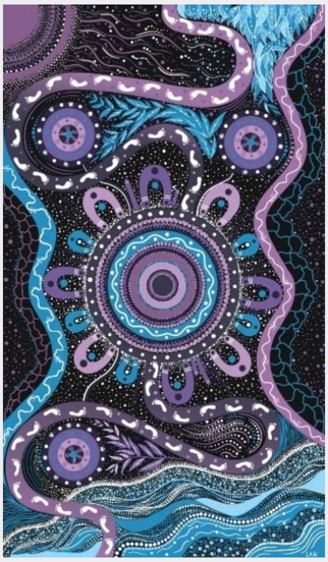
AEMO
AUSTRALIAN ENERGY MARKET OPERATOR
Victorian Planning

Harmonic Studies Guideline for Victorian Transmission Connections

AEMO Victorian Planning and Connections



We acknowledge the Traditional Custodians of the land, seas and waters across Australia. We honour the wisdom of Aboriginal and Torres Strait Islander Elders past and present and embrace future generations.

We acknowledge that, wherever we work, we do so on Aboriginal and Torres Strait Islander lands. We pay respect to the world's oldest continuing culture and First Nations peoples' deep and continuing connection to Country; and hope that our work can benefit both people and Country.

'Journey of unity: AEMO's Reconciliation Path' by Lani Balzan

AEMO Group is proud to have launched its first Reconciliation Action Plan in May 2024. 'Journey of unity: AEMO's Reconciliation Path' was created by Wiradjuri artist Lani Balzan to visually narrate our ongoing journey towards reconciliation - a collaborative endeavour that honours First Nations cultures, fosters mutual understanding, and paves the way for a brighter, more inclusive future.

Important notice

Purpose

The purpose of this document is to provide guidance as to the types of studies AEMO Victorian Planning and Connections expects to receive for evidence of compliance with S5.2.5.2 and S5.3.8 of the National Electricity Rules as part of an application to connect in the Victorian Declared Shared Network.

Disclaimer

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Version control

Version	Release date	Changes
1.0	06/02/2025	First Version

Contents

1 Introduction

This guideline is intended to improve clarity and consistency of assessments against the S5.2.5.2 or S5.3.8 of the National Electricity Rules (NER) for connection applications in the Victorian Declared Shared Network (DSN), as well as to reduce the likelihood of harmonic issues occurring after the connection of plant through early identification of potential issues.

This document is not an exhaustive list of all information, or studies required as part of a connection application. Appropriate engineering judgment should be applied to the results of harmonic studies to ensure that all conclusions are well founded and align with best practices.

If any clarification is required, AEMO Victorian Planning and Connections may be contacted at vic.connections@aemo.com.au.

2 Input data from AEMO Victorian Planning and Connections

The following inputs would be provided by AEMO Victorian Planning and Connections for harmonic studies as part of a pre-application or transmission data pack:

- Emission allocation limits, E_h (these allocations are based on the rated active power of the proposed plant at the connection point and the ultimate arrangement[1] of the connecting terminal station).
- Impedance polygons of the present network (these will change over time with Victorian network augmentations).
- Site-specific future background harmonics, $V_{FB,h}$.
- Present day background harmonics, $V_{CB,h}$ (if available, only for observation and comparison against future background levels).

2.1 Data validity

The data provided should be valid at the time of delivery. If the connection package is delayed, AEMO Victorian Planning and Connections can be contacted at vic.connections@aemo.com.au to confirm whether the data is current.

In the case of changes to the maximum capacity of the plant or any alteration to the ultimate arrangement of the terminal station at the connection point, emission limits may also change. AEMO Victorian Planning and Connections can confirm the emission limits.

[1] Where a new terminal station is being proposed, an existing ultimate arrangement will not exist. As a result, harmonic limits can only be provided after AEMO Victorian Planning and Connections has developed an ultimate arrangement as part of a pre-application or connection application.

3 Assumptions

Based on the details of the proposed connection there may be some differing assumptions applied on a case-by-case basis, however the below assumptions should generally be used for harmonic studies for all Victorian projects.

3.1 Future background harmonics

The site-specific future background harmonic levels are calculated based on the below formula applying general summation law:

- Site-specific future background harmonic levels ($V_{FB,h}$) = Reference future background levels ($V_{RFB,h}$) – E_h

The reference future background levels ($V_{RFB,h}$) are as below:

- 85% of planning levels for 5th and 7th harmonic orders.
- 50% of planning levels for all other harmonic orders.

The site-specific future background harmonics levels are used when considering the amplification of background harmonic distortions to define the overall voltage distortion at the connection point unless otherwise specified by AEMO Victorian Planning and Connections.

Where the site-specific future background harmonic level is calculated to be less than 0.1% (often for even and triplen harmonic orders), then a value of 0.1% should be substituted for the calculation of background amplification.

3.2 Alpha factor (summation law exponents) inside the plant

A value of Alpha = 1 (implying no phase angle diversity) should be used for the summation of inverter, wind turbine, or rectifier harmonic current contributions inside the plant. The exponents for the general summation law defined is AS61000.3.6 (2001)[2] are not considered a suitable assumption for inverters inside same plant[3].

Nevertheless, AEMO Victorian Planning and Connections notes that there is expected to be some level of phase angle diversity between inverters within the plant and that it is expected to be more pronounced at higher harmonic orders[4]. While AEMO Victorian Planning and Connections expects an alpha factor of 1 to be used for undertaking the power quality studies, the understanding that there is some degree of diversity may form part of the analysis of the results and engineering judgement in the conclusion of the studies.

[2] AS/NZS 61000.3.6:2001: Electromagnetic compatibility (EMC) — Part 3-6: Limits — Assessment of emission limits for distorting loads in MV and HV power systems.

[3] This is explored in detail in CIGRE Technical Brochure 672 “Power quality aspects of solar power”, written in 2016.

[4] This is explored in section 4 of the University of Wollongong’s “Harmonic Study – Large Renewable Energy Generators”, at https://arena.gov.au/knowledge-bank/harmonic-study-large-renewable-energy-generators-final-report/.

3.3 Alpha factor (summation law exponents) between the plant and the network

When summing the plant's total harmonic contributions including both the harmonic current injection and the increase in network voltage harmonics from the amplification of future harmonic levels, apply the general summation law and alpha factors from AS61000.3.6 (2001). These alpha factors are:

Alpha = 1 for h < 5

= 1.4 for 5 ≤ h ≤ 10

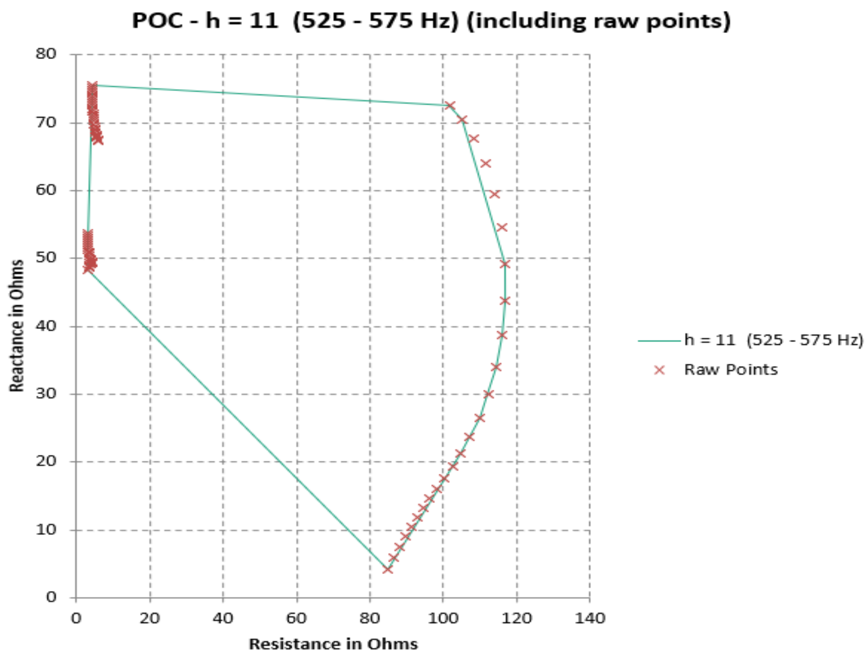
= 2 for h > 10

This assumption is to represent the fact that the harmonic current injections of the plant are not expected to be in phase with the existing harmonics in the network for orders above the fourth.

3.4 95th percentile of harmonic impedances

The area within the polygon should be covered using appropriately sized equal steps in impedance, with only the 95th percentile of points included as shown in Figure 1 Example of an eleventh harmonic order Impedance Polygon applying 95th percentile (provided that no system normal points are excluded). The polygons provided by AEMO Victorian Planning and Connections also contain the data for the specific scenarios the impedance scans were taken from.

Figure 1 Example of an eleventh harmonic order Impedance Polygon applying 95th percentile.



AEMO Victorian Planning and Connections does not specify size of the steps to be used, as it will depend on the specific network impedances at the proposed connection point.

3.5 Impedance-frequency dependency

Assumptions considered in the harmonic assessment to account for any variation in impedance to account for ordinary system frequency movement should be clearly stated in the power quality report. For example, if any buffer has been given to impedances to account for the fact that system frequency is not always at 50 hertz (Hz) (for example, meaning the 2nd harmonic is not always exactly 100 Hz).

Allowances for different impedance ranges based on frequency are prudent to reduce the risk that proposed harmonic mitigation solutions are ineffective in operation.

4 Model Requirements

AEMO Victorian Planning and Connections expects consistency in both how different connections are modelled for compliance purposes as well as the type of information provided for updating the Victorian harmonic model.

4.1 PowerFactory model requirements

AEMO Victorian Planning and Connections' harmonic model is built in DIgSILENT PowerFactory. If the studies are undertaken in PowerFactory, the PowerFactory harmonic model of the plant would need to be provided for addition to the Victorian model.

In the case of carrying out the studies in a different software, AEMO Victorian Planning and Connections should be contacted to understand any additional requirements for data to be provided. In these cases, AEMO Victorian Planning and Connections may need to develop a PowerFactory model of the plant based on the supplied data for the purpose of updating the Victorian model.

4.2 Reticulation network model

The full reticulation network of the plant should be included in the harmonic model of the plant, including inverters, cables, transformers, and the grid represented as Thevenin equivalent voltage source.

The 50 Hz aggregation of the plant used for PSS®E and PSCAD™ models is not sufficiently detailed for harmonic studies.

The full reticulation data would be required in any PowerFactory model submitted to AEMO Victorian Planning and Connections, or sufficient detail to represent them if a PowerFactory model is not able to be provided.

4.3 Generating unit representation

Inverters or wind turbines should be represented as a Norton Equivalent and the highest source-current magnitude should be used in the studies based on different active power outputs. Manufacturer datasheets showing Norton Equivalent impedances and currents at different levels of active power should be provided, including when the inverter is absorbing active power for battery projects.

4.4 Transformer saturation

The impact of transformer saturation should be considered in the studies. At the application stage, detailed saturation information is not often available but typical data should be used based on manufacturer recommendations where available.

For R1 stage projects with detailed design information, the appropriate saturation information to use should be advised by the transformer manufacturer.

If the transformer is operated outside of its linear region (such as when voltages in the network are greater than 1 per unit) then the saturation of the transformer may have a greater impact on harmonic compliance[5]. This is a consideration for the design and specification of the transformers as a transformer which saturates at voltage levels which occur in normal operation would require additional representation of transformer harmonic contributions.

4.5 Credible operational scenarios

The below variations in the operation of the plant should be investigated at the application stage:

- Transformer impedance tolerances (±10%).
- Overhead line and cable lengths (±10%).
- Dispatch modes/levels of the plant (such as battery charging and discharging, or wind/solar farms generating at different power levels) based on the data supplied by the original equipment manufacturer (OEM).
- Both daytime and night-time operation for a solar farm where Q at night mode differs from normal operation.
- Wind-free mode for wind farm connections.

Once detailed design information is available at the R1 stage, then appropriate tolerances should be assumed based on the level of information available.

Partial operation such as collector group outages should also be modelled to understand the impact on proposed commissioning plans. The specific scenarios to be considered depends on the details of how the site is planned to be operated and its commissioning plan.

4.6 Filter design

Initial studies without the filter should be undertaken prior to the determination of whether a filter is required.

Where mitigation is determined to be needed, AEMO Victorian Planning and Connections should be contacted to discuss before commencing a filter design process to understand any other considerations or the potential for a negotiated standard, particularly in the case where designing a filter on the high voltage side of your site is being considered.

Where a filter is included in an application package, the filter design should be included in the power quality report and the plant's level of emissions including the filter calculated according to this guideline.

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[5] Considerations for transformer saturation modelling is discussed in section 2.6.2 of the University of Wollongong's "Harmonic Study – Large Renewable Energy Generators", at https://arena.gov.au/knowledge-bank/harmonic-study-large-renewable-energy-generators-final-report/.

5 Methodology

AEMO Victorian Planning and Connections expects the harmonic assessment to be undertaken in three parts.

Part A

This part determines harmonic emissions at the connection point in the absence of future background harmonic distortions (using the impedance points determined from the polygons).

The acceptance criterion for Part A is:

- The contribution of the plant to voltage distortion at the connection point ($V_{POC,h,plant}$) in the absence of background harmonic amplification should be less than emission limits (E_h).

$$V_{POC,h,plant} \leq E_h$$

In case of exceedances of emission limits, the results should be discussed with AEMO Victorian Planning and Connections.

Part B

This part investigates the expected level of amplification of existing network harmonics.

To undertake Part B:

1. Include the Norton impedance of the connected inverters/turbines.
2. Set the current injection from sources inside the plant to zero.
3. Calculate maximum amplification factors at the connection point.

Amplification Factor = Impedance including Plant / Impedance without Plant

$$AF = (\frac{Z_{Plant,h} * Z_{Grid,h}}{Z_{Plant,h} + Z_{Grid,h}})/(Z_{Grid,h}) = \frac{Z_{Plant,h}}{Z_{Plant,h} + Z_{Grid,h}}$$

For Part B there are no strict pass or fail criteria, however in the case of high amplification factors, the results should be discussed with AEMO Victorian Planning and Connections.

Part C

This part investigates the comprehensive contribution of the plant including expected future levels of harmonic distortion in the network.

In the presence of Site-Specific future background harmonics ($V_{FB,h}$), ensure that the voltage distortion at the connection point does not exceed the emission limits (E_h) when including the contribution of amplification factor via the general summation law.

Using the values determined in Part A and Part B, the total emissions can be calculated as per:

$$\Delta V_{POC,h} = V_{POC,h,plant} + V_{FB,h} * AF - V_{FB,h} \leq E_h$$

or more simply

$$\Delta V_{POC,h} = \sqrt[\alpha]{V_{POC,h}{}^{\alpha} - V_{FB,h}{}^{\alpha}} \leq E_h$$

Total harmonic voltage ($V_{POC,h}$) at the connection point is the sum of the contributions from the internal and external sources.

The Power Quality Testing Guidelines[6] assists understanding of compliance testing during the commissioning of new generators on the Victorian DSN, bridging the gap between initial design assessments and commissioning phase testing.

Please note, the $V_{FB,h} * AF$ Component of the calculation assumes that an increase in harmonic impedance due to a network amplification will cause a linear increase in the future background harmonic levels in the network. This assumption may not always hold, particularly when present day harmonic levels are far lower than the future background levels. Further, where the calculated harmonic impedance is very low a small change in network impedance because of amplification will yield a very large amplification factor.

AEMO Victorian Planning and Connections notes these shortfalls in the assumptions, but expects all studies undertaken to be undertaken using this methodology to ensure consistent approaches. The understanding of this difference can form part of the analysis of the results and engineering judgement in the conclusions of the studies where there are very low network impedances and low present day harmonic levels for the applicable harmonic order.

6 Results

The final results submitted in the report for the connection application should highlight the calculated level of harmonic emissions based on the methodology specified in this guideline as well as the engineer's determination as to the level of compliance.

Where appropriate engineering justification is given, compliance may still be demonstrated when the methodology in Section 5 indicates a non-compliance. The engineer preparing the report may give reference to the impact of the methodologies and/or the accuracy of the model used for the assessment to determine whether compliance is expected to be met. This justification should be assessed on a case-by-case basis taking into account the specific site details and the nature of the network at the connection point.

An example would be where a marginal exceedance is seen at the 43rd harmonic order using the methodology in this guideline. The engineer undertaking the studies may conclude that a noncompliance is not expected to occur when accounting for the conservatism of assuming an exponent of 1 at the 43rd order.

AEMO Victorian Planning and Connections would review the engineer's results and conclusions as part of the application assessment.

[6] At https://aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2021/inter-network-test-guidelines/aemo-vpc-power-quality-testing-guideline-v10.pdf?la=en.

6.1 Study results

The below results are expected to be included in the report:

- Voltage emissions at the connection point in the absence of background harmonics.
- Amplification factors at the connection point.
- Voltage emissions at the connection point in the presence of site-specific future background harmonics.
- Where applicable, proposed harmonic filter solutions.
- The distortion plots should be provided in box and whisker plot format with percentiles of the dataset. However, the distortion limit comparison should be based on the maximum distortion caused by all the scenarios considered.

6.2 Other documentation and models

The below documents/models should be submitted as part of the studies report/package:

- PowerFactory Model if PowerFactory has been used, if not then equivalent information to allow AEMO Victorian Planning and Connections to create a detailed PowerFactory model. These should be provided in Version PF2022 and 2024 but AEMO Victorian Planning and Connections should be contacted if any other version is preferred.
- OEM Norton/Thevenin equivalent harmonic models.
- Main and inverter transformer excitation harmonic currents.