not

[7] https://www.entsoe.eu/active-library/codes/cnc/

[8] The member state, which is not marked, did not implement the requirements or did not deliver information of the requirements implementation in the monitoring session 2020.

[9] Due to the varying nature of software versions, the Netherlands has chosen to not include these requirements in the grid code, but publish them in the compliance verifications requirements of the network operators.

publish EMT modelling guidelines as other TSOs overseas do. Table 4 details the high-level requirements for the EMT modelling of PPM and SPGMs at AEMO, Energinet, ERCOT and RTE. It is important to highlight that the EMT model must represent all components, control systems and protection systems relevant for EMT analyses.

Table 4: Available EMT modelling guidelines for PPM and SPGMs from different TSOs around the world.

	AEMO	Energinet	ERCOT	German Technical Connection Rules	National Grid	Dutch Network Code	French Grid Code
EMT Modelling guideline	**Yes**	**Yes**	**Yes**	**No**	**No**	**No**	**Yes**

Table 5: EMT model requirements for PPM and SPGMs at AEMO, Energinet and ERCOT

	AEMO	Energinet	ERCOT	RTE
Submit model	All	PPM Type D	Modelling generators in weak grids and subsynchronous resonance	PPM Type C and D
Software	PSCAD 4.6 and above	PSCAD version used by TSO	PSCAD 4.5.3. or higher	EMTP or other EMT tool + DLL of control and protection system
Open / encrypted	Precompiled and encrypted parts	Precompiled and encrypted parts	Precompiled and encrypted parts	Control and protection system encrypted
Compiler Intel	Fortran 12 and higher	Intel Fortran 12 and higher	Intel Fortran 9 and 12	Not mentioned
Time Step	1 µs	Not mentioned	10 µs – 20 µs	Not mentioned
List of parameters	Yes	Yes	Yes	Yes
Block diagrams	Yes	Yes	Yes	Yes
Manual	Yes	Yes	Yes	Yes
Validation	PSCAD model with PSSE results	PSCAD model shall be validated	PSCAD model with measurements	EMTP or other EMT tool + DLL and onsite measurement or real-time simulation
Snapshot function	Yes	Yes	Yes	Not requested
Initialisation	In less than 3 seconds	In less than 3 seconds	In less than 5 seconds	Not requested

5.3 Model requirements for HVDC systems

RMS modelling requirements

For the purpose of electromechanical (RMS) simulation models which are used in network studies, the relevant TSO shall have the right to specify the modelling requirements. For the national implementation of the NC HVDC (and specifically of the Article 54) without prejudice to the Member State's rights to introduce additional requirements, the RMS simulation models of the HVDC system shall:

(a) be valid for the specified operating range and all control modes of the HVDC system;
(b) include representation of HVDC converter unit, HVDC lines/cables and control systems that influence the dynamic behaviour of the HVDC transmission system in the specified time frame;
(c) include the relevant protection function models as agreed between the relevant TSO and the HVDC system owner;
(d) be open source generic model for RMS simulations delivered for cross-border network stability studies. Open source generic RMS models require simplified converter control representation due to intellectual property rights. This could impact the model performance and model accuracy.
(e) In the case that encrypted detailed RMS models are accepted by the relevant TSO, the relevant TSO together with the HVDC system owner shall specify the requirements of the model encryption (for example use of source code, the model structure and the signal interfaces to be observable in the network studies) according to national regulations. The agreement should be made on project specific basis according to national regulations;
(f) The above listed simulation model requirements and information must not violate manufacture’s intellectual property;

EMT modelling requirements

For the purpose of electromagnetic transient simulations (EMT), the relevant TSO shall have the right to specify the simulation model requirements. For the national implementation of the NC HVDC (and specifically the Article 54) without prejudice to the Member State's rights to introduce additional requirements, the EMT simulation models of the HVDC system shall:

(a) be valid at least in the frequency range 0.2Hz to 2500 Hz for relevant studies;
(b) be valid for the specified operating range and all operation modes of the HVDC system in both the positive and in the negative phase sequence;
(c) be able to reproduce the detailed transient response of the HVDC system and its control blocks (including synchronisation) during balanced and unbalanced AC network faults in the valid frequency range;
(d) include an accurate representation of the semiconductor valves (switching patterns if required), the frequency dependency of the HVDC system lines and sufficient representation of communication systems instruments;
(e) represent transformers models (including saturation), resistors, filter, breaker, AC and DC arrester in the valid frequency range;

(f) include all the control and protection models as agreed between the relevant TSO and the HVDC system owner (under/overvoltage, overcurrent, chopper and frequency sensitive control functions);

(g) be capable to be used for the numerical calculation of the frequency dependent impedance of the HVDC converter station (magnitude and phase angle of the Z(f)) in the frequency range that the model is valid;

(h) In the case that encrypted EMT models are accepted by the relevant TSO, the relevant TSO together with the HVDC system owner shall specify the level of the model encryption (for example the model structure and the signal interfaces to be observable in the network studies); The agreement should be made on project specific basis according to national regulations; In case public documents or standards are available, it should be utilised;

(j) The above listed simulation model requirements and information must not violate manufacture's intellectual property;

Frequency dependent impedance model requirements

For the purpose of the risk assessment of the resonance stability of the HVDC converter station, the TSO shall have the right to request from the HVDC system owner the frequency dependent impedance model of the HVDC converter station at the AC side. In that case, without prejudice to the Member State's rights to introduce additional requirements, the following requirements shall apply:

(a) The impedance model of the HVDC converter station shall be requested in the frequency range 5Hz till 2500 Hz; The TSO has the right to extend the required applicability of the model up to 9 000 Hz;

(b) The relevant TSO together with the HVDC owner shall agree if the calculation of the impedance model of the HVDC converter station will be either numerically (using the EMT model) or analytically (using transfer function) or both; In the case of numerical calculation, the TSO shall specify the frequency steps where the impedance is provided. The number of different frequency step shall be reasonably limited to provide acceptable results and at the same time limit the simulation effort and data storage to an acceptable amount. In both cases, the impedance model should have a sufficient accuracy in a defined range around its operating point;

(c) The relevant TSO shall have the right to request the impedance model of the HVDC station through the specified operating range and all control modes of operation;

(d) The impedance model of the HVDC converter station shall be provided for both the positive and for the negative phase sequence;

(e) The HVDC system owner shall take into account the influence of the whole HVDC unit control and measurement system as well as other parts of the HVDC unit which influences the output impedance in the specified frequency range; If coupling between different frequencies exists in a given frequency range, this should be sufficiently represented;

(f) The HVDC system owner shall specify and justify simplifications made in the calculation of the impedance model;

5.4 Model requirements for SPGMs

RMS modelling requirements in large network studies

This section provides RMS model requirements for SPGMs to be used in network dynamic simulations. The table attached to this report as Annex I is based on the European Network Codes and Guidelines and shows all the required simulations for SPGMs together with proposals for the details of the necessary procedures.

In that frame, without prejudice to the Member State's rights to introduce additional requirements, it is recommended for the national implementation of the NC RfG Article 15 that the RMS simulation models of SPGMs should include the following points:

a) Dynamic RMS model of AVR (Automatic Voltage Regulation): The model shall simulate the AVR response including the static or rotating excitation system. In line with IEEE 421.5, it shall be fit for dynamic simulations of steps, short circuits and oscillations up to 3 Hz and grid frequency deviations within +/- 5 % from the rated frequency. The model shall also contain internal limiters (e.g. V/Hz, over-/under-excitation, stator current etc.). A reduced order model in accordance with IEEE Std. 421.5 is preferred.
b) Dynamic RMS model of PSS (Power System Stabilizer): The model shall simulate the PSS and be fit for dynamic simulations of steps, short circuits and oscillations up to 3 Hz and grid frequency deviations within +/- 5 % from the rated frequency. The model shall also contain internal limiters and automatic (de-) activating equipment (e.g. only if active power > x p.u. will the PSS be activated. with a time delay and/or hysteresis). A reduced order model in accordance with IEEE Std. 421.5 is preferred.
c) Dynamic RMS model of turbine-governor: The model shall simulate the turbine-governor including the actuators and valves with their specific curves. It shall be fit for small-signal stability simulations as well as for rotor angle transient stability simulations and include the initial response of the turbine-governor in the seconds following a grid disturbance or islanding (e.g. the concept of fast-valving) and be fit for grid frequency deviations within +/- 5 % from the rated frequency. The model shall also contain internal limiters, dead bands and where applicable automatic switch-over between power control and speed control. A model in accordance with IEEE[10] or CIGRE[11] is preferred.
d) Two-axis model of alternator: The two-axis model of the alternator shall be based on the standard Park's model. This model has been used for several decades and has been demonstrated to be fit for stability and dynamic grid simulations. For enhanced performance in capturing both the transient and steady-state field current response of

[10] IEEE Task Force on Turbine-Governor Modeling, "Dynamic Models for Turbine-Governors in Power System Studies," *IEEE Technical Report PES TR1*, Jan. 2013.
[11] CIGRE Task Force C4.02.25, "Modeling of Gas Turbines and Steam Turbines in Combined Cycle Power Plants," *CIGRE Technical Brochure 238*, Dec. 2003.

synchronous generators some recent generator model development have been recommended[12] by the Western Electricity Coordinating Council (WECC).

EMT modelling requirements for near-synchronous and sub-synchronous torsional interaction studies

For the purpose of electromagnetic transient (EMT) simulations (especially for sub-synchronous and near synchronous torsional interactions), without prejudice to the Member State's rights to introduce additional requirements, the SPGM models (type C and D) should contain the following:

a) be valid in the agreed frequency range;
b) be valid for the specified operating range and all operation modes of the SPGM;
c) be fit for EMT simulations of active/reactive power and voltage steps, short circuits and grid frequency deviations within +/- 5 % from the rated frequency;
d) should represent the AVR control module in the given freqeuncy range including the static or rotating excitation system. As stated in the IEEE Std. 421.5[13], the models are reduced order models, valid for oscillation frequencies up to 3 Hz and these models would not normally be adequate for use in studies of sub-synchronous resonance or other shaft torsional interaction behaviour. Based on this, the adequacy of an IEEE model for AVR should be evaluated and accepted before use in studies of sub-synchronous resonance or other shaft torsional interaction behaviour.
e) should represent the PSS control module in the given frequency range and be fit for EMT simulations of steps, short circuits and grid frequency deviations within +/- 5 % from the rated frequency. As stated in the IEEE Std. 421.5[13], these models are reduced order models, valid for oscillation frequencies up to 3 Hz and these models would not normally be adequate for use in studies of sub-synchronous resonance or other shaft torsional interaction behaviour. Based on this, the adequacy of an IEEE model for PSS should be evaluated and accepted before use in studies of sub-synchronous resonance or other shaft torsional interaction behaviour.
f) should represent the mass-spring model of turbine and alternator shaft. The mass-spring model of the turbine, alternator and where applicable the exciter shall correctly simulate all eigen-frequencies and associated eigen-modes up to the agreed frequency. The accuracy of the three lowest eigen-frequencies should be better than +/- 0.5 Hz. The accuracy of the fourth eigen-frequency and higher should be better than +/- 1.0 Hz.
g) Where available, the mechanical damping of the shaft should be part of the model. If not available, the mechanical damping will be assumed a conservative value close to zero to be delivered by the owner of the SPGM;
h) include a dynamic model of turbine-governor;
i) In the case that encrypted EMT models of AVR or PSS are accepted by the relevant TSO or where applicable RSO, the relevant TSO or where applicable RSO together with the

---

[12] P. Pourbeik, B. Agrawal, S. Patterson, R. Rhinier, "Modeling of synchronous generators in power system studies," *CIGRE Science & Engineering, No. 6*, October 2016.

13 IEEE Std. 421.5 "IEEE Recommended Practice for Excitation System Models for Power System Stability Studies,", IEEE May 2016.

PGM owner should specify the model encryption (the model structure and the signal interfaces to be observable in the SSTI studies);

j) The above listed simulation model requirements and information must not violate manufactures intellectual property;

It is current VGB position that the frequency range should be at least 0.2Hz to 200 Hz.

However, it is the position of the EG that this frequency range needs to be established by future research activities.

In a future power electronic dominated grid where grid conditions change, concerns may arise for performing accurate torsional interaction studies. The EMT models for the machine controllers in the agreed frequency range (AVR and PSS if it is applicable) may require more effort and time from the SPGM owner and OEM. Especially the lack of such models for existing SPGMs might lead to delays and risks for a new project. Up to date AVR and PSS models for higher frequency ranges are not yet always available in commercial tools or provided for EMT torsional interaction studies. The use of models, not adequate for the frequency range of torsional interactions, may lead to false conclusions.

It is therefore recommended by the EG to further investigate and study the impact of the application of these RMS based standard AVR and PSS models on the SSTI risk assessment and mitigation measures, and other torsional interactions. Especially in comparison to extended frequency range models as described in this section 5.4.

5.5 Model requirements for PPMs

RMS modelling requirements

For the purpose of electromechanical dynamic simulations (RMS simulation studies) the relevant system operator or the relevant TSO shall have the right to specify the model requirements. For the national implementation of the NC RfG Article 15 without prejudice to the Member State's rights to introduce additional requirements, the RMS simulation models of PPMs shall include the following points:

a) be valid for the specified operating range and all control modes of the power-generating facility;
b) include a proper representation of the converter modules and its control systems (including the synchronization module) that influence the dynamic behaviour of the power-generating module in the specified time frame;
c) be open source/standard generic model for cross border network stability studies;
d) In the case that encrypted detailed RMS models are accepted by the relevant TSO, the relevant TSO shall specify the requirements of the model encryption according to national regulations (for example use of source code, the model structure and the signal interfaces to be observable in the network studies);
e) Include the relevant protection function models;

f) The above listed simulation model requirements and information must not violate manufactures intellectual property;

EMT modelling requirements

For the purpose of time domain electromagnetic transient (EMT) simulations the relevant system operator or the relevant TSO shall have the right to specify the model requirements. In that frame, it is recommended that for the national implementation of the NC RfG Article 15, without prejudice to the Member State's rights to introduce additional requirements, the EMT simulation models of PPMs shall include the following points:

a) be valid in the frequency range 0.2 Hz – 2500 Hz for relevant interaction studies; The validity of the PPM model shall be ensured for the given frequency range at the connection point;
b) be valid for specified operating range and control modes of the PPM in both the positive and in the negative phase sequence;
c) reproduce the detailed response of the power-generating module and its control blocks during balanced and unbalanced AC network faults in the valid frequency range;
d) include the power plant level control and the power plant relevant functionalities if applicable;
e) include the frequency dependence of the lines and/or cables in the power-generating facility;
f) represent the power park module (PPM) transformers models including saturation, resistors, filter, breaker and AC arrester in the valid frequency range;
g) include all the relevant protection function models for the relevant interaction studies;
h) be capable to be used for the numerical calculation of the frequency dependent impedance of the PPM at the connection point (impedance amplitude and impedance phase angle) in the frequency range that the model is valid);
i) In the case that encrypted detailed EMT models are accepted by the relevant system operator or the relevant TSO, the relevant system operator or the relevant TSO shall have the right to specify the model encryption based on national regulations (for example the model structure and the signal interfaces to be observable in the network studies);
j) The above listed simulation model requirements and information must not violate manufacture’s intellectual property;

Frequency dependent impedance modelling requirements

For the purpose of frequency domain simulation for the risk assessment of the resonance stability of the power plant module, the relevant system operator or the relevant TSO shall have the right to request from the power-generating facility owner the frequency dependent impedance model of the power-generating facility at the point of interconnection to the grid. In that case, without prejudice to the Member State's rights to introduce additional requirements, the following requirements shall apply:

a) The impedance model of the power-generating facility shall be requested at least in the range 5.0 Hz - 2500Hz; As an additional requirement, the relevant system operator can extend the required applicability of the model to up to 9 000 Hz;

b) The relevant system operator or the relevant TSO shall have the right to request the calculation of the impedance model of the power-generating facility either numerically (using the EMT model) or analytically (using transfer function);
c) The relevant system operator or the relevant TSO shall have the right to request the impedance profile of the power-generating facility at the connection point through the whole operating range and control modes of operation;
d) The impedance model of the power-generating facility shall be provided for both the positive and for the negative phase sequence;
e) The power-generating facility owner shall take into account the influence of the power-generating module control and measurement system as other parts of the power-generating module which influences the output impedance in the specified frequency range;
f) The power-generating facility owner shall specify and justify simplifications made in the calculation of the impedance model;

For the purpose of the steady-state harmonic component examinations of the PPMs, the TSO shall have the right to request from the HVDC system owner the harmonic component emissions in the positive and in the negative sequence considering a set of frequency dependent impedances of the grid connection point.

5.6 Data and models exchange

In case models and data are provided to any party (e.g. a manufacturer) with the purpose to carry out interaction studies, the provider of the model shall ensure that:

a) The models are validated and comply with the requirements stated in this section for the relevant study purpose. The receiving party of the model is not obliged to verify again compliance to the requirements and validity of the model.

b) In case of encrypted models, they shall be provided in a pre-tested and executable (running case) example file for the agreed simulation tool.

c) If models can´t be provided in the relevant simulation tool and need to be transferred to another simulation tool, supporting documentation is required. This can be in form of functional block diagrams or other form which allow a straight-forward implementation.

d) It is acknowledged that the provision of models and information shall not violate manufacturer intellectual property.

5.7 Further information for model encryption

Today most TSO or where applicable RSOs require the models in the used software specific programming language (Fortran, Dsl etc.). This results in very high development and maintenance effort on the manufacturer’s side. Target shall be to use unified simulation models which fulfil the needs of the TSOs or where applicable the RSOs regarding usability, functionalities and observable signals, but also allow an efficient procedure regarding model development and model maintenance by the manufacturers. Therefore, the target is to use software independent models, to allow the same code base in all software environments. This can be done by DLL based models which can be called in software specific model interfaces. In case that the TSO or RSO needs access to the source code, the DLL code may also be delivered as open source code (C-Code etc.), without violating manufacturers' intellectual property. At the moment, there are only a few experiences how to implement software independent models on RSO side.

This EG recommends to develop forward this topic in a following working group, set up by the European Commission, ENTSO-E, WindEurope and other stakeholders as an outcome of this Expert Group, to define interfaces and interface descriptions. This future working group shall develop an agreed procedure for using software independent models while protecting manufacturers' intellectual property. The working group shall also test the agreed procedure in an example study.

6. VALIDATION OF THE SIMULATION MODELS

6.1. Background

Prior to going into details about methodologies and the validation process, a common understanding of model verification and validation needs to be established based on the references[14], [15]and [16].

- Validation is the process of determining the degree to which a simulation model and its associated data are an accurate representation of the real world from the perspective of the intended uses of the model.
- Verification is the process of determining that a model implementation and its associated data accurately represent the conceptual description and specifications.
- Accepted Models: Models provided with the description of what the model or simulation will represent, the assumptions limiting those representations, and other capabilities needed to satisfy the user's requirements. They could also be certified models, but this is not a prerequisite.
- Certification: The official certification that a model, simulation, or federation of models and simulations and its associated data are acceptable for use for a specific purpose.

Additionally, the demonstration of compliance monitoring of equipment with regulations, specifications, and requirements is the core definition of verification. Compliance verification of equipment can be done by:

- testing of the real equipment in the system or
- simulations with validated / certified models or
- testing of a combination of real equipment and validated / certified model(s) of other equipment or parts of the system.

[14] https://en.wikipedia.org/wiki/Software_verification_and_validation

[15] https://www.easterbrook.ca/steve/2010/11/the-difference-between-verification-and-validation/#:~:text=Validation%20is%20the%20process%20of,the%20software%20meets%20the%20specification

[16] https://www.mitre.org/publications/systems-engineering-guide/se-lifecycle-building-blocks/other-se-lifecycle-building-blocks-articles/verification-and-validation-of-simulation-models

Please note that in the following sections for simplification and better readability the wording "validation" is mainly used. However, it comprises in many cases verification and validation.

As elaborated in the previous sections, a simulation model is only a representation of the reality. It shall be valid for the defined phenomena and study purposes. Therefore, the accuracy of the model under extreme conditions (for example high frequencies, large disturbances, non-linearities, etc.) may be of importance or may not for the specific purpose. To provide efficient models (considering both the model development effort and simulation efficiency), simplifications are applied. It is important to describe the application purpose and the limits of simulation models in their documentation, for example in the validation report.

6.2. Methodologies / process followed for model validation

To provide a solid overview of the possible methodologies and processes, the following subsections provide examples for model validation of different systems such as wind turbine generators (WTG), HVDC, SPGMs, and PPMs. If possible, general recommendations and conclusions are developed based on these examples.

6.2.1 Model Validation for HVDC

The compliance with the technical specifications, connection network codes or other stakeholders requirements are investigated, evaluated and demonstrated in the design and engineering phase for a new or refurbished HVDC system. Figure 6-1 presents the design and engineering phase as well as the test phases for the control and protection (C&P) of HVDC systems.

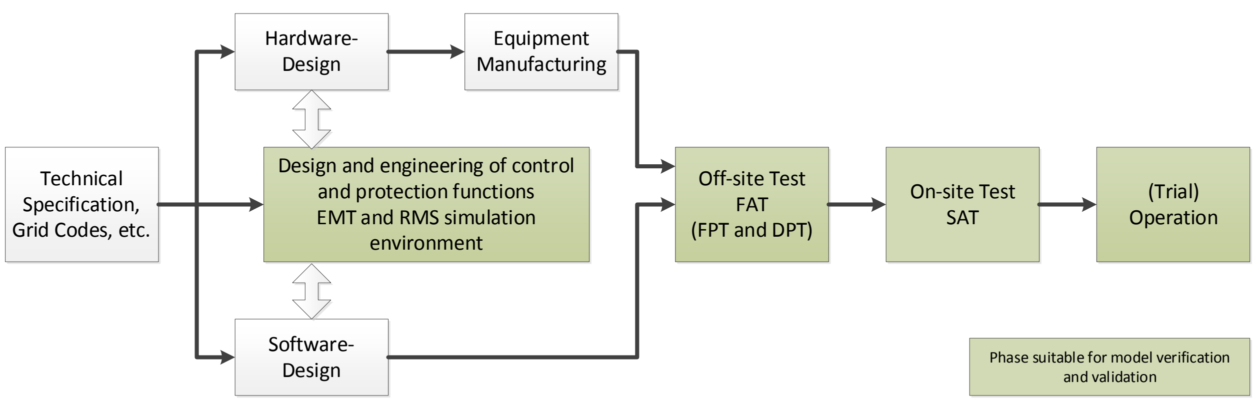


Figure 6-1: HVDC C&P development, design and testing phases.

The software design is interlinked with the design and engineering of the control and protection functions in the EMT and RMS simulation environments. In the course of the study phase, models with verified and validated electrical components and control & protection system representation are developed. The compliance of the software functions and HVDC system behaviour is demonstrated in:

- Studies (such as RMS Stability Study, EMT Dynamic Performance Study, EMT Interaction Study)

- Factory acceptance test (FAT) (which may be carried out with real-time and/or non-real-time simulation environment)
- On-site tests during the commissioning phase.

The on-site tests and trial operation, as well as commercial operation, also provide information for the model validation. This is also related to NC HVDC Articles 54(4) and 54(5). Finally, all these individual steps contribute to the development and improvement of verified and validated simulation models. As it can be seen from the above process, different simulation models for individual tools and simulation environments are used. Figure 6-2 illustrates the possible verification and validation steps of the different models and simulation environments.

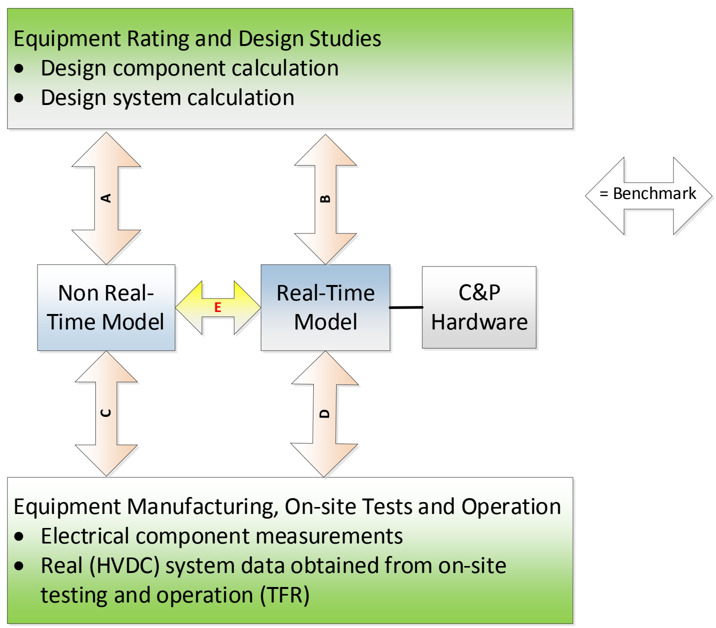


Figure 6-2: Model Verification and Validation in HVDC projects – Overview.

The real-time and the non-real time (offline) simulation models can be validated by:

- Design calculations obtained during the equipment rating and design study phases
- Metrics of electrical components or the complete system. This data is obtained during equipment manufacturing, on-site testing phase or operation of the system.

As a minimum, the following aspects should be considered:

- The most valuable validation is a comparison of models with measured data (path C and D)
- If measured data are not available (for example during the engineering phase of a new project), the models can be initially validated with design calculations and theoretical data (path A or B)
- A validated and verified model can be used as a benchmark for other models. This applies for all kind of combinations, for example non real-time EMT with RMS models or

non real-time with real-time models. As a prerequisite, at least one of the paths A, B, C or D is done for the base model.

- Measured data can be also used to verify design calculations

During the Factory Acceptance Test (FAT) different test groups are performed on a real-time simulator environment, as exemplarily listed below.

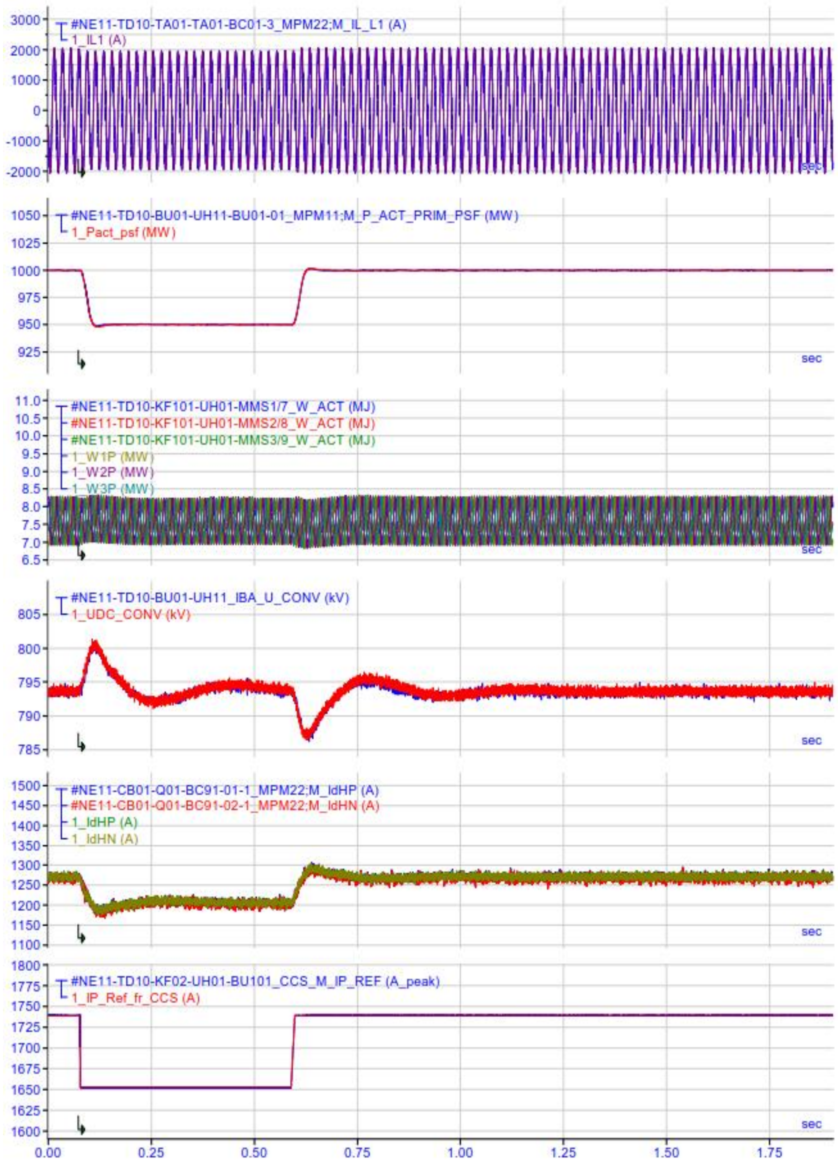
- Steady-state performance
- Trip tests (e.g. emergency-switch off)
- Converter and transformer energization
- DC voltage control step response
- Active power control step response
- Reactive power control step response
- AC circuit current control step response
- Capacitor charge balancing controls
- AC fault performance
- DC fault performance
- Stability and modulations function tests

These test groups can be used to validate EMT and RMS type simulation models and the correct C&P system implementation. This is for example also shown in Figure 6-2. The evaluation of the results can be done with as:

- Qualitative approach (as used for the example)
- Quantitative approach (as for example proposed by AEMO[17])

The following Figure 6-3 presents an example for a qualitative model verification and validation approach. A FAT test result is compared with an EMT-tool simulation results.

[17] AEMO, “Power System Model Guidelines”. Available online: https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/System-Security-Market-Frameworks-Review/2018/Power_Systems_Model_Guidelines_PUBLISHED.pdf

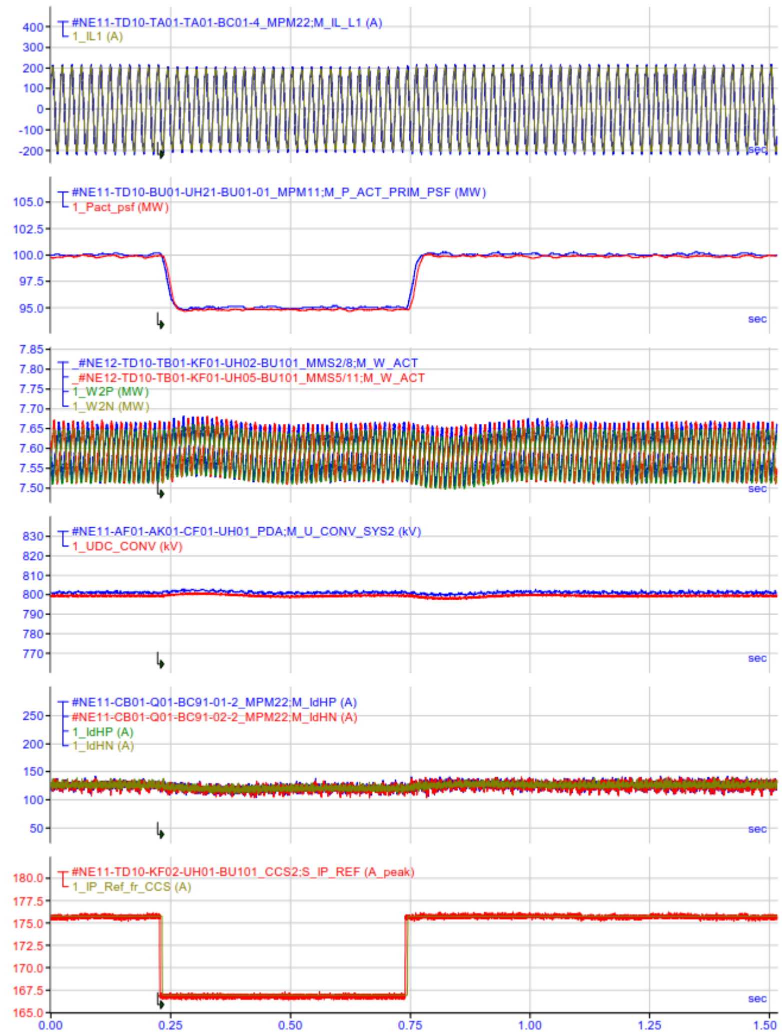


#... = TFR (transient fault recorder) from FAT (real-time simulator)

1... = Offline EMT Tool

Figure 6-3: Example for comparison of FAT real-time test case with non-real time EMT tool Model.

Figure 6-4 presents an example of an on-site test comparison with the EMT tool. It can be both used for model verification and validation.



#... = TFR (transient fault recorder) from on-site test

1... = Offline EMT Tool#

Figure 6-4: Comparison of on-site test case with non-real time EMT tool.

6.2.2 Model Validation for PPMs

This chapter describes validation procedures for each phenomenon to be investigated in interaction studies according to Table 2.

The following sections describe a validation procedure, which covers the bullet points from the different sub headers (blue line). In some cases, different models are suitable for different phenomena. In these cases, it is up to the PGM owner in accordance with the TSO/RSO to decide which model to provide (RMS/EMT etc).

Near steady state control

To fulfil the requirements for "near steady state (slow control)" the dynamic model has to represent all relevant control modes for the specific power plant. Examples of relevant controller are shown in the following list:

- Active power control (set point change)
  - Pitch dynamic (for wind)
  - Active power ramps etc.
- Power frequency control
- Reactive power control / voltage control
  - Converter dynamic
  - Set points
  - Reactive power characteristics (Q(U) etc.)
  - Reactive power/current limitation
  - Reactive / active power priorities

In general, the different control modes can be part of the power-generating module or the power plant controller. In case the functions are implemented in the power plant controller, the step response dynamic of the power-generating module has to be taken into account.

For the relevant control functions, at least one step response test is necessary for validation. The base for the validation can be:

- On-site tests
- Simulations with accepted models
- Tests from validated test benches

The choice of the testing method has to be justified by the manufacturer. The validation procedure for step response tests is explained in IEC 61400-27, chapter 6.4.5 (step response characteristics).

The RMS model is valid if the maximum deviation during the settling time (acc. IEC 61400-27) is not exceeding a maximum limit of 15% of the rated value of the control variable. The tolerance band for steady state conditions is 5% of the rated value of the control variable.

Higher deviations have to be explained in the validation report (for example bad wind or irradiation conditions during active power control tests). Further, the qualitative characteristic of the step response shall be correct. For the validation, onsite tests as well as tests from test bench are allowed as long as the test bench is valid for the specific control functionality. For frequency dependent tests, a simulated frequency can be used.

failure type	unit	value	limit
Active Power max steady state Error	%	0.4	5.0
Active Power max transient state Error	%	0.4	15.0
Reactive Power max steady state Error	%	0.89	5.0
Reactive Power max transient state Error	%	2.21	15.0

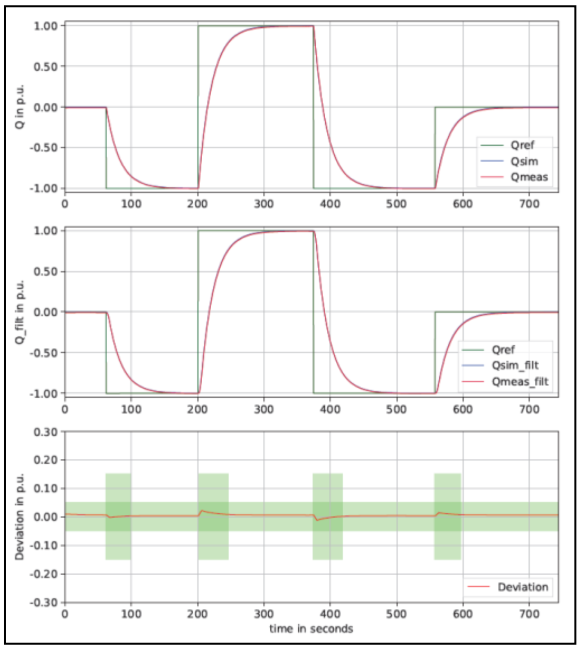


Figure 6-5: example validation graph for reactive power control.

Dynamic (fast controls)

To fulfil the requirements for “Dynamic (fast control)” the model has to represent the correct controller dynamic for interactions in a required frequency range. To show the correct controller dynamic the model reaction for different oscillations in grid voltage and frequency shall be validated. The base for the validation can be:

- On-site tests
- Simulations with accepted models
- Tests from validated test benches incl. HiL systems and Real time simulator

The choice of the testing method has to be justified by the manufacturer.

The validation should show the comparison between the real controller behaviour and the model behavior at different frequency and voltage oscillations.

Parameter	Value	Parameter	Value	Parameter	Value
f_{osc}	2.4 Hz	Δf_1	0.2 Hz	ΔU_0	2.5%
Δf_0	0.1 Hz	Δf_2	0.3 Hz	ΔU_1	5.0%

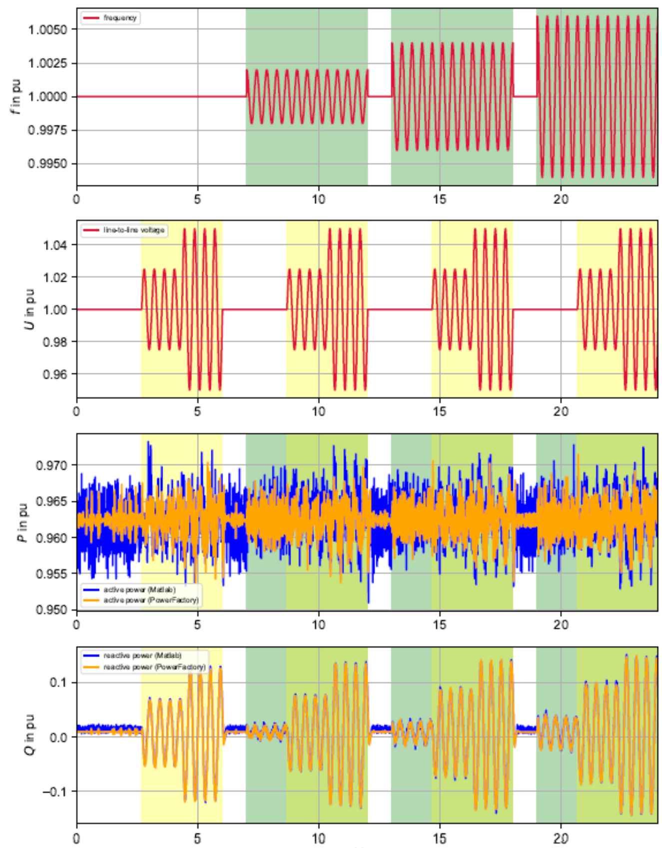


Figure 6-6: Example validation for "Dynamic (fast controls).

AC fault performance

To fulfil the requirements for "AC fault performance / transient stress" the model has to represent the correct behaviour for switching events and abrupt changes in voltage or phase angle. The existing FRT testing procedure, in general, covers these or similar phenomena. So, these points can be covered by FRT validation.

The FRT validation procedure is described in the IEC 61400-27 and in some TSOs grid codes. For the validation, on-site tests (FRT container) can be used as well as test bench tests. The test benches used have to be valid for FRT tests. Specifications for testing procedures are included in IEC 61400-21.

IEC 61400-27 specifies different fault categories for different time windows. For transient conditions, only the XME value is taken into account.

$$X_E = S_{Sim}(n) - X_{mea}(n)$$

$$X_{MXE} = \max(|X_E(1)|, |X_E(2)|, \ldots, |X_E(N)|$$

$$X_{ME} = \frac{\sum_{n=1}^{N} X_E(n)}{N}$$

$$X_{MAE} = \frac{\sum_{n=1}^{N} |X_E(n)|}{N}$$

The model is valid if the deviations are not exceeding the following limits for the different fault categories:

Typ 2 Generation Units		**Positive and zero sequence**											
		P			**Q**			**I_w**			**I_b**		
		MXE	**ME**	**MAE**	**MXE**	**ME**	**MAE**	**MXE**	**ME**	**MAE**	**MXE**	**ME**	**MAE**
	Pre	**0,150**	**±0,100**	**0,120**	**0,150**	**±0,100**	**0,120**	**0,150**	**±0,100**	**0,120**	**0,150**	**±0,100**	**0,120**
Permissible limit	**Fault**	**0,170**	**±0,150**	**0,170**	**0,170**	**±0,150**	**0,170**	**0,500**	**±0,300**	**0,400**	**0,170**	**±0,150**	**0,170**
	Post	**0,170**	**±0,150**	**0,170**	**0,170**	**±0,150**	**0,170**	**0,170**	**±0,150**	**0,170**	**0,170**	**±0,150**	**0,170**

For negative sequence, the limits can be multiplied by two.

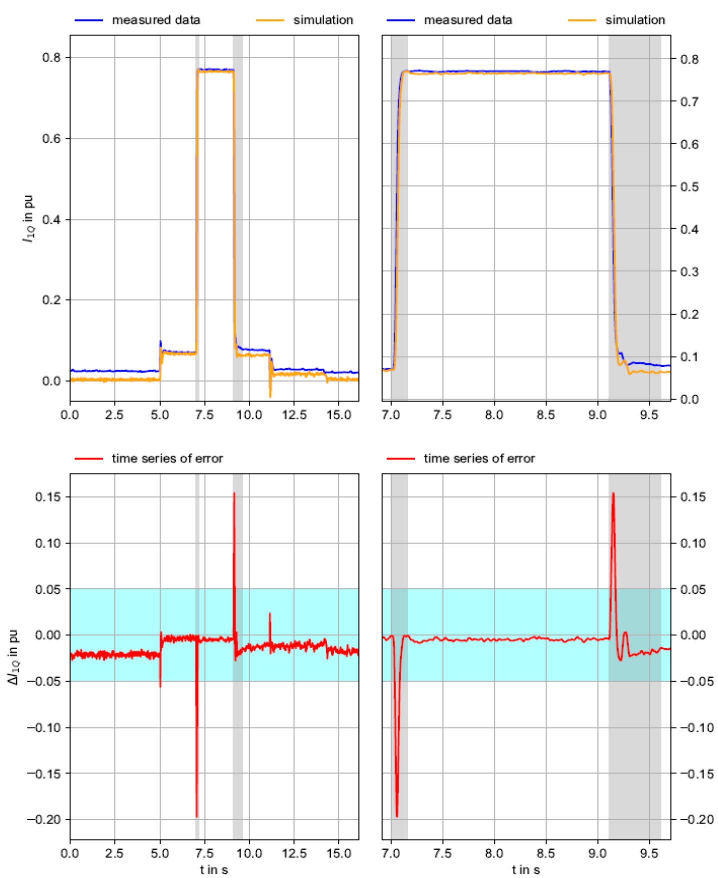


Figure 6-7: Example model validation acc. To IEC 61400-27.

Table 89: Test 153: positive sequence error calculation results in %

Window	Error	P_1 value	P_1 limit	Q_1 value	Q_1 limit	I_{1P} value	I_{1P} limit	I_{1Q} value	I_{1Q} limit
prefault	MXE	5.6	15.0	4.5	15.0	7.1	15.0	4.7	15.0
	ME	2.5	10.0	-3.4	10.0	2.9	10.0	-3.4	10.0
	MAE	2.5	12.0	3.4	12.0	2.9	12.0	3.4	12.0
fault	MXE	0.3	17.0	0.8	17.0	7.3	50.0	0.6	17.0
	ME	0.8	15.0	-0.9	15.0	6.8	30.0	-0.3	15.0
	MAE	0.3	17.0	0.8	17.0	6.8	40.0	0.4	17.0
postfault	MXE	4.2	17.0	8.1	17.0	4.0	17.0	8.7	17.0
	ME	1.9	15.0	-2.8	15.0	1.7	15.0	-2.8	15.0
	MAE	2.0	17.0	2.8	17.0	1.9	17.0	2.9	17.0

Table 89: Test 153: positive sequence error calculation results in %

Window	Error	P_1 value	P_1 limit	Q_1 value	Q_1 limit	I_{1P} value	I_{1P} limit	I_{1Q} value	I_{1Q} limit
prefault	MXE	4.8	15.0	9.2	15.0	6.0	15.0	9.5	15.0
	ME	-0.0	10.0	5.1	10.0	1.9	10.0	5.4	10.0
	MAE	0.8	12.0	5.1	12.0	2.3	12.0	5.4	12.0
fault	MXE	0.1	17.0	0.6	17.0	1.5	50.0	8.1	17.0
	ME	-0.0	15.0	0.7	15.0	-2.6	30.0	8.7	15.0
	MAE	0.1	17.0	0.5	17.0	1.4	40.0	7.9	17.0
postfault	MXE	2.7	17.0	15.1	17.0	5.5	17.0	15.1	17.0
	ME	0.3	15.0	-0.3	15.0	-0.0	15.0	-0.4	15.0
	MAE	1.0	17.0	1.3	17.0	1.2	17.0	1.4	17.0

be compared. The simulated and measured values as well as the deviation shall be shown graphically. Both values shall be superimposed on the same graphics to improve model validation. The graphics shall show the behaviour in steady state conditions as well as at the point of fault inception and clearance. For this validation, it is beneficial to use the playback method according to IEC 61400-27 to match the exact grid frequency. The tuning of the reactive and active power set point, to fit the exact phase angle is allowed.

The quality of the current dynamics shall be shown in the validation report. For the assessment, only the correct dynamic and general accuracy should be considered. Higher deviation between the instantaneous currents can occur especially at zero crossings but should be explained within the model validation report.

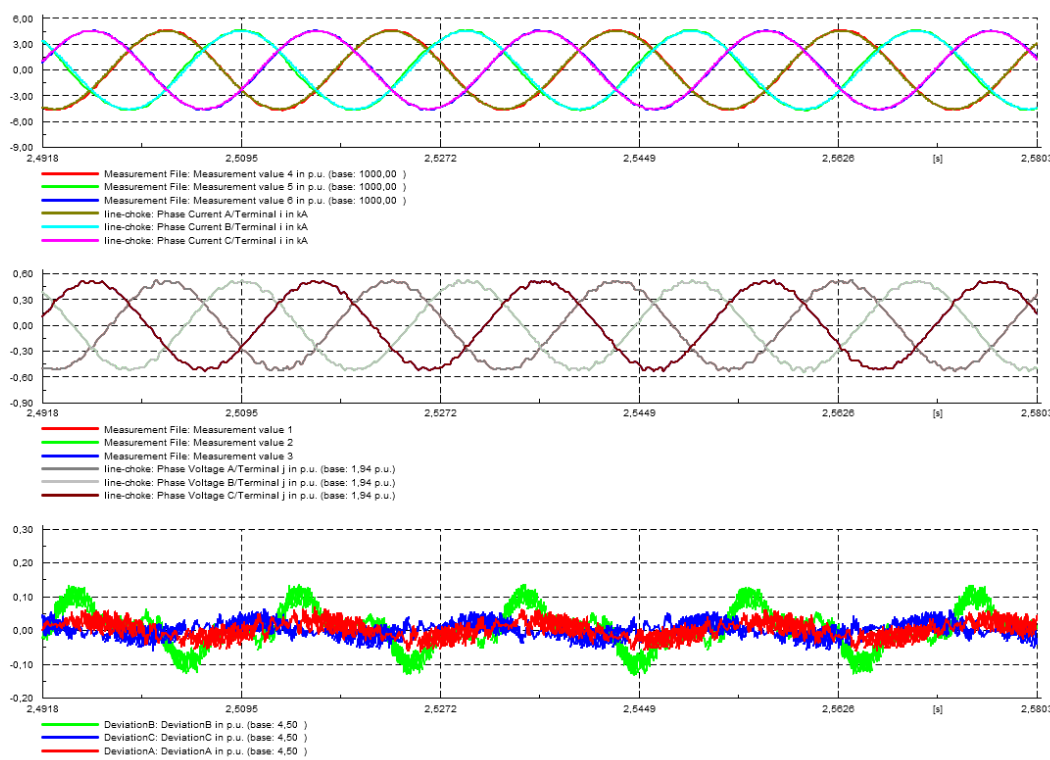


Figure 6-8: Example model validation for instantaneous values (steady state).

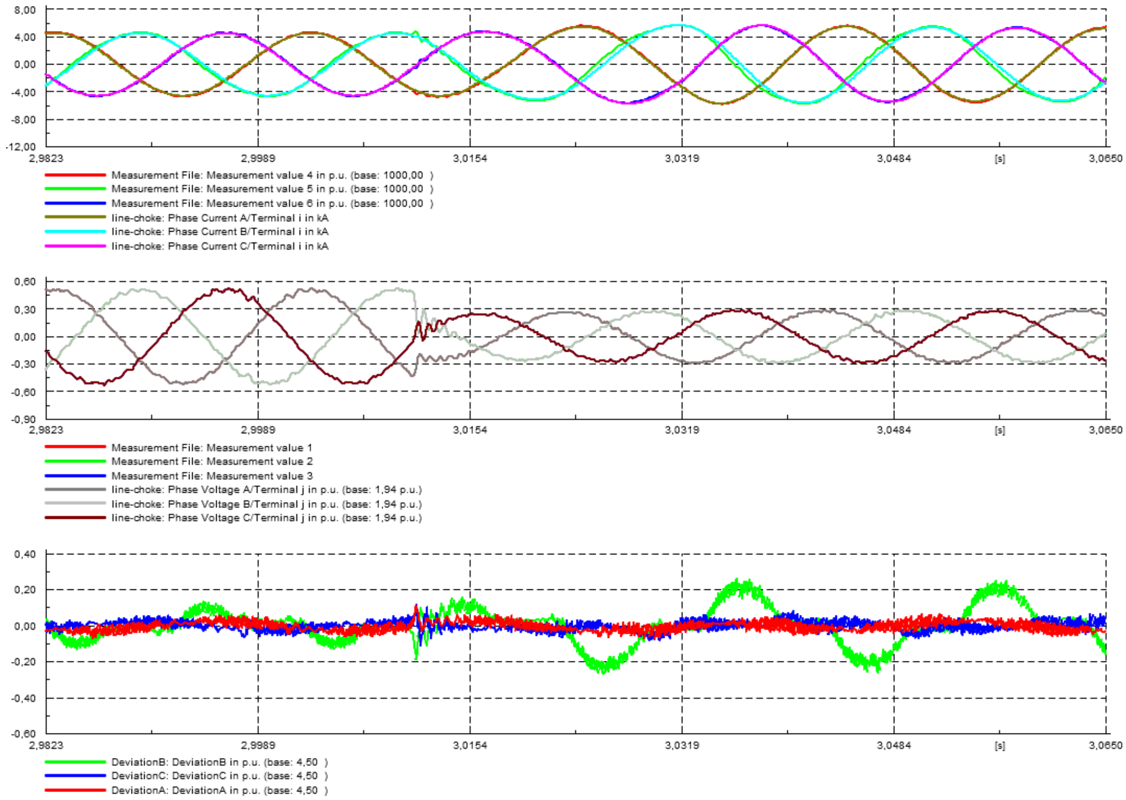


Figure 6-9: Example model validation for instantaneous values (fault inception).

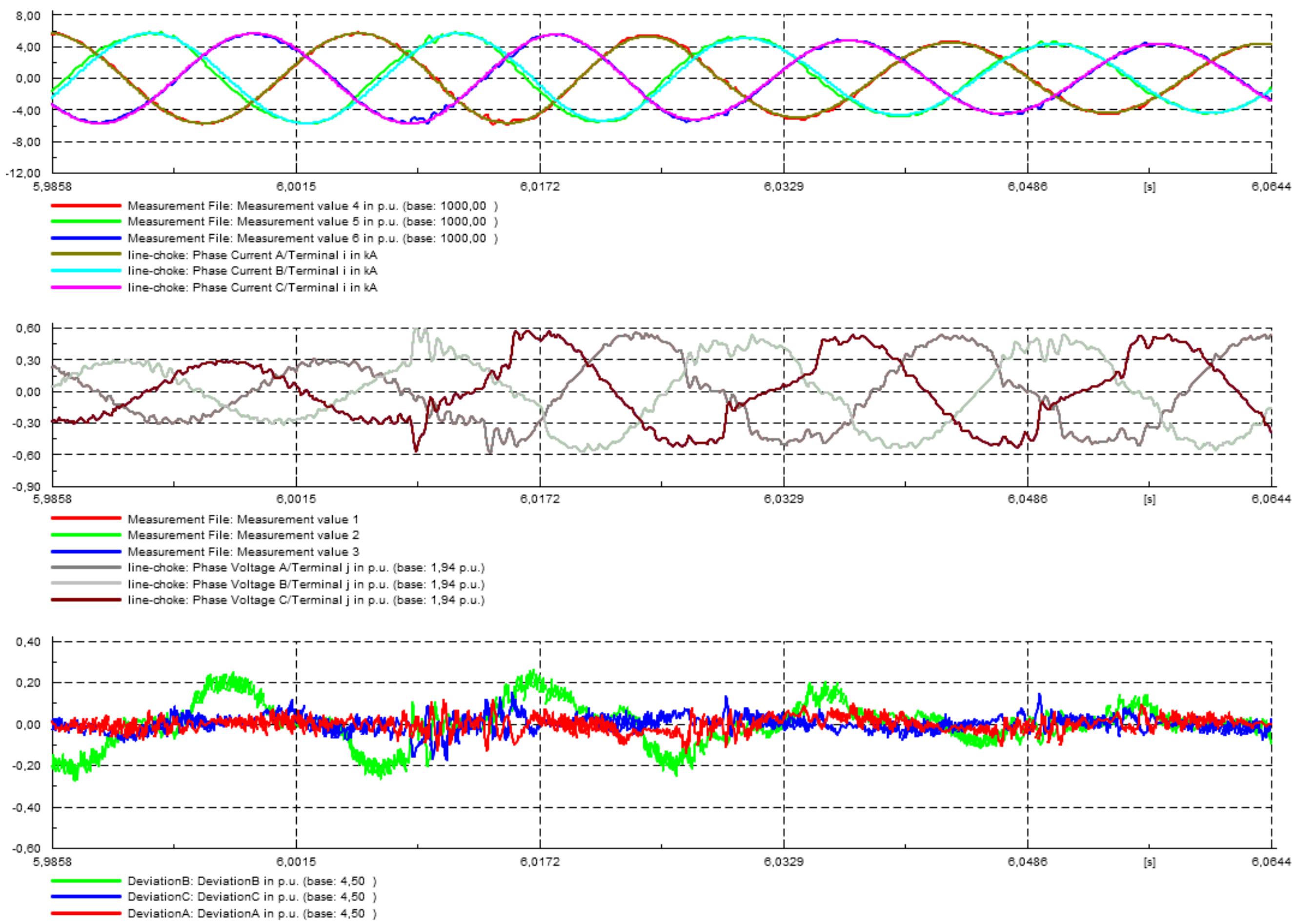


Figure 6-10: Example model validation for instantaneous values (fault clearance).

Transient stress

In addition to the tests of the previous chapter, the model behaviour after opening the MV circuit breaker shall be validated. Therefore, it is sufficient to compare the model behaviour with the behaviour from the onsite test.

Passive devices (incl. transformer saturation etc.) have to be parameterized accordingly to the devices datasheets. The responsible stakeholder shall provide the data. The validation of software specific library models is not part of the validation procedure.

Subsynchronous resonance

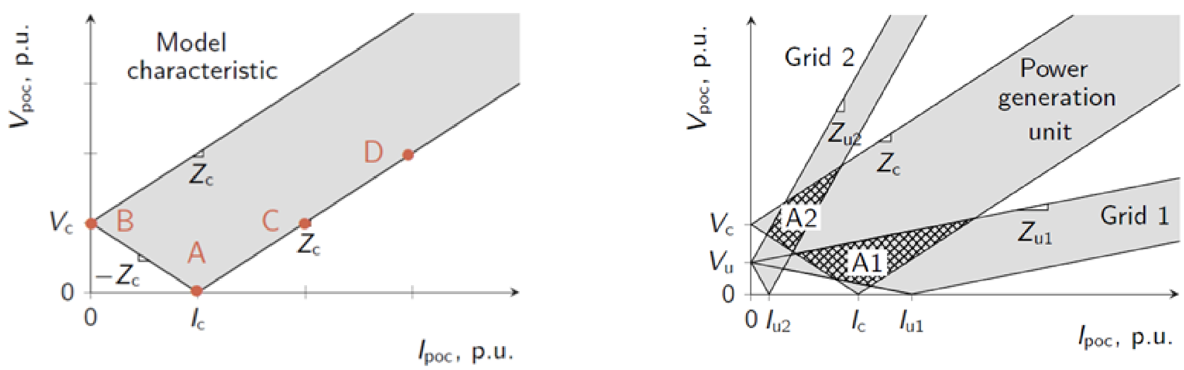
The tests from previous chapters (Dynamic (fast control) / AC fault performance) will also give validation evidence of the mechanical model of the wind turbine generator. For instance, FRT test cases will provide the means to compare the post fault mechanical oscillations and the active power damping.

In addition, it is critical to ensure the impedance profile is accurate in order to use an EMT model for sub-synchronous resonance. This can be done by comparing the impedance measurements against the EMT model impedance, or a baseline model impedance against the EMT model impedance.

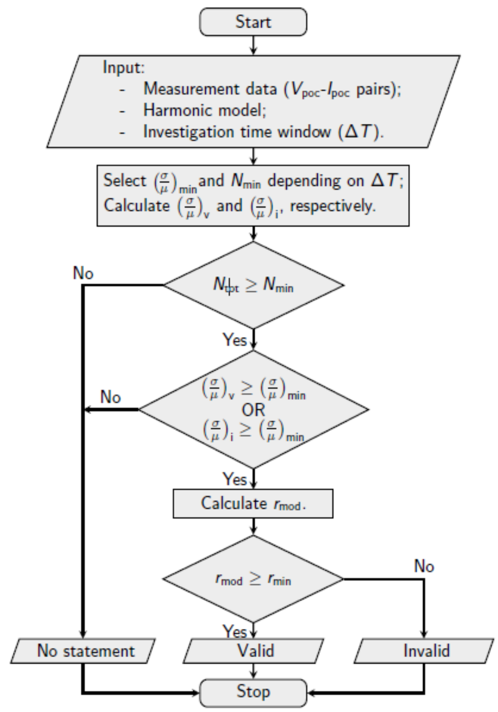
Harmonic emission and resonance

The validation of harmonic models is discussed in the IEC 61400-21/3. The validation is based on the comparison of measured harmonic voltage and current pairs (on site or in test lab) and the harmonic Norton Thévenin equivalent model.

If an EMT mode with the correct representation of the frequency depended impedance is required, the same procedure can be used. The comparison of the harmonic impedance of the EMT model shall be compared with the measured impedance or with the valid Norton Thévenin equivalent model.



(a) (b)



(c)

Figure 6-11: (a, b) polygonal model characteristic, (c) calculation process.

Model validity limits of the model

The model developer shall mention the models validity limits in the model documentation. Validity limits can be:

- Limitations for weak grid conditions: under some conditions like weak grid conditions, the validation procedure above may require an additional monitoring of internal control loops. In general, a weak grid model can be validated in the same way as mentioned above. The stability of all relevant control loops has to be monitored during the validation process.
- Limitations in frequency ranges: The manufacturer may use different models for different project requirements; eg the validity of the harmonic impedance may be different for different level of details.
- Operation modes: Some models, especially RMS models, may only be valid for specific operation modes.

6.2.3 Model Validation for SPGMs

In general, model validation for SPGMs, involves some form of testing (factory and/or on-site). If testing is not viable, for example due to the possible system security impact, detailed RMS simulations are required to verify model performance.

In terms of testing work, the following objectives are to be met:

- Confirmation that the grid connection code requirements are met.
- Identification of the characteristics of the plant that are needed to set up modelling parameters.
- Verification that the SPGM's models are correct and appropriately accurate.

When tests cannot be carried out to validate the generating unit performance, detailed simulation studies using validated model shall be allowed instead. Examples of these studies for medium and large SPGMs includes:

- FRT withstand studies.
- U - Q capability studies

Model validation consists of the verification of steady-state operational performance, dynamic response as well as small signal response. For SPGMs the following model equipment, control systems and associated parameters are to be considered:

- Generator.
- Generator step-up transformer (where applicable)
- Positive, negative and zero sequence impedance sequence data.
- Generator capability curve.
- Excitation system (including automatic voltage regulator (AVR), over excitation limiter (OEL), under excitation limiter (UEL) and power system stabilizer (PSS) where applicable.
- Governor control (including turbine and associated plant control system affecting the operation of the governor).

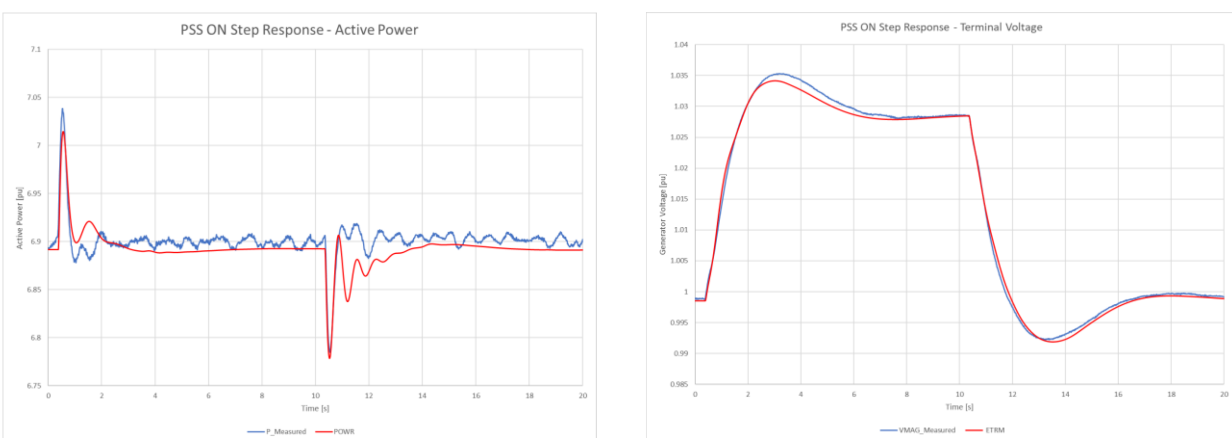


Figure 6-12: PSS model validation – Positive voltage step injection in the exciter voltage reference.

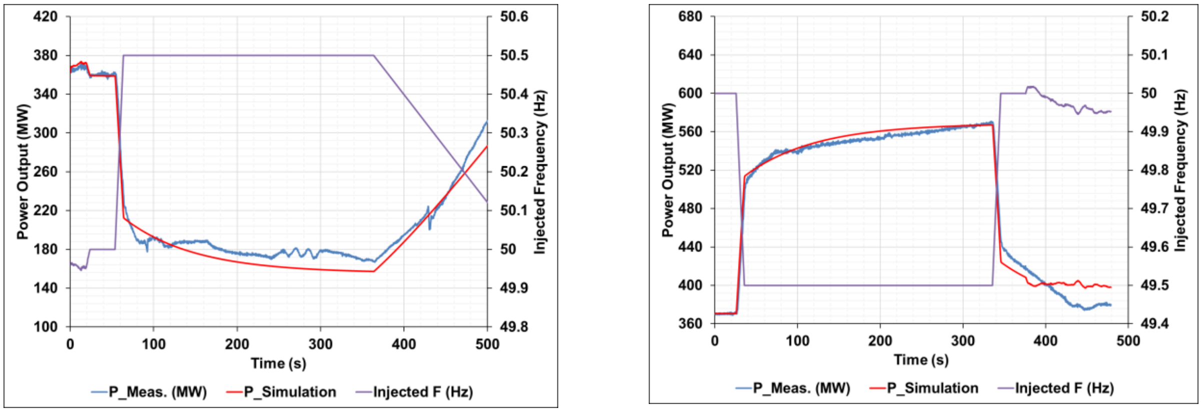


Figure 6-13: Turbine-governor model validation - Positive and negative frequency step injections in the governor control.

For time domain response several TSOs[18] have stipulated simulated response compared to actual plant response be within 10%.

The SPGM model validation or the use of validated model is frequently requested during a unit certification process aimed to verify the compliance of the generating unit with grid connection codes or in general to verify compliance to the requirements for the plant where the unit is installed. The model validation is carried out by comparing the measurements taken during assessment tests and the corresponding model performance. The model validation consists of verifying the expected fidelity of the unit dynamic and steady state behaviour. A quantitative or a qualitative approach is used to evaluate the fidelity of the model.

A quantitative approach is defined in terms of the maximum allowed deviation between the measurements and the corresponding model behaviour.

A qualitative approach implies that the deviation between measurements and the simulated behaviour are less stringent, while the measurements and the simulation shall be reasonably similar, and deviation can be justified.

A mix of the two approaches is also used, for example in case the exception from the maximum allowed quantitative deviation can be technically justified by manufacturers.

The model validation process can be different depending on unit size, but also depending on the modularity and uniqueness of some generating units. There are two main processes in place today for model validation.

In one case compliance tests are carried out on the units. These tests aim to verify the functional performance of the generating unit, including FRT capabilities. The model is validated

[18] AEMO, "Power System Model Guidelines". Available online: https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/System-Security-Market-Frameworks-Review/2018/Power_Systems_Model_Guidelines_PUBLISHED.pdf

against the measurements carried out during such tests. The model is the last point of the process.

Plant Certificate Type A and Plant Certificate Type B

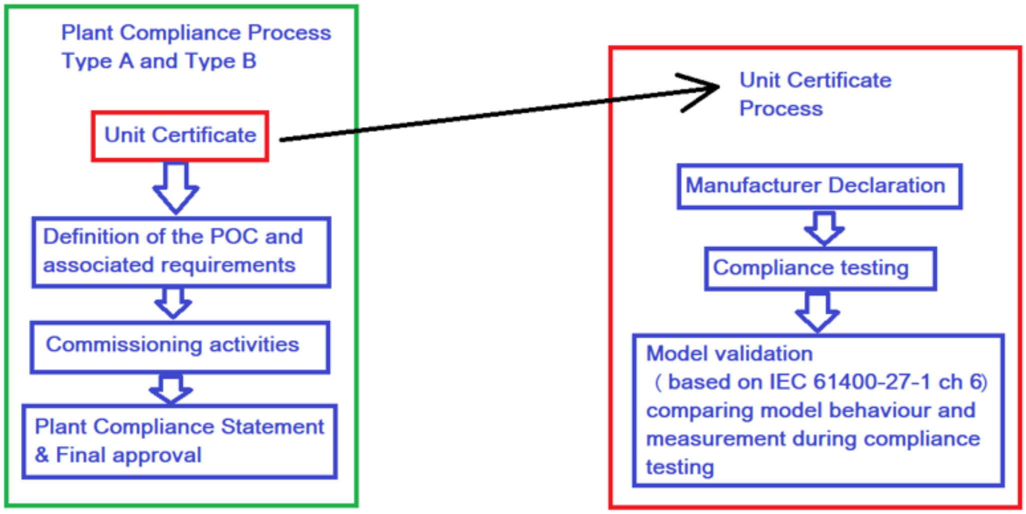


Figure 6-14: Germany Plant Certificate Type A and Plant Certificate Type B process (note that the "Type" is not correlated to the Module Type classification).

In other cases some tests cannot be carried out due to a variety of reasons (e.g. grid impact, no facility available, etc.). In this case, some specific tests are carried out to validate the model in advance and then specific requirements are demonstrated by the use of the validated model.

Individual Verification Procedure - Plant certificate Type C (unit above 5 MVA and HV system)

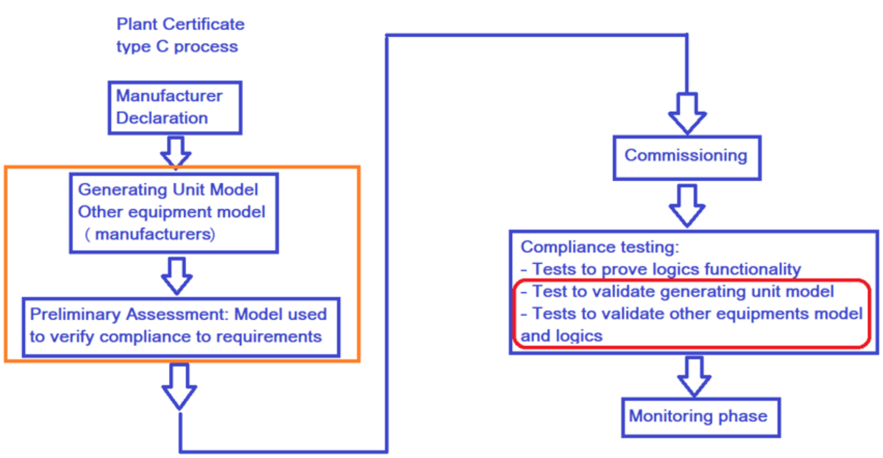


Figure 6-15: Germany Type C certification principle

Typically the tests carried out on the units are aimed to validate the model of the components and their behaviour. They can be summarized as shown in figure 6-16.

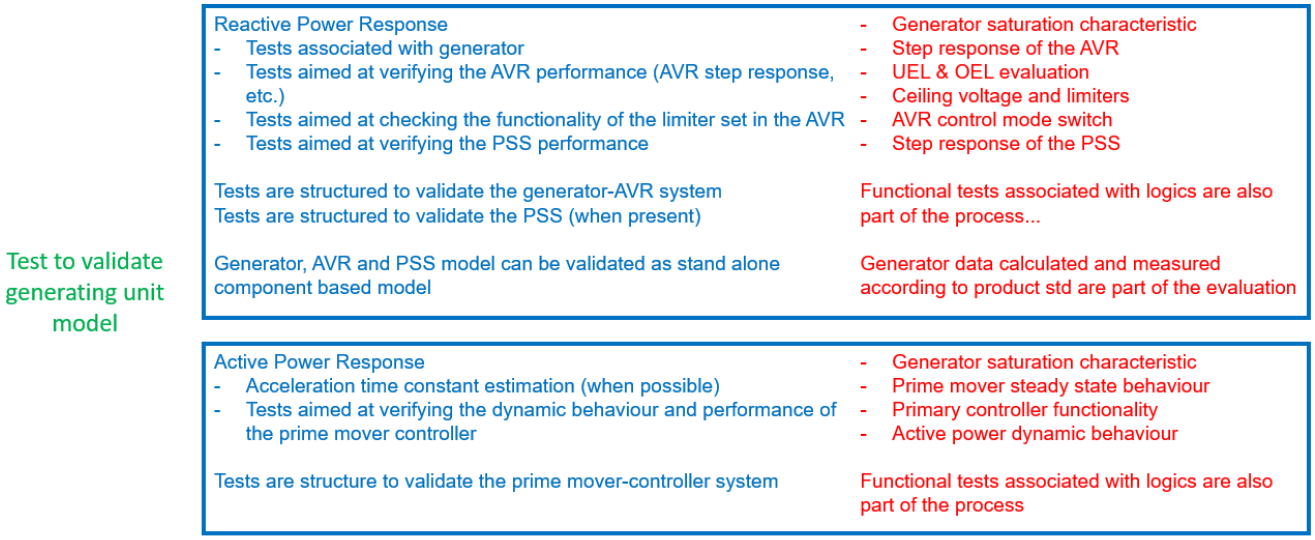


Figure 6-16: Tests associated with PGMs.

In fact the generating unit can be represented in a very schematic way as shown below. The model of the main components can be identified and it would be also possible to test the single components. This approach permits reasonable modularity and a reasonable simplification of the process.

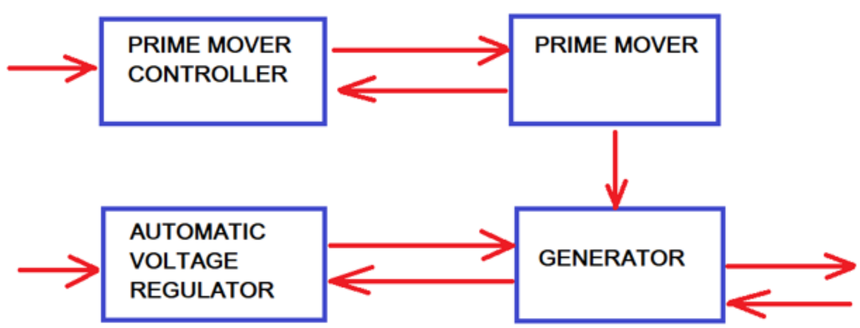


Figure 6-17: Separation of the PGM in models layers.

Component model validation

The generating unit model can be validated by validating separately the main components. The models of the components are defined at their interface values (inputs and outputs) which are different from the ones of the complete generating units. A typical example is the model of the synchronous generator which is defined by the reactance and time constants values measured and calculated according to consolidated test procedure described in international standards (e.g. IEC 60034 series). This approach is helpful when due to whatever reason it is not feasible to test the complete unit.

Generating unit families and associated models

It is today common practice in many countries in Europe to accept the definition of generating unit families.

Such a family is composed by generating units of same technology with a similar behaviour where differences lay mainly on the output power. The generating units within a family has components with similar design (scalability factor) or in some cases with the same components (e.g. same AVR).

In the case of families the validation is normally based on the test of a single generating unit. The validated model in this case is extended to the generating units that are part of the same family by adapting the model parameters (e.g. the generator reactances and time constants, the AVR parameters to adapt to the specific generating unit, etc.).

The manufacturer shall provide plausible explanation and documentation that justifies a generating unit belonging to a family.

Variants of generating units and associated model

A variant of a generating unit is defined as the same generating unit, but with one of the main component with a different design.

In such a case it is expected that the validation of the model can be verified by conducting a limited number of tests associated to the functionality or by using a validated component model.

6.2.4 Model Validation Methodologies - Summary and conclusions

For the different interaction phenomena described in chapter 4, models are developed. These models can be purpose and technology specific, for example to investigate the fault-ride through behaviour of an HVDC system or the transient stresses on a single wind turbine component. Therefore, the models need to be validated to be suitable for the intended study context and interaction phenomena.

There are mainly three types of models and their validation described in the previous subsections:

- RMS time domain models
- EMT time domain models (real-time and non-real time)
- Frequency dependent (harmonic) impedance models

The classical validation approach using measurement data from site tests and operation is not feasible for all phenomena, project stages, fault conditions, or operating conditions. Therefore, the following alternative approaches are also applied:

- Validation with the usage of measured grid data and playback of such in the models
- Validation with real-time simulator or hardware-in the-loop simulation results

- Validation with design calculations
- Validation on components or control level (e.g. in the scope of IEC 61400-21-4 for wind energy generation systems)
- Validation with other accepted simulation models (of the same or different simulation tool)

A cross-tool validation is for example used for HVDC applications in section 6.2.1.

Another example for the transferability of validation results is applied for wind turbine generators: WTs have larger variations so a full validation campaign for each iteration of turbines will be costly. Many of these iterations are built upon a common electrical layout and control code. In some cases, the only difference is the name-plate rating while in other cases the hardware may scale together with the current rating of the new turbine type. So, it should be considered that a validated model of one iteration is used as a benchmark to validate the subsequent iteration provided that the manufacturer can provide reasonable justification and change log.

Provision for extension of validated models should also be considered within reasonable justification because validating models on all corners can be very challenging. For e.g. unbalanced earth fault testing is not allowed in many test sites due to equipment and health hazards caused by over voltages in one or several phases. Instead, models fully validated for three phase earth faults can be extended to demonstrate single phase to earth fault capabilities.

In general, the evaluation of the validation results is carried out by using a

- Qualitative approach
- Quantitative approach
- or a combination of both.

The qualitative approach is for example shown for HVDC systems in section 6.2.1. The quantitative approach is described for wind turbine generators in section 6.2.2. More information or grid compliance tests are described in IEC 61400-27-2.

Section 6.2.2 describes also the application of the quantitative and qualitative approach for model validation.

A quantitative approach is defined in terms of the maximum allowed deviation between the measurements and the correspondent model behaviour.

A qualitative approach implies that the deviation between measurements and the simulated behaviour might be less stringent for some values or transient responses, while the measurements and the simulation shall be reasonably similar and deviation can be justified.

A mix of the two approaches is also used, for example in case the exception from the maximum allowed quantitative deviation can be technically justified by manufacturers.

It is concluded that the acceptance of the quantitative and qualitative comparison results depends also on engineering judgement and mutual agreement of the involved parties such as manufacturers and model users, e.g. TSOs. A simple quantification does not always provide a fast and simple validation answer.

6.3. Model maintenance during lifetime of the installation (PPMs, HVDC and SPGMs)

6.3.1. Model maintainability for HVDC systems

A sound description of model maintainability for HVDC systems is provided in the CIGRÉ technical brochure[19] and is the main base for this section.

As described in section chapter 3, simulation models are used by TSOs and manufactures for many purposes. Thoroughly validated, realistic models are developed in the engineering phase of a project and provided to the TSOs. However, such models might require maintenance and upgrade process during the lifetime of the project.

Responsibility for the model upgrade is basically the HVDC system owner. The HVDC system owner is also the main user of the simulation models, although not in all cases. Therefore, the requirements of all the stakeholders and users of the model and simulation tools must be considered. Typical stakeholders for a simulation model are: the HVDC manufacturer, the HVDC owner, the TSO, the main user of the model, and the vendor of the simulation tools and simulation environments.

The main issues on model access and maintainability are related to control and protection models, including converter models. The modelling of general AC and DC components is normally not encrypted, and simulation tool standard models are mainly applied. Therefore, the lifetime of a model with respect to maintainability and especially support from manufacturers is related to the lifetime of the control and protection system. Other components, such as transformers, have a greater lifespan. For HVDC systems it is expected that the control and protection system will be refurbished after approximately 20 years of operation. And along with such a refurbishment new models will be provided.

This section elaborates the main reasons for initiating a model upgrade during the operation of a project. Model upgrades due to deficiencies identified during the initial operation and warranty period of a project in its first years (and not previously identified in the intense engineering and testing phase) are usually already covered by the project contract. The main reasons for a model upgrade after the initial operation and warranty period are:

- Functional control and protection system changes
- Plant AC or DC component changes
- Model purpose changes

[19] CIGRÈ technical brochure 563 „Modelling and Simulation Studies to be performed during the lifecycle of HVDC Systems“.

- Simulation environment changes

Simulation environment changes are for example net tool versions, a simulation tool change, compiler or operating system upgrades, etc. They can be minor or significant with respect to the model upgrade efforts.

The CIGRÉ brochure 563 describes four different approaches for the model maintenance:

1) Usage of encrypted detailed models
2) Usage of detailed models with open source information
3) Usage of simplified response models with open source information
4) Usage of replicas of the control and protection system cubicles

Encrypted detailed models

The benefit of detailed models for interaction studies is obvious. However, due to intellectual property reasons, encrypted detailed models are provided. They vary from full black-box models to partial black-box models. Interfaces with settable parameters and output signals are provided.

Due to the encryption, the debugging capabilities of such models are limited. An addition of selectable parameters or output signal changes for debugging can only be done by the model developer. Also, the functional change or addition of new functions within the encrypted part is not possible.

To minimize the impact of the encryption on future studies and upgrades, the model documentation and the extent of encrypted model parts shall be addressed in the technical specification. A compromise between the protection of intellectual property and maintainability must be found on a project specific base or even on a study purpose specific base. This also comprises the content of interfaces or the provision of models to third parties.

A possible solution is a model maintenance contract with the manufacturer. Please note that it must be distinguished between simple compiler and simulation tool upgrades, and major changes of functions or model parts.

A challenge with encrypted models is the ability to perform interaction studies in multi-vendor environment[20],[21]. Ensuring interoperability of future multi-vendor HVDC projects in the design phase and planning phase of such projects (including also offshore wind turbine OEMs) would require a certain level of standardisation in the encrypted models as well as the signal interfaces

---

[20] ENTSO-E Position on Offshore development and Interoperability. Available online: https://eepublicdownloads.entsoe.eu/clean-documents/Publications/Position%20papers%20and%20reports/210125_Offshore%20Development_Interoperability.pdf .

[21] ENTSO-E, T&D Europe and WindEurope Workstream for the development of multi-vendor HVDC systems and other power electronics interfaced devices. Published in March 2021. Available online: https://windeurope.org/intelligence-platform/product/workstream-for-the-development-of-multi-vendor-hvdc-systems/ .

to be observed. In that frame, a first attempt has been made by ENTSO-E[22] which needs to be developed further with the stakeholders in the upcoming years.

Detailed models with open source information

According to CIGRÉ technical brochures, one solution to maintain the model during the lifecycle of the equipment is to have continuing access to the control system source code. This comprises the provision of the complete environment to generate the detailed model from source code to static or dynamic libraries. However, as described earlier, this can interfere with the manufacturers' need to protect their intellectual properties. This is especially true for interaction studies as these might be performed by third parties (example: a competitor) as well as RSOs. Moreover, detailed open source models could not facilitate multi-vendor design and studies.

Simplified generic models with open source information

Instead of vendor specific implementation of the control and protection system, an open and generic model is provided. This model should have for the specific study purpose a general response characteristic as the highly detailed model. This is the main drawback and problem of such a generic model. Due to the usage of standard simulation tool library components and not providing detailed open information (to avoid the violation of intellectual property issues), the simplified model response is less realistic. Its application to detailed interaction studies is limited. The user needs to understand the effect of the simplification on the simulation results and the applicability of the model. Usually such models are used in the planning phase or feasibility studies of the projects.

Replica of the control and protection system cubicles

The main application of control system replicas for interaction studies is described in sections 3.2 and 6.2.1. With respect to simulation model maintenance, a control system replica supports the validation of model updates and can provide additional investigation on interaction phenomena (during FAT & commissioning and Operation). Since replicas are physical equipment installed in a real-time laboratory at TSOs or third party, for interaction studies (for instance between 2 HVDC links owned by two different vendors), each manufacturer can have physical access to their own replicas to test mitigation solutions and to improve their own C&P system. Therefore, such approach improves the preservation of intellectual property of each vendor when performing the interaction studies between several vendors.

6.3.2. Model maintainability for PPMs and SPGMs

Only in the case of modification(s) of a SPGM or a PPM with impact on the electrical behaviour at the grid connection point, the owner has the obligation to adapt the delivered models

[22] ENTSO-E Standardized control interface for HVDC SIL/HIL conformity tests. Available online: https://eepublicdownloads.entsoe.eu/clean-documents/Publications/Position%20papers%20and%20reports/ENTSO-E_Standardized_control_interface__update_2020_07_15_.pdf

consequently. The power-generating facility owner shall provide RMS and/or EMT simulation models at the request of the relevant system operator or the relevant TSO.

7 RECOMMENDATIONS FOR CNC AMENDMENTS

Based on the identified model requirements discussed in chapter 5, the EG ISSM recommends the following CNC amendments as below.

Proposed amendments of the NC RfG

The EG ISSM has discussed the provisions of the following articles and recommends the following amendments (with recommended changes in red).

NC RfG	Legal Text (with red the new proposal)
Art.15.6.c **General requirements for type C power-generating modules**	**6.** Type C power-generating modules shall fulfil the following general system management requirements: … **c.** with regard to the simulation models: (i) at the request of the relevant system operator or the relevant TSO, the power-generating facility owner shall provide simulation models which properly reflect the behaviour of the power-generating module for the relevant study purpose in both steady- state, and dynamic simulations (root mean square), or in electromagnetic transient simulations. The simulation model requirements and data provided shall not violate manufactures intellectual property; The power-generating facility owner shall ensure that the models provided have been verified against the results of compliance tests referred to in Chapters 2, 3 and 4 of Title IV, and shall notify the results of the verification to the relevant system operator or relevant TSO. Member States may require that such verification be carried out by an authorised certifier; (ii) the Synchronous PGM simulation models provided by the power-generating facility owner shall contain the following sub-models, depending on the existence of the individual components: • alternator and prime mover, • speed and power control, • voltage control, including, if applicable, power system stabiliser ('PSS') function and excitation control system, • power-generating module protection models, as agreed between the

relevant system operator and the power- generating facility owner, ~~and converter models for power park modules;~~

(iii) For the purpose of electromechanical dynamic simulations (RMS simulation studies) of power park modules, the relevant system operator or the relevant TSO shall have the right to specify the power park modules simulation model requirements. Without prejudice to the Member State's rights to introduce additional requirements, the simulation models of the power park modules provided by the power generation facility owner shall:

a) be valid for the specified operating range and all control modes of the power-generating facility;

b) include a proper representation of the converter modules and its control systems (including the synchronization module) that influence the dynamic behaviour of the power-generating module in the specified time frame;

c) be open source generic model for cross border network stability studies;

d) in the case that encrypted detailed RMS models are accepted by the relevant TSO, the relevant TSO shall specify the requirements of the model encryption according to national regulations (for example use of source code, the model structure and the signal interfaces to be observable in the network studies);

e) include the relevant protection function models;

(iv) For the purpose of time domain electromagnetic transient (EMT) simulations of power park modules, the relevant system operator or the relevant TSO shall have the right to specify the power park module model requirements. Without prejudice to the Member State's rights to introduce additional requirements, the models shall contain the following:

a) be valid in the frequency range 0.2 Hz – 2500 Hz for relevant interaction studies. The validity of the PPM model shall be ensured for the given frequency range at the connection point;
b) be valid for specified operating range and control modes of the PPM in both the positive and in the negative phase sequence;
c) reproduce the detailed response of the power-generating module and its control blocks during balanced and unbalanced AC network faults in the valid frequency range;
d) include the power plant level control and the power plant relevant functionalities if applicable;
e) include the frequency dependence of the lines and/or cables in the power-generating facility;
f) represent the Power Plant Module transformers model including saturation, resistors, filter, breaker and AC arrester in the valid frequency;
g) include all the relevant protection function models for the relevant interaction studies;
h) be capable to be used for the numerical calculation of the frequency

dependent impedance of PPM at the connection point (impedance amplitude and impedance phase angle) in the frequency range that the model is valid);

i) In the case that encrypted detailed EMT models are accepted by the relevant system operator or the relevant TSO, the relevant system operator or the relevant TSO shall have the right to specify the model encryption based on national regulations (for example the model structure and the signal interfaces to be observable in the network studies);

(v) For the purpose of frequency domain simulations for the risk assessment of the resonance stability of the power park module, the relevant system operator or the relevant TSO shall have the right to request from the power-generating facility owner the frequency dependent impedance model of the power-generating facility at the point of interconnection to the grid. Without prejudice to the Member State's rights to introduce additional requirements, the following requirements shall apply:

a) The impedance model of the power-generating facility shall be requested at least in the range 5.0 Hz - 2500Hz; As an additional requirement, the relevant system operator or the relevant TSO can extend the required applicability of the model to up to 9 000 Hz.

b) The relevant system operator or the relevant TSO shall have the right to request the calculation of the impedance model of the power-generating facility either numerically (using the EMT model) or analytically (using transfer function);

c) The relevant system operator or the relevant TSO shall have the right to request the impedance profile of the power-generating facility at the connection point through the whole operating range and control modes of operation;

d) The impedance model of the power-generating facility shall be provided for both the positive and for the negative phase sequence;

e) The power-generating facility owner shall take into account the influence of the power-generating module control and measurement system as other parts of the power-generating module which influences the output impedance in the specified frequency range;

f) The power-generating facility owner shall specify and justify simplifications made in the calculation of the impedance model.

(vi) the request by the relevant system operator referred to in point (i) and (ii) shall be coordinated with the relevant TSO. It shall include:

- the format in which models are to be provided,
- the provision of documentation on a model's structure and block diagrams,

	• an estimate of the minimum and maximum short circuit capacity at the connection point, expressed in MVA, as an equivalent of the network; (vii) the power-generating facility owner shall provide recordings of the power-generating module's performance to the relevant system operator or relevant TSO if requested. The relevant system operator or relevant TSO may make such a request, in order to compare the response of the models with those recordings; (viii) with regard to the installation of devices for system operation and devices for system security, if the relevant system operator or the relevant TSO considers that it is necessary to install additional devices in a power-generating facility in order to preserve or restore system operation or security, the relevant system operator or relevant TSO and the power-generating facility owner shall investigate that matter and agree on an appropriate solution; (ix) the relevant system operator shall specify, in coordination with the relevant TSO, minimum and maximum limits on rates of change of active power output (ramping limits) in both an up and down direction of change of active power output for a power-generating module, taking into consideration the specific characteristics of prime mover technology; (x) earthing arrangement of the neutral-point at the network side of step-up transformers shall comply with the specifi- cations of the relevant system operator or relevant TSO.

NC RfG	Legal Text (with red the new proposal)
ArticleArticle 52 **Compliance simulations for type C synchronous power-generating modules**	1.In addition to the compliance simulations for type B synchronous power-generating modules set out in Article 51, type C synchronous power-generating modules shall be subject to the compliance simulations detailed in paragraphs 2 to 5. Instead of all or part of those simulations, the power-generating facility owner may use equipment certificates issued by an authorised certifier, which must be provided to the relevant system operator. 2.With regard to the LFSM-U response simulation the following requirements shall apply: (a) the power-generating module's capability to modulate active power at low frequencies in accordance with point (c) of Article 15(2) shall be demonstrated

	by RMS simulation; (b) the simulation shall be carried out by means of low frequency steps and ramps reaching maximum capacity, taking into account the droop settings and the deadband; (c) the simulation shall be deemed successful in the event that: (i) the simulation model of the power-generating module is validated against the compliance test for LFSM-U response described in of Article 45(2); and (ii) compliance with the requirement of point (c) of Article 15(2) is demonstrated. 3.With regard to the FSM response simulation the following requirements shall apply: (a) the power-generating module's capability to modulate active power over the full frequency range in accordance with point (d) of Article 15(2) shall be demonstrated by RMS simulation; (b) the simulation shall be carried out by simulating frequency steps and ramps big enough to trigger the whole active power frequency response range, taking into account the droop settings and the deadband; (c) the simulation shall be deemed successful in the event that: (i) the simulation model of the power-generating module is validated against the compliance test for FSM response described in Article 45(3); and (ii) compliance with the requirement of point (d) of Article 15(2) is demonstrated. 4.With regard to the island operation simulation the following requirements shall apply: (a) the power-generating module's performance during island operation referred to in the conditions set out in point (b) of Article 15(5) shall be demonstrated by RMS simulation; (b) the simulation shall be deemed successful if the power-generating module reduces or increases the active power output from its previous operating point to any new operating point within the P-Q-capability diagram within the limits of point (b) of Article 15(5), without disconnection of the power-generating module from the island due to over- or underfrequency. 5.With regard to the reactive power capability simulation the following requirements shall apply: (a) the power-generating module's capability to provide leading and lagging reactive power capability in accordance with the conditions set out in points (b) and (c) of Article 18(2) shall be demonstrated by simulation in the outer corners of the U-Q/Pmax diagram. In addition two simulations of the executed tests shall be performed with the real grid voltage and load points during the tests; (b) the simulation shall be deemed successful if the following conditions are fulfilled: (i) the simulation model of the power-generating module is validated against the

	compliance tests for reactive power capability as far as these tests were accommodated (grid voltage deviations) and allowed by the RSO described in Article 45(7); and (ii) compliance with the requirements of points (b) and (c) of Article 18(2) is demonstrated.

Proposed amendments of the NC HVDC

The EG ISSM based on the ToR has discussed the provisions of the following articles and recommends the following amendments. The recommendation for new provisions are based on the discussion of the EG and aim to facilitate interaction studies in various study phases, as presented in chapter 3 and chapter 5.

NC HVDC	Legal Text (with red the new proposal)
Art.54	1. The relevant system operator in coordination with the relevant TSO may specify that an HVDC system owner deliver simulation models which properly reflect the behaviour of the HVDC system in ~~both~~ steady-state, in time domain dynamic simulations (root mean square) and in electromagnetic transient simulations. 2. The format in which models shall be provided and the provision of documentation of models structure and block diagrams shall be specified by the relevant system operator in coordination with the relevant TSO. In the case that encrypted detailed RMS or EMT models are accepted by the relevant TSO, the relevant TSO together with the HVDC system owner shall specify the requirements of the model encryption (for example use of source code, the model structure and the signal interfaces to be observable in the network studies). The agreement should be made on project specific basis according to national regulations; 3. For the purpose of electromechanical (RMS) simulations used in network studies, the relevant TSO shall have the right to specify the model requirements. Without prejudice to the Member State's rights to introduce additional requirements, the HVDC system models shall contain at least the following: (a) be valid for the specified operating range and all control modes of the HVDC system; (b) include representation of HVDC converter unit, HVDC lines/cables and control systems that influence the dynamic behaviour of the HVDC transmission system in the specified time frame; (c) include the relevant protection function models as agreed between the relevant TSO and the HVDC system owner;

(d) be open source generic model for RMS simulations delivered for cross-border network stability studies;

(e) The above listed simulation model requirements and information must not violate manufactures intellectual property;

4. For the purpose of electromagnetic transient simulations (EMT), the relevant TSO shall have the right to specify the model requirements. Without prejudice to the Member State's rights to introduce additional requirements, the models shall contain the following:

(a) be valid at least in the frequency range 0.2Hz to 2500 Hz for relevant studies;

(b) be valid for the specified operating range and all operation modes of the HVDC system in both the positive and in the negative phase sequence;

(c) be able to reproduce the detailed transient response of the HVDC system and its control blocks (including synchronisation) during balanced and unbalanced AC network faults in the valid frequency range;

(d) include an accurate representation of the semiconductor valves, the frequency dependency of the HVDC system lines and sufficient representation of communication systems instruments where deemed necessary for the respective HVDC system model and study purpose;

(e) represent transformers models (including saturation), resistors, filter, breaker, AC and DC arrester in the valid frequency range;

(f) include all the control and protection models as agreed between the relevant TSO and the HVDC system owner (under/overvoltage, overcurrent, chopper and frequency sensitive control functions);

(g) be capable to be used for the numerical calculation of the frequency dependent impedance of the HVDC converter station (magnitude and phase angle of the Z(f)) in the frequency range that the model is valid;

(h) The above listed simulation model requirements and information must not violate manufactures intellectual property;

5. For the purpose of the risk assessment of the resonance stability of the HVDC convert station, the TSO shall have the right to request from the HVDC system owner the frequency dependent impedance model of the HVDC converter station at the AC side. Without prejudice to the Member State's rights to introduce additional requirements, the following requirements shall apply:

(a) The impedance model of the HVDC converter station shall be requested in the frequency range 5Hz till 2500 Hz; The TSO has the right to extend the required applicability of the model up to 9 000 Hz.

(b) The relevant TSO together with the HVDC owner shall agree if the calculation of the impedance model of the HVDC converter station will be either numerically (using the EMT model) or analytically (using transfer function) or both; In the case of numerical calculation, the TSO shall specify the frequency steps where the impedance is provided. The number of different frequency steps shall be reasonably limited to provide acceptable results and at the same time limit the simulation effort and data storage to an acceptable amount.

(c) The relevant TSO shall have the right to request the impedance model of the HVDC station through the specified operating range and all control modes of operation;

(d) The impedance model of the HVDC converter station shall be provided for both the positive and for the negative phase sequence;

(e) The HVDC system owner shall take into account the influence of the whole HVDC unit control and measurement system as well as other parts of the HVDC unit which influences the output impedance in the specified frequency range; If coupling between different frequencies exists in a given frequency range, this should be sufficiently represented.

(f) The HVDC system owner shall specify and justify simplifications made in the calculation of the impedance model;

6. The HVDC system owner shall verify the models against the results of compliance tests carried out according to Title VI and a report of this verification shall be submitted to the relevant TSO. The models shall then be used for the purpose of verifying compliance with the requirements of this Regulation including, but not limited to, compliance simulations as provided for in Title VI and used in studies for continuous evaluation in system planning and operation.

7. An HVDC system owner shall submit HVDC system recordings to the relevant system operator or relevant TSO if requested in order to compare the response of the models with these recordings.

8. An HVDC system owner shall deliver an equivalent model of the control system when adverse control interactions may result with HVDC converter stations and other connections in close electrical proximity if requested by the relevant system operator or relevant TSO. The equivalent model shall contain all necessary data for the realistic simulation of the adverse control interactions.

Proposed amendments of the NC DC

The EG ISSM has discussed the provisions of the following articles and recommends the following amendments

NC DC	Legal Text
Art. 21 (3,4) Simulation models	1. Transmission-connected demand facilities and transmission-connected distribution systems shall fulfil the requirements set out in paragraphs 3 and 4 related to the simulation models or equivalent information. 2. Each TSO may require simulation models or equivalent information showing the behaviour of the transmission- connected demand facility, or the transmission-connected distribution system, or both, in steady and dynamic states. 3. Each TSO shall specify the content and format of those simulation models or equivalent information. The content and format shall include: (a) steady and dynamic states, including 50 Hz component; (b) electromagnetic transient simulations in time domain at the connection point, (c) frequency domain simulations including the frequency dependent grid impedance at the connection point; (d) structure and block diagrams. 4. For the purpose of dynamic simulations, the simulation model or equivalent information referred to in paragraph 3(a) shall contain the following sub-models or equivalent information: (a) power control; (b) voltage and frequency control; (c) transmission-connected demand facility and transmission-connected distribution system protection models; (d) the different types of demand, that is to say electro technical characteristics of the demand; and (e) converter models. 5. Each relevant system operator or relevant TSO shall specify the requirements of the performance of the recordings of transmission-connected demand facilities or transmission-connected distribution facilities, or both, in order to compare the response of the model with these recordings. 18.8.2016 L 223/26 Official Journal of the European Union EN

ANNEX 1 – MODELS OF SPGMS

VGB position as provided to the EG ISSM for discussion

Network Code	Article	Valid for Type	Phenomena	Description	Unclear part of description	Proposed Procedure	Kind of model
NC RfG	51.2	B, C and D	LFSM-O	Simulation of active power modulation in accordance with Art. 13.2 in case of overfrequency by simulating steps and ramps in frequency until minimum active power regulating level is achieved.	Number and size of steps In which operating point	3 steps in frequency until Pmin is achieved. Ramping rate for the simulation shall be agreed between RSO and SPGM owner.	Dynamic model of turbine-governor
NC RfG	51.3	B, C and D	FRT	Simulation of grid voltage dip in accordance with Art. 14.3.a.	In which operating point	Simulation at maximum active power and power factor 1.0 at grid connection point, connected to an infinite grid via an impedance in line with the pre-fault and post-fault conditions described in Art. 14.3.a.(iv).	Dynamic RMS model of AVR, PSS and 2-axis model of synchronous alternator.
NC RfG	51.4	B, C and D	Post Fault active power recovery	Simulation of the power-generating module's post fault active power recovery referred to in the conditions set out in Article 17.3.	How to simulate. Starting from which operating point	The required simulations shall be agreed between the RSO and the SPGM owner.	Dynamic RMS model of AVR, PSS and 2-axis model of synchronous alternator.
NC RfG	52.2	C and D	LFSM-U	Simulation of active power modulation in accordance with Art. 15.2.c in case of underfrequency by simulating steps and ramps in frequency until maximum capacity is achieved.	Number and size of steps In which operating point	3 steps in frequency until Pmax is achieved. Ramping rate for the simulation shall be agreed between RSO and SPGM owner.	Dynamic model of turbine-governor
NC RfG	52.3	C and D	FSM	Simulation of active power modulation in accordance with Art. 15.2.d in case of frequency deviations by simulating sufficiently large steps and ramps in frequency to activate the whole active frequency response range.	Number and size of steps In which operating point	Simulations up to the max. deviation for FSM according to the national required values according to table 5 (between 1,5-10% of Pmax) with a frequency step resulting in a power variation equal to 50% of window according to table 5. The starting point for each of the four simulations shall be agreed between RSO and SPGM owner.	Dynamic model of turbine-governor
NC RfG	52.4	C and D	Island operation	Simulation of active power modulation in accordance with Art.	Model of the island grid (inertia, short circuit power, other	Given the fact that the data of all involved PGMs and	Dynamic model of turbine-governor and Dynamic RMS model

				15.5.b when changing from the previous operation point to a new operating point within the P-Q capability diagram in island mode.	generators, demand behavior etc.) is only available for the RSO! From which operation point to which new operation point? Island identification is not defined (Art. 15.5.b.(iii))	demand facilities are not available for third parties due to intellectual property rules, this simulation has to be done by the TSO / RSO with data submitted by the connected grid users.	of AVR and 2-axs model of synchronous alternator.
NC RfG	52.5	C and D	Reactive power capability	Simulation of provision of leading and lagging reactive power in accordance with the conditions set out in points (b) and (c) of Article 18.2.	In which operating point	Six simulations have to be made for P ≥ 90% Pmax: - Qmin at Umax - Qmax at Umax - Qmin at Umin - Qmax at Umin - Qmin tested at real operational Voltage - Qmax tested at real operational Voltage	RMS model of AVR and 2-axs model of synchronous alternator
NC RfG	53.2	D	Active power oscillation damping	Simulation of the power-generating module's performance in terms of its control system ('PSS function') in damping active power oscillations in accordance with Article 19.2.b.(v)	What kind of situations and in which operation point? Only the infinite grid with an impedance to the SPGM can be simulated by the owner (the grid model, including other generators and demand are confidential and only available for the RSO).	During maximum active power and power factor 1.0 at the grid connection point, connected to an infinite grid via an impedance of 0.20 pu, a step of + 2% in the voltage at the setpoint of the AVR, followed after damping out by a step of - 2 % will be simulated without and with activated PSS.	Dynamic RMS model of AVR, PSS and 2-axis model of the synchronous alternator.
NC RfG	53.2.c.(ii)	D	Active power oscillation damping	Simulation of the power-generating module's performance in terms of its control system ('PSS function') in damping active power oscillations by simulating a sudden load reduction of the power-generating module from 1 pu to 0,6 pu of the maximum capacity	Only the infinite grid with an impedance to the SPGM can be simulated by the owner (the grid model, including other generators and demand are confidential and only available for the RSO).	During maximum active power and power factor 1.0 at the grid connection point, connected to an infinite grid via an impedance of 0.20 pu, this step will be simulated without and with activated PSS.	Dynamic RMS model of AVR, PSS and 2-axis model of the synchronous alternator.
NC RfG	53.3	D	FRT	Simulation of grid voltage dip in accordance with Art. 16.3.	In which operating point	Simulation at maximum active power and power factor 1.0 at grid connection point, connected to an infinite grid via an impedance in line with the pre-fault and post-fault conditions described in Art. 16.3.a.(ii).	Dynamic RMS model of AVR, PSS and 2-axis model of synchronous alternator.
NC E&R	51	SGU	Restoration	Each TSO shall review the measures of its restoration plan using computer simulation tests, using data from	What will be simulated, which models and what kind of models are required?	The required models and their capabilities shall be clearly described in and be part of the system	To be described in the system service contract.

				the DSOs identified pursuant to Article 23(4) and the restoration service providers, at least every five years. The TSO shall define these simulation tests in a dedicated testing procedure...		service contract for the restoration service provision by the SGU.	
NC HVDC	29.3	SPGM	Torsional oscillations	All parties identified by the relevant TSO as relevant to each connection point, including the relevant TSO, shall contribute to the studies and shall provide all relevant data and models as reasonably required to meet the purposes of the studies. The relevant TSO shall collect this input and, where applicable, pass it on to the party responsible for the studies in accordance with Article 10.	The required models (e.g. AVR, PSS, Turbine control, mass-spring for the shaft etc.) are not listed. The quality and purpose (what kind of simulations shall the models be fit for, e.g. frequency range, RMS, dynamic etc.) of required models is not described. The models are necessary for the design of the HVDC unit.	For SSTI studies, the damping of eigen-frequencies up to 200 Hz have to be studied. For that reason the models shall be fit for simulations from static up to 200 Hz.	Dynamic SSTI models of AVR, PSS, dynamic model of turbine-governor and 2-axis model of the synchronous alternator; the models shall be fit for simulations up to 200 Hz (be aware that the standard IEEE models are reduced models, only fit for simulations up to 3 Hz).A mass-spring model of whole shaft with the turbine, the alternator and where applicable the exciter rotors.
NC HVDC	31.3	SPGM	Torsional oscillations	All parties identified by the relevant TSO as relevant to each connection point, including the relevant TSO, shall contribute to the studies and shall provide all relevant data and models as reasonably required to meet the purposes of the studies. The relevant TSO shall collect this input and, where applicable, pass it on to the party responsible for the studies in accordance with Article 10.	The required models (e.g. AVR, PSS, Turbine control, mass-spring for the shaft etc.) are not listed. The quality and purpose (what kind of simulations shall the models be fit for, e.g. frequency range, RMS, dynamic etc.) of required models is not described. The models are necessary for the design of the HVDC unit.	For SSTI studies, the damping of eigen frequencies up to 200 Hz have to be studied. For that reason the models shall be fit for simulations from static up to 200 Hz.	Dynamic SSTI models of AVR, PSS, dynamic model of turbine-governor and 2-axis model of the synchronous alternator; the models shall be fit for simulations up to 200 Hz (be aware that the standard IEEE models are reduced models, only fit for simulations up to 3 Hz). A mass-spring model of whole shaft with the turbine, the alternator and where applicable the exciter rotors.

ANNEX 2 - ABBREVIATIONS

RMS	Root Mean Square
EMT	Electromagnetic Transient
PED	Power Electronic Device
HVDC	High Voltage Direct Current
HV	High Voltage
C&P	Control and Protection
TSO	Transmission System Operator
RSO	Relevant System Operator
AVR	Automatic Voltage Regulator
PSS	Power System Stabiliser
AC	Alternative current
DC	Direct Current