

Passivity Explainer: Stability of Inverter-Based Resources



This explainer provides an overview of how passivity concepts can be applied to assess inverter-based resource (IBR) stability.

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Overview

This explainer aims to provide the reader with foundational understanding of the passivity concept by providing:

- clarification on how passivity applies to IBRs,
- an explanation on how to compute passivity indices from immittance frequency responses, and
- four practical applications, including:
 - early-stage identification of frequency bands which could pose oscillation risks,
 - prediction of oscillation rejection/amplification,
 - post-event source location, and
 - passivity-oriented controller retuning relevant to planning, commissioning, and operations.

The four applications above have been implemented and integrated into AEMO's Frequency-domain Admittance-based Stability Tool (FAST) to enable efficient and repeatable wideband stability screening and controller design workflows.



Introduction

Modern power systems are increasingly relying on inverter-based resources (IBRs), whose stability is affected by grid strength, operating conditions, and controller settings. In networks with low grid strength, these dependencies can result in sub-synchronous oscillations (SSOs) and lightly damped control interactions that are difficult to diagnose using existing modelling techniques such as electromagnetic transient (EMT) simulations. This is especially true when vendor control systems are obscured (black-boxed) to protect intellectual property.

Passivity analysis offers an intuitive, energy-based lens for understanding IBR-grid interactions and system stability which offers benefits over existing EMT methods and is not impacted by black-boxed models.

The concept is simple: a passive system does not generate energy; it can only store or dissipate the energy supplied to it. In contrast, a non-passive (or active) system can inject energy.

When considering oscillations in these systems, a passive system will absorb energy from an oscillatory mode (effectively providing damping), whereas a non-passive system can supply energy to it, potentially introducing an unstable oscillation or amplifying existing oscillations.

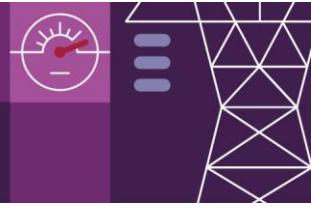
This concept is particularly relevant for IBRs, which interact dynamically with the grid. The passivity of an IBR can be assessed using indices, which are frequency-dependent metrics indicating whether the IBR behaves passively or non-passively at each frequency. If all passivity indices are positive for a given frequency or frequency range, the IBR cannot amplify grid oscillations within this frequency range. Conversely, if any passivity index becomes negative within this specific frequency range, due to operating point changes, the IBR may contribute energy to oscillations at those frequencies.

However, a negative passivity index should be interpreted as a risk indicator rather than a deterministic instability criterion. It indicates that the IBR has the potential to amplify oscillations within the corresponding frequency ranges if the grid conditions provide a valid interaction path. It does not necessarily mean that unstable behaviour will occur, or that controller retuning is automatically required. In practice, negative passivity identifies frequency ranges and operating conditions that inform further investigation through grid condition variations, such as Short Circuit Ratio and X/R ratio, and EMT validation.

One benefit of passivity-based analysis is its ability to offer clear measurable stability margins. By examining the terminal immittance (impedance or admittance) frequency responses of an IBR and the grid it is connected to, we can test if the real part of the impedance or admittance is positive (positive realness) in the frequency domain and quantify if each subsystem is passive (if real) or how far it is from passivity (depending on magnitude of real part).

The resulting indices convert a binary property (passive or non-passive) into actionable margins that can:

- pinpoint frequency ranges vulnerable to SSO instability,
- predict grid oscillation rejection/amplification behaviour,
- guide controller changes, and
- explain post-event behaviour.



Mathematical definition of passivity for IBRs

This section provides the mathematical basis for using passivity to assess whether an IBR can absorb or inject energy from/into an oscillation. This section also defines the scalar passivity indices used later to identify frequency ranges where energy can potentially be injected into an oscillation, providing negative damping.

Concept: In the small-signal linearised setting considered in this work, passivity at a given frequency means that the terminal response does not generate net positive incremental energy for a perturbation at that frequency¹; formally, there exists a storage function whose time derivative is bounded by supplied power. Connections of passive or strictly passive subsystems are unconditionally stable².

Single-input-single-output (SISO) condition: For a scalar transfer function $G(s)$ passivity is equivalent to positive realness:

1. $G(s)$ has no right-half-plane poles, and
2. $\Re\{G(j\omega)\} > 0$ for all $\omega \in \mathbb{R}$, where $\Re$ denotes the operator for real part extraction.

Multiple-input-multiple-output (MIMO) condition: For a transfer matrix $G(s)$, define its Hermitian part as

$$H(j\omega) = \frac{1}{2}(G(j\omega) + G^H(j\omega)),$$

where $(*)^H$ denotes the conjugate transpose. A matrix is called Hermitian if it is equal to its own conjugate transpose. Such matrices are the complex-valued generalisation of real symmetric matrices and possess real eigenvalues. Passivity holds if and only if $H(j\omega) \geq 0$ (positive semidefinite) for all ω . With power-invariant variable scaling, this inequality expresses that the system cannot extract net energy at a frequency (ω) over any time window.

IBR context: In IBR-grid studies, the appropriate choices for $G(s)$ are the terminal immittances $Y_{ibr}(s)$ or $Z_{ibr}(s)$ (2x2 matrix) in the synchronous dq or sequence domain. Under power-invariant scaling, MIMO passivity can be assessed directly on these matrices.

Indices: Let

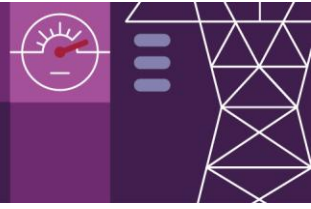
$$\pi_{\min}(j\omega) = \lambda_{\min}(H(j\omega))$$

be the eigenvalue of $H(j\omega)$ with the minimum magnitude. Passivity holds at ω if and only if $\pi_{\min}(j\omega) \geq 0$. In addition, passivity shortage³ can be quantified as $S(j\omega) = \max\{0, -\pi_{\min}(j\omega)\}$. These scalar curves serve as key diagnostic metrics: negative $\pi_{\min}(j\omega)$, or equivalently positive $S(j\omega)$, identifies frequencies where negative damping is possible.

¹ Resistors, capacitors and inductors are examples of passive systems as they cannot produce energy.

² Zhou, Weihua. "Operating-condition-adaptive RLC equivalence of black-boxed inverter-based resources for efficient oscillations replication, elucidation, and mitigation." *Authorea Preprints* (2025).

³ Passivity shortage is a condition in which the passivity index approaches or falls below zero at a given frequency, indicating insufficient passivity margin to guarantee stable interaction.



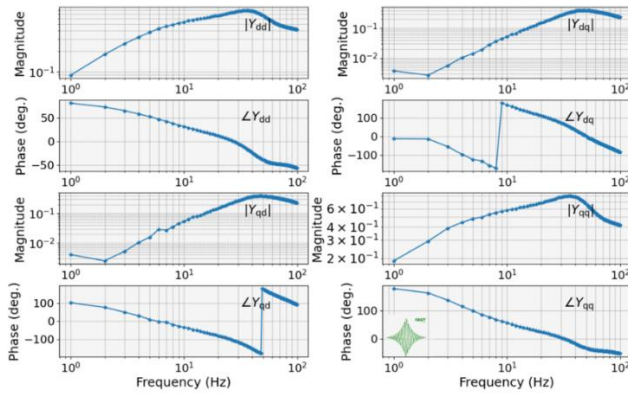
Computing passivity indices from immittance frequency responses

Passivity indices allow engineers to determine frequencies where negative damping is possible. Computing passivity indices from immittance frequency responses, can be achieved through the following steps:

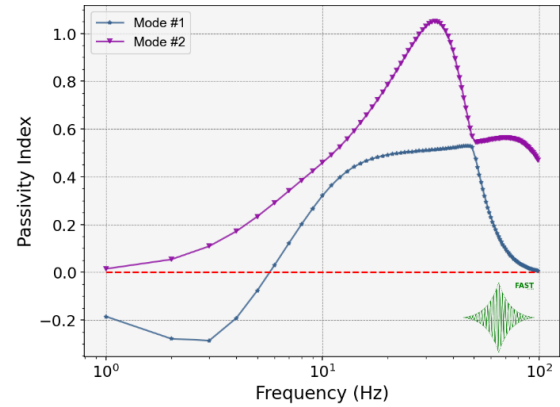
1. **Acquire frequency responses:** Obtain $G(j\omega) = Y_{ibr}(j\omega)$ (or Z_{ibr}) of the IBR and the grid at the point of common coupling (PCC) over the frequency range of interest. Use power-invariant scaling and consistent sign conventions.
2. **Form $H(j\omega)$:** Compute $H(j\omega) = \frac{1}{2}(G(j\omega) + G^H(j\omega))$ at each sampled ω .
3. **Eigenvalue analysis:** Evaluate $\pi_{\min}(j\omega)$ and derive $S(j\omega)$. Optional smoothing may be applied if measurement noise is present but avoid filtering that distorts the sign of $\pi_{\min}$.
4. **Grid-IBR combination (for interconnection tests):** When needed, form the series/parallel combinations of terminal models (for example, $Y_{\text{tot}}(j\omega) = Y_{\text{IBR}}(j\omega) + Y_{\text{grid}}(j\omega)$ for parallel admittances) before computing indices.

As an example, Figure 1 illustrates one IBR's dq-domain admittance matrix and its associated passivity indices. The Bode response is smooth with negligible measurement noise. The minimum-eigenvalue index $\pi_{\min}(j\omega)$, and equivalently the shortage $S(j\omega) = \max\{0, -\pi_{\min}(j\omega)\}$, is negative in the 1–6 Hz range. This indicates that the IBR exhibits non-passive behaviour within this frequency range and **may** contribute negative damping to grid oscillations, particularly under weak-grid conditions.

Figure 1 Measured dq-domain admittance of an IBR



(a) Bode magnitude and phase responses (ie $G(s)$)



(b) Corresponding passivity index, $\lambda(H(j\omega))$, with negative regions indicating frequency bands prone to instability

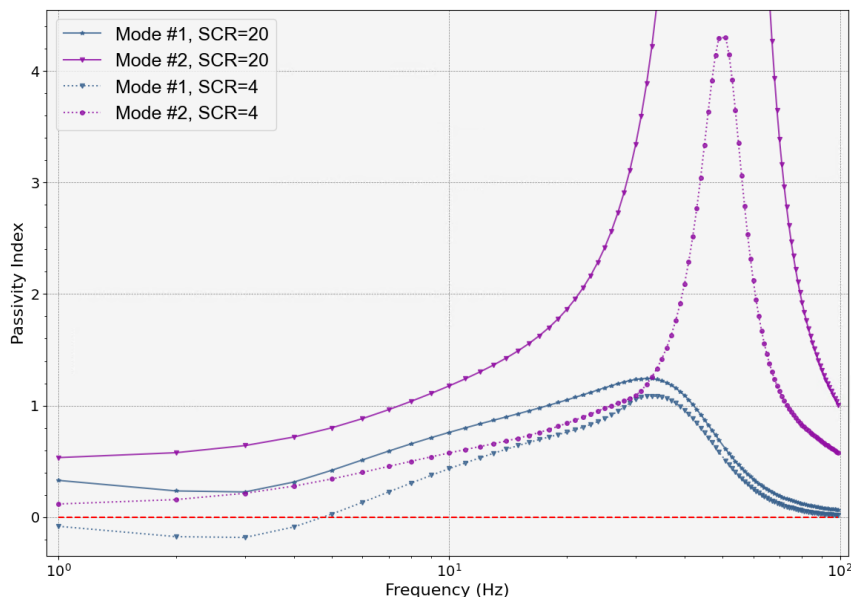


Applications of passivity index in stability studies of IBRs

Early-stage instability-risk band identification

The passivity method can be used to identify frequency ranges of concern before performing large volumes of EMT studies. Based on the IBR and grid immittance frequency responses, $\pi_{\min}(j\omega)$ is computed across a broad frequency range to identify frequencies where $\lambda_{\min}[H(j\omega)] < 0$, indicating a risk of negative damping. The identified frequency bands can then be ranked according to the passivity shortage severity $S(j\omega)$ and assessed across key operating conditions, including dispatch P/Q , terminal voltage, and phase-locked loop (PLL) settings. In weak-grid conditions, the low-frequency non-passive band typically becomes more pronounced as the effective grid strength decreases. This is illustrated in Figure 2 which shows the comparison of the passivity index of the IBR-grid whole system's dq-domain total admittance at differing grid strength. The results identify non-passive frequency bands to monitor and inform EMT studies.

Figure 2 Comparison of passivity indexes under ideal- and weak-grid conditions.



When a non-passive frequency range is identified, the selection of subsequent EMT studies should be guided by the dominant control mechanisms associated with that frequency range.

In general, low-frequency non-passive bands are primarily influenced by slower outer-loop dynamics and operating-point variations, such as power plant controller (PPC) functions, voltage regulation loops, and active/reactive power control loops. Accordingly, for low-frequency bands, EMT studies should focus on operating conditions and setpoints that significantly reshape these outer-loop dynamics. This could include dispatch level, voltage targets, or irradiance-driven operating changes, together with disturbances that can effectively excite the corresponding slow modes.

In contrast, high-frequency non-passive bands are typically dominated by fast inner-loop dynamics, for example inner voltage and current control loops, as well as digital control delays and measurement/actuation dynamics. These mechanisms are generally weakly dependent on the operating point, meaning that the location and severity of high-frequency non-passivity are more sensitive to controller bandwidth, delay, and filter or interfacing parameters than to power-flow setpoints. Accordingly, for high-frequency bands, the selection and design of EMT studies should focus on



stressing inner-loop interactions and delay effects. This could include through grid-strength variations, impedance shaping, converter-side filter parameters, and switching or control sampling characteristics, rather than sweeping a wide range of operating points.

Grid oscillatory rejection/amplification behaviour prediction

Passivity concepts can be applied to predict whether the interconnected IBR–grid system will attenuate or amplify oscillations within a given frequency band, using passivity margins derived from immittance frequency responses. If both the IBR and the grid are passive across a band, their interconnection is dissipative and oscillatory components are expected to be attenuated. Whereas, individually either the IBR or the grid may have a shortage of passivity.

However, when the IBR and the grid are combined, the net result may be adequately passive and result in stable operation. If the combined passivity is negative, zero, or close to zero, the resulting passivity is inadequate and may result in a risk of oscillations or oscillation amplification. These frequency bands where the passivity margin is low or negative may indicate an EMT assessment focus area.

For example, if an IBR exhibits passivity shortage only within a limited frequency range, for example 1–5 Hz in Figure 1, detailed NER S5.2.5.13 spot checks and EMT validation could be focused on that frequency range. If the passivity indices remain positive above 5 Hz, the IBR cannot, in the small-signal sense, amplify oscillations above that frequency under the assessed operating condition. Therefore, passivity analysis can guide targeted wide-area EMT studies within the most pertinent frequency ranges, supporting engineering judgment and focused validation.

Post-event instability source location

For post-event analysis, the passivity shortage at the observed oscillation frequency can be used to compare the negative-damping contribution of nearby plants. At the event frequency ω_o , the Hermitian part $H(j\omega_o)$ is formed for each nearby plant using the immittance frequency responses corresponding to the plant operating conditions immediately before the event, or the closest available representative operating condition. Plants can then be ranked using a score, where a larger score indicates a stronger potential contribution of negative damping at the event frequency. This score is referred to as the shortage score, and can be calculated as

$$S(j\omega_o) = \max\{0, -\lambda_{\min}[H(j\omega_o)]\}.$$

If two plants have similar shortage scores, the attribution can be further refined by considering whether the scan condition closely matches the event operating condition, determining if there are sufficient passivity margins in the surrounding grid at the event frequency, and considering the electrical proximity of the plant to the observed oscillation.

For example, suppose an oscillation is observed at 3 Hz, and Plants A, B, and C are electrically proximate to the measurement location. Using immittance frequency responses corresponding to the operating conditions closest to those at the time of the event, Plant A gives $\lambda_{\min}[H_A] = -0.3$, corresponding to $S_A = 0.3$; Plant B gives $\lambda_{\min}[H_B] = -0.05$, corresponding to $S_B = 0.05$; and Plant C gives $\lambda_{\min}[H_C] = +0.11$, corresponding to $S_C = 0$. Therefore, Plant A has the largest shortage score at 3 Hz and would be the highest-priority candidate for further investigation among the three assessed plants.

Passivity-oriented controller design

Passivity methods can assist in IBR controller design to reshape the terminal immittance so that $H(j\omega)$ becomes non-negative within the identified non-passive frequency bands. Once the peak shortage frequency ω^* is identified from $S(j\omega)$,



the relevant controller parameter can be adjusted according to the frequency range and the dominant source of non-passivity.

For sub-synchronous frequency passivity shortages associated with PLL dynamics, the PLL damping ratio may be increased or its bandwidth reduced. If the shortage occurs near the current-loop bandwidth, virtual resistance or current-loop gain retuning may be used to improve damping.

For very low-frequencies, shortages may be linked to outer-loop dynamics or negative incremental resistance, and the gains of active-power, reactive-power, voltage, or DC-link control loops may need to be moderated. Where controller retuning alone is insufficient, grid-side measures such as frequency selective resistive damping at the PCC or retuning of nearby devices may also be considered.

After the selected mitigation is applied, the passivity shortage should be reduced toward zero around the targeted frequency, or equivalently the underlying passivity index should move toward a positive margin. This should not be interpreted as a general requirement to eliminate passivity shortage across all frequency ranges. Rather, it is a targeted mitigation objective where passivity-based assessment identifies a material risk around a specific oscillation frequency. The final design should then be verified through EMT studies to confirm that the targeted oscillation decays, that no unintended adverse effects are introduced in other frequency bands, and that the modified plant performance remains consistent with the applicable Generator Performance Standards clauses.



Implementation notes and caveats

The passivity-based framework presented above is effective for stability screening, interpretation, and stability-oriented controller retuning. However, its correct application requires careful attention to several practical details. In particular, the interpretation of passivity margins depends on consistent variable definitions, sufficient operating-point coverage, and proper treatment of model combination and numerical artefacts.

1. **Scaling and sign conventions:** All transfer matrices must be expressed using power-invariant variable definitions and a consistent PCC polarity. Inconsistent scaling or sign conventions may artificially change the sign of the Hermitian part and lead to incorrect interpretation of passivity margins.
2. **Operating-point dependence:** Passivity margins are operating-point dependent and should be re-evaluated across dispatch levels and controller parameter settings. In practice, the effect of operating-point variation on passivity shortages tends to become more pronounced under weak-grid conditions, such as low short-circuit ratio (SCR), or when outer-loop dynamics dominate. Therefore, a single operating-point assessment is insufficient under these conditions.
3. **Model combination:** When predicting IBR-grid interconnection behaviour, the terminal models of both subsystems should first be combined at the PCC, for example by forming the closed-loop interconnection admittance or impedance model. Passivity indices should then be evaluated on the combined system, rather than interpreting individual subsystem indices independently. This ensures that interaction effects are properly captured before assessing the net passivity margin or shortage.
4. **Noise and smoothing:** Limited smoothing of frequency-response data is acceptable when numerical noise is present, particularly near the PPC sampling frequency, switching frequency sidebands, or when frequency resolution is coarse. If significant smoothing is needed, frequency scanning should be re-run to obtain data that requires less smoothing. However, smoothing must not artificially enforce non-negativity of the Hermitian eigenvalues. The indices should reflect the underlying physical response; smoothing is only intended to reduce measurement or discretization artefacts, not to modify physical trends.
5. **Complementarity with EMT:** Passivity analysis provides a fast, frequency-local diagnostic and efficient screening capability. It does not fully replace EMT time domain simulations, which remains the final behavioural validation step for nonlinear, large-signal, or protection-related phenomena.
6. **Broad-spectrum passivity:** Non-passive frequency bands may indicate a risk of negative damping and warrant targeted analysis; however, an IBR is not expected to achieve passivity across the entire frequency spectrum.



Conclusions

Passivity provides a rigorous and practical framework for assessing and improving IBR–grid stability without requiring access to internal controller details. By evaluating if the real part of the impedance or admittance is positive, tracking passivity margins and shortage across frequencies, engineers can obtain a frequency-local indication of damping adequacy, oscillation risk, and potential mitigation options. The passivity analysis applications include early identification of instability-risk frequency bands, prediction of oscillation attenuation or amplification, post-event source localisation, and controller retuning and damping improvement.

In practice, robust workflows should combine reliable immittance measurements with routine passivity mapping to support fast screening, clear attribution, and physics-based stabilisation. EMT studies remain essential for validation of oscillation mitigation controls and to ensure that no unintended adverse behaviour is introduced. Overall, these passivity-based assessment features have been established in the FAST tool, providing a consistent and repeatable basis for bridging theoretical passivity guarantees with practical connection and operational studies.

Where can I find more information?

See AEMO's [frequency scanning website](#) for more information.

For any further enquiries, please contact AEMO's connections team via

- Contact.connections@aemo.com.au

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