Hybrid simulation methods to perform grid integration studies for large scale offshore wind power connected through VSC-HVDC

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Keywords

<<VSC-HVdc>>, <<Large-scale offshore wind power>>, and <<Hybrid simulation methods>>

Abstract

This paper deals with the inclusion of VSC-HVdc transmission schemes into stability-type simulations by hybrid methods. These methods allow selected parts of the network to be simulated in detail by including electro-magnetic behaviour of devices and network elements whereas the remainder of the network is simulated in a simplified fashion with emphasis on electro-mechanical interactions. The paper discusses the interface methods needed for coupling both simulations, and presents a simple but robust interface, particularly designed for VSCs. Several aspects that determine the performance of the hybrid simulation are discussed and tested by simulations on an example network. The hybrid simulations have been implemented in Matlab and verified against a full EMT-type simulation in PSS®NETOMAC.

Introduction

High-voltage direct-current transmission based on voltage-sourced converters (VSC-HVdc) is becoming a mainstream technology and is considered a promising type of connection for future offshore wind power plants (WPP). These interconnections may be point-to-point or multi-terminal, a configuration for which VSC technology is particularly well-suited and hence may lead to development of offshore dc networks [1]. Due to the power electronic interfaces, offshore systems are to a large extent dynamically decoupled from the mainland system. This gives rise to new challenges that need to be addressed in grid integration studies in detail.

An important aspect in grid integration studies is the transient stability focusing on electro-mechanical interactions between generators, loads, and the transmission system. The inclusion of power electronic devices into these stability-type simulations is challenging. This is mainly due to the fact that the dynamics of power electronic converters and their controls are much faster compared to synchronous generators.

Such fast dynamics in itself are not crucial to the transient stability problem. They may lead, however, to the activation of protection logic or control mode changes that do have a significant impact on a longer time scale. Moreover, the behaviour of power electronics may be highly non-linear. Generally speaking, stability-type simulators do not allow a structured consideration of these aspects. Therefore, presently, the detailed analysis of power electronic converters is only possible with electro-magnetic transient (EMT) type simulators, which allow a more detailed representation of the power system. Because of the much higher computational complexity of such simulators they are generally not well suited for the study of large networks. This conflicting situation highlights the need for a simulation method that allows detailed modelling of power electronics such as VSC-HVdc, yet at the same time enable the simulation of transient stability of large networks with reasonable computational effort.

This paper deals with the inclusion of VSC-HVdc systems into stability-type simulations by hybrid methods. This is achieved by including the parts of the network that require detailed modelling into an EMT-type simulator whereas the remainder of the network is simulated in a stability-type simulator. Hybrid simulations offer the accuracy provided by EMT-type simulations while minimising the increase in numerical complexity of the simulation as a whole, which to a large extend maintains the simulation speed provided by stability-type simulations. Moreover, considerable flexibility is gained as heuristic, project-specific stability models can be replaced by re-usable building blocks. The proposed methods include the network around the VSC connection node into both solvers. The simulations are interfaced by exchanging data about network quantities after each calculation step of the stability-type simulation. Several aspects that determine the performance of the hybrid simulation environment will be discussed, most prominently the accuracy. Among these are: the transformations required to exchange network quantities between both solvers, the representation of VSCs in both simulation environments, and the network arrangement around the ac-side VSC connection node.

The paper is organised as follows: First, VSC models for several time frames of interest are discussed. Second, the dynamic interaction between VSCs and both ac and dc networks is briefly explained. The paper continues with an overview of the hybrid simulation methods and the interfacing methods used in this work. Several aspects of the hybrid simulation are tested on an example network. The paper ends with conclusions and directions for further research.

Representation of VSC-HVdc for several time frames of interest

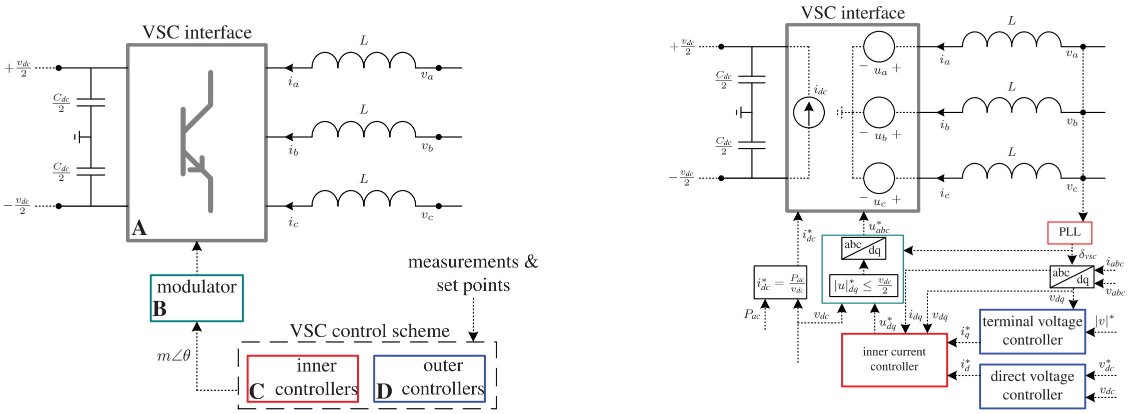
The representation of VSCs into grid integration studies depends on the electro-magnetic and/or electro-mechanic phenomena of interest. Fig. 1a shows a general VSC model, subdivided in four main blocks. Block A includes the representation of the physical elements of the VSC and block B the modulation scheme. The converter controls, assuming the typical cascaded nature, consist of relatively slow outer controllers (block D) and faster inner controllers (block C). The requirements on the model determine which blocks are implemented and to what level of detail.

Modelling VSC-HVdc for electro-magnetic transient studies

The highest level of detail is provided in case the VSC is represented topologically correct including all power electronic switches. This approach is usually taken if one is interested in a detailed assessment of power quality aspects such as harmonics, inter harmonics, and transient over voltages. Such models can only be solved by EMT-type simulators. To take into account detailed switching behaviour, small integration time steps are necessary, resulting in high numerical complexity.

In fact, most EMT-type simulators can handle the discontinuities in the simulation caused by power electronics very well. Therefore, detailed models of converter valves can be included into block A if required. The EMT-type simulation also allows detailed inclusion of fast acting protection circuits in blocks A and B. The modulation signals are provided by the (cascaded) control scheme, of which the inner (fast) part may contain current-limiting protection mechanisms.

Not all studies that require a three-phase representation of the network quantities, must contain full details of the converter switching behaviour. In this case, the physical part of the VSC (block A) can



(a) Generalised VSC representation

(b) Averaged VSC model for EMT-type simulations

Figure 1: commonly used VSC representations

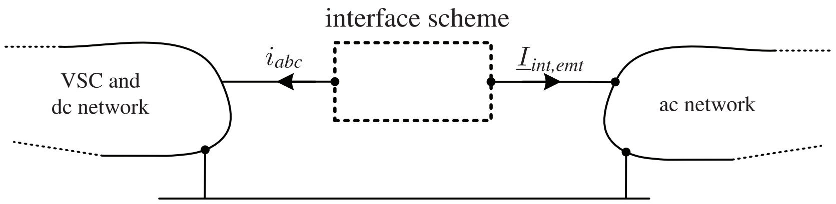
be represented by a three-phase voltage source on the ac-side and a current source on the dc side [2, 3], which are coupled by power balance. This significantly improves execution times as the discontinuities caused by the power electronic switching are replaced by continuous sources. This allows the simulation to be executed using a larger time-step size. Moreover, the modulator can be represented by a simple time delay element rather than detailed modulating schemes, which relieves the otherwise high computational burden. The outer controllers can be modelled with the same level of detail as compared to more detailed EMT-models. It must be noted that such averaged models do generally no longer allow the simulation of faults on the dc side, as the fly-back diodes are not included in the model. A typical implementation of an averaged VSC model is provided in Fig. 1b.

Simplifications for stability studies

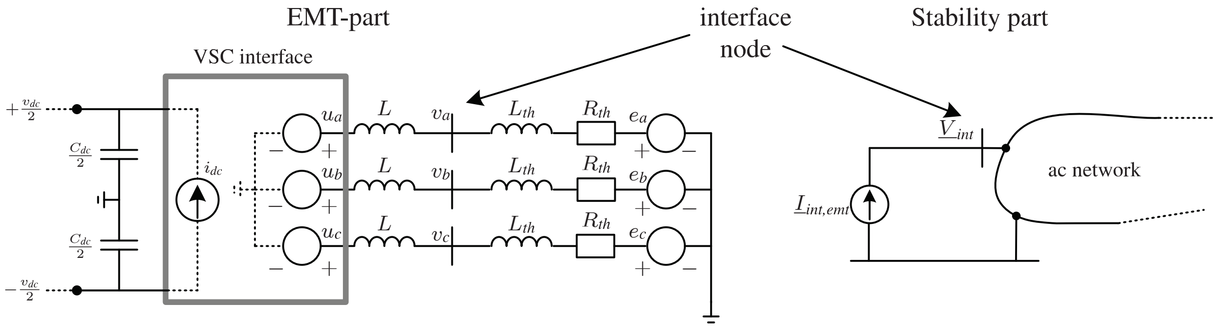
Contrary to EMT-type simulations, stability-type simulations represent transmission lines and cables by a single-phase equivalent, modelled by complex impedances rather than differential equations. Voltages and currents appear as stationary complex phasors and are assumed balanced. Connected models are simplified according to the desired frequency bandwidth of interest, typically 0.1–10 Hz. Generally speaking, VSCs can be included into stability-type simulations by representing their averaged behaviour, which is mainly dictated by the outer control loop (block D of Fig. 1a). The detailed behaviour of the relatively fast current controllers, the synchronisation loop, and the modulator (block B and C) can be included by algebraic relations and time delay functions without significant loss of simulation accuracy [4].

Including VSC-HVdc into stability studies by hybrid methods

Hybrid simulators were first proposed and built in the 1980s by including a detailed model of a classical HVdc link into a stability-type simulation [5]. In [6], this approach was extended by investigating the influence of the network size of the system simulated by EMT. A transition from detailed to quasi steady-state representation was implemented shortly (500 ms) after the applied disturbance in [7], which introduced a significant improvement in execution times. Currently, the *IEEE task force on interfacing techniques for simulation tools* elaborates on the coupling of several power system simulation tools, among which EMT-type and stability-type simulators [8]. Here, the focus will be on the inclusion of the averaged VSC model into a stability-type simulation by hybrid methods. This allows accurate inclusion of dc networks into stability studies.



(a) General interface scheme for hybrid simulations



(b) Interface network used in this paper

Figure 2: Network arrangement around the interface location

Simulation approach

EMT-type simulations usually apply a fixed time-step size, i.e. $t_{m+1} = t_m + h_{emt}$. These time step-sizes are several orders of magnitude smaller than those employed for stability-type simulations ($h_{emt} = 50\,\mu s$ is a typical value). The stability simulator is assumed to be the main simulation environment because the largest part of the network is expected to be ac. VSC models and dc cables are included in a minor EMT-type integration loop. At or around the VSC connection node, both simulations are connected by an interface network, included into the EMT-part, in which both simulations are represented by equivalent sources and Thévenin impedances. Subsequently, the voltage at the interface node is measured and used to update the ac voltage source in the detailed system. The general structure in shown in Fig. 2a. Here, both simulations are coupled at the connection point of the VSC and the interfacing techniques are a variation on the ones used in [9]. The equivalent Thévenin impedance of the ac network seen from the interface node, represented by the series connection of L_{th} and R_{th}, is calculated at $t = 0\,s$ and is assumed to be constant until a disturbance occurs. The Thévenin impedance of the VSC is equal to the phase reactance and the VSC is modelled according to the averaged model shown in Fig. 1b, which allows the interface network to be included into the EMT-type simulation as depicted in Fig. 2b. In the stability-type simulation, the interfaced system is included by an equivalent complex current injection.

Equivalent source representations

Due to the chosen network arrangement, the voltage dictated by the VSC equals the Thévenin equivalent needed for the interface network. At the start of each EMT calculation step, t_m, the Thévenin equivalent voltage $\underline{E}_{th}$ of the ac network is calculated by

$$\underline{E}_{th} = \underline{V}_{int} + \underline{I}_{int} Z_{th} = E_{th} \mathrm{e}^{\mathrm{j}\theta_{th}} \tag{1}$$

where $\underline{V}_{int}$ and $\underline{I}_{int}$ are the interface node voltage and current injection phasors at the start of the stability time step t_n respectively, E_{th} is the Thévenin voltage amplitude, and θ_{th} the angle with respect to the reference source. The three-phase voltage source in Fig. 2b is then updated each EMT calculation step according to

$$\begin{cases} e_a^{t_m} = \dfrac{\sqrt{2}}{\sqrt{3}} E_{th}^{t_n} \cos\left(\delta_{ref} + \theta_{th}\right) \\ e_b^{t_m} = \dfrac{\sqrt{2}}{\sqrt{3}} E_{th}^{t_n} \cos\left(\delta_{ref} + \theta_{th} - \dfrac{2\pi}{3}\right) \\ e_c^{t_m} = \dfrac{\sqrt{2}}{\sqrt{3}} E_{th}^{t_n} \cos\left(\delta_{ref} + \theta_{th} + \dfrac{2\pi}{3}\right) \end{cases} \tag{2}$$

in which

$$\delta_{ref} = \int_{t_0}^{t_m} \omega_{ref} \, \mathrm{d}t \tag{3}$$

where ω_{ref} is the ac network fundamental frequency. The network quantities in (2) can be updated after each calculation step of the stability-type simulation (i.e. at $t = t_{n+1}$), or can be kept fixed during the simulation run.

The network simulated by EMT is represented into the stability-type simulation by an equivalent current source, $\underline{I}_{int,emt}$. Because of the chosen implementation of the interface network, $\underline{I}_{int,emt}$ can be extracted from the current through the phase reactor by Fourier techniques relatively easy. As stability studies assume balanced conditions, $\underline{I}_{int,emt}$ is computed as the positive sequence part of the complex phasors calculated from i_{abc} (see Fig. 2a), which are given by

$$\begin{aligned} i_r &= \hat{\imath} \cos\left(\omega_{ref} t_m + \phi_r\right) = \hat{\imath} \cos\left(\frac{2\pi}{N} m + \phi_r\right) \\ &= \frac{\hat{\imath}}{2} \left[\mathrm{e}^{\mathrm{j}\left(\frac{2\pi}{N} m + \phi_r\right)} + \mathrm{e}^{-\mathrm{j}\left(\frac{2\pi}{N} m + \phi_r\right)} \right] \end{aligned} \tag{4}$$

with $r = \{a, b, c\}$, $\hat{\imath}$ the current amplitude, m the EMT calculation step, ϕ_r the phase angle with respect to the reference source, and N the amount of simulation steps that span one fundamental period, i.e. $N = \frac{\omega_{ref} h_{emt}}{2\pi}$. Then, the discrete Fourier series spectral coefficients of the phase currents are given by

$$a_{k,r} = \frac{1}{N} \sum_{p=m-N}^{m} i_r(t_p) \mathrm{e}^{\mathrm{j}\frac{2\pi}{N} km} = A_{k,r} \mathrm{e}^{\mathrm{j}\theta_{k,r}} \tag{5}$$

with k the k^{th} harmonic component. Only the fundamental frequencies are of interest in this case, i.e. $k = \{-1, 1\}$ and as the current is real, $a_k = a_{-k}^*$. By the time-shifting property, the current phasors can be derived from the spectral coefficients by

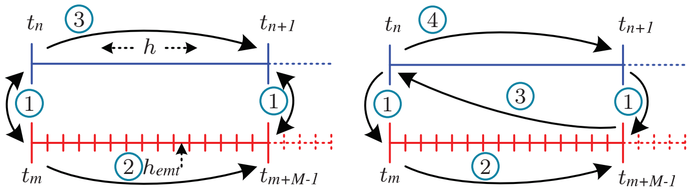
$$\underline{I}_r = I_r \mathrm{e}^{\mathrm{j}\phi_r} = \sqrt{2} A_{k,r} \mathrm{e}^{\mathrm{j}\theta_{k,r}} \mathrm{e}^{-\mathrm{j}\delta_{ref,N}} \tag{6}$$

here $\delta_{ref,N}$ equals δ_{ref} at $t = t_{m-N}$. The current injection into the network included into the stability-type simulation can now be obtained by

$$\underline{I}_{int,emt} = -\frac{1}{3} \left(\underline{I}_a + \underline{I}_b \mathrm{e}^{\mathrm{j}\frac{2\pi}{3}} + \underline{I}_c \mathrm{e}^{-\mathrm{j}\frac{2\pi}{3}} \right) \tag{7}$$

Integration into numerical routine

The variables to be exchanged between the two solvers at the interface location are $\underline{E}_{th}$ and ω_{ref} from the stability-type simulation and the current injection $\underline{I}_{int,emt}$ from the EMT-type simulation. The way in which this coupling is performed in time may substantially influence the performance of the simulation, most notably the accuracy. Here, both simulations use a fixed time-step size, with $h > h_{emt}$, which allows the exchange of network quantities at predefined points in time. The overall solution schemes of the hybrid simulation environment used for this paper are depicted in Fig. 3. In Fig. 3a, interfacing takes place after each calculation step of the stability-type simulation, which implies that only information from the previous time step is available for both solvers. A slightly different order is shown in Fig. 3b, where the EMT-part of the simulation is solved before the stability part. This offers the advantage of knowing information about the network and models simulated in detail before each stability calculation step. More elaborate interface protocols are summarised in [8], but are considered outside the scope of this paper.



(a) Normal calculation order

(b) Alternative calculation order

Figure 3: Numerical interface between stability-type and EMT-type simulation

Simulation studies

The numerical performance, particularly the accuracy, of the discussed interfacing methods for hybrid simulation will now be tested on the network shown in Fig. 4. It consists of a 600 MVA offshore WPP, which is connected to the mainland system by two 300 kV bipolar VSC-HVdc cable connections. The onshore system is rated 230 kV and is represented by a slack node, two aggregated local loads, and a 150 MVA-rated synchronous generator. The two onshore VSC terminals are rated 300 MVA each and have 10% over current capability. In normal operation it is assumed that VSC1 and VSC2 feed an equal amount of active power to the ac system, hence there is no considerable power flows along the transmission line in between N2 and N3.

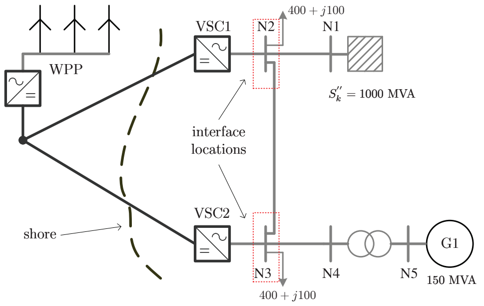


Figure 4: Test network used for simulation studies

The onshore system is simulated by the stability-type simulation whereas the offshore system is simulated by an EMT-type simulation. The offshore WPP is represented in a simplified fashion by a variable power source in the dc network, including appropriate power reduction mechanisms for riding through onshore faults [10]. As this work focuses on the simulation method no detailed modelling of the WPP has been performed. The onshore VSCs are included in the EMT simulation by the averaged model, shown in Fig. 1b. The model employs vector control to regulate the active and reactive power exchange with the network, with giving precedence to the active power component of the current in case operating limits are violated. The interface scheme represents both VSCs into the stability part by a complex-phasor current injection, taking N2 and N3 as interface locations at which Thévenin equivalents are determined.

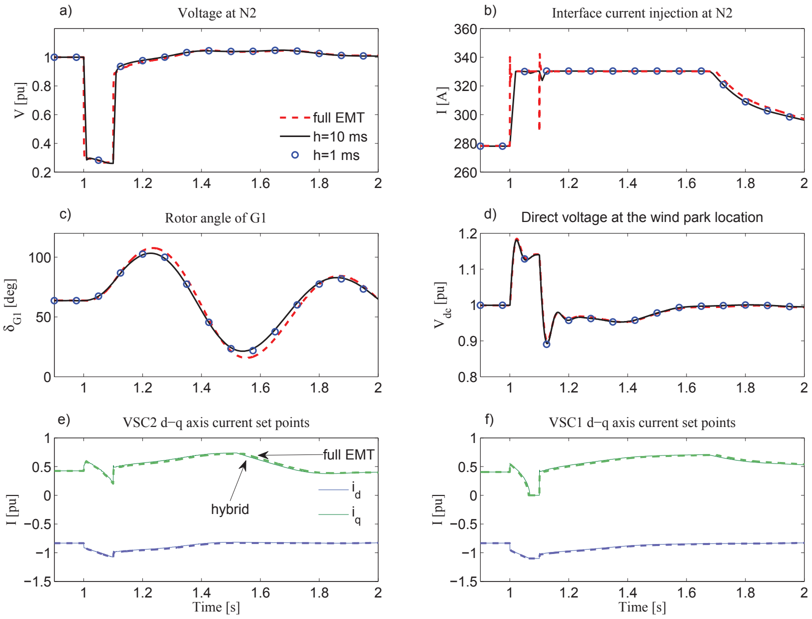


Figure 5: System response for a voltage dip in the infinite grid for two different time-step sizes.

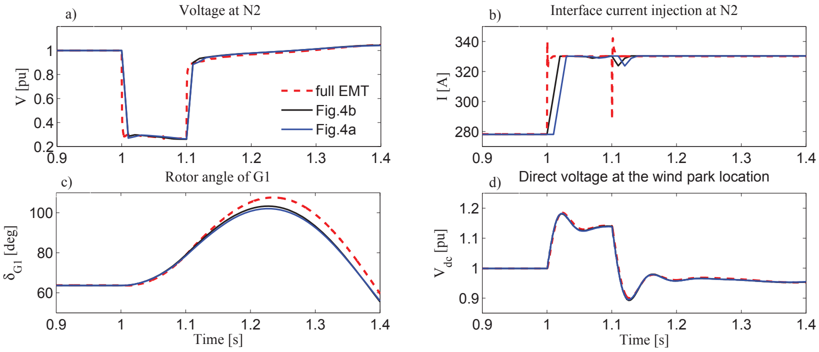


Figure 6: System response for a voltage dip in the infinite grid for two different interface orders.

Loads are included as fixed impedances, and G1 is represented by a 5^{th}-order model, with elimination of stator transients, but including effects of damper windings [11].

The hybrid simulation was implemented in Matlab. The stability part of the simulation is based on a partitioned explicit method for solving the resulting system of differential-algebraic equations, using a predictor-corrector method for numerical integration [12]. The EMT part of the simulation is based on the nodal analysis method, which uses numerical integrator substitution to include branch elements into an implicit trapezoidal integration algorithm, with $h_{emt} = 50\,\mu\text{s}$ as time-step size [13]. At both interface locations, the interface network shown in Fig. 2b is implemented. The network was also simulated entirely in EMT using PSS®NETOMAC for verification reasons.

First, the hybrid simulation is tested by using the numerical interface of Fig. 3b to couple both solvers. At $t = 1\,\text{s}$, a three-phase fault occurs in the infinite grid, which is subsequently cleared after 100 ms. The system response for two different stability-type simulation time step sizes, $h = 10\,\text{ms}$ and $h = 1\,\text{ms}$, is shown in Fig. 5. During the fault, the offshore WPP curtails its power output to keep the direct voltage at an acceptable level. After the disturbance, the wind power is assumed to be fully available and the prefault operating conditions to be restored. It can be observed that the voltage and current profiles following the disturbance show great similarity to the full EMT simulation, which suggests a proper functioning of the proposed interface. However, a few differences can be observed. First, the amplitude of the current injection phasor shows small ripples. This is due to the discontinuities caused by VSC1, which runs into its current limit during the fault, and the rapidly changing ac network quantities, which are updated at $t = t_n$ only. This induces a quick change in the angle of the VSC current, which is reflected in the amplitude calculation as (small) ripples. The full EMT simulation in PSS®NETOMAC uses a different method to calculate the phasor amplitude, which is faster but at the same time more sensitive. The largest difference can be noticed for the rotor angles of G1, which can be attributed to the fact that a more detailed generator model as well as a slightly different interface to the network solver is used for the full EMT-type simulation. For this network, no considerable differences between the employed time-step size for the stability-type simulation can be observed, which gives rise to use $h = 10\,\text{ms}$ for the next case.

To show the effects of the order in which both simulations communicate, the previous case was also performed with the numerical interface shown in Fig. 2a. As can be seen in Fig. 6, the current injection phasor lags 10 ms behind as compared to the previously used interface, which may result in too optimistic results, particularly for stability studies. The network quantities that are provided to the EMT-type simulation from the stability-type simulation are derived from the previous stability calculation step, and hence no notable differences can be observed in, for instance, the direct voltage. Finally, the response of the rotor angle shows that the results according to interface shown in Fig. 3b lie slightly closer to the full EMT solution.

Conclusions and outlook

On transmission level, VSC-HVdc is becoming a mainstream technology, to a large extent due to grid connection of renewables. Indispensable for grid integration studies is a thorough assessment of the influence on system dynamics of these future transmission expansions, which is traditionally performed with stability-type simulations. In many cases, idealised models of VSC-HVdc can be used. For multi-terminal schemes with high power ratings, however, complex protection mechanisms and other nonlinearities may seriously affect the dynamic behaviour of power systems and its corresponding transient stability. To assess these phenomena properly, more detailed models and network representations are necessary, most prominently a suitable inclusion of the dc part of the network.

This paper discussed the inclusion of detailed VSC-HVdc models and dc networks into stability-type simulations by hybrid simulation methods, as well as the particular cases in which these methods can facilitate these dynamic studies. At the coupling location, network quantities are exchanged between both simulations. In this contribution, the ac connection node of the VSC terminals was chosen to be the interface node. The ac network was included into the EMT-type simulation by a Thévenin equivalent, which was updated every calculation step, whereas the part of the network simulated in EMT was included into the stability-type simulation by a current injection phasor, calculated from the discrete Fourier transform.

The interfacing methods were implemented in Matlab, tested on an exemplary network, and compared to a full EMT-type simulation, executed in PSS®NETOMAC. It can be concluded that in general, the hybrid simulation resembled the full EMT-type simulation comparatively well. The method to capture current phasors from the EMT waveforms performs as expected: rapidly changing network quantities and limiting actions are reflected in the calculated amplitudes as small ripples. The sensitivity toward the time-step size used for the stability-type simulation was studied by repeating the simulation at a smaller time-step size, and it turned out that this sensitivity was low for this network. Subsequently, the order in which both simulation are solved in time was changed. It was shown that, for each calculation step of the stability-type simulation, the accuracy of the simulation slightly improved in case the EMT-type simulation was run before the stability part was executed.

The presented work gives rise to new research directions. First, the method was examined on a very small network with a relatively high penetration of VSC-HVdc, which was mainly done to show the accuracy of the interface method. Future work will focus on the expected gain in execution times with respect to full EMT-type simulations as well, which needs a larger test network. Furthermore, the proposed method was particularly designed for representing VSCs into stability simulations. Hence, future work will focus on interfacing in a more general sense, i.e. by interfacing arbitrary networks to each other.

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