IMDEA Energy Institute

# User Project: Inertia emulation with offshore windfarms connected through HVDC links

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MaRINET2

## ABOUT MARINET

The MaRINET2 project is the second iteration of the successful EU funded MaRINET Infrastructures Network, both of which are coordinated and managed by Irish research centre MaREI in University College Cork and avail of the Lir National Ocean Test Facilities.

MaRINET2 is a €10.5 million project which includes **39 organisations** representing some of the top offshore renewable energy testing facilities in Europe and globally. The project depends on strong international ties across Europe and draws on the expertise and participation of **13 countries**. Over 80 experts from these distinguished centres across Europe will be descending on Dublin for the launch and kick-off meeting on the 2nd of February.

The original MaRINET project has been described as a *"model of success that demonstrates what the EU can achieve in terms of collaboration and sharing knowledge transnationally".* Máire Geoghegan-Quinn, European Commissioner for Research, Innovation and Science, November 2013

MARINET2 expands on the success of its predecessor with an even greater number and variety of testing facilities across offshore wind, wave, tidal current, electrical and environmental/cross-cutting sectors. The project not only aims to provide greater access to testing infrastructures across Europe, but also is driven to improve the quality of testing internationally through standardisation of testing and staff exchange programmes.

The MaRINET2 project will run in parallel to the MaREI, UCC coordinated EU marinerg-i project which aims to develop a business plan to put this international network of infrastructures on the European Strategy Forum for Research Infrastructures (ESFRI) roadmap.

The project will include at least 5 trans-national access calls where applicants can submit proposals for testing in the online portal. Details of and links to the call submission system are available on the project website www.marinet2.eu

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# 1 Introduction & Background

## 1.1 Introduction

The large amount of windfarms connected to electricity grids is giving rise the opportunity to use them to provide additional grid services such as virtual inertia [1]. These additional services can be used to damp power system oscillations [2-3]. Also, the emulation of synchronous machines has become a popular control technique to simplify the integration of windfarms to electricity grids. This control alternative is commonly referred to as Virtual Synchronous Machine (VSM), among other names, and its implementation details have drawn much in the literature [4]. Parameter design, current limitation, synchronisation, and performance under voltage sags are relevant topics to be addressed when a converter emulates a synchronous machine. Practical solutions to solve these issues are highly relevant to promote the use of VSMs and many studies have already been done in this regard [5]. Another relevant issue of VSMs is their design and integration at the system level. However, this subject received much less attention compared to implementation aspects [6].

Electromechanical oscillations are common in electric power systems and there exist many classical solutions to damp them. For example, Power Systems Stabilizers (PSSs) are commonly added to synchronous generators to damp inter-area oscillations [7]. These solutions are developed and designed taking into account physical limitations of electric rotating machines. However, for the case of VSMs, the formulation of the controller can be modified so that a more efficient and robust damping of oscillations is obtained. The study of damping alternatives for the integration of VSMs to electricity grids is the main objective of this work.

Parameter design and solutions to damp VSM oscillations at the converter level have already been studied in the literature. D'Arco et al. [8] presented a small-signal modelling and stability analysis of VSMs. This type of analysis is a powerful tool to analyse non-linear systems like synchronous generators. The parameters of the VSM were designed and a parametric analysis was carried out in order to highlight their influence on the system dynamics. However, the grid dynamics were not taken into account. Alrajhi and El-Shatshat [5] presented a comparative analysis of VSM alternatives. Different VSM formulations were tested and it was highlighted that low-order models are a more suitable solution since they exhibit less stability problems. Zhao et al. [9] presented a multi-loop control strategy for a VSM. A simplified small signal model was presented and its stability properties were analysed. It was shown that the use of internal controllers improved the stability properties of VSMs. Natarajan and Weiss [10] presented a virtual impedance to improve the transient performance of VSMs. The proposed methodology improved the transient performance and the dynamic properties of a VSM under grid faults. Alipoor et al. [11] presented a VSM with variable inertia. In that work, it was shown that transient performance can be improved by changing the value the inertia in real time. Also, it was shown that stability indices can be improved by applying this control alternative. Ashabani and Mohamed [12] presented a non-linear damping controller for VSMs that improved their integration in electrical networks with SCR values smaller than two. Stability against large-signal disturbances was guaranteed by using the Lyapunov stability analysis. Dong and Chen [13] presented a non-linear control loop to adjust the dynamic response of a VSM. This loop added a damping term that reduced the oscillations generated by a VSM connected to an infinite bus. Li et al. [14] presented a self-adaptive version of a VSM that suppressed oscillations without needing additional control loops.

At the system level, some developments have been done to damp oscillations with electronic power converters by using classical controllers. Torres et al. [15] presented a method to tune the parameters for an energy storage system. The parameters were selected so that the energy required to damp system oscillations was minimized. However, the integration of VSMs in large electrical networks has been seldom studied in the literature. Blau and Weiss [7] presented the application of a VSM to damp inter-area oscillations. Some basic ideas were presented, but there were not analytical developments. Weiss and Venezian [16] presented a stability analysis of two VSMs with virtual friction. Oscillations generated by VSMs were studied, and it was demonstrated that stability can be guaranteed by adding a damping term to the VSM. However, fast communications between the VSMs were required.

The main objective of this project is to study control techniques for HVDC links in order to mimic the dynamics of synchronous generators on the AC side. This will provide virtual inertia to the AC grid. In addition, supplementary control loops with the aim of damping oscillations will be included in the control system. This can help stabilize electrical systems, improving the integration of windfarms to electricity grids.

Short-term objectives:

1. **Control techniques for HVDC terminals:** Emulation of synchronous machines with the terminals of HVDC links will be investigated, including additional methods for oscillation damping.

2. **Modelling of AC grids:** AC grids dynamics are not easy to reproduce by using simplified models. Therefore, a representative model of an AC grid will be developed. This model will be analysed and then simulated.

3. **Laboratory implementation:** The HVDC terminal control system will be tested in the laboratory setup. Meanwhile, the network dynamics will be emulated by using the grid generator (OPAL-RT). Therefore, the control system will be tested in a realistic environment.

Medium term objectives:

1. **Extension to multi-terminal HVDC links:** In the medium-term, it is expected to extend the proposed method to multi-terminal systems.

## 1.2 Development So Far

### 1.2.1 Stage Gate Progress

Previously completed: ✓

Planned for this project: ➲

| STAGE GATE CRITERIA | Status |
|---|---|
| **Stage 1 – Concept development and simulation** | |
| • Conceptual development of damping strategies | ✓ |
| • Mathematical derivations | ✓ |
| • Proof of concept by using mathematics | ✓ |
| • Development of a simulation. Test of developments in simulation. | ✓ |
| • First results and reports | ✓ |
| | |
| **Stage 2 – Test in laboratory facilities** | |
| • Selection of the realistic test system | ✓ |
| • Extensive simulation and analytic studies | ✓ |
| • Test the scenario in a real-time platform | ➲ |

| STAGE GATE CRITERIA | Status |
|---|---|
| • Development of the control strategy for a MMC | ➲ |
| • Test the scenario in a laboratory environment | ➲ |
| • Combined test of the realistic scenario and the MMC converter | ➲ |
| • Results and reports | ➲ |
| | |
| **Stage 3 – Extension to MTDC systems** | |
| • Investigate the extension to MTDC systems. Selection of a test case | - |
| • Evaluation of the speed variation effect in wind turbines | - |
| • Evaluation of the power variation effect in electrical grids | - |
| • Development of a simulation model | - |
| • Test in a realistic scenario | - |

### 1.2.2 Plan for This Access

The main theoretical developments were already done in previous research stays at SINTEF. For this stay, the main task was to test these theoretical developments in a laboratory environment. The plan can be summarised as follows:

1. Test a realistic scenario to recreate inter-area oscillations in a laboratory setup.

2. Test a MMC emulating the dynamics of synchronous machines, with additional damping terms.

3. Test both systems together. Verify that the MMC with the proposed additions can effectively reduce inter-area oscillations.

4. Finally, make a report with the results, and try to publish them in a journal.

# 2 Outline of Work Carried Out

## 2.1 Setup

Fig. 2.1 shows the laboratory facilities used in at SINTEF Smart Grid Lab. The grid was emulated by using a 200 kVA source that is shown in Fig. 2.1 (a). The HVDC terminal consisted of a 24 level MMC that is shown in Fig. 2.1 (b). All the systems were coordinated with by using a computer that is shown in Fig. 2.1 (c). Fig. 2.2 shows one of the group members operating the facilities.


Figure 2.1: Laboratory facilities. (a) Grid emulator, (b) MMC and (c) computer interface

Figure 2.2: Group member operating the laboratory facilities.

## 2.2 Tests

### 2.2.1 Test Plan

The following organisation was considered for the stay:

1. **Before Stay:** A simulation of the electrical model and the VSM will be carried out by using Simulink and SimPowerSystems.

2. **Week 1:** Implementation of the electrical model in the grid emulator. This includes the discretization of the electrical system for its implementation in the OPAL-RT FPGA. Calculation of the initial conditions. Measurements. Validation of oscillatory modes. For this task, the assistance of one experienced technician will be required.

3. **Week 2:** Implementation of the VSM control strategy. The VSM control system that is already developed will be implemented on a control platform. The additional damping loops will be incorporated. These loops will be adjusted based on the theoretical analyses already performed. Assistance will be required for this step.

   Complete test. During this week the VSM will be tested together with the electrical grid model. The VSM should be able to damp the low-frequency resonance of the electrical grid while providing virtual inertia.

4. **After stay:** The data collected during the test will be acquired in csv format for the offline analysis in Matlab. If any additional test is needed, it will be done at a later stage with the help of SINTEF staff.

### 2.2.1 Test Carried Out

During the access, the following tests were carried out:

1. **Emulation of the grid, with PSS:** In this first test, the model of the grid was executed in the real-time platform. Then, the grid emulator was used to generate the voltage

waveforms. The PSS of electrical machines was used during all the tests so that the system remained stable.

2. **Emulation of the grid, without PSS:** In this second test, the PSS of electrical machines was deactivated. Then, an increased oscillation in the power transferred between the electrical areas was expected.

3. **Power injection with a VSM into the grid:** In order to test the VSM, a basic test was carried out. The idea was to inject active power into the grid, and to validate the transient performance.

4. **VSM operation without additional damping terms (without PSS):** In this test, the VSM was connected to the grid, and the PSS of electrical machines was deactivated. Then, it was expected that the system became unstable due to the inter-area oscillation.

5. **VSM operation with the additional damping terms (without PSS):** For this final test, the VSM was connected to the grid emulator. The PSS of the electrical machines were deactivated. Meanwhile, the additional damping terms of the VSM were connected in order to damp the oscillation.

## 2.3 Results

In this section, the results obtained during the stay are summarised. These results were obtained by using the real-time platform, and they have been depicted by using Matlab.

1. **Emulation of the grid, with PSS:** Fig. 2.3 shows the power transfer between electrical areas and the frequency of the four generators, when an additional load was connected to the bus of the HVDC terminal. It can be seen that the transient was well damped, and no oscillations were observed.

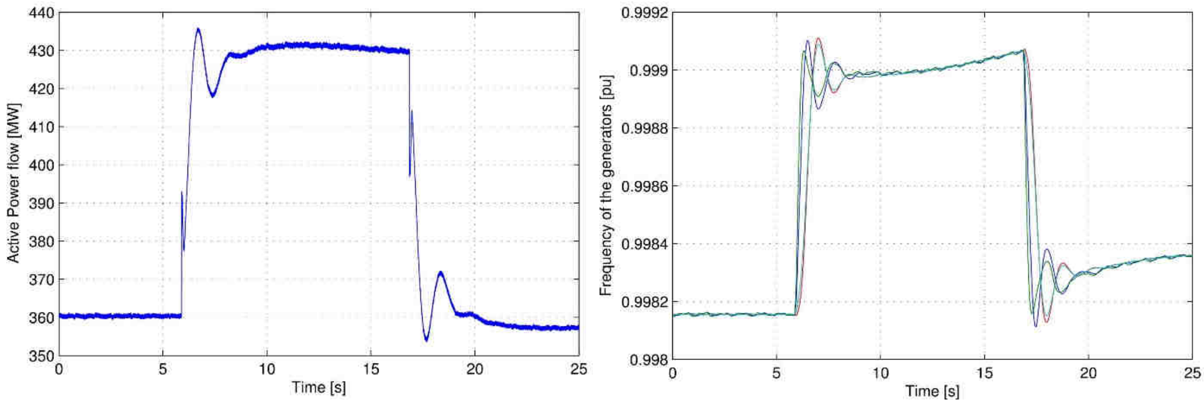


**Figure 2.3: Experimental results. Step change in the additional load connected to the HVDC terminal. The PSS of the electrical machines was active during this test.**

2. **Emulation of the grid, without PSS:** Fig. 2.4 shows the power transfer between areas and the frequency of the electrical generators, when a step change in the load was applied. The PSS of electrical machines was deactivated. It can be seen that there is an increasing oscillation.

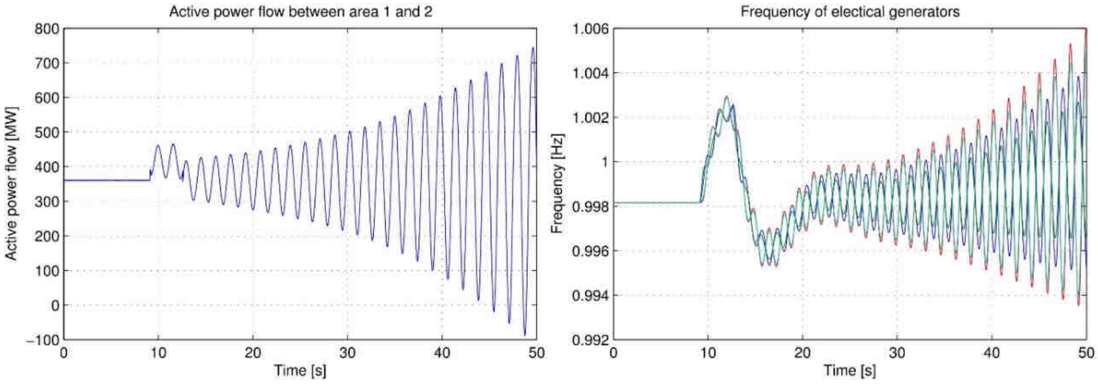


**Figure 2.4: Experimental results. Step change in the additional load connected to the HVDC terminal. The PSS of the electrical machines was deactivated during this test**

3. **Power injection with a VSM into the grid:** Fig. 2.5 shows the experimental results obtained when the reference power of the VSM was modified. Initially, the active and reactive power reference was set to zero. Then, a step in the active power command was applied.

   A small variation in the reactive power can be observed. This is due to the reactive-power droop coefficient of the VSM. Also, the frequency of all the electrical generators change because the power exchanged between them need to be rebalanced.

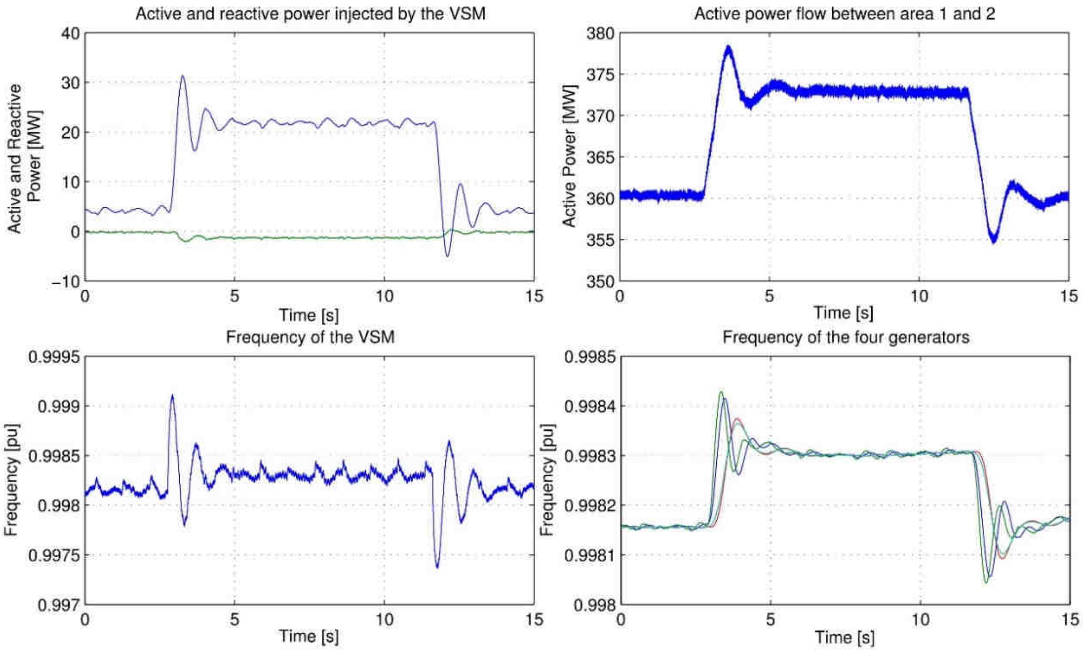


**Figure 2.5: Experimental result. Step change in the active power injected by the HVDC terminal.**

4. **VSM operation without additional damping terms (without PSS):** Fig. 2.6 shows the experimental results obtained when the VSM was connected to the electrical system, and no PSS was used in the electrical generators.

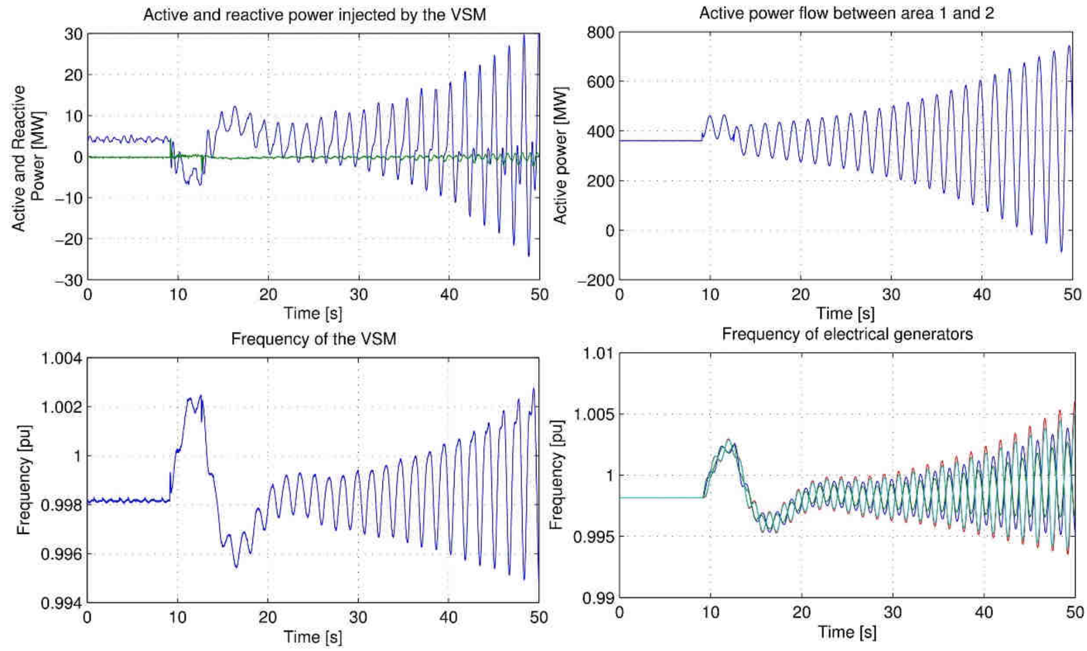


**Figure 2.6: Experimental results. Step in the load, and the PSS of the electrical machines was not connected.**

It can be seen that system, initially, seem to be stable. However, when the load was connected (at 10 seconds), an increased oscillation was generated. This oscillation was due to the inter-area oscillation.

5. **<u>VSM operation with the additional damping terms (without PSS):</u>** Fig. 2.7 shows the experimental results obtained when the additional damping terms were added to the VSM. It can be seen that, initially, the inter-area oscillation started to grow. However, the oscillation decreased over time until it vanishes.

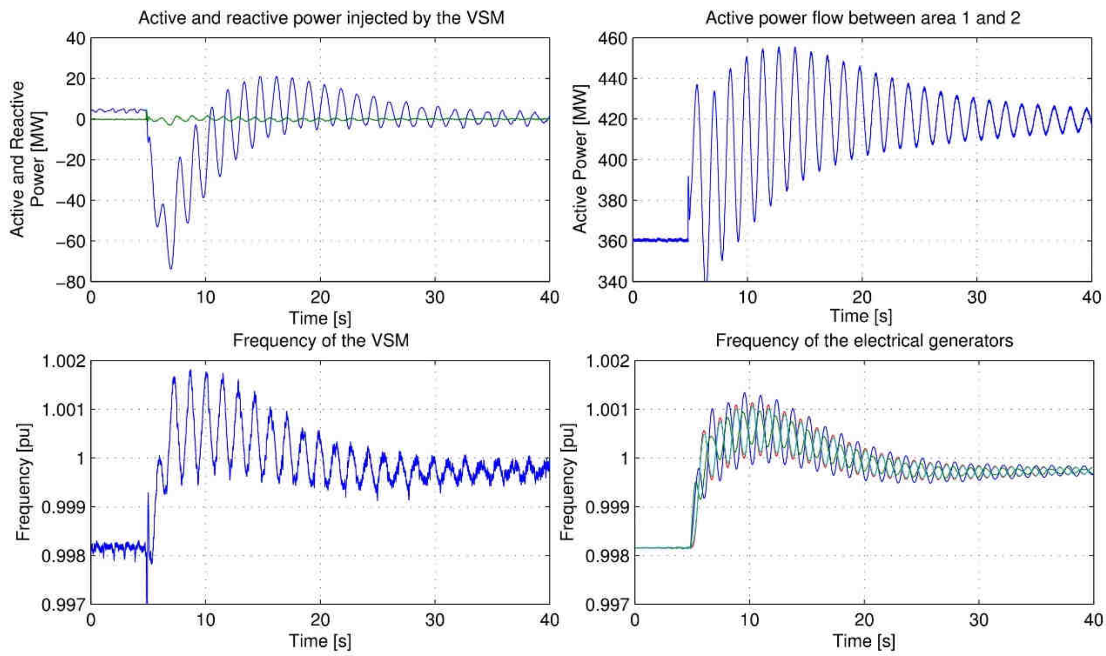


**Figure 2.7: Experimental results. Load step change applied before 10 seconds. The VSM with the additional damping terms was used.**

## 2.4 Analysis & Conclusions

Results have shown that the PSS in electrical machines is necessary in order to avoid inter-area oscillations. However, if this control solutions is not available, additional damping loops of the HVDC terminal can be used to this end. It has been shown that they provide an effective reduction of the oscillation.

The proposed control strategy was able to reduce the oscillation between areas. However, the oscillation still needed time to vanish. Therefore, it would be of interest to look for alternative damping strategies to damp the oscillation in a faster manner.

# 3 Main Learning Outcomes

## 3.1 Progress Made

The main task of this access was to verify the active damping strategies for power system oscillation damping with offshore wind farms. All the tests planned for the stay were carried out, successfully:

1. The emulation of the realistic scenario to generate oscillations provided remarkable results.

2. The strategies used to damp oscillations successfully reduced oscillations in the proposed scenario.

3. The oscillation required several seconds to vanish. For the future developments, it would be necessary to reduce this time.

### 3.1.1 Progress Made: For This User-Group or Technology

The tests done during this access made it possible to validate theoretical developments. Also, it is expected that this laboratory facilities will be used in the future to validate control strategies for multi-terminal DC microgrids.

### 3.1.2 Next Steps for Research or Staged Development Plan

In this work, basic aspects of power oscillation damping with offshore wind farms have been addressed. Results have been satisfactory. For the next steps, the following issues will be addressed:

1. Power oscillation damping require additional power from wind turbines. However, this sudden variation in the energy taken from turbines can lead to variations in rotor speeds. This can have a relevant impact on the performance of wind turbines.

2. In this work, only point-to-point HVDC systems have been considered. However, multi-terminal DC links are becoming popular to connect offshore wind farms. Therefore, it would be of interest to extend this study to this type of technology.

### 3.1.3 Progress Made: For Marine Renewable Energy Industry

In the following list, the main progress made for the renewable energy industry are summarised:

1. Power Hardware-In-the-Loop systems can be used to accurately evaluate the integration of onshore terminals to electricity networks.

2. The emulation of rotating electric machines simplify the integration of onshore terminals to electricity grids.

3. Oscillation damping with HVDC terminals require a transient source of power/energy. This energy can be taken from the rotors of wind turbines, or from other grids interconnected by the MTDC network. The effect of reducing the rotor speed in order to obtain the additional power should be carefully assessed in order to avoid damaging the wind turbines.

## 3.1 Key Lessons Learned

In the following list, the main lessons learned during the access to the laboratory facilities are summarised:

1. The two-area power system can be effectively simulated in real time by using an OPAL-RT platform and a grid emulator.

2. Power Hardware-In-the-Loop systems can be used to accurately evaluate the integration of onshore terminals to electricity networks.

3. The onshore terminal of the HVDC connection can mimic the characteristics of a synchronous machine.

4. A MMC converter can be used as the onshore terminal.

5. Additional damping terms should be added to the VSM formulation in order to damp oscillations.

6. The power required to damp oscillations is a key factor in order to scale the HVDC terminal.

7. There are dynamic limitations in the damping terms that mainly depend on the grid and the VSM dynamics.

# 4. Further Information

## 4.1 Scientific Publications

The main developments of this work were already published in the following conference:

[C1] J. Roldán-Pérez, J. Are Suul, S. D'Arco, A. Rodriguez-Cabero, M. Prodanovic "Virtual Synchronous Machine Control of VSC HVDC for Power System Oscillation Damping", *44th Annual Conference of IEEE Industrial Electronics Society (IECON) 2018*, Oct 2018, Washington D.C. (USA).

The results used for that publication were simulations. The theoretical developments and the experimental validation will be used to develop a manuscript that will be submitted to a journal.

## 4.2 Website & Social Media

Website: https://www.energia.imdea.org/

# 5. References

[1] H. A. Peterson and P. C. Krause, "Damping of power swings in a parallel ac and dc system," *IEEE Transactions on Power Apparatus and System*, vol. 85, no. 12, pp. 1231 - 1239, December 1966.

[2] A. M. Vural, "Contribution of high voltage direct current transmission systems to inter-area oscillation damping: A review," *Renewable and Sustainable Energy Reviews*, vol. 57, pp. 892 - 915, May 2016.

[3] L. Harnefors, N. Johansson, L. Zhang, and B. Berggren, "Interarea oscillation damping using active-power modulation of Multiterminal HVDC transmissions," IEEE Transactions on Power Systems, vol. 29, no. 5, pp. 2529 - 2538, Sept. 2014.

[4] J. Roldán-Pérez, A. García-Cerrada, J. L. Zamora-Macho and M. Ochoa-Giménez, "Helping all generations of photo-voltaic inverters ride-through voltage sags," *IET Power Electronics*, vol. 7, no. 10, pp. 2555-2563, 10 2014.

[5] H. Alrajhi Alsiraji and R. El-Shatshat, "Comprehensive assessment of virtual synchronous machine based voltage source converter controllers," *IET Generation, Transmission & Distribution*, vol. 11, no. 7, pp. 1762-1769, 11 5 2017.

[6] J. Roldán-Pérez, M. Prodanovic and A. Rodríguez-Cabero, "Detailed discrete-time implementation of a battery-supported synchronverter for weak grids," *IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society*, Beijing, 2017, pp. 1083-1088.

[7] M. Blau and G. Weiss, "Synchronverters used for damping inter-area oscillations in two-area power systems," International Conference on Renewable Energies and Power Quality (ICREPQ), March 2018.

[8] S. D'Arco, J. A. Suul, O. B. Fosso, "A Virtual Synchronous Machine implementation for distributed control of power converters in Smart Grids," *Electric Power Systems Research*, vol. 122, 2015, pp. 180-197.

[9] H. Zhao, Q. Yang and H. Zeng, "Multi-loop virtual synchronous generator control of inverter-based DGs under microgrid dynamics," in *IET Generation, Transmission & Distribution*, vol. 11, no. 3, pp. 795-803, 2017.

[10] V. Natarajan and G. Weiss, "Synchronverters With Better Stability Due to Virtual Inductors, Virtual Capacitors, and Anti-Windup," in *IEEE Transactions on Industrial Electronics*, vol. 64, no. 7, pp. 5994-6004, July 2017.

[11] J. Alipoor, Y. Miura and T. Ise, "Power System Stabilization Using Virtual Synchronous Generator With Alternating Moment of Inertia," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 3, no. 2, pp. 451-458, June 2015.

[12] M. Ashabani and Y. A. I. Mohamed, "Integrating VSCs to Weak Grids by Nonlinear Power Damping Controller With Self-Synchronization Capability," *IEEE Transactions on Power Systems*, vol. 29, no. 2, pp. 805-814, March 2014.

[13] S. Dong and Y. C. Chen, "Adjusting Synchronverter Dynamic Response Speed via Damping Correction Loop," in *IEEE Transactions on Energy Conversion*, vol. 32, no. 2, pp. 608-619, June 2017.

[14] D. Li, Q. Zhu, S. Lin and X. Y. Bian, "A Self-Adaptive Inertia and Damping Combination Control of VSG to Support Frequency Stability," in *IEEE Transactions on Energy Conversion*, vol. 32, no. 1, pp. 397-398, March 2017.

[15] M. A. Torres L., L. A. C. Lopes, L. A. Morán T. and J. R. Espinoza C., "Self-Tuning Virtual Synchronous Machine: A Control Strategy for Energy Storage Systems to Support Dynamic Frequency Control," *IEEE Transactions on Energy Conversion*, vol. 29, no. 4, pp. 833-840, Dec. 2014.

[16] G. Weiss and E. Venezian, "Stability analysis for coupled synchronous generators with virtual friction," *2017 22nd International Conference on Digital Signal Processing (DSP)*, London, 2017, pp. 1-5.