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Guidance Notes for Synchronous Condensers

EU Code Users - Issue 1

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Foreword

These Guidance Notes have been prepared by National Grid Electricity System Operator (NGESO) to describe how compliance with the technical requirements defined in the Bilateral Connection Agreement will be evaluated for Synchronous Condensers. Throughout this document NGESO refers to National Grid Electricity System Operator and NGET refers to the Transmission Owner part National Grid.

These Guidance Notes are prepared, solely, for the assistance of customers providing services to NGESO using Synchronous Condenser technology. In the event of dispute, the Bilateral Connection Agreement documents shall take precedence over these notes.

The Electricity Customer Connections Manager (see contact details in Appendix D) will be happy to provide clarification and assistance required in relation to these notes.

NGESO welcomes comments including ideas to reduce the compliance effort while maintaining the level of confidence. Feedback should be directed to the NGESO Electricity Connection Compliance team at:

Telephone: +44 (0)777 502 7428

Email: Biniam.Haddish@nationalgrideso.com

Biniam Haddish
Connections Compliance Manager
Faraday House, Warwick.

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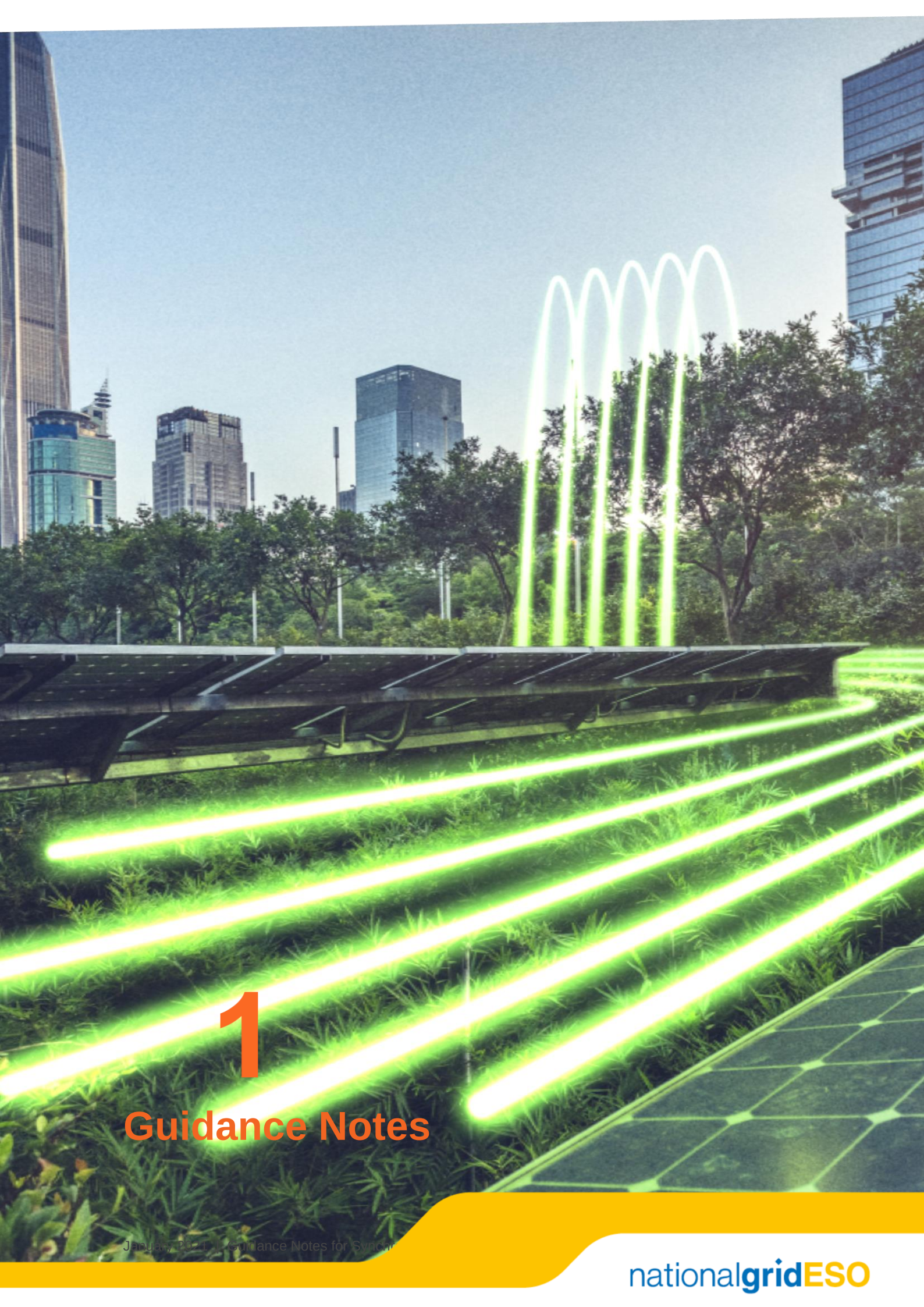
Abbreviations

This section includes a list of the abbreviations that appear in this document.

Abbreviation	Description
AVR	Automatic Voltage Regulator
BA / BCA	Bilateral Agreement / Bilateral Connection Agreement
CP	Compliance Processes
FON	Final Operational Notification
FRT	Fault Ride Through
NGESO	National Grid Electricity System Operator
NGET	National Grid Electricity Transmission
OC	Operating Code
OEL	Over Excitation Limiter
PSS	Power System Stabiliser
SO	System Operator (NGESO)
SPT	Scottish Power Transmission
SHET	Scottish Hydro Electric Transmission
UEL	Under Excitation Limiter



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Guidance Notes

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Introduction

This document aims to provide additional information on the technical studies and compliance testing data Synchronous Condenser owners and Generators seeking to operate Synchronous Power Generating Modules as Synchronous Condensers need to submit to NGESO to obtain a FON (Final Operational Notification).

To achieve Operational Notification, the company owning and operating a Synchronous Condenser must demonstrate compliance with the Bilateral Connection Agreement. The BCA is a site-specific document agreed by NGESO and the plant owner, which for technical reasons specify requirements or specific parameters within a range indicated in the Grid Code.

Synchronous Condenser providers may, if they wish, suggest alternative tests or studies, which they believe will demonstrate compliance in accordance with the requirements placed on themselves and NGESO.

Model

The owner of a Synchronous Condenser or Synchronous Power Generating Module capable of operating as a Synchronous Condenser is required to provide NGESO and the Transmission Owner (for sites in Scotland) with a model of their Synchronous Condenser unit. The excitation system control model data is to be provided as Laplace transfer functions in a block diagram format. Control systems with several discrete states or logic elements may be provided in flow chart format if a block diagram format does not provide a suitable representation.

The model structure and complexity must be suitable for NGESO to integrate into their power system analysis software (currently DIgSILENT Power Factory). In cases where the model's functionality cannot be correctly or satisfactorily represented within NGESO's power system analysis software, the plant owner may be required to liaise with NGESO to determine appropriate simplifications or changes in representation to produce an appropriate model.

In general, excitation system models provide adequate responses without the need for integration time steps smaller than 10ms. However, should the model need a smaller time constant a brief description of the associated transfer function block purpose shall be provided for NGESO to understand the impact of a simplification on the model performance.

Models submissions implemented in DIgSILENT PowerFactory shall not use DPL codes or require running separate scripts. All model parameters must be identified along with units and site-specific values. A brief description of the model should ideally be provided as ultimately this will save time and money for both parties.

The model representation provided should ideally be implemented on a power system analysis software package of the plant owner's choosing, as it is otherwise highly unlikely to produce valid results when compared with the test results from the real equipment. In the event the model does not produce the correct output, the data submission will be considered incorrect and not

contractually compliant. NGESO will confirm the model accuracy. Validation of the model is to be completed by the plant owner following the compliance tests.

The model also needs to be suitable for integration into the power system analysis software used by the relevant Transmission Owner (NGET, SPT or SHET). Support may be required from the plant owner to implement and, if necessary, modify the model representation for use on the Transmission Owner's power system analysis software (ordinarily this will not be the case if the model has already been satisfactorily implemented by NGESO).

Simulation Studies

Simulation studies are required from the owner of the Synchronous Condenser or Synchronous Power Generating Module capable of operating as a Synchronous Condenser to provide evidence that the plant and apparatus comply with the provisions of the Bilateral Connection Agreement prior to connection.

The simulation studies should be submitted in the form of a report to demonstrate compliance with the Bilateral agreement in sufficient time to allow NGESO to review the content and validity of the report and models utilised prior to the planned synchronisation date (typically 3 -6 months).

The simulation studies shall be carried out using the validated models supplied to NGESO in accordance with requirements specified in the BCA. The simulation study report shall include the following topics:

Reactive Capability across Voltage Range

Load flow study to demonstrate the Synchronous Condenser can provide full lagging reactive power output for 1.05pu system voltage. The study shall display the plant terminal voltage, reactive power output and connection voltage.

Load flow study to demonstrate the Synchronous Condenser can provide full leading reactive power output for 0.95pu system voltage. The study shall display the plant terminal voltage, reactive power output and connection voltage.

Open circuit response test.

A time series dynamic simulation study to demonstrate the synchronous condenser meets the open circuit performance requirements defined in the BCA.

The study initial condition shall set the Synchronous Condenser terminal voltage at 0.9pu nominal voltage. After 5 to 10 seconds of simulation run showing the steady initial conditions a 10% voltage step injection into the excitation system voltage setpoint shall be applied. The study shall display the plant terminal voltage, field voltage and field current.

Voltage control

A time series dynamic simulation study showing the response of the Synchronous Condenser while connected to the network to a -2%, +2%, -5% and +5% voltage step in the excitation system voltage setpoint.

A time series dynamic simulation study showing the response of the Synchronous Condenser to a -5% and +5% change in voltage at the connection point with transmission network.

The studies shall be carried out with the transmission network at its expected minimum fault level and the plant initially operating at zero reactive power output.

The study shall display the unit terminal voltage, the connection point voltage, reactive power output at the unit terminals, reactive power at the connection point, field voltage, field current and voltage setpoint change.

Fault Ride Through (FRT)

A time series dynamic simulation study showing the behaviour of the Synchronous Condenser for faults lasting 140ms applied at the point the plant connects to the transmission network. The study shall include the following faults:

- Balanced Three phase fault
- Phase to Phase fault
- Two Phase to Ground fault
- A Single Phase to Ground fault.

The FRT simulations shall be carried out with the Synchronous Condenser operating at maximum leading reactive power output and the fault level at the connection point at the expected minimum.

A time series dynamic simulation study showing the behaviour of the Synchronous Condenser for balanced voltage dips lasting over 140ms in duration applied to the nearest network node operating at 275kV or above. The voltage dips and duration to be studied are:

- 50% retained voltage at the supergrid node lasting 0.45 seconds.
- 70% retained voltage at the supergrid node lasting 0.81 seconds.
- 80% retained voltage at the supergrid lasting 1 second.
- 85% retained voltage at the supergrid lasting 180 seconds.

The simulations shall be carried out with the Synchronous Condenser operating at zero reactive power output and the fault level at the connection point at the expected minimum.

Performance Tests

Tests will be required to demonstrate that the Synchronous Condenser or Synchronous Power Generating Module capable of operating as Synchronous Condenser meets the relevant provisions of the BCA.

The tests are carried out by the owner of the Synchronous Condenser or Synchronous Power Generating Module capable of operating as a Synchronous Condenser, or by their agent, and not by NGESO.

Tests shall be completed following the test procedures supplied by the plant owner or by their agent. The test procedures are required to obtain an Interim Operational Notification, well in advance to the plant connecting to the network to ensure NGESO has enough time to review and comment.

Test results need to be provided to NGESO in an Excel spreadsheet. The data within the Excel files must be arranged as detailed in the Appendix C - Table 7 as experience has shown that significant time can be saved by avoiding re-submission requests due to lack of clarity over the data being submitted.

The tests required with their associated data, as well as examples of testing procedures are also shown in the Appendices A and B.

National Grid ESO Data Recording Equipment

In some cases, the Synchronous Condenser owner might prefer NGESO to witness and separately record performance tests data; should that be requested by the user and specified in the bilateral agreement, NGESO will provide a digital recording instrument on site for the tests witnessed by NGESO.

The list below shows the minimum signals NGESO requires to monitor and record for witnessed tests to establish the Synchronous Condenser dynamic performance:

- MW – Active Power output at the Synchronous Condenser unit terminal.
- MVAr – Reactive Power Output from the unit at the point of connection[1].
- Vt – Synchronous Condenser Terminal Voltage.
- Vc – Synchronous Condenser Connection Voltage.
- Efd – Synchronous Condenser Field Voltage and /or Main Exciter Field Voltage.
- Ifd – Synchronous Condenser Field Current (where possible).

The station shall be responsible for providing the listed signals above for NGESO's recording equipment. The signals provided are required to be in the form of dc voltages within the range -10V to +10V. The input impedance of the NGESO equipment is in the region of 1MOhm and its loading effect on the signal sources should be negligible.

The station should advise NGESO of the signals and scaling factors prior to the test day. The form of a typical test signal schedule is shown below.

[1] Note 1: Alternatively, Reactive Power output at the unit terminals if applicable.

Signal	Unit	Voltage Range	Signal Representation
Reactive Power Output	MVAr	-8V to +8V	- Reg Capacity to +Reg Capacity
Terminal Voltage	kV	0 to 8V	Nominal Voltage –10% to Nominal Voltage +10%
Field Voltage	V	0 to 8V	
Field Current	A	0 to 8V	
List of other signals ……			

Table 1 - A typical test signal schedule

The station should provide its own digital recording equipment to record the same plant variables. This will provide a back up to the test results should one of the recording instruments fail at the time of testing. The recording equipment shall be capable of recording data with a minimum 1Hz rate.

Compliance Test Log sheet

Where test results are completed without any NGESO presence but are relied upon as evidence of the compliance with the Bilateral Agreement they should be accompanied by a log sheet. This sheet should be legible, in English and detail the items as indicated in Appendix C in tables 8 and 9.

Test Notification to Control Room

The owner of the Synchronous Condenser or Synchronous Power Generating Module capable of operating as a Synchronous Condenser is responsible for notifying the 'NGESO Control Centre' of any tests to be carried out on their plant, which could have a material effect on the National Electricity Transmission System. The procedures for planning and co-ordinating all plant testing with the 'NGESO Control Centre is detailed in OC7.5 of the Grid Code (i.e. Procedure in Relation to Integral Equipment Tests). For further details relating to this procedure, refer to "Integral Equipment Tests - Guidance Notes" which can be found by following the link below:

https://www.nationalgrideso.com/document/33971/download.

Alternatively, go to National Grid's Internet site in Grid Code, Associated Documents

The Synchronous Condenser owner should be aware that this interface with NGESO transmission planning will normally be available in weekday working hours only. As best practice, the plant owner should advise the 'NGESO Control Centre' and in Scotland the relevant Transmission Owner, or Distribution Network Operator (if embedded) of the times and nature of the proposed tests at the earliest stage possible. If there is insufficient notice or information provided by the plant owner, then the proposed testing may not be allowed to proceed.

Model Validation

The results recorded during the plant performance tests may be used to validate the model of synchronous condenser and its excitation control system.

The performance tests may have proved that the Synchronous Condenser and its control systems meet the technical requirements of the BCA. However, the plant's tested behaviour may be different from the behaviour predicted by the simulation studies using the provided models.

Therefore, following successful tests the Synchronous Condenser owner or its agent shall validate the performance of the submitted model by providing overlays of recorded tests with simulations replicating as far as reasonably practical the same conditions. If the results are identical or matched very well, then the submitted model has been validated and accepted as the accurate model of the plant. If the results are different then the Synchronous Condenser owner, or his agent, i.e. consultant or equipment manufacturer, should resubmit a modified model. This process will be repeated until there is close alignment with the test results and simulation results.

Protection Requirements

Islanding Protection

NGESO does not require islanding protection for Synchronous Condensers. Should the plant owner need this type of protection and inter-tripping scheme as detailed in G59/99 recommendation would be the preferred method. The use of Rate of Change of Frequency (ROCOF) protection relays for this purpose shall be discussed and agreed with NGESO.

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Appendices

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Appendix A: Reactive Capability

Summary of Requirements

The reactive capability requirements for the Synchronous Condenser or the Synchronous Power Generating Module capable of operating as a Synchronous Condenser are set out in the Bilateral Agreement.

The Synchronous Condenser or Synchronous Power Generating Module capable of operating as a Synchronous Condenser shall be capable of delivering its reactive power range across a variation in system voltage. The voltage variation on a 400kV system should remain within +/-5% of the nominal voltage in normal system conditions. For transmission system with voltages of 275kV, 132kV and 110kV the variation must stay between +/-10%. The Synchronous Condenser operational point is normally varied through the application of on load tap changes to the unit step-up transformer. Therefore, the tap changer shall have enough taps and being capable of on-load changes in tap position to satisfy the combined requirements.

Reactive Capability Testing

In order to demonstrate that a Synchronous Condenser can satisfy the reactive capability requirements it is necessary to perform reactive capability tests.

Below are two standard methods used to achieve the plant range limits which might aid the plant owner or its agent to draft their own test procedures for reactive capability tests.

Step No	Description	Notes
0	Before test commence confirm: • AVR is set to automatic control. • AVR voltage setpoint set to control the unit terminal voltage to 1pu of nominal voltage.	
1	• Synchronous Condenser transformer tapped to generate maximum continuous lagging reactive power output. • If required adjust AVR voltage setpoint to achieve maximum lagging value. • Hold for 60 minutes.	
2	• Synchronous Condenser transformer tapped to generate maximum continuous leading reactive power output. • Hold for 60 minutes.	

Table 2 - Method 1: Combination of Transformer tapping and terminal voltage setpoint change

Step No	Description	Notes
1	• Plant in Voltage Control Mode. • Select Target Voltage to achieve maximum continuous lagging reactive power output. • Keep selected target voltage for 60 minutes.	
2	• Plant in Voltage Control Mode. • Select Target Voltage to achieve maximum continuous leading reactive power output. • Keep selected target voltage for 60 minutes.	
3	• Return Target Voltage to the value required to achieve zero reactive power.	

Table 3 - Method 2: Adjustment of voltage setpoint

Appendix B: Voltage Control Testing

Summary of Requirements

The Synchronous Condensers or Synchronous Power Generating Modules capable of operating as Synchronous Condensers are required to meet the performance requirements with regards to excitation control specified in the Bilateral Agreement.

Open Circuit Tests

Synchronous Condenser without a prime mover capable of continuously spinning the machine's rotor at rated speed are not required to carry out open circuit test.

Synchronous Power Generating Modules capable of operating as Synchronous Condensers and Synchronous Condensers capable of continuously running at rated speed in open circuit condition prior to first synchronising onto the system are required to perform an open circuit test.

The test initial conditions shall be set by running the Synchronous Condenser up to rated speed and setting the Automatic Voltage Regulator (AVR) into to automatic mode to control the unit terminal voltage at 0.9pu of nominal voltage. Around 5 to 10 seconds of steady initial conditions shall be recorded before a 10% voltage step is applied into the AVR Voltage Reference.

The recording of the following signals shall be provided to a minimum of 100[Hz] sampling rate.

- Vt – Synchronous Condenser Terminal Voltage
- Efd – Synchronous Condenser Field Voltage and /or Main Exciter Field Voltage
- Ifd – Synchronous Condenser Field Current (where possible).

The results should be submitted to NGESO in the form of graphs with legible axes and scaling plus the complete set of data in an Excel file arranged as shown in Appendix C table 7. NGESO will indicate acceptance of the open circuit tests in writing whereupon the unit owner, provided there are no other active restrictions, may synchronise the relevant unit to the system.

On load Excitation System Tests

After the Synchronous Condenser has been synchronized with its AVR set to automatic control the on-load excitation system tests can be commence.

Starting with the Synchronous Condenser generating zero reactive power voltage steps changes corresponding to +/-1% and +/-2% shall be applied to the AVR voltage reference.

Below is an example of a standard procedure used to carry out these tests.

Step No	Description	Notes
0	Before tests commence confirm • AVR is set to Automatic control • Condenser generating zero reactive power output.	
1	• Record steady state for 10 seconds. • Inject +1% voltage step into AVR voltage setpoint. Record at least 10 seconds. • Remove the voltage step by returning the AVR voltage setpoint to 1pu of nominal voltage. Record at least 10 seconds.	
2	• Record steady state for 10 seconds. • Inject -1% voltage step into AVR voltage setpoint. Record at least 10 seconds. • Remove the voltage step by returning the AVR voltage setpoint to 1pu of nominal voltage. Record at least 10 seconds.	
3	• Record steady state for 10 seconds. • Inject +2% voltage step into AVR voltage setpoint. Record at least 10 seconds. • Remove the voltage step by returning the AVR voltage setpoint to 1pu of nominal voltage. Record at least 10 seconds.	
4	• Record steady state for 10 seconds. • Inject -2% voltage step into AVR voltage setpoint. Record at least 10 seconds. • Remove the voltage step by returning the AVR voltage setpoint to 1pu of nominal voltage. Record at least 10 seconds.	

Table 4 - Example of an on-load step test procedure

Under Excitation (UEL) Testing

This test is carried out to establish the setting of the limiter and to verify its correct operation including adequate damping.

Synchronous machine stability margin is reduced while operating close to the UEL limit; therefore, it is recommended to carry out a preliminary UEL functionality test to avoid plant instability risk. The test can be carried out by moving the UEL setting close to the Synchronous Condenser point of operation while the plant output is close to zero reactive power followed by 2% reduction in the AVR voltage setpoint.

After successful completion of the UEL functionality test the UEL setting shall be restored to its design value and the UEL test repeated; this time the Synchronous Condenser point of operation shall be moved and stepped over the UEL design setting as declared in the Reactive Capability Chart submitted to NGESO.

Below is an example of a traditional method used for carrying out UEL tests.

Step No	Description	Notes
0	Before tests commence confirm; • AVR is set to Automatic control. • Condenser generating zero reactive power output.	
1	• Move UEL setting close to the Synchronous Condenser point of operation. Record steady state for 10 seconds. • Inject -2% voltage step into AVR voltage setpoint. Record at least 10 seconds. • Remove the voltage step by returning the AVR voltage setpoint to pre-voltage step value. Record at least 10 seconds.	
2	• Move UEL setting back its design value. • Move Synchronous Condenser point of operation close to the Under-excitation limit. Record 10 seconds. • Inject -2% voltage step into AVR voltage setpoint. Record at least 10 seconds. • Remove the voltage step by returning the AVR voltage setpoint to pre-voltage step value. Record at least 10 seconds.	

Table 5 - Example of UEL Test procedure

Over Excitation Limiter (OEL) Testing

The action of an OEL differs from that of an UEL so the OEL test requirements are normally discussed with NGESO prior to testing in order to establish a sensible test procedure, appropriate to the control system design.

NGESO are particularly interested in ensuring the OEL is set as high as possible, whilst ensuring the machine design limits are not breached and that the machine protection will not operate before or whilst the OEL is active.

The OEL action is typically initiated by injecting a +2% to +10% positive voltage step into the AVR voltage reference. The OEL would be set at the maximum value within the design limit for the Synchronous Condenser unit, normally well above excitation at rated MVA. For this reason, the test is not normally carried out at the OEL setting, typically the setting is reduced to a level equivalent to the maximum continuous lagging MVAr output. A positive step is then applied to the AVR Voltage reference or the Synchronous Condenser step-up transformer is tapped to take the MVAr output higher. If the OEL is working correctly, the OEL should operate after sufficient time delay to bring back the excitation within limits.

The steady state accuracy of the limit level and any overshoot are of particular interest, as the Synchronous Condenser owner and NGESO may need to determine the limit level once the setting is restored and ensure that any protection does not operate.

If the OEL has multiple levels to account for heating effects, an explanation of this functionality will be necessary and if appropriate, a description of how this can be tested.

Below is a step by step description of a standard method used to tests the OEL to aid Synchronous Condenser owners or their agents to develop their own testing procedures.

Step No	Description	Notes
0	Before tests commence confirm; • AVR is set to Automatic control.	
1	• Move the Synchronous Condenser OEL setting to the maximum continuous lagging reactive power output. • Move the Synchronous Condenser point of operation closer to the OEL setting chosen for the test. • Record 10 seconds of steady state. • Inject +5% voltage step into AVR voltage setpoint. Record at least 10 seconds. • Remove the voltage step by returning the AVR voltage setpoint to pre-voltage step value. Record at least 10 seconds.	
2	• Return OEL to its final setting position.	

Table 6 - Example of OEL Test procedure

Appendix C: Test Signal Schedule and Log sheet

Compliance Test Signal Schedules

Where Synchronous Condenser performance tests are carried out without the presence of NGESO personnel the content and format of the test data shall be arranged as displayed in the table 7 below before it is submitted to NGESO for review.

- Where any additional test signals to those indicated in table 7 are presented, these should only be added with the agreement of NGESO and entered within the files as additional columns to the right of the required signals.
- Where a signal cannot be provided, and this has been agreed with NGESO in advance of tests, a blank column should be retained within the data.
- Where additional signals are included, or the signals are presented but not in the arrangement detailed in table 7 the data may be rejected, and the customer will be asked to resubmit the data in the agreed format.

Synchronous Condenser AVR, UEL/OEL Limiters								
	Col 1	Col 2	Col 3	Col 4	Col 5	Col 6	Col 7	Col 8
1	Time (10ms)	Active Power	Reactive Power	Terminal Voltage	Connection Voltage	Speed /Frequency	Field Voltage	Field Current
	Col 9	Col 10	Col 11	Col 12	Col 13	Col 14	Col 15	Col 16
1	Logic/Test Start #	PSS Output #	Noise Injection #					
# Columns may be left blank, but the column must still be included in the files								

Table 7 - Compliance Test Data template

Compliance Test Log sheet

Where test results are completed without any NGESO presence but are relied upon as evidence of the compliance they should be accompanied by a log sheet. This sheet should be legible, in English and detail the items as indicated below:

- Time and Date of test.
- Name of Power Station and module if applicable.
- Name of Test engineer(s) and company name.
- Name of Customer(s) representative and company name.
- Type of testing being undertake e.g. Voltage Control.
- Ambient Conditions e.g. Temperature, pressure.
- Controller settings, e.g. Voltage slope, Voltage setpoint.

For each test the following items should be recorded as relevant to the type of test being undertaken. Where there is uncertainty on the information to be recorded this should be discussed with NGESO in advance of the test.

Voltage Control Tests

- Start time of each test step.
- Active Power.
- Reactive Power.
- Connection Voltage.
- Voltage Control Setpoint, if applicable or changed.
- Terminal Voltage if applicable.
- Generator tap position or Grid Transformer tap position, as applicable.

Example Voltage Control Log sheet

Test No.	Time	Initial Conditions					Noise inj	PSS in/out	PSS Gain	Description	Saved File
		MW	MVAr	Vt	HV	Tap					

Table 8 - Voltage Control Test Log sheet

Reactive Power Capability Tests

- Start time of test.
- Active Power.
- Reactive Power.
- Connection Voltage.
- Terminal Voltage if applicable.
- Generator tap position or Grid Transformer tap position as applicable.

Example Reactive Capability Log sheet

Test No.	Time	Initial Conditions					Description	Saved File
		MW	MVAr	Vt	HV	Tap		

Table 9 - Reactive Capability Test Log sheet

Appendix D: Contacting National Grid

There are a number of different departments within National Grid that will be involved with this connection. The initial point of contact for National Grid will be your allocated Customer Connection Contract Manager for your Bilateral Agreement. If you are unsure of who your allocated Customer Connection Contract Manager is then the team can be contacted on transmissionconnections@nationalgrid.com.

For any correspondence relating to testing on the system following the Grid Code the IET process should be followed with notifications made to the '.Box.Tranreq' (tranreq@nationalgrideso.com) email address for England and Wales connections and '.Box.TR.Scotland' (TRScotland@nationalgrideso.com) for all connections in Scotland.

Contact Address:

National Grid ESO, Faraday House, Warwick Technology Park, Gallows Hill, Warwick, CV34 6DA.

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Faraday House, Warwick Technology Park,
Gallows Hill, Warwick, CV346DA

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