Objetivo 1
The Application of Power Electronics to Smart Grids.
Simulation tools for AC/DC systems in smart grid applications.

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1 Executive Summary

The available simulation tools for steady-state analysis (power-flow calculation) and dynamic analysis of hybrid AC/DC grids will be studied, in this report. Dynamic simulation of power systems can be divided into (a) electromechanical simulation, which neglects some fast dynamics and is suitable for large power systems with a good deal of conventional generators, and (b) electromagnetic simulation, which uses more detailed models and is appropriate to test the control system of power electronics devices.

Findings can be summarised as follows:

- All the tools reviewed can carry out power flow analysis of AC grids, but some of them cannot be used for Hybrid AC/DC grids. Nevertheless, programming sequential-type power flow algorithms to fill this gap is always possible with a reasonable effort.

- Electromechanical simulation is appropriate for large power systems with a good deal of conventional generation in which the inertia of the rotating machinery makes it possible to ignore fast dynamics (i.e. line dynamics).

- Small signal analysis based on electromechanical simulation is also appropriate for large power systems, as described above.

- Electromagnetic simulation is more appropriate for small-size power systems in which power electronics is involved. In most tools, converter switches can be included and detailed.

- Small signal analysis based on electromagnetic simulation must be used in power systems where the fast dynamics of the power lines cannot be neglected. A clear example of this case is when there is little (or no) conventional generation and load supply relies on power electronics converters.

- DigSilent can be signalled out from the electromechanical simulation tools while Matlab+Simulink can be signalled out from the electromagnetic simulation tools.

- Real-time simulators can also be used when fast simulation is required. Besides, they make it possible to interact with physical devices to run hardware-in-the-loop (HIL) tests. While RTDS is, probably, the tool most widely spread in industry, OPAL-RT has been gradually gaining a relevant position in the market. An important advantage of the latter is that it runs seamlessly with Matlab+Simulink and, therefore, it can benefit to the already large community of users they have.

This report also includes some simulation examples and small signal simulation studies using a microgrid with power electronics converters. Special attention has been give to the comparison of different tools and to the explanation of droop control in microgrids.

2   Control of changes

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3   Introduction

Smart grids are being planned to be efficient, reliable and sustainable. To make this possible, communication systems and power electronics devices will play a relevant role. Future smart grids are expected to contain some of the following elements:

- Generators based on renewable resources (wind turbines and Photovoltaic (PV)).

- Distributed generators (renewable and conventional).

- Storage devices.

- Microgrids (AC, DC or hybrid).

- Communication systems.

- Flexible AC Transmission Systems (FACTS).

- High Voltage Direct Current (HVDC) point to point links either based on Line Commutated Converters (LCCs) or based on Voltage Source Converters (VSCs).

- HVDC grids based on VSCs.

Under this scenario, it is essential to have suitable simulation tools for AC/DC systems.

In this report, the available simulation tools for steady-state analysis (power-flow calculation) and dynamic analysis of hybrid AC/DC grids will be studied. Dynamic simulation of power systems can be divided into (a) electromechanical simulation, which neglects some fast dynamics and is suitable for large power systems with a good deal of conventional generators, and (b) electromagnetic simulation, which uses more detailed models and is appropriate to test the control system of the devices. Specifically, this study will cover the following types of simulation of power systems:

- Seady-state simulation

    - Power-flow calculation

- Dynamic simulation

    - Non-linear time-domain simulation

        * Electromagnetic simulation
        * Electromechanical simulation

    - Small-signal analysis (SSA)

        * Electromagnetic approach
        * Electromechanical approach

The applicability of some of the most relevant currently available tools to the following type of systems will be explored:

- Hybrid AC/DC systems in general.

- AC microgrids with VSC-based generation (without interest on the DC side of the converters).

- Hybrid AC/DC microgrids with VSC converters.

The classification above covers typical scenarios in smart grids.

Some tools are only prepared to simulate AC grids, although they may include models of some specific devices, such as VSC generators. These tools could be used for the simulation of AC microgrids , but they do not allow the study of systems in which the terminals at the DC side are connected (DC multi-terminal systems). On the other hand, other tools may admit the simulation of hybrid AC/DC systems, but whether they can deal with the particularities of AC/DC microgrids (small size), must be investigated. These aspects will be discussed in this report and the characteristics of the most relevant simulation tools will be described and compared.

A complete summary and the description of several tools for power system simulation can be found in [1, 2, 3] whilst a description of open-source simulation tools can be found in [4, 5]. The information given in those references has been very useful for this work, although the possibility of simulation of hybrid AC/DC systems with each tool was not reported explicitly there. The present report tries to fill this gap and pays special attention to the applicability of the current simulation tools to the simulation of hybrid AC/DC systems.

4 Power Flow Tools

Power-flow algorithms are used to solve power system equations in steady-state in order to obtain viable operating points of the system. These points can then be studied in detail and/or used as initial equilibrium points for dynamic simulation. This is why, almost all dynamic-simulation tools also include the possibility of performing power-flow calculation. However, it is obvious that using powerful dynamic simulators only to perform steady-state analysis would not be practical and, moreover, some specifically-designed steady-state tools will often be more reliable, flexible and complete for this purpose.

Power-flow calculations are commonplace in traditional AC systems and, therefore, all software tools can carry out this type of studies. The inclusion of VSC generators (without interest in their DC side) is trivial, since they can be modelled as traditional generators (as PV buses, PQ buses or slack buses). Therefore, it should not be a problem to find tools to carry out power-flow calculations in AC microgrids.

A different situation is found when hybrid AC/DC systems are considered. In this case, the electrical system could contain meshed AC grids and meshed DC grids which are coupled through (DC-to-AC) electronic converters (VSCs are the best alternative in this context); and upgrading of traditional power-flow tools is required.

Hybrid AC/DC power-flow algorithms can be classified into two categories, namely, unified and sequential methods. The former solve the power flow equations of the AC and DC grids simultaneously, whereas the latter have an external iteration in which the AC and DC power flows are calculated sequentially. The unified methodology has better numerical stability while sequential methods have the advantage that they can be incorporated to existing AC power-flow tools without modifying the AC power-flow algorithms. Several steady-state solvers for AC/DC power-flow calculation with multi-terminal VSC-HVDC systems (MTDC, for short) have been reported in the literature with unified methods [6, 7] and with sequential methods [8, 9, 10, 11]. Among those references, the study of a unified algorithm proposed in [7] and the one for a sequential algorithm proposed in [10] are worth pointing out. In both cases, hybrid AC/DC grids with arbitrary topology can be studied and all the components of VSC stations, converter losses and converter limits can be included.

The following simulation tools for power-flow calculation are described in this report:

- PSS/E (Siemens)

- PowerFactory (DigSilent)

- EUROSTAG (Tractebel Engineering)

- MatACDC

- PSAT

- SimPowerSystems (Matlab + Simulink)

4.1 PSS/E

PSS/E is a commercial simulation tool for power system analysis developed by Siemens and it is widely used in industry. PSS/E can be used to perform power-flow calculation and dynamic analysis (electromechanical) of power systems and it is often used to solve large electrical grids [12]. AC grids can be included easily for power-flow analysis, since any generator or load can be modelled as a PQ, PV or AC-slack bus, depending of the particular device, just like the traditional generators and loads.

Models of VSC generators and other FACTS devices, such a STATCOMs, can also be included in the the power-flow calculation. PSS/E also offers a VSC-HVDC point-to-point model within its libraries but it does not offer VSC-MTDC models. However, power-flow algorithms for VSC-MTDC systems can be developed with an external python script, using sequential methods and calling PSS/E to solve the AC power flow, as detailed in [13].

Hybrid AC/DC power-flow algorithms have also been implemented in PSS/E in [14, 15, 16, 17].

4.2 PowerFactory

PowerFactory is also a popular commercial tool for the analysis of large power systems. It was developed by DigSilent and it can be used to perform power-flow calculations and dynamic (both electromechanical and

electromagnetic) simulation [18].

PowerFactory libraries offer many devices, such as wind generators, PhotoVoltaic (PV) generators, FACTS, VSC converters and DC grids, among others. Therefore, this software can be used successfully to perform steady-state analysis of hybrid AC/DC systems.

Examples of power-flow calculations for hybrid AC/DC grids using PowerFactory can be found, for example, in [11, 19].

4.3 EUROSTAG

EUROSTAG is a commercial simulation tool for power-flow calculation and dynamic simulation of large power systems developed by Tractebel Engineering (GDF Suez).

This tool includes models for hybrid AC/DC grids and, hence, it is suitable for power-flow calculations on this type of systems [20]. An example of simulation of VSC-HVDC multi-terminal systems using EUROSTAG tool can be found in [21].

4.4 MatACDC

MatACDC is an open-source tool for power-flow calculation of AC/DC grids [22]. It is based on Matlab + Matpower [23] and it was developed by Prof. Jef Beerten and Ronny Belmans at the University of Leuven (KU Leuven). This tool uses the sequential AC/DC power-flow algorithm proposed in [10]. Its applicability to AC/DC microgrids is straightforward.

Different test examples have been included in the toolbox and a comprehensive description and a full case study can also be found in [22]. This tool was also used in [17] to validate the PSS/E AC/DC power-flow algorithm for hybrid AC/DC grids developed in the project reported there.

4.5 PSAT

PSAT is a Matlab-based open-source tool for power-flow calculation and dynamic simulation of power systems [24].

For power-flow calculation, different FACTS models can be used. To start with, it is only valid for AC grids. Nevertheless, in a similar way as explained for PSS/E, AC/DC power-flow algorithms, using sequential methods [10], can be implemented to perform steady-state analysis of hybrid AC/DC systems.

PSAT was used to simulate hybrid AC/DC systems in [25], although the details of the implementation of the power-flow algorithm were not given in that paper.

4.6 SimPowerSystems

SimPowerSystems is a toolbox in Matlab + Simulink and it is aimed to perform steady-state and dynamic (electromagnetic) simulation of electrical systems [26]. The tool is commercial and it was developed by Hydro-Quebec and Mathworks. SimPowerSystems has been used successfully for the simulation of synchronous machines, VSC-HVDC systems and FACTS devices. It is suitable for the simulation of relatively small systems and its application for large systems is limited due to the computational effort required and also due to the box-based graphical environment, which is very friendly but it becomes very clumsy when the number of buses is big.

Although SimPowerSystems focuses on dynamic simulation and control, the initial operating point is obtained with the calculation of power flow, which allows to perform steady-state analysis. Power-flow calculations can be done for AC systems with synchronous machines and loads, among other devices. Power electronics devices, VSC-HVDC links for example, are also included in the libraries. However, a power-flow calculation can not be done when using those devices because the power converters are represented with detailed switching models in order to carry out electromagnetic simulation. Nevertheless, VSC converters can be easily modelled as ideal voltage or current sources, depending on the application, and this makes it possible to perform power-flow calculations in AC grids with VSC generators, as in AC microgrids, for example. Power-flow analysis of DC grids is not readily available with this tool, but the flexibility provided by simulink tool can be used to model a DC grid as a compact block containing the necessary differential equations and AC/DC power-flow algorithms could be implemented by the user.

4.7 Summary of power-flow analysis tools

PowerFactory, EUROSTAG and MatACDC can be used successfully, without any extra work, to perform power-flow analysis of both: (a) AC girds with VSC-type generators and (b) hybrid AC/DC grids. Meanwhile, PSS/E and PSAT can be used straightforward for steady-state analysis of AC grids with conventional and/or VSC-based generation, while power-flow algorithms for hybrid AC/DC grids must be implemented by the user. SimpowerSystems can be used for power-flow analysis of AC grids, but hybrid AC/DC systems are not readily admitted by this tool. Power-flow algorithms suitable for hybrid AC/DC systems could be implemented making use of extra scripts prepared by the user. Furthermore, SimPowerSystems is not appropriate to work with large-size grids.

A summary of the applicability to power-flow calculations of the tools analysed is reported in Table 1.

Tool (Power flow)	type	large systems	AC grids with VSC gens.	AC/DC grids
PSS/E	commercial	yes	yes	user defined
PowerFactory	commercial	yes	yes	yes
EUROSTAG	commercial	yes	yes	yes
MatACDC	open source	yes	yes	yes
PSAT	open source	yes	yes	user defined
SimPowerSystems	commercial	no	yes	user defined

Table 1: Summary of the applicability of different simulation tools for power-flow calculation in hybrid AC/DC grids.

5 Electromagnetic simulation tools

ElectroMagnetic Transient (EMT) simulators are used to analyse fast transients in power systems. The time constants of interest are between $10^{-7} - 10^{-2}$ s. Typical applications of ETM simulation are [27]:

- Insulation coordination studies (over-voltages due to lightning and energisation).

- Transient recovery voltage studies.

- Harmonic studies.

- Power electronic devices (and their interaction with the power system).

Depending on the application, different types of EMT models should be used. In this work, the following EMT simulators will be described and classified:

- Average models

    - Simulink
    - PowerFactory

- Switching models

    - Simulink + SimPowerSystems
    - PSCAD
    - PowerFactory
    - EMTP-RV

- Real-time simulators.

    - RTDS
    - eMEGAsim (OPAL-RT)
    - HYPERSIM (OPAL-RT & IREQ)

- Summary.

EMT average models only take into account the first harmonic (50 or 60 Hz) and they are suitable for power system studies or to study the stability of the main loops of electronic converter controllers. They cannot describe harmonics or internal commutation failures of the converters, for example. On the other hand, switching models represent the switches of the power converters and they are used for more detailed studies (e.g. harmonics or to study the behaviour of semiconductor devices). A detailed comparison of ETM average and switching models of Modular Multi-level Converters (MMC) in VSC-HVDC systems can be found in [28].

Real-time time simulation tools are intended for very fast simulation of electrical systems combined with hardware devices (this situation is often called Hardware-in-the-loop or HIL simulation). To achieve this, the differential equations must be solved in several computer cores working in parallel (parallel computing). While the simulators discussed previously run in general purpose computers, real-time simulators require special and dedicated hardware.

5.1 EMT average simulators

EMT average models are used when only the fundamental-frequency component of the variables is of interest. For example, these type of models are used to study the interaction of power electronics devices with the rest of the system. Naturally, the computational cost is much lower than when the switches of the semiconductors are modelled.

5.1.1 Matlab Simulink

Matlab + Simulink can be used for electromagnetic simulation of AC (or hybrid AC/DC) power systems using average models and a very-friendly user interface. Devices should be modelled by the user using a global synchronous rotating frame (DQ0 frame), including the states of the lines (AC or DC). VSCs can be modelled by the user, implementing their controllers using vector control (in local synchronous rotating axes, dq0 frames), whilst each DC grid can be represented as a linear model inside a single block. Relatively small systems can be simulated with this tool. The initial operating point can be calculated using power flow tools, solving a set of non-linear algebraic equations ("trim" command) or running the simulator and ignoring the initial transient.

5.1.2 PowerFactory

Electromagnetic transient simulation using fundamental-frequency models can also be carried out with PowerFactory. Models for VSC and hybrid AC/DC grids are readily available and they can be used "out of the box". However, PowerFactory models will often not include all the control loops needed for the electronic converters, but the user can include them easily in what is called DSL language. For example, this is the case of the outer controllers of VSCs (power and AC voltage controllers). Electromagnetic simulation of large systems can easily be done with PowerFactory.

5.2 EMT switching simulators

EMT switching models include the switches of the power electronics converters and, in general, these type of simulators are aimed to:

- Analyse the dynamic behaviour of the whole system, including the more detailed and realistic models of the power converters.

- Analyse the dynamics of converter components which are omitted in simplified models. For example, voltage at the semiconductors terminals, commutation failures, etc.

- Harmonic analysis.

- Validation of fast-dynamics models.

Naturally, switching simulators also include the possibility of simulating average models of those devices which need not be analysed in detail. A summary of all the EMT simulators will be presented at the end of this section (Table 2).

5.2.1 SimPowerSystems

The main application of Simulink + SimPowerSystems is to perform electromagnetic transient simulation of power systems, including switching models of power electronics converters. Hybrid AC/DC systems can be modelled and simulated with this tool. For example, electromagnetic simulation of hybrid AC/DC microgrids with SimPowerSystems has been treated in [29]. As has been mentioned before, one disadvantage of this tool is that it is aimed to simulate relatively-small systems.

5.2.2 PSCAD

PSCAD is an EMT simulator developed by Manitoba HVDC Research Centre and it has been widely used for electromagnetic transient simulation of electrical systems with power electronics devices. It is suitable for dynamic simulation of hybrid AC/DC grids. Several models of power electronics devices are provided and user-defined models can also be easily implemented.

5.2.3 PowerFactory

PowerFactory has the option to simulate the switches of some power electronics devices. For example, models of VSCs with Pulse Width Modulation (PWM) are included in its libraries.

5.2.4 EMTP-RV

EMTP-RV is an electromagnetic transient simulator developed by Jean Mahseredjian. Currently, it is developed by POWERSYS [3]. Power electronics switches can be simulated as part of power converters in electric systems.

5.3 Real-time simulators

In real-time simulators, the simulation time must be almost equal to the real-world time. In other words, the simulation of 10 ms should spend almost 10 ms of real time. The fast dynamics involved in electrical systems makes real-time simulation more difficult than in other types of physical systems, such as mechanical ones, for example. Therefore, to be able to simulate large power systems in real time, the simulator must split the grid into several parts and solve them in parallel using several processors or cores [30]. A typical value for the time step in real-time simulation of power systems is 50 μs.

In the context of smart grids, real-time simulation can be useful for [30]:

- Hardware-in-the-loop (HIL) simulation. In this process, hardware and software can be simulated together. For example, protection systems (hardware) can be plugged into a simulation model of a power system (software). The protection relay will read variables from the simulator and will send back orders accordingly. HIL simulation can also be used for testing communication systems, Phasor Measurement Units (PMUs) or control systems.

- Fast simulation. It aims to simulate large and/or complex systems (including power electronics converters with switching details) (only software) within a reasonable time.

5.3.1 RTDS

RTDS is a real-time simulation developed by RTDS Technologies Inc. This simulator is, probably, the most extended in industry and it has been widely used for real-time simulation of electrical systems. The software libraries include models for power electronics converters. This simulator can readily handle hybrid AC/DC systems An example of real-time simulation with a microgrid using RTDS can be found in [31].

5.3.2 eMEGAsim (OPAL-RT)

eMEGAsim is a tool for real-time simulation developed by OPAL-RT. It interfaces naturally with Simulink + SimPowerSystems and, therefore, it is an attractive solution for those already familiar with Matlab, Simulink and their toolboxes. It can be used to simulate power converters and hybrid AC/DC systems in general. In fact, its libraries include several models for power electronics converters.

Several smart grids projects in which eMEGAsim has been used for real-time simulation of microgrids are described in [32] whilst [33] describes how eMEGAsim was used to study oscillation damping algorithms using PMUs.

5.3.3 HYPERSIM (OPAL-RT & IREQ)

HYPERSIM is a real-time simulator developed by IREQ (Hydro-Quebec) and OPAL-RT. It can easily handle hybrid AC/DC systems. HYPERSIM is more appropriate than eMEGAsim to simulate larger power systems [34]. For example, the transmission system operator in France (Réseau de Transport d'Électricité, RTE) has used it for real-time simulation of SVCs and VSC-HVDC systems. The real-time simulation of the new VSC-HVDC interconnection between France and Spain (INELFE) using HYPERSIM was reported in [35].

5.4 Summary

A summary of all the ETM simulators described is reported in Table 2, concluding that all ETM can be used for the simulation of hybrid AC/DC systems with power electronics. If necessary, simulation can be carried out including the switching behaviour of converters.

Tool (ETM)	type	large systems	average models	switching models	real time sim.	AC/DC systems	AC systems (VSC gens.)
Simulink	C	no	yes	no	no	yes	yes
PowerFactory	C	yes	yes	yes	no	yes	yes
SimPower	C	no	yes	yes	no	yes	yes
PSCAD	C	yes	yes	yes	no	yes	yes
EMTP-RV	C	yes	yes	yes	no	yes	yes
RTDS	C	yes	yes	yes	yes	yes	yes
eMEGAsim	C	yes	yes	yes	yes	yes	yes
HYPERSIM	C	yes	yes	yes	yes	yes	yes

Table 2: Summary of the applicability of different simulation tools for ETM simulation, including real-time simulators. Type: C=commercial, F=free.

6 Electromechanical simulation tools

The main concern of electromechanical transient simulation of power systems is the electromechanical dynamics of the electrical machines and it covers time constants from 0.1-10 s [36]. In this type of simulation, dynamic models of the generators, excitation systems and prime governors are used while the dynamics of the AC branches are assumed to be instantaneous and they are represented by impedances. Therefore, the relation between currents and voltages is modelled with a set of algebraic equations. This simulation has been used extensively in traditional power systems where conventional synchronous generators where the only (or at least the most important) energy sources. Tools available for electromechanical simulation are specially suitable to handle large systems.

However, in the context of microgrids with non-conventional generation power electronics converters (VSC type) are bound to be the most important sources of energy (if not the only ones). In this situation, the dynamics of the system will be governed by the interaction of the control actions of the VSCs and the grid (AC and/or DC). Therefore, in some cases, electromechanical simulation will not be appropriated to analyse microgrids, in particular for stability analysis. Nevertheless, if it is known a priori that the system is stable, this type of simulation may still be useful in the context of microgrids without conventional generation to study low-frequency dynamics. The applicability of electromechanical simulation in microgrids will be further investigated in the case study of Section 8.3.

The following tools for nonlinear time-domain electromechanical simulation will now be described:

- PSS/E (Siemens)

- PowerFactory (DigSilent)

- EUROSTAG (Tractebel Engineering)

- PSAT

- MatDyn

- SimPowerSystems (Matlab + Simulink)

6.1 PSS/E

PSS/E is suitable for electromechanical simulation of large power systems. Its libraries include dynamic models of wind turbines, FACTS (a generic shunt+series combination of VSCs), LCC-HVDC point-to-point links and VSC-HVDC point-to-point links. Also one LCC-HVDC multi-terminal model is included. PSS/E does not provide models of VSC-HVDC multi-terminal systems. However, as shown in [13], the simulation of this type of systems and hybrid AC/DC systems is possible by developing user-defined models. In PSS/E, user-defined models can be coded in FORTRAN programming language. The VSCs can be modelled as generators and the user can write the state equations of the desired dynamic parts and controllers. A DC grid model coupling the DC buses of the different VSCs can also be developed with an external user-defined model. The DC grid model must exchange variables with the AC grid. The initial operating point must be obtained from the AC/DC power-flow algorithm, which can be implemented as described in Section 4.1.

PSS/E models for electromechanical simulation of hybrid AC/DC systems using VSC technology have been presented in [14, 15, 16, 17].

6.2 PowerFactory

PowerFactory can also be used for electromechanical simulation of electrical systems. Library models of VSCs and DC grids are provided, making this tool a very attractive alternative for electromechanical simulation of hybrid AC/DC grids. VSC models include their inner current controllers and the outer controllers have to be developed by the user, using DigSilent Simulation Language (DSL), which has a user friendly block-diagram type of interface, similar to Simulink.

PowerFactory has been used for electromechanical simulation of VSC-HVDC multi-terminal systems in, for example, [19, 37].

6.3   EUROSTAG

Electromechanical simulation of power systems can be carried out in EUROSTAG. LCC-HVDC links, VSC-HVDC links and VSC-HVDC multi-terminal systems can be readily handled [20]. For example, this tools has been used to simulate VSC-HVDC multi-terminal systems in [21]. It is also appropriate to simulate large systems.

6.4   PSAT

PSAT can be used for the electromechanical simulation of power systems, including large ones. As mentioned in Section 4.5, it includes models of many power electronics devices. To star with, it is valid only for AC grids. However, the structure of the tool and its open code, makes relatively easy for users to implement their own models. Dynamic models of VSC converters and DC grids connecting VSCs can be coded by the user, as done in [25].

6.5   MatDyn

MatDyn is an open-source and free tool for electromechanical dynamic simulation of power systems developed in KU Leuven [38]. It has been written using Matlab and it uses Matpower (also open source and free) [23] to calculate the initial operating point. The libraries in MatDyn do not include either models of VSCs or DC grids. However, similarly to PSAT, the tool is more user friendly than the commercial simulators and these type of models can be developed and included by the user. For example, VSC-HVDC multi-terminal models for electromechanical simulation using MatDyn are reported in [39, 21]. Large-scale systems can also be simulated with this tool. In comparison with PSAT, MatDyn offers much less models within its libraries and it is not as consolidated as PSAT. Nevertheless, a big effort has been done to give the tool a user-friendly structure, in order to facilitate the development of dynamic models. Altogether, it is an attractive tool to be used in research and education.

6.6   SimPowerSystems

SimPowerSystems can also tackle electromechanical simulation of power systems. Models of synchronous machines, exciters and governors are provided. Power electronics device models available are of electromagnetic type and, in general, they cannot be used for electromechanical simulation. If only the electromechanical time constants are of interest in systems with electrical machines, power electronics converters and DC grids, the user has two options: (a) to do electromagnetic simulation (including the switches of the converters), which inevitably will require more computational effort than necessary or (b) to carry out electromechanical simulation, modelling the VSCs as controllable voltage (or current) sources and introducing dynamic models of the DC grids as simulink blocks (not with SimPowerSystems electrical elements). This tool is clumsy when used for the simulation of large grids.

6.7   Summary

The characteristics of several electromechanical simulation tools are reported in Table 3. In principle, electromechanical simulation of hybrid AC/DC system is possible with all the tools studied. Some of them provide suitable models and, in others, users have to (and can) develop their own models. However, in microgrids, electromechanical simulation can be misleading. In the case of microgrids with only power electronics based generation, the interaction of the dynamics of the converters and the dynamics of the AC grid may be relevant and should be taken into account. In these cases, electromagnetic simulation should be used. In some other cases, this interaction may be neglected without an important loss of information. These open possibilities call for a study to investigate this point before one or the other type of simulation is chosen.

Tool (TDS)	type	large systems	AC/DC systems	AC microgrids (VSC gens.)
PSS/E	C	yes	used defined*	yes*
PowerFactory	C	yes	yes*	yes*
EUROSTAG	C	yes	yes*	yes*
PSAT	OS	yes	user defined*	yes*
MatDyn	OS	yes	yes*	yes*
SimPowerSystems	C	no	user defined*	yes*

Table 3: Summary of the applicability of different tools for non-linear time-domain electromechanical simulation of AC/DC microgrids. (*) In some microgrid scenarios (without large synchronous generation) electromechanical simulation would not be appropriate. Type: C=Commercial, OS=Open source and free.

7 Small signal analysis tools

Small signal analysis (SSA) is devoted to study the stability of the electrical system when small disturbances occur. Firs of all, a valid operating point has to be calculated. Secondly, the non-linear differential equations of the system are linearised around the operating point and a state-space type of model is written. Thirdly, the eigenvalues of the system matrix are computed. Finally, the participations of each system state variable on each eigenvalue are calculated in order to determine which variable is related to which system mode. SSA has been widely and long used in electric power systems. One can find old [40] and modern [41] monographs on this topic. For example, SSA has been used to design Power System Stabilizers (PSS) to damp electromechanical oscillations or to design the controllers of power converters, among other applications. A comparison and description of different SSA commercial tools is reported in [42].

Similarly to the case of time-domain simulation, two different approaches can be used for SSA:

- Electromechanical approach: Typically used for small-signal analysis of angle stability in power systems, where the electromechanical oscillations are of interest and the fast dynamics of the AC grid can be neglected.

- Electromagnetic approach (average models): It is useful in systems where the dynamics of interest are comparable with the dynamics of the AC grid, from the time constant involved viewpoint. Indeed, this is the case of microgrids with no synchronous generation. As will be shown in the case study of Section 8.5. SSA of microgrids (with VSC generators) will only give reliable results when electromagnetic models are used.

A description of the following SSA tools will be given in the following sections:

- PSS/E (Siemens)
- PowerFactory (DigSilent)
- EUROSTAG (Tractebel Engineering)
- SMAS3 (IIT)
- PSAT
- Simulink (Matlab)

7.1 PSS/E

The name of the commercial package to perform linear analysis in PSS/E is NEVA which uses an electromechanical approach, e.g., the dynamics of the AC lines are neglected. The tool can be used to study the power oscillation phenomena in large systems or to design Power System Stabilizers (PSSs), for example. Not all the dynamic models of PSS/E are supported by NEVA. For example, new models offered in the latest version of PSS/E such as wind turbines can not be used with the NEVA. User-defined models cannot be used, either. Therefore, for the time being, there is no way PSS/E environment can be used to fully address SSA of hybrid AC/DC grids.

7.2 PowerFactory

Small signal analysis of power systems can also be done using PowerFactory. Large systems can be simulated and the SSA approach given by the tool is of electromechanical-transient type. It includes VSC-MTDC models. However, when hybrid AC/DC systems are considered, the results of the SSA present some inconsistencies. In particular: some unexplained eigenvalues appear [43]. These eigenvalues appear only when hybrid AC/DC grids are considered and they were referred by DigSilent support team as "numerical" artefacts. They have only real part, which is negative and they have a high module (of the order order -10^{10}). This problem has been reported, but not explained, in the literature in [44, 45, 46]. Nevertheless, other references use PowerFactory for SSA of hybrid AC/DC systems without reporting any problem [47, 48, 49]. The authors of this report analysed the results of SSA analysis for hybrid AC/DC systems obtained with PowerFactory and they concluded that the results are reliable and the inconsistent eigenvalues should just be excluded of the analysis [43]. This result was possible when GEA-IIT modified an SSA tool previously developed in IIT (see Section 7.4) with the necessary elements to tackle hybrid AC/DC systems so that the results obtained with DigSilent could be compared with those obtained with a different software.

7.3 EUROSTAG

EUROSTAG is suitable for small-signal stability analysis of power systems when using its package called HERCULES. It uses models that can represent electromechanical dynamics. This tool is also suitable for the analysis of grids with a large number of buses. Small signal analysis of hybrid AC/DC systems can also be done [20].

7.4 SMAS3

SMAS3 is a commercial Fortan-based tool for small-signal stability analysis of large power systems [50]. The tool was developed by IIT (Comillas Pontifical University) and it has been used successfully in Industry, for example, in Iberdrola, Red Eléctrica de España (REE), Réseau de Transport d'Électricité (RTE) and CAMESA. Small Signal Stability Toolbox (SSST) is a matlab-based version of SMAS3 [51]. These tools were initially intended for AC grids but GEA-IIT has already included models for VSC-MTDC systems, under project ENE2014-57760-C2-1R of the Spanish RETOS programme.

7.5 PSAT

PSAT also give the option to carry out small-signal analysis of power systems and, as mentioned previously, study cases of grids with a good number of buses can be analysed. For example, in [52], small-signal stability analysis of Nordic32A system is performed. As for time-domain simulation, it admits several models of FACTS devices, wind turbines or HVDC links for small-signal analysis. Models of specific VSCs or DC grids must be coded by the user.

7.6 Matlab + Simulink

Matlab + Simulink (Mathworks) offers the possibility of modelling electrical systems using blocks diagram to represent differential equations (in DQ0 axes) and small-signal stability studies can be done. The advantage is that those models can be electromagnetic (including dynamic models for cables and lines) and, therefore, is appropriate for small-signal stability analysis of microgrids, where the interaction of the AC lines and the converter dynamics is important. The disadvantage of this software is that only relatively small test systems can be used. Hybrid AC/DC systems can be easily modelled using this tool.

In [53], small-signal stability of an AC microgrid is done and in [54, 55], small-signal analysis of VSC-HVDC multi-terminal systems is carry out.

7.7 Summary

A summary of the available simulation tools for small signal analysis and their applicability to hybrid AC/DC systems (including AC/DC microgrids) is shown in Table 4. Lack of SSA of AC and AC/DC microgrids has been identified as a shortcoming in most commonly used commercial tools, since they use electromechanical models, which can not be used in all possible scenarios in microgrids. For example, in AC microgrids with non conventional generation, the interaction of the converter controllers and the grid dynamics may play a relevant role and electromagnetic models must be used for SSA.

Simulink has been identified as the most suitable tool for SSA of hybrid AC/DC microgrids.

Tool (SSA)	type	approach	large systems	AC microgrids with VSC gens.	AC/DC microgrids
PSS/E	C	Electromechanical	yes	yes	no
PowerFactory	C	Electromechanical	yes	yes	yes
EUROSTAG	C	Electromechanical	yes	yes	yes
SMAS3	C	Electromechanical	yes	yes	user defined
PSAT	OS	Electromechanical	yes	yes	user defined
Simulink	C	Electromagnetic	no	yes	yes

Table 4: Summary of the applicability of different tools to small signal stability analysis of AC/DC microgrids.Type: C=Commercial, OS=Open source and free.

8 Case study: AC microgrid with VSC-based generators

This section reports the simulation results of AC microgrid using Matlab + Simulink and PowerFactory. The AC microgrid is similar to the test systems used in [56, 57] (see data in Appendix A.1.1). The system consists of three VSC converters (non-synchronous generators) which are connected to a 13.8 kV AC microgrid with several loads.

A microgrid can have three different modes of operation [56]:

- Grid-connected mode: The switch connecting the utility grid with the AC microgrid is closed. The frequency is fixed by the main grid.

- Autonomous microgrid mode: The switch connecting the utility grid with the AC microgrid is open. The VSC converters maintain the frequency of the micro-grid and they supply all the demand.

- Transition mode: When the mode of operation changes from grid-connected to autonomous mode or vice-versa.

This study will be focused on the autonomous microgrid mode, which is also known as "islanded" or "stand-alone" operation.
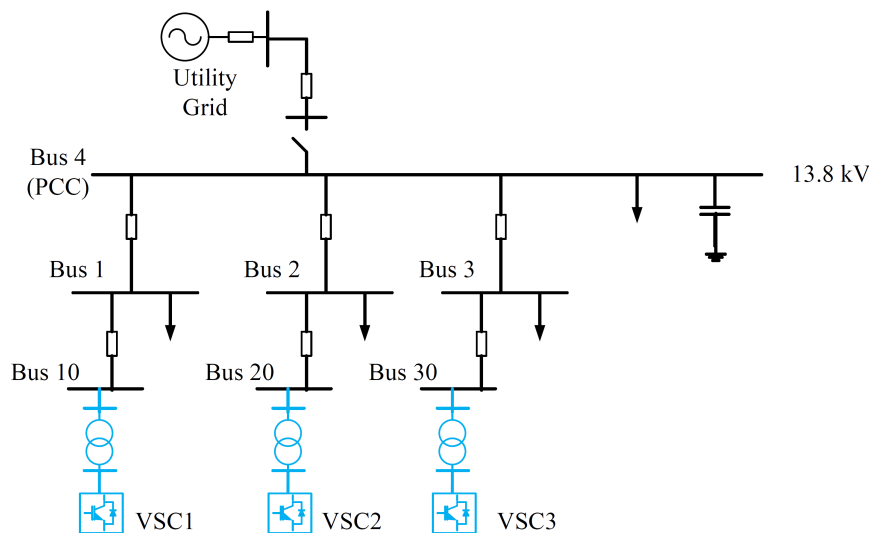

Figure 1: AC microgrid with VSC generators.

The objetives of this study can be summarised as:

- To study the frequency droop control in islanded AC microgrids.

- To analyse the differences between electromechanical and electromagnetic transient simulation of AC microgrids.

- To study the stability of an AC microgrid via SSA.

- To compare Simulink and PowerFactory for the analysis and simulation of AC microgrids.

8.1 Droop control in microgrids

When an AC microgrid is operating in islanded mode, the VSC generators must be able to supply the load and maintain the microgrid frequency and its output voltage close to the nominal ones. This is very much like the role of synchronous generators in conventional grids. However, there are important differences: (a) in a VSC the operating frequency is set using a microprocessor, (b) there is no inertia with kinetic energy stored and (c) if any of the VSCs deviates from the nominal frequency, it will not be affected by any "synchronising torque".

Popular (primary) control strategies for VSCs connected to an autonomous grid are called "frequency droop control" [58] and "voltage droop control" [59]. From the frequency point of view, VSCs are controlled to behave like synchronous generators would: each VSC would increase (reduce) its output frequency if the load is reduced (increased). This behaviour simulates the acceleration or deceleration of a rotating generator when the load torque is reduced or increased, respectively. The load increase or reduction is calculated by each VSC, independently, measuring its output voltage and its output current to calculate the active power (P) delivered by each unit. Therefore, no coordination is required. Meanwhile, each VSC increases (decreases) its output voltage (RMS value) if the reactive power delivered decreases (increases). Again, each VSC calculates its reactive-power delivery using its own output voltage and current. Therefore, the voltage droop control simulates an inductor-like output impedance in each VSC. Since all VSCs are connected by the grid, the two droop schemes are proportional controllers in order to share the contribution among all VSC. In each VSC (subscript -i-), frequency and AC voltage set points are calculated from:

$$f_i^* - f_0 = -\frac{K_{P,i}}{\tau_c s + 1}(P_i - P_{0,i}), \tag{1}$$

$$U_i^* - U_0 = -\frac{K_{Q,i}}{\tau_c s + 1}(Q_i - Q_{0,i}), \tag{2}$$

where τ_c is the time constant of a low-pass filter, f^* and U^* are the frequency and voltage to be imposed by the converter, respectively, f_0 and U_0 are the nominal values of frequency and voltage, respectively, P and P_0 are the active power delivered and the one expected for the operating point and, finally, Q and Q_0 are the reactive power delivered and the one expected for the operating point. $K_{P,i}$ and $K_{Q,i}$ are the frequency and voltage droop gains, respectively. Very often τ_c is made zero.

Two main factors should be taken into account for the design of the droop gains $K_{P,i}$ and $K_{Q,i}$:

- The maximum allowable frequency and AC voltage deviations [58].

- The stability of the system [53].

8.2   Simulation and analysis

The AC microgrid in Fig. 1 has been implemented in Simulink (using average electromagnetic models). The VSC converters are controlled as voltage sources with the droop controllers (frequency and voltage droops), following the guidelines given in [53], making $\tau_c = 0$ in (1) and (2). The droop gains have been selected to be proportional to the nominal power of each converter and they are reported in 10 of Appendix A.1. The system is represented in a global DQ0 frame and the states of the AC lines are included in the model.

The following event have has simulated:

- Load 4b was lost at $t = 1$ s.

The active power injection of each VSC, the frequency imposed by each VSC and the total active power consumed by the loads at bus 4 are depicted in Figure 2. The VSCs respond to the load loss increasing their frequencies, which converge to the same value. This produces a reduction of the active power injection of each converter in order to correct the power imbalance caused by the load loss. The active power change is distributed among the converters according to their frequency-droop gains.

The reactive-power injections of the converters and their AC voltages are shown in Figure 3, which present very small variations, since only changes on the active power have been produced.
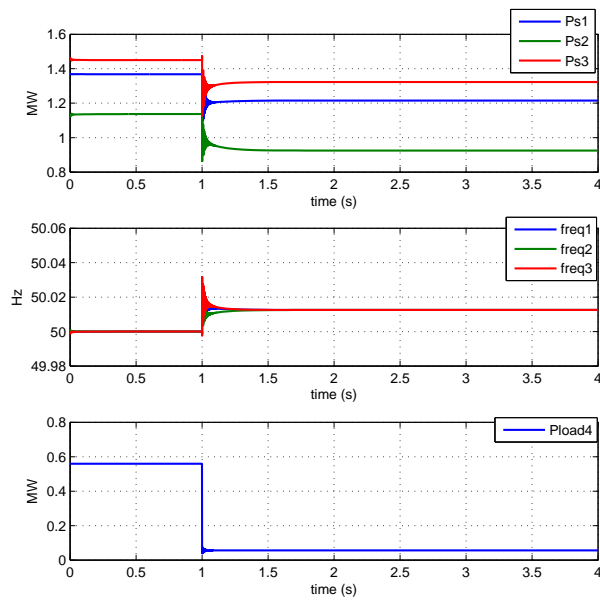
Figure 2: AC microgrid. Load loss. Active power injections of the VSCs, frequencies of the VSCs and total active power consumed by the loads at bus 4.
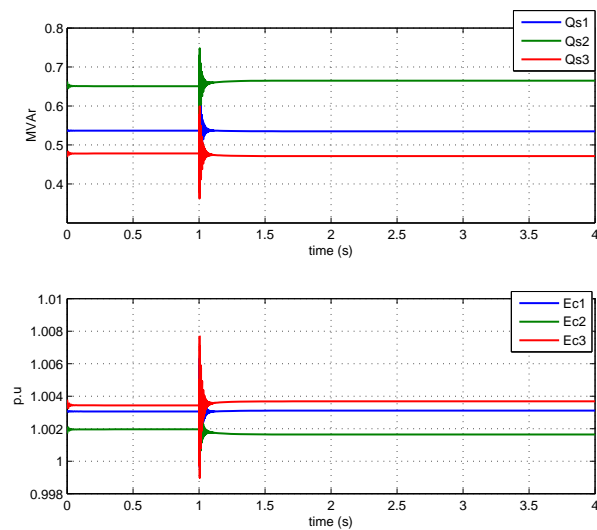

Figure 3: AC microgrid. Load Loss. Reactive power injections and AC voltages of the VSCs.

8.3 Validation: Simulink v/s PowerFactory

The model of the AC microgrid of Fig. 1 was implemented in PowerFactory, for electromechanical simulation, in order to (a) compare both tools and (b) explore the differences between electromagnetic (Simulink) and electromechanical (PowerFactory) simulation.

The same load loss in bus 4 used in Section 8.2 was simulated with both tools (Fig. 4). The active power injections of the VSCs and their frequencies are shown in Figs. 5 and 6, respectively. The results show good agreement between Simulink and PowerFactory tools. However, fast transient oscillations appear after the load change when using Simulink. These are caused by the dynamics of the states of the AC grid (i.e. the line inductances and the shunt capacitor bank placed at bus 4).
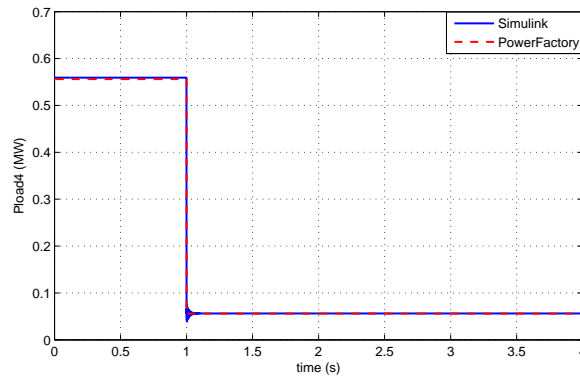

Figure 4: AC microgrid simulation. Simulink v/s PowerFactory. Load loss at bus 4.
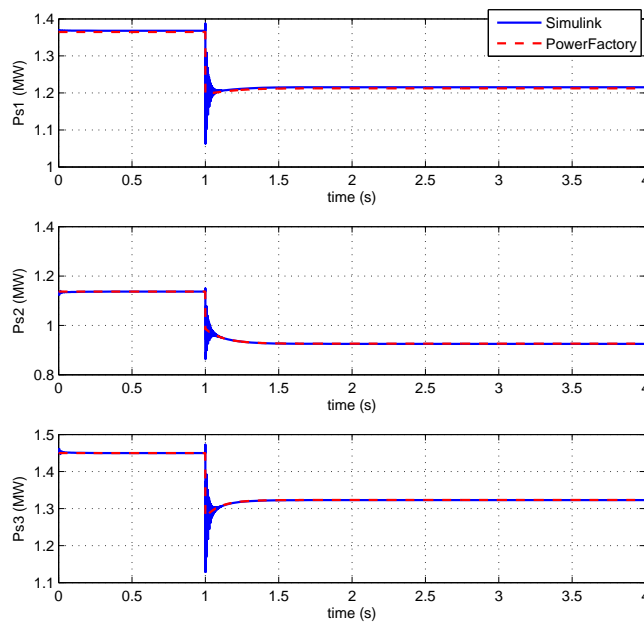

Figure 5: AC microgrid simulation. Simulink v/s PowerFactory. Active power injections of each VSC.
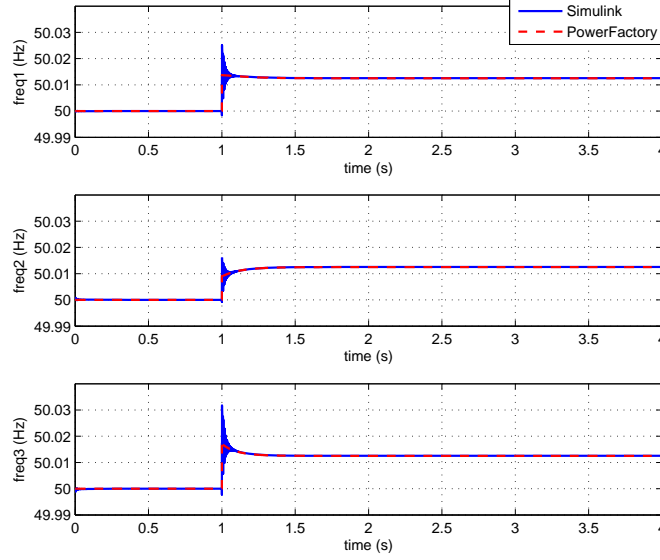
Figure 6: AC microgrid simulation. Simulink v/s PowerFactory. Frequency imposed by each VSC.

8.4 Investigating the effects of the frequency-droop gains

Two aspects should be taken into account for the design of the frequency-droop gain of each converter in the microgrid:

- The actual gain value.
- The relative gain value of each converter of the microgrid.

In order to analyse systematically the effect of the total and relative droop gains separately, the frequency-droop gain of each converter has been written as:

$$K_{P,i} = K_{P,T} g_i \tag{3}$$

where:

- $K_{P,T}$ is the total frequency droop gain of the microgrid ($K_{P,T} = \sum_j K_{P,j}$)
- $g_i \in [0,1]$ is the relative frequency-droop gain of each converter with respect to the total one ($\sum_j g_j = 1$)

For example, the base case for the simulations that follows has been configured as (Table 10):

$$\begin{aligned} K_{P,1} &= 2.4 \times 0.34 \simeq 0.82 \text{ p.u} \\ K_{P,2} &= 2.4 \times 0.25 \simeq 0.59 \text{ p.u} \\ K_{P,3} &= 2.4 \times 0.41 \simeq 0.99 \text{ p.u} \end{aligned} \tag{4}$$

8.4.1 Effect of the total frequency-droop gain ($K_{P,T}$)

Figure 7 shows the active power injections and the frequencies of the VSCs in the microgrid for different values of $K_{P,T}$, maintaining fixed relative gain values ($g_1 = 0.34$, $g_2 = 0.25$ and $g_3 = 0.41$). Higher values of $K_{P,T}$ produce higher frequency deviations in steady state, whilst the active power contribution of each converter (load sharing) does not change. Therefore, when designing the total gain $K_{P,T}$, the maximum frequency deviation desirable for a given load change should be taken into account.

Besides, as shown in [53], the system could became unstable if $K_{P,T}$ is too high. For example, Figure 8 shows the frequencies of the VSCs for $K_{P,T} = 28$ p.u and $K_{P,T} = 30.5$ p.u. The latter value of the parameter causes instability. Hence, the design of $K_{P,T}$ must ensure stability above all other considerations [53].
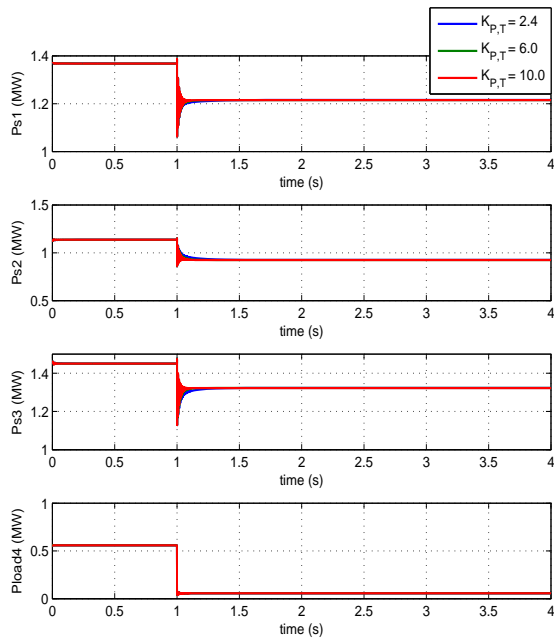
(a) Active power injections of the VSCs and active power consumed by the loads at bus 4.
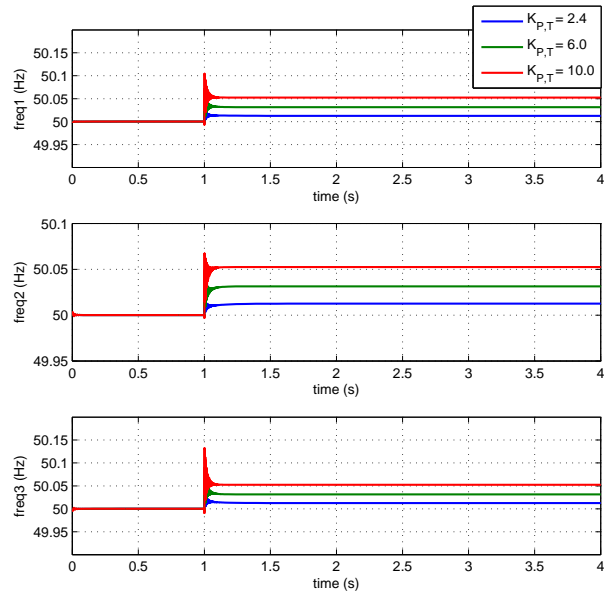
(b) Frequencies of the VSCs

Figure 7: AC microgrid simulation. Effect of the total frequency-droop gain ($K_{P,T}$).

Figure 8: AC microgrid simulation. Effect of the total frequency-droop gain ($K_{P,T}$).

8.4.2   Effect of the relative frequency-droop gain (g_i)

The active power generated by the VSCs and their frequencies obtained using different values of the relative gain of each converter g_i, with a const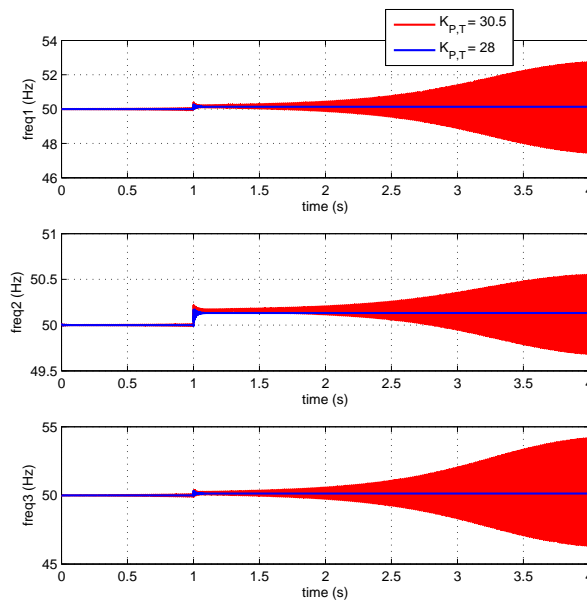ant value of the total gain ($K_{P,T} = 2.4$ p.u), are shown in Fig. 9. Clearly, the relative gains determine the active power contribution share of each VSC. Similar frequency changes are obtained in all cases.

As illustrated here, the relative gain of each converter should be made proportional to the relative size of each converter with respect to the total nominal power of all the converters of the microgrid which participate in the frequency-droop control strategy:

$$g_i = \frac{S_{N,i}}{S_{N,T}}, \ S_{N,T} = \sum_j S_{N,j}, \tag{5}$$
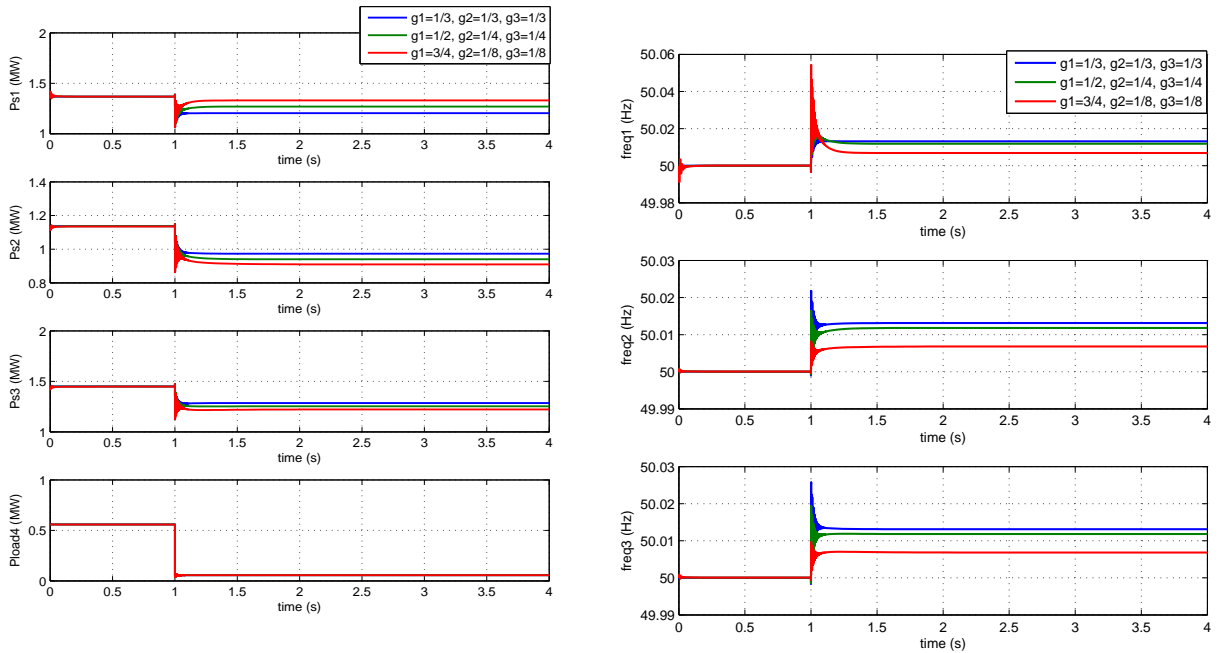
(a) Active power injections of the VSCs and active power consumed by the loads at bus 4.

(b) Frequencies of the VSCs

Figure 9: AC microgrid simulation. Effect of the relative frequency-droop gain (g_i).

8.5   Small signal analysis

This section presents a small signal stability analysis of the microgrid of Fig. 1 using Simulink. The analysis has been carried out following the guidelines given in [53]. To start with, the parameters of the base case have been selected ($K_{P,T} = 2.4$ p.u, $g_1 = 0.34$, $g_2 = 0.25$ and $g_3 = 0.41$). Secondly, the system was linearised and the eigenvalues in the complex plane are shown in Figure 10. The system is stable, since all the eigenvalues have negative real part (positive damping). Some fast eigenvalues with large modulus appear, which are associated to dummy states, such as small dummy capacitors at the AC buses, and they can be excluded of the analysis. These dummy eigenvalues make difficult to see the relevant ones in Fig. 10.

The relevant eigenvalues obtained for different values of $K_{P,T}$ are represented in Figure 11. The relative gains are the same in all cases ($g_1 = 0.34$, $g_2 = 0.25$ and $g_3 = 0.41$). When $K_{P,T} = 2.4$ p.u, $K_{P,T} = 10$ p.u and $K_{P,T} = 28$ p.u, the system is stable, but if $K_{P,T} = 30.5$ p.u, a pair of eigenvalues with positive real part appear, causing instability. This is consistent with the results obtained in Section 8.4.1.

The participation matrix gives information about the effect of each state on each mode [60] and it makes it possible to identify the origin of the instabilities. The list of states obtained in the Simulink model is shown in Figure 12 in order to facilitate the interpretation of the results. The angle reference is the angle of VSC1.
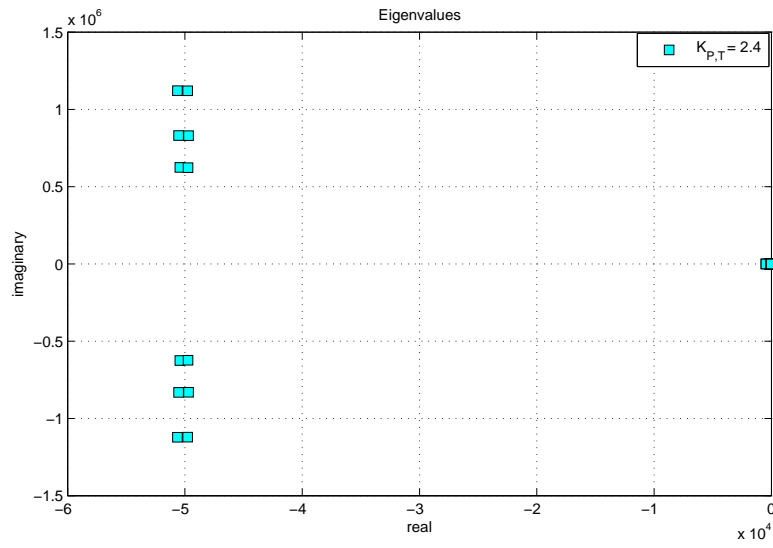

Figure 10: AC microgrid analysis. SSA. Eigenvalues ($K_{P,T} = 2.4$ p.u, $g_1 = 0.34$, $g_2 = 0.25$ and $g_3 = 0.41$).
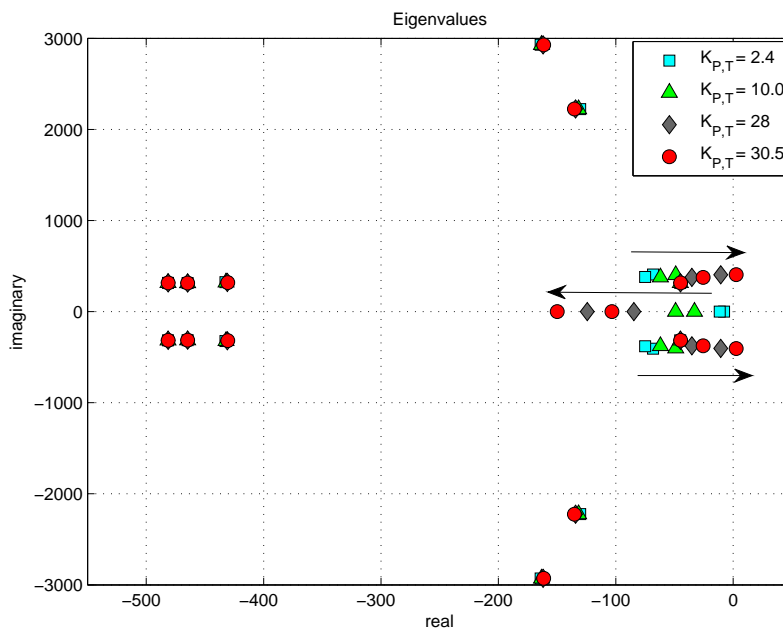
Figure 11: AC microgrid analysis. SSA. Eigenvalues obtained for different values of $K_{P,T}$. From $K_{P,T} = 2.4$ to $K_{P,T} = 30.5$ (and $g_1 = 0.34$, $g_2 = 0.25$ and $g_3 = 0.41$ remain constant).

```
sys1_statenames =

  1  'BUS 1 RC shunt1/Integrator1'
  2  'BUS 1 RC shunt1/Integrator2'
  3  'BUS 2 RC shunt2/Integrator1'
  4  'BUS 2 RC shunt2/Integrator2'
  5  'BUS 3 RC shunt3/Integrator1'
  6  'BUS 3 RC shunt3/Integrator2'
  7  'BUS 4 RC shunt PCC/Integrator1'
  8  'BUS 4 RC shunt PCC/Integrator2'
  9  'Load 1 RL series /Integrator'
 10  'Load 1 RL series /Integrator1'
 11  'Load 2 RL series 1/Integrator'
 12  'Load 2 RL series 1/Integrator1'
 13  'Load 3 RL series 2/Integrator'
 14  'Load 3 RL series 2/Integrator1'
 15  'Load 4 RL serIes/Integrator'
 16  'Load 4 RL serIes/Integrator1'
 17  'branch 1-4 RL series 1/Integrator'
 18  'branch 1-4 RL series 1/Integrator1'
 19  'branch 2-4 RL series 2/Integrator'
 20  'branch 2-4 RL series 2/Integrator1'
 21  'branch 3-4 RL series 3/Integrator'
 22  'branch 3-4 RL series 3/Integrator1'
 23  'VSC1    (Freq-Vac control  = complex Vac) REFERENCE/RL series /Integrator'
 24  'VSC1    (Freq-Vac control  = complex Vac) REFERENCE/RL series /Integrator1'
 25  'VSC2    (Freq-Vac control  = complex Vac) /Integrator'
 26  'VSC2    (Freq-Vac control  = complex Vac) /RL series /Integrator'
 27  'VSC2    (Freq-Vac control  = complex Vac) /RL series /Integrator1'
 28  'VSC3    (Freq-Vac control  = complex Vac) /Integrator'
 29  'VSC3    (Freq-Vac control  = complex Vac) /RL series /Integrator'
 30  'VSC3    (Freq-Vac control  = complex Vac) /RL series /Integrator1'
```

Figure 12: AC microgrid analysis. SSA. List of states.

The participation matrix will now be studied in detail, for two cases:

- Case 1: $K_{P,T} = 2.4$ p.u, $g_1 = 0.34$, $g_2 = 0.25$ and $g_3 = 0.41$ (stable).

- Case 2: $K_{P,T} = 30.5$ p.u, $g_1 = 0.34$, $g_2 = 0.25$ and $g_3 = 0.41$ (unstable).

The eigenvalues obtained for each case are reported in Table 5.

Mode	Case 1 Eigenvalue (rad/s)	Damping (-)	Case 2 Eigenvalue (rad/s)	Damping (-)
1	-50632.2023+j1121906.7703	0.045085	-50701.7813+j1121844.3539	0.045149
2	-50632.2023-j1121906.7703	0.045085	-50701.7813-j1121844.3539	0.045149
3	-49764.5015+j1120645.9364	0.044363	-49694.944+j1120708.478	0.044299
4	-49764.5015-j1120645.9364	0.044363	-49694.944-j1120708.478	0.044299
5	-50537.0421+j831729.0754	0.06065	-50536.7447+j831728.689	0.060649
6	-50537.0421-j831729.0754	0.06065	-50536.7447-j831728.689	0.060649
7	-49687.109+j830369.3631	0.059731	-49687.6082+j830369.762	0.059731
8	-49687.109-j830369.3631	0.059731	-49687.6082-j830369.762	0.059731
9	-50435.2226+j625023.821	0.080432	-50479.4142+j624974.7132	0.080508
10	-50435.2226-j625023.821	0.080432	-50479.4142-j624974.7132	0.080508
11	-49734.7082+j623704.9916	0.079488	-49690.5477+j623754.2528	0.079412
12	-49734.7082-j623704.9916	0.079488	-49690.5477-j623754.2528	0.079412
13	-163.974+j2930.0293	0.055876	-161.3854+j2928.1194	0.055032
14	-163.974-j2930.0293	0.055876	-161.3854-j2928.1194	0.055032
15	-130.355+j2222.1338	0.058561	-135.2448+j2224.3521	0.06069
16	-130.355-j2222.1338	0.058561	-135.2448-j2224.3521	0.06069
17	-432.5038+j322.4772	0.80169	-430.5367+j319.1614	0.80334
18	-432.5038-j322.4772	0.80169	-430.5367-j319.1614	0.80334
19	-481.4195+j314.8028	0.83695	-481.3543+j314.5219	0.83714
20	-481.4195-j314.8028	0.83695	-481.3543-j314.5219	0.83714
21	-464.7651+j314.2158	0.82844	-464.762+j314.1918	0.82845
22	-464.7651-j314.2158	0.82844	-464.762-j314.1918	0.82845
23	-68.2532+j406.8954	0.16543	2.5542+j405.999	-0.006291
24	-68.2532-j406.8954	0.16543	2.5542-j405.999	-0.006291
25	-75.0322+j380.2594	0.19359	-25.5219+j376.0715	0.067709
26	-75.0322-j380.2594	0.19359	-25.5219-j376.0715	0.067709
27	-45.1042+j314.7701	0.14184	-44.7388+j314.7178	0.14074
28	-45.1042-j314.7701	0.14184	-44.7388-j314.7178	0.14074
29	-7.6858+j0	1	-103.2811+j0	1
30	-11.4124+j0	1	-149.8408+j0	1

Table 5: AC microgrid. SSA. Eigenvalues obtained in cases 1 and 2.

The moduli of the participations versus the modes of the system will now be plotted.

8.5.1 Case 1: $K_{P,T} = 2.4$ p.u, $g_1 = 0.34$, $g_2 = 0.25$ and $g_3 = 0.41$ (stable case)

The moduli of the participation matrix elements and the damping of each mode have been used in Figure 13 to try to show a comprehensive picture (participation map). The shadowed areas mark those states that participate in each one of the system modes. The darker the colour, the higher the participation is

Making use of the list of states (Fig. 12), it is concluded that:

- The states "angle" of converters VSC2 and VSC3 are associated with the two real eigenvalues (modes 29 and 30) which will never became unstable. These states are directly related to the frequency droop.

- The interaction between the states "angle" of converters VSC2 and VSC3 with the current through the connection impedance (transformers) of these converters are related to the two problematic pairs of complex conjugate eigenvalues that could cause instability for high values of $K_{P,T}$.

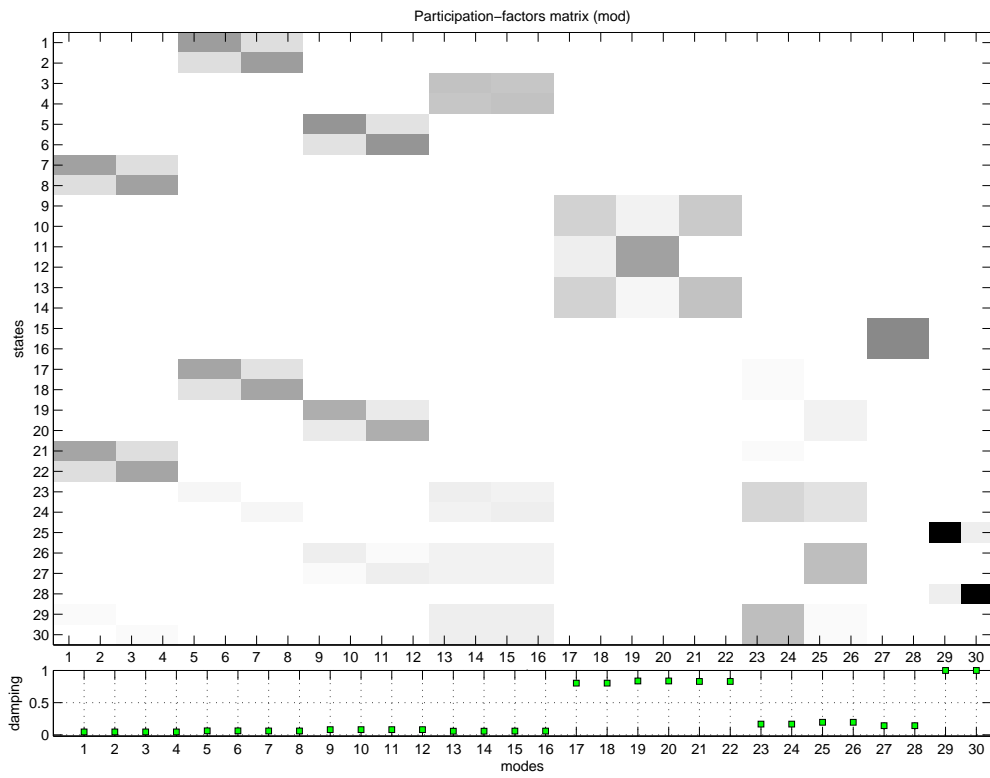Figure 13: AC microgrid SSA analysis. Eigenvalues obtained in Case 1 ($K_{P,T} = 2.4$ p.u, $g_1 = 0.34$, $g_2 = 0.25$ and $g_3 = 0.41$) using Simulink and PowerFactory.

8.5.2 Case 2: $K_{P,T} = 30.5$ p.u, $g_1 = 0.34$, $g_2 = 0.25$ and $g_3 = 0.41$ (unstable)

The participation map for this case is shown in Figure 14 and the conclusions obtained for Case 1 are confirmed.
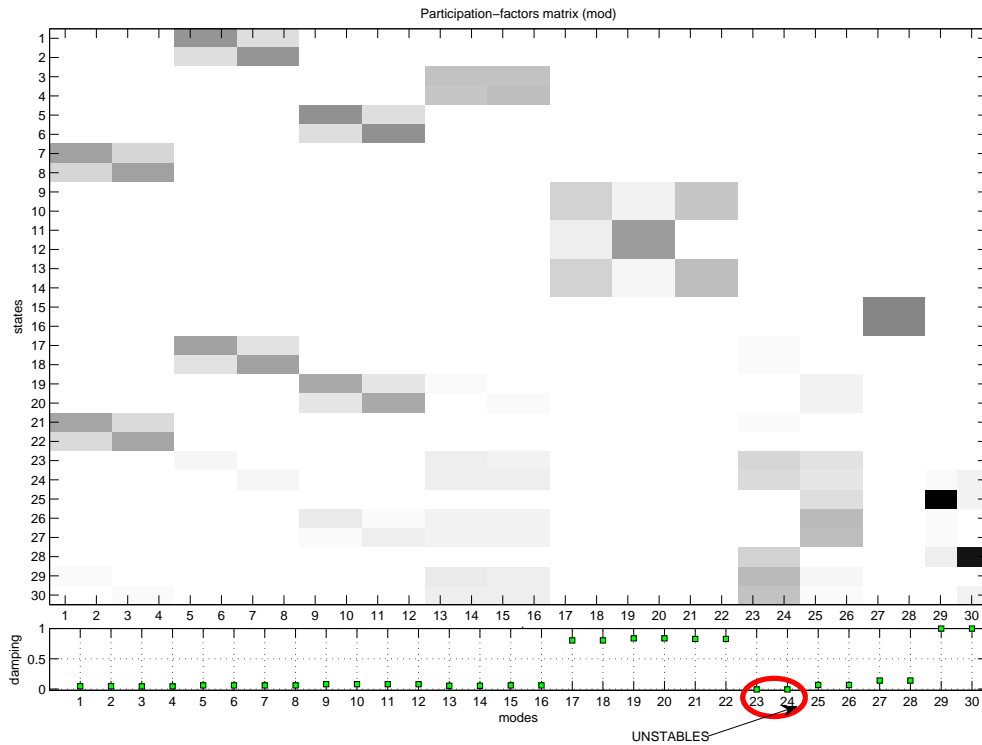

Figure 14: AC microgrid SSA analysis. Eigenvalues obtained in Case 2 ($K_{P,T} = 30.5$ p.u, $g_1 = 0.34$, $g_2 = 0.25$ and $g_3 = 0.41$) using Simulink and PowerFactory.

8.5.3 Simulink v/s PowerFactory

A relevant question that arises is whether SSA of microgrids could be performed with the available and commonly used commercial tools. In this section, SSA of the microgrid of Figure 1 will be carried using Simulink and PowerFactory, and the results given by both tools will be compared and discussed.

As described in Section 7,

- Simulink: The linearisation of the system is of the electromagnetic type, i.e., the current through the inductances of the AC lines are states of the system. Therefore, with this tool, the states of the microgrid will be the angles of the converters (except VSC1, which is the reference), the current through the lines, and the voltage of the shunt capacitors.

- PowerFactory: The linearisation of the system follows an electromechanical approach, i.e., the dynamics of the AC lines is assumed instantaneous. Although PowerFactory allows electromagnetic time-domain simulation, small signal analysis can only be carried out using electromechanical models. Hence, PowerFactory will assume as states only the angles of the converters while the currents and voltages of the AC grid will be related by algebraic equations.

Therefore, the modes which are associated to the angles of the converters will be given by both tools, whilst the rest of eigenvalues will appear only in the Simulink model. The eigenvalues that should appear when using both tools (associated to the angle of converters VSC2 and VSC3) are compared for the two cases studied in Table 6. Very close results are obtained. Since the states of the AC grid are neglected in PowerFactory, this tool will never predict unstable cases and, therefore, this tool is not appropriate for SSA of microgrids.

Mode	Simulink Eigenvalue (rad/s)	PowerFactory Eigenvalue (rad/s)
Case1 (stable)		
29	-7.6858	-7.7276
30	-11.4128	-11.4088
other modes	28 more	no more
Case 2 (unstable)		
29	-103.2811	-98.2309
30	-149.8408	-145.0255
other modes	28 more	no more

Table 6: AC microgrid SSA analysis. Simulink v/s PowerFactory.

8.6 Conclusions

An AC microgrid with VSC-based generators controlled using droop control has been simulated using Simulink (electromagnetic approach) and PowerFactory (electromechanical approach). The effect of the frequency droop gain has been analysed, both simulation tools have been compared and small signal analysis has been carried out. The results have shown good agreement between both tools (when possible). Nevertheless, it must be pointed out that some instabilities (produced for some values of the parameters) are correctly predicted by Simulink but not by Powerfactory. The reason is that the dynamics of the VSC converters and the AC grid are comparable and, in some cases, electromechanical simulation will fail when predicting instability.

9 Case study: Hybrid AC/DC microgrid

A hybrid AC/DC microgrid with frequency-droop control has been simulated and analysed using Matlab + Simulink. The AC system is the same as in the previous section, but now the DC buses of the VSC converters are connected to a common DC grid (or multi-terminal system), as shown in Fig 15. Converters VSC1, VSC2 and VSC3 play the same role as before: they are controlled as voltage sources with the frequency-droop and voltage-droop controllers, although only the frequency droop will be investigated here. A fourth converter has been included (VSC4). This is in charge of supplying the active power required by VSC1, VSC2 and VSC3. Converter VSC4 is controlled as a current source and it controls the DC voltage (DC slack). VSC4 is connected to a different (and asynchronous) AC system which may represent a wind farm, for example, but it has been simplified and been modelled as an infinite bus. The details of the wind turbine models have been omitted, since this study is only focused on the hybrid AC/DC microgrid. The data of the hybrid AC/DC system are reported in Appendix A.1.2.
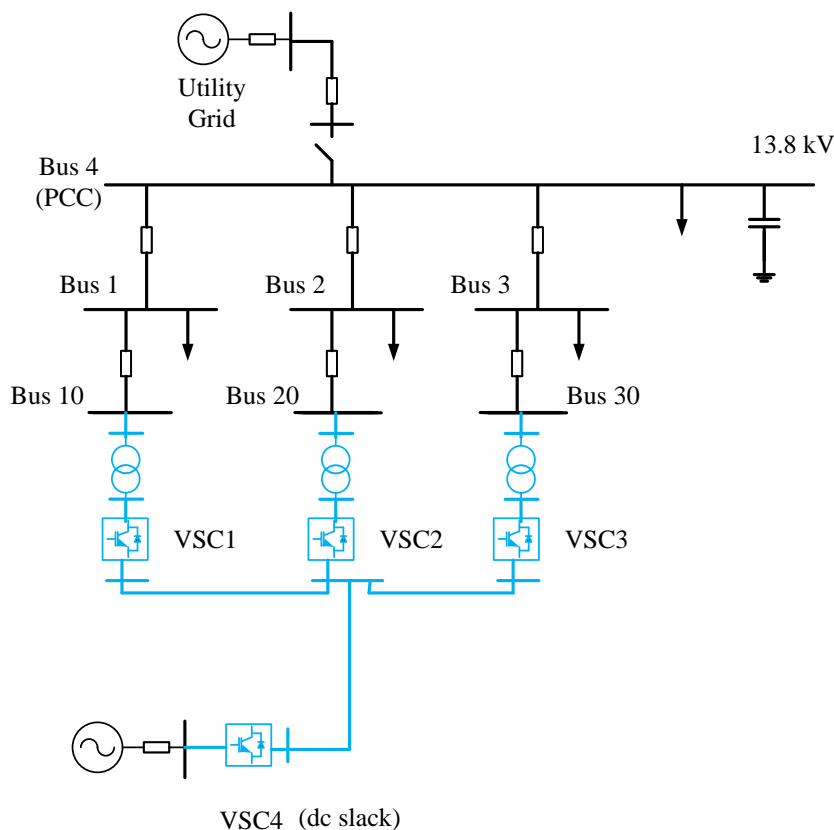
Figure 15: Hybrid AC/DC microgrid.

Figure 16 shows the active power injections and the frequencies of converters VSC1, VSC2 and VSC3; and the active power of the load. Figure 17 shows the active-power injections of the four converters and the DC voltages. The frequency of the microgrid and the DC voltage of the DC grid increas due to the load loss. The active power injected by converters VSC1, VSC2 and VSC3 is fully supplied by converter VSC4, which controls the DC voltage, as shown in Figure 17.

Figure 16: Load loss. Active power injections of the VSCs, frequencies of the VSCs and total active power consumed by the loads at bus 4. (only VSC1, VSC2 and VSC3).

Figure 17: Load loss. Active power injections of the VSCs and DC voltages.

10 Case study: VSC-HVDC multi-terminal system

Although PSS/E is one of the most widely used commercial simulation tools for steady state and transient behaviour of large power systems, no MTDC model is available in the commercial package and only a VSC-HVDC point-to-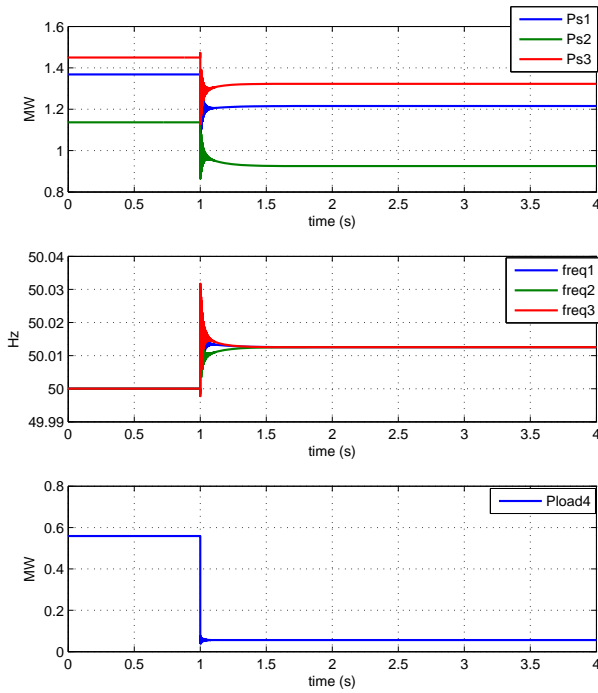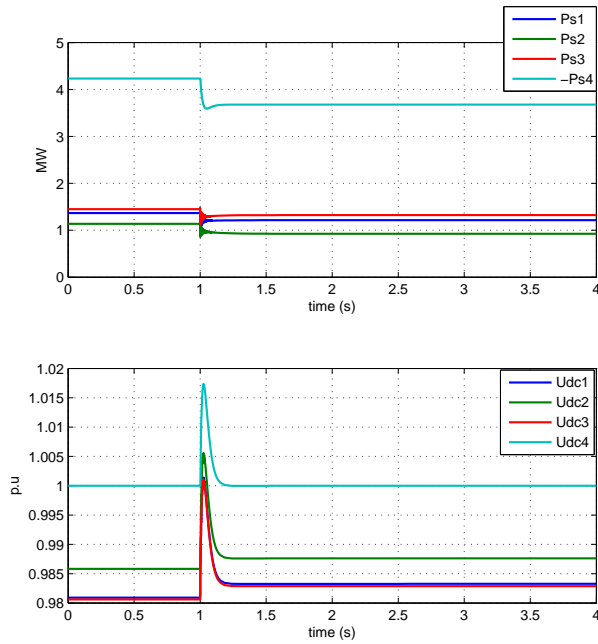point model is offered. As pointed in Sections 4.1 and 6.1, IIT developed a PSS/E tool for VSC-HVDC multi-terminal systems in collaboration with REE during ESP-LIDER project [17]. The tool is suitable for power-flow calculation and for electromechanical time-domain simulation. The model developed in PSS/E was compared with a detailed electromagnetic model in Matlab + SimPowerSystems in ESP-LIDER project and it has been compared with an electromechanical model in PowerFactory during the present project. A guideline for modelling MTDC systems in PowerFactory can be found in [19].

The test case, shown in Figure 18, consists of three infinite grids coupled synchronously with AC lines and a 3-terminal VSC-HVDC system. The parameters of the system are shown in Table 12 of Appendix A.
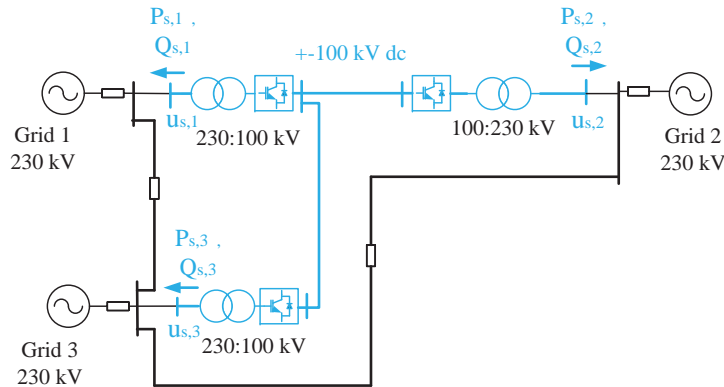
Figure 18: Test system for validation of a PSS/E tool to analyse MTDC systems.

The following initial steady-state point of the MTDC system were used:

- VSC1: (bus s,1): $P_s - Q_s$ control: $P_{s,1}^0 = -100$ MW and $Q_{s,1}^0 = 0$ MVAr.

- VSC2: (bus s,2): $U_{dc} - Q_s$ control: $u_{dc,2}^0 = 1$ p.u and $Q_{s,2}^0 = 0$ MVAr.

- VSC3: (bus s,3): $P_s - Q_s$ control: $P_{s,3}^0 = -50$ MW and $Q_{s,3}^0 = 0$ MVAr.

The following step changes were simulated:

- From $u_{dc,2}^{ref} = 1$ p.u to $u_{dc,2}^{ref} = 1.05$ p.u at $t = 1$ s.

- From $P_{s,1}^{ref} = -100$ MW to $P_{s,1}^{ref} = -50$ MW at $t = 1.5$ s.

- From $Q_{s,2}^{ref} = 0$ MVAr to $Q_{s,2}^{ref} = -50$ MVAr at $t = 3$ s.

The simulation results for the above transients are compared in Figs. 19 and 20, which show good agreement within the scope of each simulation. Only the results obtained with SimPowerSystems show a high-frequency ripple, because the power electronics switches and the dynamics of the AC lines are modelled.
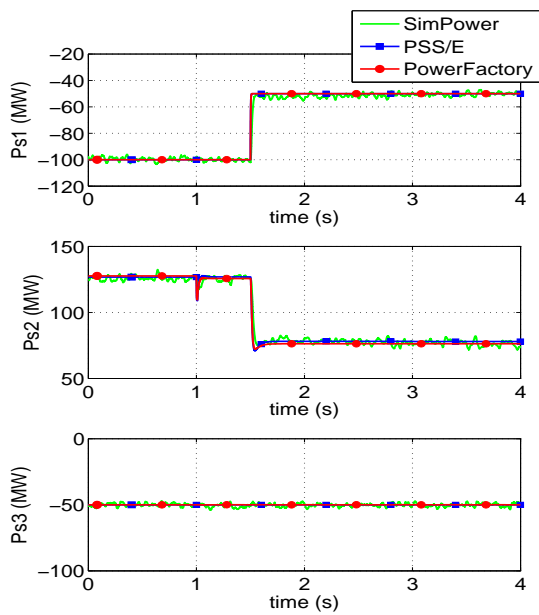
(a) Active power injections.
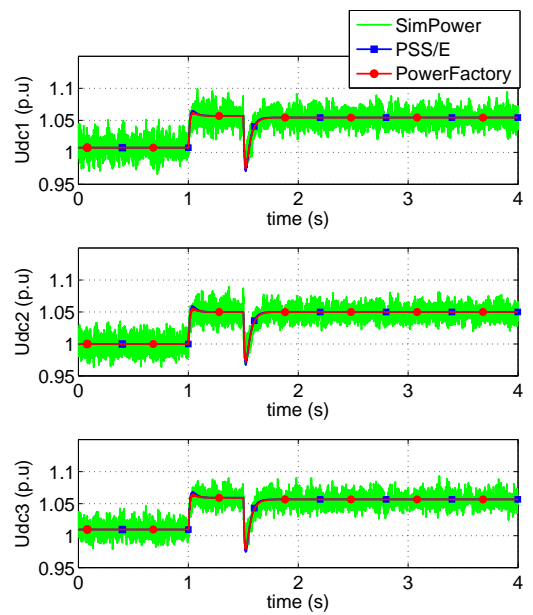
(b) DC voltages.

Figure 19: Validation of the VSC-HVDC multi-terminal model. PSS/E vs Matlab SimPowerSystems and PowerFactory.
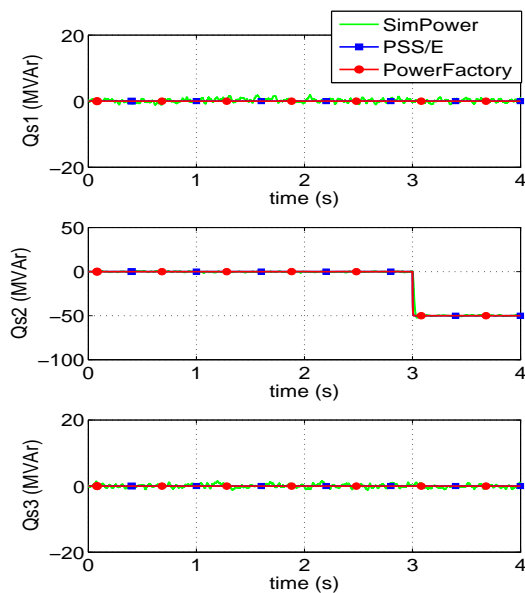
(a) Reactive power injections.
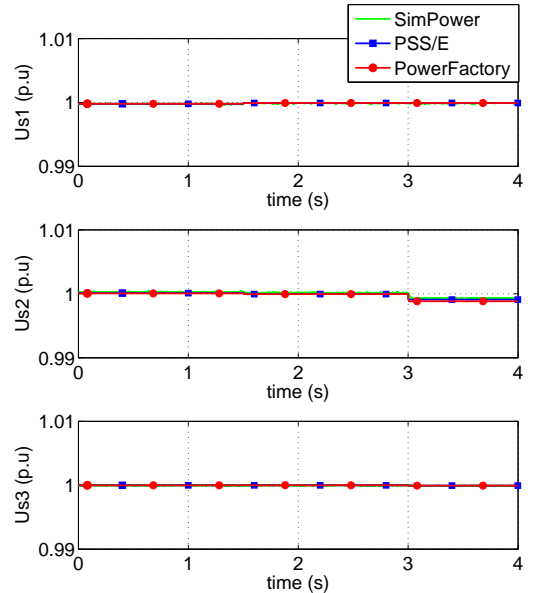
(b) AC voltages.

Figure 20: Validation of the VSC-HVDC multi-terminal model. PSS/E vs Matlab SimPowerSystems and PowerFactory.

11 Conclusions

In this report, the description and classification of many simulation tools which may be applicable in the context of smart grids have been presented. Simulation tools for power-flow calculation, electromagnetic transient simulation, electromechanical simulation and small signal analysis have been studied. The possibility of the simulation of hybrid AC/DC systems with the simulation tools explored has been given special attention.

Three relevant type of systems have been tackled during the study reported here:

- Hybrid AC/DC systems in general .

- AC microgrids with VSC generation.

- Hybrid AC/DC microgrids with VSC converters.

Three test systems have been studied with different simulation tools: (a) an AC microgrid, (b) a hybrid AC/DC microgrid and (c) a VSC-HVDC multi-terminal system.

The conclusions of the study can be summarised as follows:

- All power-flow tools can be used for the simulation of AC systems. However, only some of them admit hybrid AC/DC grids "off the shelf". In those which do not take hybrid AC/DC grids, user-defined models can be prepared.

- All the electromagnetic simulators studied in this work can be used for the simulation of hybrid AC/DC systems, since one of their purposes is to simulate power electronics devices.

- Some (but not all) electromechanical simulators admit hybrid AC/DC systems. However, if models for hybrid AC/DC systems are missing, user-defined models can be coded.

  It has been concluded that this type of simulation is not appropriate in all possible scenarios in microgrids. For example, in microgrids with no synchronous generator (only with power electronics converters), instability could not be detected in some cases using electromechanical simulators. This is due to the fact that these simulators neglect the dynamics of the AC grid, which may be relevant in this context.

- Regarding small-signal analysis (SSA) tools: some of them (but not all) readily admit hybrid AC/DC systems. However, user-defined models can always be used in this context, if necessary. SSA tools can also be of electromagnetic type or electromechanical type, being the latter more suitable for the analysis of microgrids. Clearly, there is a lack of reliable SSA models in most commercial tools for the analysis of microgrids, since most of them follow an electromechanical approach. Simulink has been found to be the most reliable tool for SSA of hybrid AC/DC microgrids (using electromagnetic models), although the maximum number of buses that it can simulate is limited because the situation soon becomes cumbersome and clumsy.

A   Appendix: System Data Used in this Report

A.1   Microgrid Data

A.1.1   AC microgrid (Section 8)

The data of the AC microgrid of Figure 15 are reported here.

- Bus data in Table 7.

- Transformer of each VSC: 13.8/0.69 kV, $\bar{z}_{cc} = 0.01 + j0.08$ (p.u rating). Rating of the transformer: the same as the converter (Table 9).

- Operating point of the VSCs in Table 9.

- Droop gains of teh VSCs in Table 10.

Bus		r (p.u)	x (p.u)	b (p.u)
1	Load1	5.7070	3.0135	-
2	Load2	4.7581	3.0135	-
3	Load3	7.6136	5.1603	-
4	Load4a	3.3333	23.3333	-
	Load4b	18.5185	0.1015	-
	Shunt4	-	-	0.1

Table 7: AC microgrid. Bus data (loads and shunts). Bases: 13.8 kV and 10 MVA.

Branch	r (p.u)	x (p.u)
1-10	0.0840	0.4376
1-4	0.0398	0.0513
2-20	0.0840	0.4376
2-4	0.0607	0.1015
3-30	0.0840	0.4376
3-4	0.0356	0.0266

Table 8: AC microgrid. Branch data. Bases: 13.8 kV and 10 MVA.

Converter	S_N (MVA)	e_c (p.u)	δ_c (deg)	P_s (MW)	Q_s (MVAr)
VSC1	1.8	1.0031	0.00	1.368	0.535
VSC2	2.5	1.0017	-0.86	1.138	0.663
VSC3	1.5	1.0038	0.23	1.450	0.469

Table 9: AC microgrid. Branch data. Operating point of the VSCs.

Converter	S_N (MVA)	K_P (p.u)	K_Q (p.u)	τ_c (s))
VSC1	1.8	0.82	0.31	0
VSC2	2.5	0.59	0.22	0
VSC3	1.5	0.99	0.37	0

Table 10: AC microgrid. Droop gains. Bases: 13.8 kV and 10 MVA.

A.1.2 AC/DC microgrid (Section 9)

The data of the AC/DC microgrid of Figure 15 are reported here.

- Bus data in Table 7.

- Branch data in Table 8.

- Transformer of each VSC: 13.8/0.69 kV, $\bar{z}_{cc} = 0.01 + j0.08$ (p.u rating). Rating of the transformer: the same as the converter (Table 11).

- Operating point of the VSCs in Table 11.

- Droop gains of the VSCs in Table 10 (only for VSC1-3).

- DC grid data [61]: Voltage level: ± 1.2 kV, lines: $R_{dc,ij} = 0.01\Omega$, $L_{dc,ij} = 0.1$ mH, buses: $C_{dc,i} = 25$ mF.

- VSC 4 data: As in Table 11 and the parameters of the PI controllers used to control the DC voltage are:

  - Inner current loop PI: $K_{int,p} = 6$ p.u, $K_{int,i} = 6$ p.u/s. (p.u-rating)
  - Outer loop PI: $K_{d,p2} = 2.45$ p.u, $K_{d,i2} = 49$ p.u/s. (p.u-rating)

Converter	S_N (MVA)	e_c (p.u)	δ_c (deg)	P_s (MW)	Q_s (MVAr)	u_{dc} (p.u)
VSC1	1.8	1.0031	0.00	1.368	0.537	0.9809
VSC2	2.5	1.0020	-0.85	1.137	0.651	0.9858
VSC3	1.5	1.0034	0.22	1.450	0.478	0.9806
VSC4	10.0	0.9840	0.00	-4.235	0.000	1.0000

Table 11: AC/DC microgrid. Operating point of the VSCs.

A.2 Data of the MTDC system case study (Section 10)

The data of the VSC-HVDC multi-terminal of Fig. 18 is reported in Table 12.

Table 12: Converter and DC grid parameters

Parameters Converter ratings are base values for p.u.	values
Rating VSC apparent power DC voltage	 200 MVA ± 100 kV
VSC limits maximum active power maximum reactive power maximum current maximum DC voltage	 ± 200 MW ± 200 MVAr 1 p.u (d-prio.) ± 10 %
Current controller time constant (τ)	 2 ms
AC connection resistance (r_s) reactance (x_s)	 0.008 p.u 0.30 p.u
P-control prop. gain $(K_{d,p1})$ int. gain $(K_{d,i1})$	 0 0
Vdc-control prop. gain $(K_{d,p2})$ int. gain $(K_{d,i2})$	 2.45 p.u 49 p.u/s
Q-control prop. gain $(K_{q,p1})$ int. gain $(K_{q,i1})$	 0 0
Vac-control prop. gain $(K_{q,p2})$ int. gain $(K_{q,i2})$	 10 100
Losses coefficients constant (a) linear (b) rec. quadratic (c_{rec}) inv. quadratic (c_{inv})	 0.035 p.u 0 p.u 0 p.u 0 p.u
DC grid shunt capacitance $(C_{dc,i})$ shunt conductance $(G_{dc,i})$ series resistance $(R_{dc,ij})$ series inductance $(L_{dc,ij})$	 90.6625 μF 0 1.0925 Ω 27.925 mH

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