# System Oscillation Assessment of Inverter Based Resources (IBRs)

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# Foreword

These Guidance Notes have been prepared by the Electricity System Operator (ESO) to describe to Users on how to demonstrate the appropriate damping performance of Inverter Based Resources (IBRs) against potential system oscillations. These Guidance Notes specify a set of small signal studies which should be carried out by Users as part of the connection compliance process to ensure the safe operation and stability of the transmission system.

The prospective Users connecting directly to the National Electricity Transmission System are required to be compliant with the Grid Code and requirements set out in Bilateral Agreement documents. These Guidance Notes are prepared, solely, for the assistance of users to demonstrate the compliance.

The Operability Policy Manager (see contact details) will be happy to provide clarification and assistance required in relation to these notes. ESO welcomes comments including ideas to reduce the compliance effort while maintaining the level of confidence.

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## Introduction

This document describes a set of small signal studies which should be carried out by Users as part of the connection compliance process. These studies are necessary to demonstrate the appropriate damping performance of Inverter Based Resources (IBRs) against potential system oscillations to ensure the safe operation and stability of the transmission system.

Energy decarbonisation requires a transition to a power system with less synchronous generation and a higher penetration of IBRs which connect the generation to the system through inverters. It is understood that IBRs behave very differently from traditional synchronous generation which creates different and new challenges in system operation.

One of the operational challenges is system oscillations especially Sub-Synchronous Oscillations (SSO). The SSOs are power system oscillations at frequencies that are less than the power system frequency. They can occur under normal system conditions due to system disturbances, these oscillations are normally damped quickly and resolved. An unacceptable SSO event can occur when there is an undamped amplification of normal background low magnitude oscillations. Asset controllers and protection systems are typically setup to avoid interaction and to dampen specific frequency bands to prevent SSO events. If left unmanaged, SSO events may cause damage to transmission and generator assets, and result in the coincidental loss of generation and circuit trips.

Sub-synchronous modes always exist in a power system but, in most cases, the oscillations arising from these modes are of low magnitude and are adequately damped. With the increased penetration of IBRs in the system, some undesirable SSOs were observed by different system operators across the world. The IEEE PES IBR SSO Task published 19 examples of SSO across the world from 2007 – 2021 [1]. In the GB system, SSOs were also observed in last few years. Most recently 5-9Hz SSO occurred on five separate days during June and July 2023 [2]. Those SSO events caused disturbances on the GB power system which included the tripping of assets; however, no demand was lost at any time.

During the SSO investigation, the ESO worked closely with relevant parties to gather and analyse data, and propose, implement, and test changes. It was recognised that there is a need to create an oscillation guidance note so that a standard approach can be taken for Users to carry out the necessary analysis to mitigate the SSO risk before connection.

The ESO have been working with academia, Transmission Owners and other key industry stakeholders on the development of this guidance. The development has also taken into consideration lessons learned from the SSO investigations and other industry best practices including CIGRE [3] and ENTSO-e [4]. As a result, the ESO proposes a set of small signal studies that should be carried out by all Users as part of the compliance process to mitigate the risk of system oscillations.

These studies shall be carried out with an AC grid either represented as a Thevenin source or by using an equivalent network model provided by the ESO. It should be noted that whilst the damping performance studies does not completely mitigate all the risk of oscillation, they have been seen to significantly reduce the risk. Further large-scale studies may still be required if necessary.

The small signal tests proposed in this guidance document include both time domain and frequency domain techniques. It is suggested to compare both time domain and frequency domain methods to establish whether there are any issues. It is advised that these studies should be performed in the early phases of the project so that if any mitigation measures are required, they can be taken in a timely manner. Please note that the small signal methods mentioned are for guidance only and alternative methods and techniques can be adopted by the User after consultation with the ESO.

# 1. Small Signal Techniques

There are many small signal techniques that can be employed to investigate the behaviour of IBRs in a non-synchronous dominated network. Some of the techniques are advised as below:

- Step change- EMT simulations.
- Small signal injection study.
- EMT Active frequency scans.
- Eigen value method.

## 1.1. Step Change- EMT Simulations:

In this study a series of small step changes is applied to the grid voltage and phase angle to demonstrate the behaviour of the scheme being studied. This study should be performed with a detailed EMT model. This study provides a good indication of scheme performance and hence it is advised to be performed as a first step.

***Recommended Test Parameters:***

1. ±5% step change in AC grid voltage from nominal voltage.
2. ±30-degree Phase Jump in AC grid voltage angle.
3. ±3% step change in AC grid Voltage combined with ±10-degree phase jump in AC grid voltage angle.

***Test Scenarios:***

4. As a minimum, the test cases should be done with both minimum and maximum SCL conditions.
5. The test should cover all different configurations of the scheme.
6. The test should be performed for the contracted control modes of the scheme under study i.e., voltage control, reactive power control or power factor control.
7. Tests should be run at 20%, 50% and 100% active power levels with both import (where applicable) and export conditions.
8. The test should be performed with Min, Max and Zero reactive power levels.

***Report***

9. Simulation study results include Vac, f, Qac, Pac, Iac magnitude and phase plots at the point of common coupling. Simulations should be run until steady state conditions are reached.
10. Summary and observation of results to be provided.

***Acceptable Response:***

11. Response time should be within the timings specified in the Grid code.[5]
12. Overshoot should not be more than 5% peak to peak and settling time should be less than 2s.

## 1.2. Small Signal Injection Study [3] & [6]

Small signal EMT perturbation simulations have widely been recognised as one of the best ways to explore the behaviour of IBRs against small test signals.

For the purposes of these studies, the AC grid is represented as a Thevenin equivalent whilst the scheme under scrutiny should be represented in detail in an EMT model. The desired frequency of oscillation is injected into an AC grid in voltage and angle to see the behaviour of the scheme being studied. The proposed test setup and scenarios to be studied are discussed below:

### 1.2.1. Small signal Voltage oscillation injection

A simple example voltage amplitude representation in PSCAD is shown in diagram below.

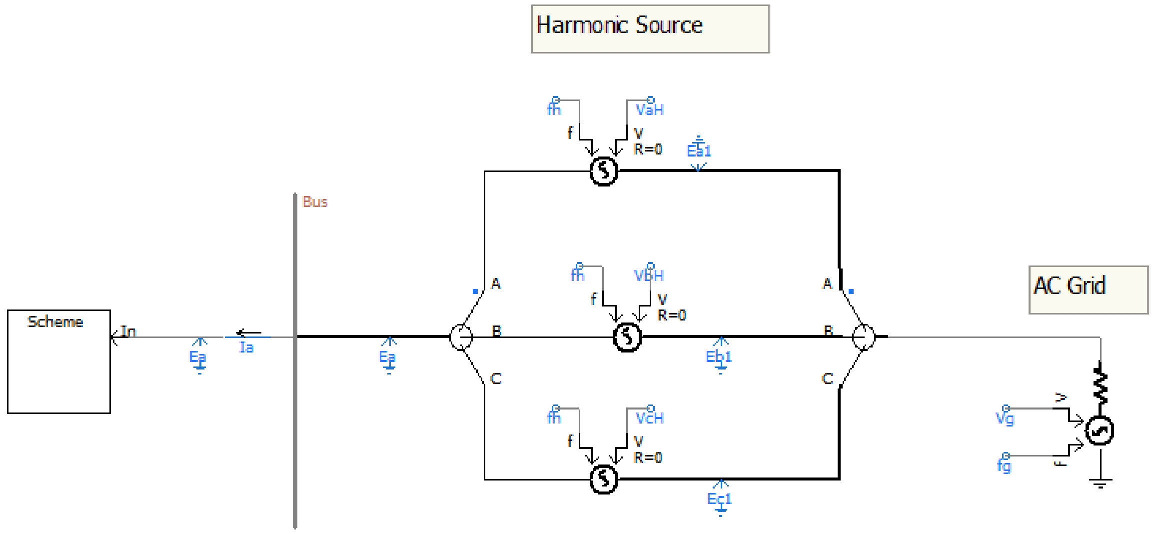



*Figure 1 Example study setup for limited time domain study.*

***Recommended Test Parameters:***

1. Frequencies ranging from 1Hz to 100Hz (or desired frequency range of interest) to be injected in series with the grid with no more than 1Hz gap in each simulation.
2. An injection signal magnitude of 1% of nominal voltage is recommended. The User is allowed to choose a different injection amplitude as long as the overall system remains in the linear region.
3. Injection should remain until steady-state conditions have been reached.

***Test Scenarios:***

4. As a minimum, the test cases should be done with both minimum and maximum SCL conditions.
5. The test should cover all different configurations of the scheme.
6. The test should be performed for contracted control modes of the scheme being studied i.e. voltage control, reactive power control or power factor control
7. Tests should be run at 20%, 50% and 100% active power levels with both import (where applicable) and export conditions.
8. Test should be performed with Min, Max and Zero reactive power levels.

***Report***

9. Simulation study results include Vac, f, Qac, Pac, Iac magnitude and phase plots at the point of common coupling. Simulations should be run until steady state conditions are reached.
10. Summary and observation of results to be provided.

***Acceptable Response:***

11. No increase in magnitude of injected oscillations, ideally the system should damp any oscillations. The response shall be demonstrated by plotting the transmission interface point (TIP) or PCC voltage with and without the scheme being studied. Refer to appendix for expected response from this study.
12. Once the injection is removed the system should recover immediately to pre-disturbance conditions.

### 1.2.2. Small signal Voltage Angle oscillation modulation

In this test, the Thevenin voltage source angle is modulated to observe the behaviour of the scheme. The test parameters and scenarios referred in section 1.2.1 should be performed for this set of simulations. The frequency control function should be disabled for this test and a phase angle modulation of ±2 degrees should be applied.

***Acceptable Response:***

1. It is expected that grid following converters show very limited response for angle oscillations.

2. Grid forming plant would have a P/f droop response below the 5Hz range. The inertia element of the grid forming plant is expected to be in phase with the modulated angle.

3. Once the injection is removed the system should recover immediately to pre-disturbance conditions.

## 1.3. Active Frequency Scans [3] & [4]

A Dynamic Frequency Scan is a method to evaluate scheme impedance and phase angle that provides insight into scheme behaviour. Moreover, it is not practical to cover a large frequency range utilising a time domain study due to model complexity and computational time constraints. Therefore, to support the small signal time domain study (specified in section 1.1-1.2) an active network frequency scan is necessary.

In order to conduct this study, the scheme under scrutiny is represented as a detailed EMT model while the AC grid is represented as a Thevenin equivalent. A small signal of a multitude of frequencies of interest is injected into the scheme being studied. The small signal can be a voltage signal in series with a grid as shown in Figure 1 or a current injection in parallel with a grid as shown in Figure 2. The impedance characteristics of the scheme under scrutiny are measured by performing Fourier transformation on the Voltage (V) and current (I) signal.

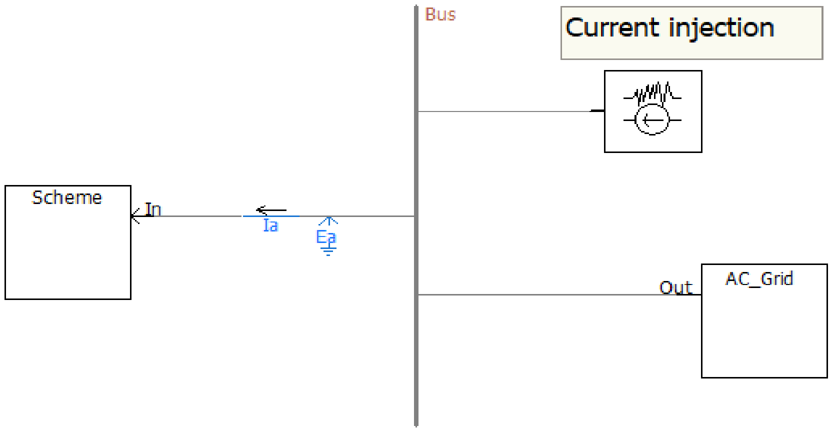



*Figure 2 Current injection model setup for frequency scan*

***Recommended Test Parameters:***

1. The injected current or voltage amplitude should not be so small that it is lost in the noise and should not be large enough to cause any non- linear effects.
2. The frequency increment should be chosen so that no impedance vs frequency information is lost.

***Test Scenarios:***

3. It is recommended that frequency scans should be done for frequency ranges from 0 to 2.5kHz or for the frequency range of interest.
4. As a minimum, the test cases should be performed with both minimum and maximum SCL conditions.
5. Tests should cover all different configuration of the scheme.
6. The test should be performed for contracted control modes of the scheme being studied i.e. voltage control, reactive power control or power factor control
7. Tests should be run at 20%, 50% and 100% active power levels with both import (where applicable) and export conditions.
8. Test should be performed with Min, Max and Zero reactive power levels.

***Report:***

The report should include:

9. Scheme impedance (R&X vs F plot)
10. Summary and observation of results
11. Conclusions on the stability of the scheme being studied and the AC grid together.

***Acceptable Response:***

12. The resistance (R) of the scheme under scrutiny should be positive throughout the frequency range. In case the negative resistance is observed further investigation shall be required.

### 1.4. Eigenvalue Method

The Eigenvalue analysis is another method of calculating the oscillation modes, frequency of oscillation and damping co-efficient. It is becoming one of the main/preferred methods of investigating interaction phenomena and applying mitigation measures.

This is a frequency domain study, but detailed EMT model assumptions are required for the scheme under scrutiny. In this methodology the linear state space representation of the system and connected AC grid are represented as a Thevenin equivalent and are used to determine the Eigenvalues of the full system.

In the past it has been considered a complicated method to estimate the Eigenvalues but nowadays this functionality has been included in power system tools which solves the state space solution and provides oscillation modes, frequency of oscillation and damping co-efficient.

In order to validate the study, it is recommended that results obtained from the Eigenvalue method should be consistent with the results obtained from studies of Section 1.1,1.2 and 1.3.

***Test Scenarios:***

1. As a minimum, the test cases should be done with both minimum and maximum SCL conditions.
2. The test should cover all different configurations of the scheme.
3. The test should be performed for contracted control modes of the scheme being studied i.e. voltage control, reactive power control or power factor control
4. Tests should be run at 20%, 50% and 100% active power levels with both import (where applicable) and export conditions.
5. Test should be performed with Min, Max and Zero reactive power levels.

***Report:***

6. Oscillation frequencies of the scheme under scrutiny.
7. Eigenvalue results comparison with frequency scan and limited time domain study.
8. Summary and observation of the results to be provided.

***Acceptable Response:***

1. Minimum 10% damping ratio is expected for all oscillation modes.

## 2. Conclusion

This guidance describes a set of small signal studies which should be carried out by Users as part of the connection compliance process. It is essential for the Users to ensure that their plant design is robust and complies with the requirements of these guidelines. These studies are required to demonstrate the damping performance of Inverter based resources (IBRs) against potential system oscillations to ensure safe operation and system stability.

# 3. References


1. IEEE PES IBR SSO Task report
   Real-World Subsynchronous Oscillation Events in Power Grids with High Penetrations of Inverter-Based Resources (osti.gov)

2. ESO Operational Transparency Forum
   https://www.nationalgrideso.com/document/293401/download

3. Interactions between HVDC systems and other connections. ENTSO-E guidance document for national implementation for network codes on grid connection, 5 March 2018
   Interactions between HVDC systems and other connections (entsoe.eu)

4. CIGRE TB 909 SSO guidance

   Guidelines for Subsynchronous Oscillation Studies in Power Electronics Dominated Power Systems | eCIGRE (e-cigre.org)

5. GB Grid Code

   Grid Code documents | ESO (nationalgrideso.com)

6. Dynamic Model Acceptance Test Guideline, AEMO. 2 Nov 2021

   model-acceptance-test-guideline-nov-2021.pdf (aemo.com.au)

# 4. Appendix

Study has been performed with a windfarm of 50MW to indicate the expected behaviour from the study explained in section 1.2.

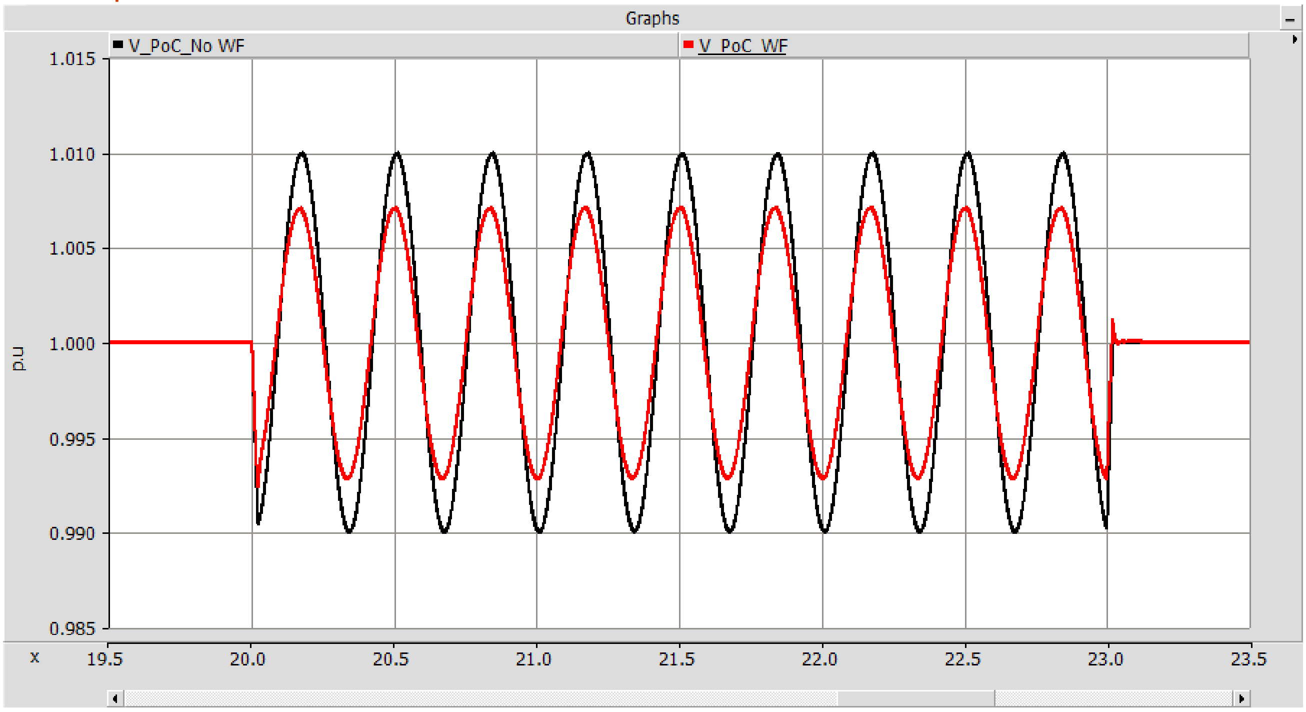
Following cases have been performed:

| Cases No. | Case Description | Response |
|---|---|---|
| 1. | Oscillations of 3Hz has been injected with a magnitude of 1% at 20s in an AC grid while windfarm is connected to the grid, producing full output i.e. 50MW. | Result compared with baseline response where no wind farm connected. It shows that windfarm produce antiphase response and hence reduce the magnitude of oscillations in an AC grid Voltage. This demonstrate WF has good damping for this particular frequency. |

Following is the list of signals recorded:

| Signal Name | Quantity | Units |
|---|---|---|
| V_PoC_No WF | Point of connection Voltage with no Windfarm connected | p.u. |
| V_PoC_WF | Point of connection Voltage with Windfarm connected | p.u. |
| Q_PoC_No WF | Point of connection Reactive Power with no Windfarm connected | MVARs |
| Q_PoC_WF | Point of connection Reactive Power with Windfarm connected | MVARs |

## Case 1 plots:



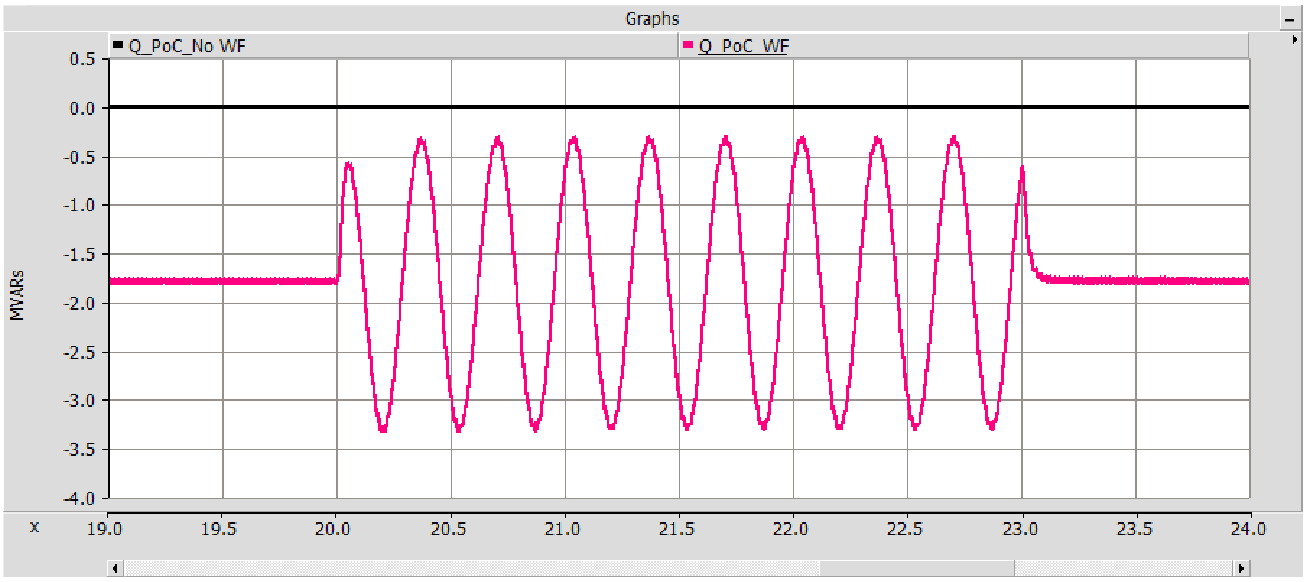



*Figure 3. PoC voltage and reactive power with WF and without WF*