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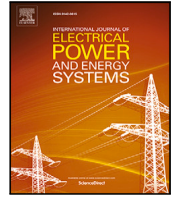
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Review

A review of resonance stability issues in renewable-dominated power systems: Mechanism-based classification, analysis, and mitigation^{☆,☆☆}

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ABSTRACT

The displacement of synchronous generation by converter-interfaced resources is reshaping power system dynamics and has made resonance stability, a category newly recognized in modern stability framework, an increasingly pressing concern. Compared with converter-driven stability, however, resonance stability has received limited systematic treatment and still lacks a unifying perspective that connects its diverse manifestations. This paper revisits resonance from a unified, mechanism-oriented viewpoint, interpreting it as an oscillatory phenomenon arising from strong coupling among closely spaced mechanical, electrical, electromechanical, or control modes of different subsystems or control loops. On this basis, resonance is classified into four types according to the interacting modal pairs, thereby placing classical subsynchronous resonance, electromechanical modal resonance, and emerging converter-related resonances within a single framework. Representative incidents are first reviewed to show how the dominant patterns have evolved from synchronous-machine interactions toward broadband, converter-dominated ones. The main analysis methods are then surveyed and mapped to the resonance types they best address. Finally, mitigation strategies are organized by resonance type around three basic levers: damping injection, impedance reshaping, and modal detuning. The review aims to provide a coherent basis for interpreting mechanisms, selecting methods, and designing mitigation measures in converter-dominated power systems.

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1. Introduction

Driven by decarbonization and sustainability goals, many countries and regions are rapidly replacing conventional fossil-fuel-based generation with renewable resources such as wind and solar power. As this transition is largely realized through converter-interfaced generation, modern power systems are gradually evolving from synchronous-machine-dominated structures to power-electronics-dominated ones [1]. While indispensable for sustainable development, such a transformation fundamentally reshapes system dynamics: it weakens the inherent inertia and short-circuit strength of the grid, broadens the dynamic bandwidth of interest, and creates new opportunities for control-induced interactions among devices. As a consequence, oscillatory stability problems associated with grid-connected power electronic converters (PECs) have already been reported in multiple power systems worldwide [2–5].

Recognizing that the classical stability taxonomy established in 2004 [6] was primarily developed for synchronous-machine-dominated networks and is no longer sufficient to characterize these emerging phenomena, the IEEE/CIGRE community revisited the framework and introduced two additional categories: *converter-driven stability* and *resonance stability* [7]. Since then, converter-driven stability has been extensively investigated from multiple perspectives, including renewable generation technologies such as the doubly-fed induction generator (DFIG) [8], permanent magnet synchronous generator (PMSG) [9], and photovoltaic (PV) systems [10]; converter control paradigms such as grid-following (GFL) [11] and grid-forming (GFM) [12]; and interaction timescales such as fast- [13] and slow-interaction [14] converter-driven stability. The state of the art has also been systematically reviewed in [15]. By contrast, resonance stability has received comparatively less systematic synthesis, and a unified perspective that connects its diverse manifestations is still lacking.

Resonance itself, however, is not unique to converter-dominated grids. In traditional synchronous power systems, the most extensively studied resonance phenomenon is subsynchronous resonance (SSR) [16, 17], which may arise either from the interaction between series-compensated transmission lines and the mechanical torsional modes of turbine-generator shafts, or from the induction generator effect, a purely electrical interaction [18,19]. With the continued large-scale integration of renewable generation, especially wind power, subsynchronous oscillations have persisted in practical systems [20]. Moreover, because PEC-based generators are characterized by multiple nested control loops, resonance is no longer restricted to phenomena involving synchronous generator mechanical modes. New oscillatory resonance phenomena dominated by converter control loops, most notably subsynchronous control interaction (SSCI), have also emerged [21–23].

More importantly, resonance-related instability is not restricted to the subsynchronous range. At lower frequencies, the electromechanical oscillation modes of bulk synchronous power systems may become closely spaced, and strong coupling among these modes, often referred to as modal resonance [24], can lead to mode repulsion, damping redistribution, and, in adverse cases, the destabilization of an otherwise well-damped mode. At the other end, the large-scale integration of converters introduces high-frequency resonances arising from the interaction between converter control loops and the electrical resonant characteristics of the grid [25,26]. Despite their distinct frequency ranges, these phenomena, together with the various forms of SSR discussed above, share a common physical essence: they all originate from strong coupling between oscillation modes of different subsystems or control loops. Such couplings can enhance energy exchange between subsystems, redistribute damping, and, in adverse cases, produce effective negative damping of certain modes. From this viewpoint, oscillations across different frequency bands should not be treated as isolated anomalies, but rather as different manifestations of a common underlying resonance mechanism.

Several reviews have addressed parts of this subject from specific entry points, including SSR analysis and control in wind turbines [23], SSR in series-compensated wind farms [21], emerging subsynchronous oscillations in practical wind power systems [20], resonances of DFIG-based wind power systems under weak networks [27], low-frequency oscillations associated with virtual synchronous generators [12], synchrophasor-based monitoring, analysis, and control of oscillatory stability [2], small-signal stability criteria in power-electronics-dominated systems [28], and the adjacent converter-driven stability category [15]. Closest in thematic scope is the review of generalized modal resonance in [29], which classifies modal interaction according to its form and analytical manifestation: it distinguishes natural modal resonance from forced oscillation and further divides natural modal resonance into near-strong, near-weak, open-loop, modal-instability, and participation-factor-instability forms. Its classification axis therefore differs fundamentally from that adopted here, as it concerns how modal interaction is mathematically manifested rather than the physical identities of the interacting modes. To the best of our knowledge, none of these reviews classifies resonance phenomena by the dominant interacting modal pair or uses such a classification as a common thread connecting mechanism interpretation, analysis-method selection, and mitigation design.

Motivated by these observations, this paper aims to move beyond a phenomenon-by-phenomenon discussion and revisit resonance stability from a more macroscopic, mechanism-oriented perspective. Specifically, resonance is here interpreted as an oscillatory phenomenon arising from strong coupling among oscillation modes, whether mechanical, electrical, electromechanical, or control modes, that are close

to each other in frequency. This mode-coupling viewpoint provides a unified basis for classifying resonance phenomena according to the physical identities of the modes involved, rather than by frequency band or device technology, thereby placing classical SSR, electromechanical modal resonance, and emerging converter-related resonances within a single coherent framework. Based on this viewpoint, the review provides three linked levels of synthesis: a mechanism-based four-type classification organized by the dominant interacting modal pair; a comparison of the principal model-based analysis methods on a common mathematical basis, together with their mapping to the resonance types they can resolve; and a mitigation framework organized by resonance type around the three basic levers of damping injection, impedance reshaping, and modal detuning. Together, these elements establish an integrated framework connecting resonance classification, analysis, and mitigation.

The remainder of this paper is organized as follows. Section 2 reviews representative cases of resonance in practical power systems. Section 3 defines resonance stability, examines its underlying mechanisms, and proposes a mechanism-based classification. Section 4 surveys the principal model-based and data-driven methods for resonance-stability analysis. Section 5 summarizes existing strategies for resonance suppression and mitigation. Section 6 identifies the main unresolved challenges and outlines promising directions for future research. Finally, Section 7 concludes the paper.

2. Review of resonance incidents in power systems

Resonance-related oscillatory events have been reported in real-world power systems across a wide frequency range and under various coupling mechanisms. Reviewing these incidents reveals how the dominant resonance patterns have evolved from conventional synchronous-machine-dominated interactions to increasingly complex converter-dominated ones.

In conventional AC power systems, resonance was confined to a relatively narrow picture: the participants were almost exclusively synchronous generators and their associated controllers or compensation devices, and the coupling occurred among a small set of well-understood modes. The five conventional cases in Table 1 illustrate this. The 1970 Nevada event represents the electrical-mechanical branch of resonance, in which a series-compensated network couples with turbine-generator shaft torsional modes; such torsional interactions were the earliest resonance phenomena to threaten equipment integrity and motivated much of the classical SSR theory [30]. The remaining four cases, Illinois (1976) [31], the U.S.–Canada interconnection (1989) [32], Greece (2006) [33], and Northeast India (2013) [36], all fall in the low-frequency range, yet they reveal two distinct sub-mechanisms: coupling between a control mode and an electromechanical mode in the Illinois case, and coupling between two electromechanical modes of separate origin in the remaining three. A common feature of the low-frequency cases is that resonance emerged only under particular operating conditions that shifted the frequency or damping of otherwise weakly interacting modes until a strong interaction was established, making such events highly dependent on the system operating state.

The Northeast India event illustrates that even a routine network operation undertaken for voltage support can materially alter modal interactions. After a 63 Mvar bus reactor was switched in at the 400 kV Silchar substation, two local electromechanical modes moved into close proximity and one became negatively damped; the oscillation subsequently subsided after the tripping of a hydro generating unit and a 132 kV transmission line [36]. A complementary planning case was reported in the China Southern Power Grid. Wide-area modulation control of three HVDC links was intended to improve the damping of the 0.516 Hz Yungui mode. Root-locus analysis showed, however, that increasing the controller gain brought this mode closer to the 0.568 Hz Guangdong mode and produced an adverse redistribution of

damping: the Yungui mode gained damping while the Guangdong mode progressively deteriorated. Coordinated design of the feedback signals across the three links mitigated this adverse modal interaction at the planning stage [29,38]. These cases demonstrate that a mode appearing benign at one operating point may become critical following a network or controller change. Resonance screening should therefore track modal proximity and damping redistribution across relevant operating conditions, rather than relying only on damping-ratio rankings at a single operating point.

The large-scale integration of converter-interfaced generation has changed this picture in two fundamental ways. First, the set of participating elements has expanded: converter control loops, phase-locked loops (PLLs), weak-grid dynamics, and broadband AC/DC impedance characteristics now take part in resonance alongside, or instead of, synchronous machines. Second, the affected frequency range has widened from the low-frequency and subsynchronous bands to higher frequency ranges. The converter-related cases in Table 1 trace this shift. The 2009 Texas event marked the emergence of converter-control-driven SSR, where DFIG control supplied negative damping to a series-compensated network and turned a passive electrical resonance into a sustained oscillation; unlike classical SSR, no mechanical mode was essential to the mechanism [34]. The 2012–2013 Hebei events showed that the same SSCI mechanism could recur at the wind-farm scale [35], while the 2015 Xinjiang event demonstrated that subsynchronous resonance could also arise from the interaction between grid-side converter control dynamics and a weak AC grid, even without series compensation [37]. The resulting oscillation reached thermal units several hundred kilometers away and tripped three of them on torsional protection. Finally, the 2017 Guangxi event extended resonance to 1270 Hz, far above the subsynchronous band, where the interaction was more naturally characterized in impedance terms as a loss of passivity at the converter-grid interface than as simple modal proximity [25]. Together, these cases show that resonance has become faster, broader in frequency, and increasingly governed by control dynamics rather than by the physical modes of synchronous machines.

These representative incidents indicate that resonance in power systems has evolved from a phenomenon mainly associated with conventional synchronous-machine interactions into a broader class of oscillatory stability problems involving multiple devices, controllers, timescales, and frequency bands. As summarized in Table 1, resonance incidents reported in different periods cover low-frequency, subsynchronous, and high-frequency ranges, while the participating equipment and coupling mechanisms have become increasingly diverse with the growing penetration of converter-interfaced generation.

3. Mechanisms and classification of resonance stability

In electrical circuits, resonance is classically defined as the condition in which inductive and capacitive reactances balance, yielding a maximal periodic exchange of energy between storage elements [39]. From a broader physical perspective, resonance can be understood as an oscillatory phenomenon associated with periodic energy exchange among the dynamic modes of different components. When the inherent damping is insufficient, such oscillations may fail to decay and can even be amplified, leading to excessive voltage, current, power, or torque oscillations. In small-signal stability terms, a resonance instability manifests as self-excitation arising from a resonant dynamic interaction between oscillatory dynamics of different subsystems or control loops. In a state-space representation, such an interaction may appear as strong modal coupling or modal proximity, whereas in an impedance-based representation it may appear as an adverse impedance interaction or a loss of passivity at a converter-grid interface. Low-frequency electromechanical modal resonances, subsynchronous resonances, and high-frequency network and converter resonances all fall under this umbrella, differing primarily in which modes—mechanical, electrical, electromechanical, or control—participate.

Table 1
Representative resonance incidents reported in power systems.

Year	Region	Freq.	Frequency band	Triggering mechanism	Main equipment	Ref.
1970	Nevada, USA	10–56 Hz	Subsynchronous resonance	Subsynchronous currents in a series-compensated network coupled with turbine-generator shaft torsional modes through electromagnetic torque feedback.	Turbine-generator shafting; series-compensated transmission line	[30]
1976	Illinois, USA	1 Hz	Low-frequency resonance	Strong coupling between the excitation system and an electromechanical oscillation mode.	Excitation system; synchronous generator	[31]
1989	USA–Canada	0.76–0.77 Hz	Low-frequency resonance	Resonance between the local mode of the Kemano units and an inherent mode of the southwestern U.S. power system.	Kemano units in British Columbia; generators in the southwestern U.S. system	[32]
2006	Greece	0.88–0.89 Hz	Low-frequency resonance	Two electromechanical modes with different origins but close frequencies interacted under the 2006 operating condition.	Generating units in South Greece and neighboring interconnected systems	[33]
2009	Texas, USA	20–30 Hz	Subsynchronous resonance	Interaction between DFIG-based wind turbine control and the resonant mode of a series-compensated network, with negative damping introduced by converter control.	Wind-turbine control loops; series-compensated transmission line	[34]
2012–2013	Hebei, China	6–10 Hz	Subsynchronous resonance	SSCI-type SSR arising from the interaction between DFIG-based wind farms and series-compensated transmission lines.	DFIG converter control loops; series-compensated transmission line; PMSG and SEIG units (passive)	[35]
2013	Northeast India	0.97–0.99 Hz	Low-frequency resonance	Switching a 63 Mvar bus reactor for voltage support shifted two local electromechanical modes into close proximity, intensifying their interaction and causing one mode to become negatively damped.	63 Mvar bus reactor at the 400 kV Silchar substation; hydro generating units and the regional transmission network	[36]
2015	Xinjiang, China	27–33 Hz	Subsynchronous resonance	Direct-drive PMSG wind farms interacting with a weak AC grid through coupling between grid-side converter control dynamics and weak-grid dynamics.	Direct-drive PMSG wind farms; grid-side converter control loops; weak AC grid	[37]
2017	Guangxi, China	1270 Hz	High-frequency resonance	Negative-damping oscillation caused by impedance mismatch between converter control impedance and the AC grid impedance, exacerbated by the disconnection of several AC transmission lines.	VSC-HVDC converter station (± 350 kV/1000 MW); 525 kV AC grid; AC transmission lines out of service; passive impedance adapter not in service	[25]

In conventional power systems, resonance has most often been explained as a two-mode interaction [24,40]. By contrast, in modern power systems with a high penetration of renewable energy, the widespread use of power electronic converters and their nested control loops makes resonance phenomena more likely to exhibit multi-modal characteristics [29], potentially involving multiple converters, several control loops, network modes, and the remaining synchronous-machine modes simultaneously [41]. As a result, the observed instability can no longer always be attributed to a clearly identifiable pair of interacting modes. In this sense, modern resonance stability can be viewed as an extension of classical oscillatory stability theory from synchronous-machine-dominated electromechanical modes to converter-dominated, multi-timescale modal interactions. On the basis of the participating modes and the underlying interaction mechanisms, resonance is classified in this paper into four types.

Accordingly, each of the four resonance types introduced below is organized according to the dominant interacting modal pair. Where the participating dynamics can be resolved into distinct modes, the pair can be identified directly from their modal properties; where individual modes are not explicitly resolved, as in some impedance-based studies, the classification follows the physical nature of the two dominant interacting dynamic counterparts. The criterion is therefore the dominant

interaction mechanism embodied by this pair, rather than the equipment technology, converter synchronization paradigm, controller name or involvement, or nominal frequency band. The same converter may consequently participate in different resonance types, depending on which of its internal dynamics and which external dynamic counterpart dominate the interaction.

3.1. Type-1: Resonance between mechanical and electrical modes

Resonance between mechanical and electrical modes mainly occurs in the subsynchronous frequency range. Its most representative form is the torsional interaction between a series-compensated transmission line and the turbine-generator mechanical shaft, which constitutes the classical form of SSR in conventional AC power systems and is commonly referred to as torsional resonance [7]. A turbine-generator shaft possesses several inherent torsional modes; when the electrical resonance introduced by the series-compensated network produces electromagnetic torque components at frequencies close to a shaft torsional mode, the interaction may excite growing torsional oscillations and lead to mechanical SSR [17,42,43]. Compared with the resonance types encountered in modern converter-dominated systems,

this type has relatively well-defined oscillation frequencies and physical mechanisms, and has accordingly been studied extensively in the literature [44–47].

3.2. Type-2: Resonance among electromechanical modes

Electromechanical mode resonance is another common form of resonance in conventional power systems. Electromechanical modes, when weakly damped, usually manifest as low-frequency oscillations in active power, rotor angle, and other system variables, typically within the range of approximately 0.1–2.5 Hz. Physically, an electromechanical mode is a rotor-angle mode in which the inertial dynamics of synchronous-machine rotors are coupled by the synchronizing torques developed through the electrical network [6,7]. The network thus provides the coupling among the rotor motions, so the term designates a coupled modal group in its own right rather than a resonance between separately existing electrical and mechanical modes. Since the number of electromechanical modes grows with the number of synchronous generators and these modes remain confined to a relatively narrow frequency band, modes can become closely spaced in bulk power systems under certain operating conditions. Strong interaction among such closely spaced modes can then give rise to electromechanical modal resonance. This type of resonance is commonly observed in traditional power systems and may occur between two or more local modes, or between local and inter-area modes [24,33].

3.3. Type-3: Resonance between electromechanical and control modes

Beyond interactions among electromechanical modes, electromechanical modes may also interact with control modes. For instance, excitation systems introduce their own control modes, often referred to as exciter modes [48]. Changes in power system stabilizer (PSS) parameters or excitation-control settings may shift these control modes or reduce their damping, thereby increasing the likelihood of their interaction with electromechanical modes [49]. Since the frequencies of excitation-related control modes may fall within the low-frequency range, resonance between an excitation-control mode and an electromechanical mode can occur under certain conditions [50–53]. Similar modal interactions may also arise in hydropower systems, where the inherent modes of turbine-governor systems, particularly those associated with PID-type governor control, can interact with electromechanical modes [54].

These electromechanical-control modal resonances were originally discussed mainly in the context of conventional power-system components. With the large-scale integration of renewable generation through power electronic converters, similar mechanisms may also appear in converter-dominated power systems. For example, the active-power/frequency dynamics of some grid-forming converters may introduce a control-induced swing-like mode whose frequency lies close to that of an electromechanical mode of the synchronous-machine system [12, 55]. When these two modes interact strongly, the resulting phenomenon is classified as Type-3 because the dominant interacting pair consists of an electromechanical mode and a control mode. The grid-forming converter is used here only as a representative example and is not itself a classification criterion. If the dynamics associated with the inner voltage or current controllers, output filter, or digital-control delay of the same grid-forming converter instead interact with a network electrical mode through the converter terminal impedance, the interaction belongs to Type-4, as discussed in Section 3.4. Conversely, a grid-following converter may participate in Type-3 when a phase-locked-loop-, DC-voltage-, or outer-power-control-dominated mode couples predominantly with an electromechanical mode [56]. Thus, the assignment follows only the dominant modal pair and its underlying interaction mechanism.

3.4. Type-4: Resonance between electrical and control modes

With the large-scale integration of renewable energy via power electronic converters, various converter control loops interact and may resonate with the grid's inherent electrical modes. These mechanisms are more complex than traditional resonance types and span a wide frequency range, from the subsynchronous band to the mid- and high-frequency ranges. In the subsynchronous range, the resulting oscillations differ markedly from the traditional torsional-interaction (TI)-type SSR, since they do not rely on any mechanical shaft mode. Their historical antecedent is the induction generator effect (IGE): an induction-type generator presents an effective negative resistance to subsynchronous currents, which, if it outweighs the network resistance, destabilizes the electrical resonance of a series-compensated network into a self-excited oscillation. In conventional systems this effect was generally regarded as far less severe than TI-type SSR [42], and throughout this paper the term IGE refers exclusively to this classical control-free form. With the large-scale deployment of converter-interfaced generation, however, non-torsional subsynchronous resonance has become a genuine practical concern, with a prominent event reported in Texas in 2009 [34], and its significance has continued to grow [20].

A representative example is the DFIG-based wind turbine, whose stator is directly connected to the grid and which therefore behaves, in part, as an induction generator. The action of its rotor-side converter control loops reshapes the effective impedance seen by the network, so that the DFIG may resonate with series-compensation capacitors—the phenomenon known as subsynchronous control interaction (SSCI) [21, 22]. Crucially, SSCI differs from the classical, control-free IGE precisely because the converter control loop is deeply involved: the destabilizing negative resistance is created and shaped by the converter control, so that the interaction is between a control-dominated mode and the network electrical mode. The classical IGE, by contrast, involves no second oscillatory subsystem at all—a single network electrical resonance is destabilized by the negative resistance of the induction machine. It therefore lies outside the four-mode-pair scheme not as a fifth modal pair but because, like a single-loop control instability without an interaction counterpart, it is not a two-mode interaction in the first place; it is retained in this discussion only as the historical precursor of SSCI, whereas it is the deep involvement of converter control that places the practically relevant modern form squarely within Type-4. In full-converter direct-drive PMSG wind turbines, the decoupling is complete, the machine is isolated from the grid by the converter, so no induction-generator effect can arise at all, and the resulting sub-/super-synchronous oscillation is driven purely by the interaction between the converter control loops and the grid electrical modes, arising even without series compensation when the grid is weak, as in the oscillation events reported for direct-drive PMSG wind farms in Northwest China [37]. The same control involvement explains why such resonances are not confined to the subsynchronous range—similar interactions between converter control loops and network electrical modes can also occur at medium and high frequencies [25,27]. A representative medium-frequency case occurs in HVDC-connected offshore wind plants, where the offshore converter control can reduce the damping of the few-hundred-hertz series resonance formed by the long export cables and transformers until the system becomes unstable [57]. Further coupling among the subsynchronous modes of multiple converters has likewise been reported [58,59]. Although the underlying mechanism remains a balance between inductive and capacitive effects, these effective inductances and capacitances are now jointly shaped by the converter control structures and the physical network components, hence the designation of this class as resonance between electrical and control modes. It should be noted that steady-state harmonic distortion, understood as a bounded forced response at integer multiples of the fundamental frequency, is treated as a power-quality issue and is outside the scope of this paper. By contrast, oscillatory instability caused by converter-network interaction or cross-frequency coupling remains

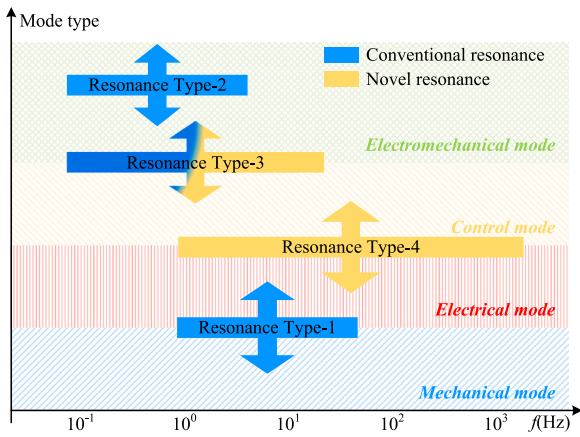


Fig. 1. Classification of resonance stability.

within the scope of Type-4 resonance, irrespective of whether it occurs in the medium- or high-frequency range.

Fig. 1 summarizes the above classification along three dimensions: the horizontal span of each resonance type indicates its frequency range, its vertical position identifies the two groups of participating modes, and the color distinguishes conventional resonance from the novel resonance phenomena in modern power systems. As the classification makes clear, the introduction of power electronic converters and their auxiliary control loops has substantially increased the complexity of resonance mechanisms. In particular, the modes involved in converter-related resonance are largely shaped by control parameters and structures, rather than being fixed physical properties of the generator as in conventional resonance; consequently, they are often difficult to identify in advance and may shift significantly when control settings change. Moreover, such a mode frequently does not belong to any single device but instead arises from the collective interaction of multiple converter-interfaced resources, making it difficult to attribute the resonance to a specific piece of equipment. The four types are, moreover, not an exhaustive enumeration of all pairs of the four modal groups. Combinations separated by a wide frequency gap, such as electromechanical and network electrical modes, do not arise as independent mechanisms. Interactions internal to one subsystem, such as those among the masses of a shaft, are already embedded in its own modes and become a stability problem only through the electromagnetic-torque feedback path covered by Type-1; a direct mechanical-control interaction, such as an HVDC or FACTS control loop destabilizing a torsional mode, acts through this same path and is likewise covered by Type-1, unless the control loop contributes its own neighboring oscillatory mode, in which case the dominant-pair rule applies. A passive network resonance is a single electrical mode rather than a pair, treated as a power-quality issue unless an active negative-damping mechanism destabilizes it, as in Type-4 or the limiting induction generator effect of Section 3.4. Interactions involving several control loops or more than two modal groups are assigned by their dominant coupling path. In the most complex cases, the four types distinguished above may themselves interact, giving rise to coupled resonance phenomena. Together, these features show that the four-type scheme is intended as a mechanism-oriented organizing framework rather than a rigid classification based on device technology, control paradigm, or frequency range.

Against this background, the proposed four-type classification should be understood as complementary to, rather than a replacement for or a one-to-one restatement of, the IEEE/CIGRE power-system-stability taxonomy [6,7]. The extended IEEE/CIGRE framework introduces converter-driven stability and resonance stability as two additional stability categories and discusses resonance stability primarily through

torsional resonance and electrical resonance. Under the modal-pair viewpoint adopted here, Type-1 aligns directly with torsional resonance, whereas the SSCI cases and related converter-control-involved subsynchronous phenomena included in Type-4 can be related to the electrical-resonance branch. The classical control-free induction generator effect, which destabilizes a single network electrical mode without a second oscillatory counterpart, is treated in Section 3.4 as a limiting case outside the four-mode-pair scheme. Type-2, Type-3, and the broader electrical-control interactions included in Type-4 are adopted in this review as finer mechanism-oriented distinctions that cut across more than one IEEE/CIGRE stability category rather than refining resonance stability alone, and are not claimed to be formally named IEEE/CIGRE subcategories. Depending on the descriptive level adopted, some converter-related instances covered by Type-3 and Type-4 may also overlap conceptually with slow- or fast-interaction converter-driven stability in the high-level IEEE/CIGRE framework. The two descriptions address different questions: the IEEE/CIGRE framework identifies the broader stability phenomenon, whereas the present scheme identifies the dominant pair of interacting dynamics and the corresponding resonance mechanism. Accordingly, this review includes converter-related oscillations when instability is driven by a resonant dynamic interaction between converter controls and another oscillatory subsystem, network resonance, or equivalent dynamic counterpart. Such an interaction may be represented as modal coupling or modal proximity in a state-space formulation, or as an adverse impedance interaction or a loss of passivity at the converter-grid interface in an impedance-based formulation. Converter-control instabilities in which an isolated control loop loses stability without such an interaction counterpart remain outside the scope of this review. The analysis methods reviewed in the next section are surveyed against this mechanism-oriented classification and according to the types of interaction that they are best able to resolve.

4. Analysis methods for resonance studies and their modeling foundations

The resonance phenomena classified in Section 3 differ not only in their participating modes and frequency ranges, but also in the kind of model on which their analysis must be based. Reflecting this, resonance-stability analysis has developed along three main lines, each resting on a distinct modeling foundation and offering a distinct analytical viewpoint: state-space models, which represent the complete system dynamics and support an eigenvalue-based modal viewpoint [24,45, 56,60–62]; terminal impedance and admittance models, which represent the external dynamics of devices and the grid and support a device-versus-grid interface viewpoint [63–68]; and s -domain nodal admittance models, which represent the entire network and support a network-level viewpoint [69–72]. Across these three families, power electronic converters, where present, are represented predominantly by linear time-invariant (LTI) averaged-value models. When residual periodicity in the adopted coordinates or the resulting cross-frequency coupling cannot be neglected, a complementary modeling foundation is provided by linear time-periodic (LTP) models and their harmonic state-space (HSS) realization, as reviewed in Section 4.5.

The evolution of resonance described in Section 3 has placed new demands on these methods. As the dominant resonance shifted from interactions among synchronous-machine and controller modes (Type-1 to Type-3) toward converter-network interactions (Type-4), and from single-device events toward multi-converter, network-wide, and wide-band phenomena, analysis methods have been required to accommodate black-box converter models whose internal control is proprietary, to cover a frequency range from sub-hertz to several kilohertz, and to locate resonance in networks where no single pair of physically inherent modes can be identified. No single method satisfies all of these requirements; rather, each method family answers a different

question—which modes interact and why, whether a given device-grid interface is stable, and where in a network a resonance resides.

This section reviews the three general method families and then presents the complex torque coefficient method and the harmonic state-space method. The five model-based methods in Sections 4.1–4.5 all operate on explicit small-signal representations, while differing in model class, partition, and representation. Section 4.6 separately reviews data-driven and learning-based approaches, and Section 4.7 concludes with a comparative summary and practical method-selection guidance.

4.1. State-space-based resonance analysis method

State-space methods describe the complete system by a linearized model and analyze resonance through its eigenstructure. In principle, this formulation is general, and all four resonance types can be analyzed within the same eigenvalue framework if every relevant device, including converters and their control loops, can be given a detailed internal model. In practice, however, state-space methods are most naturally applied when such white-box models are available, which is typically the case for synchronous machines, their shafts, and their controllers; they are therefore the standard tool for Type-1 to Type-3 resonance, and remain applicable to Type-4 whenever detailed converter models can be obtained. Two complementary formulations are reviewed below: the modal resonance method, which examines the coalescence of eigenvalues of a single system matrix, and open-loop modal resonance analysis, which examines the interaction of the modes of two interconnected subsystems.

4.1.1. Modal resonance method

The modal resonance method is one of the fundamental methods for resonance analysis in power systems [36,52,73,74]. It is developed on the basis of the state-space matrix, and its application in power systems was first proposed by I. Dobson to analyze the Type-2 resonance (between two electromechanical modes) [24].

Modal analysis is a classical approach for investigating small-signal stability and oscillatory characteristics in power systems. Around a given operating point, the nonlinear dynamic model can be linearized as

$$\Delta \dot{x} = A(\mu) \Delta x, \quad (1)$$

where Δx is the state perturbation vector, μ denotes a system parameter, and $A(\mu)$ is the state matrix evaluated at the corresponding equilibrium point. The oscillatory modes of the system are determined by the eigenvalue problem

$$A(\mu)v_i = \lambda_i v_i, \quad w_i^H A(\mu) = \lambda_i w_i^H, \quad (2)$$

where λ_i , v_i , and w_i are the i th eigenvalue, right eigenvector, and left eigenvector, respectively.

Mathematically, modal resonance can be interpreted as the coalescence of two or more eigenvalues in the complex plane. When two modal eigenvalues satisfy

$$\lambda_1(\mu_0) = \lambda_2(\mu_0) = \lambda_0, \quad (3)$$

the system may encounter modal resonance. According to the eigenstructure associated with the repeated eigenvalue, modal resonance can be further classified into strong modal resonance and weak modal resonance [75].

For a simple eigenvalue, the first-order sensitivity of λ_i with respect to the parameter μ is given by

$$\frac{\partial \lambda_i}{\partial \mu} = \frac{w_i^H (\partial A / \partial \mu) v_i}{w_i^H v_i}. \quad (4)$$

This expression shows that eigenvalue sensitivity is closely related to the biorthogonality between the corresponding left and right eigenvectors. When two eigenvalues approach each other, the denominator

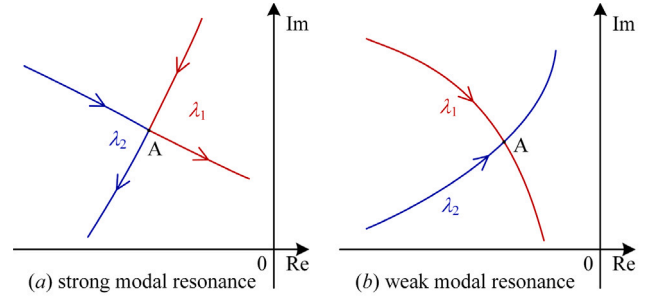


Fig. 2. Strong & weak resonance.

in (4) may become very small, leading to a significant increase in eigenvalue sensitivity.

Strong modal resonance occurs when two coincident eigenvalues share only one independent eigenvector. In this case, the repeated eigenvalue is defective and the state matrix cannot be diagonalized. Equivalently, in the two-dimensional resonant subspace, the local eigenstructure can be represented by a Jordan block:

$$J_s = \begin{bmatrix} \lambda_0 & 1 \\ 0 & \lambda_0 \end{bmatrix}. \quad (5)$$

A convenient local form for describing the eigenvalue movement near strong resonance is

$$M_s(\rho) = \begin{bmatrix} \bar{\lambda} & 1 \\ \rho & \bar{\lambda} \end{bmatrix}, \quad \lambda_{1,2} = \bar{\lambda} \pm \sqrt{\rho}, \quad (6)$$

where M_s denotes the reduced matrix of the two interacting modes, $\bar{\lambda}$ is their average eigenvalue, and ρ is a complex detuning parameter. Exact strong resonance corresponds to $\rho = 0$. Since

$$\frac{\partial \lambda_{1,2}}{\partial \rho} = \pm \frac{1}{2\sqrt{\rho}}, \quad (7)$$

the eigenvalue sensitivity tends to infinity as $\rho \rightarrow 0$. Therefore, two eigenvalues involved in strong modal resonance approach each other, coalesce, and then separate with an approximately 90° change in their moving directions, as shown in Fig. 2(a) [75]. This indicates strong interaction between the two modes.

Weak modal resonance occurs when two coincident eigenvalues have two linearly independent eigenvectors. The state matrix remains diagonalizable, and the local eigenstructure can be written as

$$J_w = \begin{bmatrix} \lambda_0 & 0 \\ 0 & \lambda_0 \end{bmatrix}. \quad (8)$$

Different from strong resonance, the eigenvalue perturbation contains ordinary integer-order terms, and the eigenvalue sensitivities remain finite. Thus, when two complex eigenvalues pass through a weak resonance, they approach, merge, and diverge almost without changing their moving directions. As illustrated in Fig. 2(b), the two modes have little mutual influence, and weak modal resonance usually appears only under special structural conditions such as symmetry or decoupling [75].

In practical power systems, exact eigenvalue coincidence is rarely observed. Therefore, near strong and near weak modal resonances are more useful for describing realistic modal interactions [24,60]. Let

$$\delta = |\lambda_1 - \lambda_2| \quad (9)$$

denote the distance between two nearby eigenvalues. If δ is small and the corresponding eigenvectors are nearly aligned, the system is close to strong modal resonance. This can be indicated by a small eigenvector angle

$$\theta_v = \cos^{-1} \left(\frac{|v_1^H v_2|}{\|v_1\| \|v_2\|} \right) \approx 0, \quad (10)$$

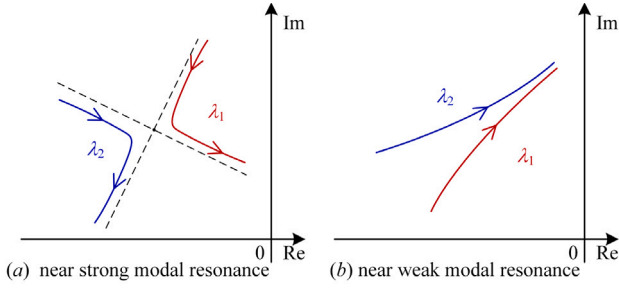


Fig. 3. Near strong & weak resonance.

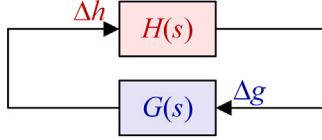


Fig. 4. Closed-loop interconnected system consisting of two open-loop subsystems.

or by a large condition number κ of the eigenvector matrix $V = [v_1 \ v_2]$,

$$\kappa(V) = \|V\| \|V^{-1}\| \gg 1. \quad (11)$$

In this case, although the sensitivity is finite, the eigenvalue trajectories may still exhibit a rapid and pronounced deflection, as shown in Fig. 3(a). This phenomenon is known as near-strong modal resonance.

By contrast, near weak modal resonance occurs when two eigenvalues are close, but their eigenvectors remain linearly independent. In this case, $\delta \ll 1$, $\theta_v \approx 0$, and $\kappa(V)$ is not excessively large. The two modes remain approximately decoupled, and their eigenvalue trajectories change smoothly. As shown in Fig. 3(b), the two eigenvalues may pass close to each other while maintaining nearly unchanged moving directions, which indicates weak modal interaction.

Overall, modal resonance analysis based on state-space models has a rigorous mathematical foundation. It can reveal the interaction mechanism between oscillatory modes through eigenvalues, eigenvectors, Jordan structures, and parameter sensitivities. However, this method is computationally demanding, as the state matrix and its eigenvalues must be recalculated for different operating conditions or parameter values to obtain the root loci. Moreover, although the method provides precise mathematical information, it does not always give a direct physical interpretation of the relationship between modal interaction and specific devices or control loops.

4.1.2. Open-loop modal resonance analysis method

Open-loop modal resonance provides another state-space-based perspective for interpreting oscillatory interactions in interconnected power systems [76–79]. Different from the modal resonance method discussed above, open-loop modal resonance explains how the interaction between two open-loop subsystems reshapes the corresponding closed-loop modes.

Consider a closed-loop interconnected system consisting of two open-loop subsystems, whose state-space models are described as

$$\begin{cases} \dot{X}_g = A_g X_g + B_g \Delta g, \\ \Delta h = C_g X_g, \end{cases} \quad \begin{cases} \dot{X}_h = A_h X_h + B_h \Delta h, \\ \Delta g = C_h X_h, \end{cases} \quad (12)$$

where Δg and Δh are the interface variables between the two subsystems. Fig. 4 illustrates the block diagram of a closed-loop system consisting of two open-loop subsystems in transfer function form.

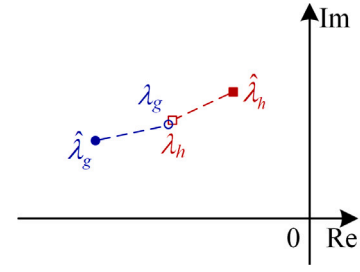


Fig. 5. Open-loop modal resonance.

The two subsystems can be expressed in residue form as follows:

$$G(s) = \sum_{i=1}^n \frac{R_{gi}}{s - \lambda_i}, \quad H(s) = \sum_{k=1}^m \frac{R_{hk}}{s - \lambda_k}, \quad (13)$$

where λ_i and λ_k are the eigenvalues of A_g and A_h , respectively, and R_{gi} and R_{hk} are the corresponding residues. The closed-loop characteristic equation of the interconnected system is

$$G(s)H(s) - 1 = 0. \quad (14)$$

When an open-loop eigenvalue λ_g of subsystem A_g is close to an open-loop eigenvalue λ_h of subsystem A_h , i.e.,

$$\lambda_g \approx \lambda_h, \quad (15)$$

the open-loop modal coupling condition is satisfied. The two subsystems may interact strongly through the interface variables. Under this condition, the corresponding closed-loop modes can deviate significantly from their original open-loop locations, as illustrated in Fig. 5.

In the neighborhood of these two resonant eigenvalues, the dominant terms of $G(s)$ and $H(s)$ can be approximated by:

$$G(s) \approx \frac{R_g}{s - \lambda_g}, \quad H(s) \approx \frac{R_h}{s - \lambda_h}, \quad (16)$$

where R_g and R_h are the residues associated with λ_g and λ_h , respectively. Substituting (16) into (14) gives

$$(s - \lambda_g)(s - \lambda_h) = R_g R_h. \quad (17)$$

Therefore, when $\lambda_g \approx \lambda_h \approx \lambda_0$, the two corresponding closed-loop eigenvalues can be approximated as

$$\hat{\lambda}_{g,h} \approx \lambda_0 \pm \sqrt{R_g R_h}. \quad (18)$$

Eq. (18) indicates that the closed-loop modes are pushed away from the original open-loop resonant eigenvalues in approximately opposite directions. The quantity $\sqrt{R_g R_h}$ determines both the magnitude and direction of this modal displacement. Its real part mainly affects modal damping, while its imaginary part affects modal frequency. Thus, if the real part of $\sqrt{R_g R_h}$ shifts one closed-loop eigenvalue toward the right-half complex plane, the damping of that closed-loop mode may be degraded. A damping degradation index (DDI) can therefore be defined as [76]:

$$\text{DDI} = \left| \text{Re} \left(\sqrt{R_g R_h} \right) \right|. \quad (19)$$

A larger DDI implies a stronger adverse interaction between the two open-loop modes and a more significant deterioration of closed-loop damping.

Besides the DDI, participation factor transition (PFT) is also used as an indicator in open-loop modal resonance analysis [62]. It describes the change in the contribution of a state variable to a certain mode after the open-loop subsystems are interconnected. For the k th state variable and the i th mode, PFT can be written as

$$\text{PFT}_{ki} = \Delta p_{ki} \hat{a}_{kk} + p_{ki} \Delta a_{kk}, \quad (20)$$

where

$$\begin{aligned}\Delta p_{ki} &= \hat{p}_{ki} - p_{ki} = \hat{w}_{ki}\hat{v}_{ki} - w_{ki}v_{ki}, \\ \Delta a_{kk} &= \hat{a}_{kk} - a_{kk}.\end{aligned}\quad (21)$$

Here, $p_{ki} = w_{ki}v_{ki}$ and $\hat{p}_{ki} = \hat{w}_{ki}\hat{v}_{ki}$ are the participation factors in the open-loop and closed-loop models, respectively, while a_{kk} and $\hat{a}_{kk}$ are the corresponding diagonal elements of the open-loop and closed-loop state matrices. The modal interaction can then be expressed as

$$\Delta\lambda_i = \sum_{k=1}^n \text{PFT}_{ki} + \Delta F_i, \quad (22)$$

where ΔF_i represents the contribution of off-diagonal terms. A large or untraceable PFT indicates that the modal contribution of key state variables changes significantly, which may lead to strong modal interaction or modal resonance.

It should be noted that open-loop modal resonance is different from near-strong modal resonance. Near-strong modal resonance describes the interaction between two closed-loop modes as system parameters vary, and it usually appears as a precursor to damping degradation. In contrast, open-loop modal resonance starts from the interaction between two open-loop modes belonging to different subsystems and directly explains the resulting displacement of closed-loop modes. Therefore, open-loop modal resonance offers clearer physical insight in three respects. First, it decomposes the complex closed-loop system into subsystems with explicit physical identities, e.g., an examined generator or controller represented by $G(s)$ and the remainder of the system represented by $H(s)$. Second, it identifies the source of the modal interaction by revealing which subsystem mode approaches a mode of the remainder of the system, as expressed by (15). Third, through (16) to (19), it establishes an explicit causal chain from modal proximity, through the dynamic interaction transmitted by the interface variables, to the resulting redistribution of closed-loop damping. The two closed-loop modes are displaced from the resonant open-loop modes by approximately $\pm\sqrt{R_g R_h}$. When $\text{Re}(\sqrt{R_g R_h})$ is nonzero, one mode is shifted toward a larger real part and therefore lower damping, while the other is shifted toward a smaller real part and gains damping. The DDI quantifies the magnitude of this real-axis splitting and hence the potential damping degradation of the adversely shifted mode. This subsystem-level explanation complements rather than replaces closed-loop eigenanalysis: the latter returns the exact modal positions of the interconnected system, whereas the former identifies which subsystems interact, through which interface variables, and how much damping degradation follows. The explanation is nevertheless local, because (16) retains only the dominant residue terms and (18) therefore holds in the neighborhood of the resonant open-loop modes.

4.2. Impedance-based resonance analysis method

Impedance-based analysis is one of the most widely used frequency-domain methods for studying converter-grid interactions and resonance stability in power-electronics-dominated power systems, making it the principal tool for analyzing Type-4 resonance. Its core idea is to partition the target system at the point of common coupling (PCC) into two subsystems, typically a device-side subsystem and a grid-side subsystem, and to represent their external dynamics by small-signal impedances or admittances rather than detailed internal state-space models. As illustrated in Fig. 6, this feature makes the method particularly attractive when detailed converter parameters are unavailable, while terminal frequency-response data can be obtained by analytical modeling, frequency scanning, or impedance measurement [57,63,67,72,80,81].

For a voltage-source system, the source subsystem can be represented by a Thévenin equivalent voltage source $V_s(s)$ in series with the source impedance $Z_s(s)$, while the load subsystem is represented by

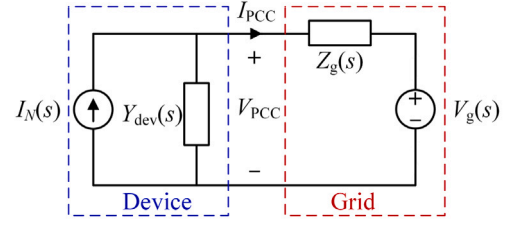


Fig. 6. Generic partition of a converter-grid system at the PCC for impedance-based resonance analysis.

the load input impedance $Z_l(s)$. The small-signal current flowing from source to load is

$$I(s) = \frac{V_s(s)}{Z_s(s) + Z_l(s)}, \quad (23)$$

and it can be rearranged as:

$$I(s) = \frac{V_s(s)}{Z_l(s)} \frac{1}{1 + \frac{Z_s(s)}{Z_l(s)}}. \quad (24)$$

If the unloaded source and the load supplied by an ideal voltage source are stable, the stability of the interconnected system is determined by the minor-loop gain:

$$L(s) = \frac{Z_s(s)}{Z_l(s)}. \quad (25)$$

Accordingly, the system is stable if the Nyquist plot of $L(s)$ satisfies the Nyquist stability criterion, i.e., the encirclement of the critical point $(-1, j0)$ is consistent with the number of right-half-plane poles of $L(s)$ [63]. For the common case where $L(s)$ has no right-half-plane poles, the Nyquist plot should not encircle $(-1, j0)$.

For a grid-connected inverter, the converter is usually controlled as a current source. In this case, the inverter can be modeled by a Norton equivalent current source $I_s(s)$ in parallel with its output admittance $Y_s(s)$, while the external network is represented by its admittance $Y_l(s)$. The terminal voltage can be written as:

$$V(s) = \frac{I_s(s)}{Y_s(s) + Y_l(s)} = \frac{I_s(s)}{Y_l(s)} \frac{1}{1 + \frac{Y_s(s)}{Y_l(s)}}. \quad (26)$$

Equivalently, using impedances, one has:

$$V(s) = I_s(s)Z_l(s) \frac{1}{1 + \frac{Z_l(s)}{Z_s(s)}}. \quad (27)$$

Thus, for a current-source-type converter system, the relevant impedance ratio is the opposite of that for a voltage-source system. For a grid-connected inverter with output impedance $Z_o(s)$ connected to a grid impedance $Z_g(s)$, the stability condition is commonly expressed by the minor-loop gain:

$$L(s) = \frac{Z_g(s)}{Z_o(s)}, \quad (28)$$

and the inverter-grid system is stable if $L(s)$ satisfies the Nyquist stability criterion [63]. This result also indicates that a grid-connected current-source inverter should have a sufficiently high output impedance to maintain stability over a wide range of grid conditions.

For resonance analysis, the same framework can be written in a more general form by using a device-side admittance $Y_{\text{dev}}(s)$ or the corresponding device-side impedance $Z_{\text{dev}}(s)$, i.e.,

$$L(s) = Z_g(s)Y_{\text{dev}}(s), \quad (29)$$

or equivalently,

$$L(s) = \frac{Z_g(s)}{Z_{\text{dev}}(s)}, \quad (30)$$

where $Z_g(s)$ is the grid-side impedance. Resonance instability is essentially caused by insufficient damping in the frequency-domain interaction between the device and network impedances. In a simplified single-input single-output case, a potential resonant frequency ω_r can be identified when the device-side and grid-side impedances have comparable magnitudes and nearly opposite phases, namely:

$$|Z_g(j\omega_r)| \approx |Z_{\text{dev}}(j\omega_r)|, \quad (31)$$

and

$$\angle Z_g(j\omega_r) - \angle Z_{\text{dev}}(j\omega_r) \approx \pm 180^\circ. \quad (32)$$

Equivalently, in terms of the minor-loop gain,

$$|L(j\omega_r)| \approx 1, \quad \angle L(j\omega_r) \approx -180^\circ. \quad (33)$$

The phase margin at the magnitude crossover frequency ω_c can be written as:

$$\text{PM} = 180^\circ + \angle L(j\omega_c), \quad |L(j\omega_c)| = 1. \quad (34)$$

The stability of an impedance interaction can be judged equivalently from the Nyquist curve of the minor loop gain L or from the Bode plots of the interacting impedances, as illustrated in Fig. 7: a potential resonance appears at the frequency f_r where the two impedance magnitudes intersect, and the phase difference between them there fixes the phase margin and hence the stability of the interaction. A small or negative phase margin implies that the impedance interaction is close to resonance instability. Therefore, sharp impedance peaks, magnitude intersections accompanied by a phase difference close to 180° , or Nyquist curves approaching the critical point $(-1, j0)$ are typical frequency-domain signatures of resonance risk.

The specific form of $Z_{\text{dev}}(s)$ or $Y_{\text{dev}}(s)$ depends on the analyzed equipment. For example, in VSC-HVDC systems, the impedance/admittance model should include inner current control, outer power or DC-voltage control, feedforward filters, and grid synchronization dynamics [82]. In DFIG-based wind power systems, the equivalent device impedance may include the rotor-side converter, induction machine, grid-side converter, and LCL filter, and can be used to reveal both series resonance between the wind turbine system and the weak grid and parallel resonance inside the DFIG system [65]. Despite these modeling differences, the underlying mechanism is the same.

For three-phase converter systems, positive- and negative-sequence impedances are often used to describe the converter terminal behavior in the phase domain. The positive-sequence and negative-sequence impedances can be defined as:

$$Z_p(s) = \frac{V_p(s)}{-I_p(s)}, \quad Z_n(s) = \frac{V_n(s)}{-I_n(s)}, \quad (35)$$

where V_p , V_n , I_p , and I_n are the positive- and negative-sequence voltage and current perturbations, respectively. Sequence impedance models are especially useful for analyzing subsynchronous and supersynchronous resonances of wind turbines and grid-connected converters, because the interaction between grid impedance and converter sequence impedance can be studied independently under many balanced operating conditions [80,83].

For multi-converter or multi-bus systems, the scalar impedance ratio is no longer sufficient, and the framework must be extended to a matrix or nodal-admittance form; this network-level formulation is treated in detail in Section 4.3.

Overall, impedance-based resonance analysis offers a unified and practical framework for resonance screening and mechanism interpretation in converter-dominated power systems, and is the method of choice for Type-4 resonance. Compared with eigenvalue-based methods, it requires far less internal information and is therefore particularly suited to black-box devices and practical engineering studies; conversely, it is less direct for resonances involving synchronous-machine modal interactions. Its accuracy still depends on the validity of the small-signal impedance model, the choice of interface, and the treatment of multi-input multi-output (MIMO) coupling in complex systems.

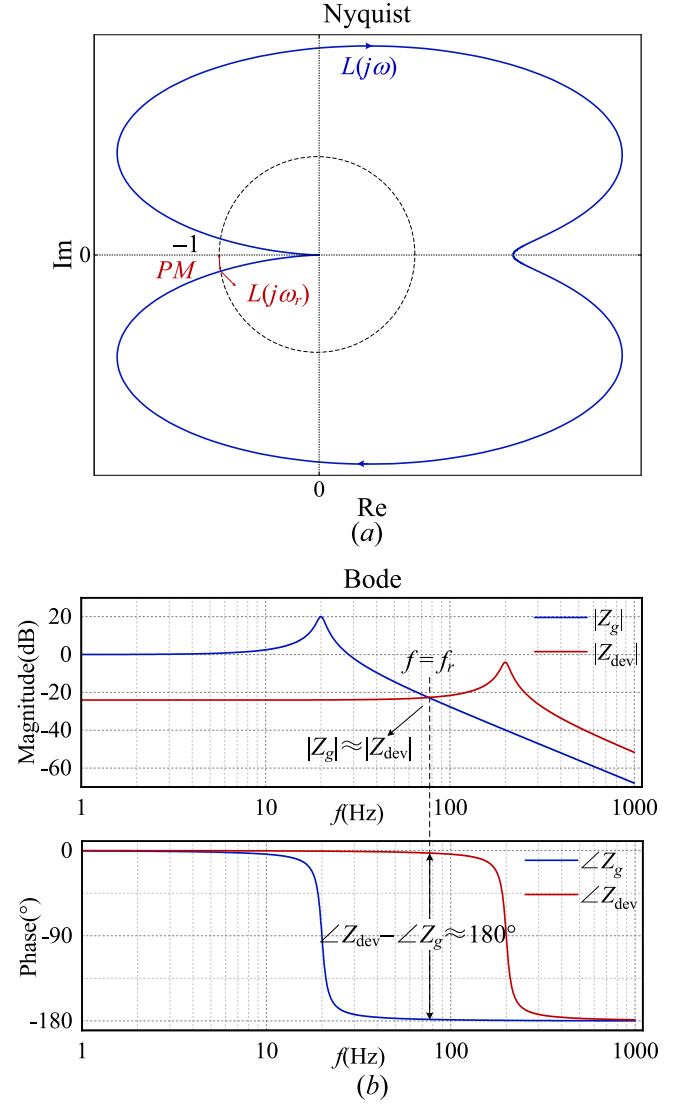


Fig. 7. Frequency-domain criteria for impedance-interaction resonance stability: (a) Nyquist plot of the corresponding minor loop gain $L(j\omega)$, where the phase margin (PM) at $L(j\omega_r)$ measures the proximity of the interaction to the critical point $(-1, j0)$; (b) Bode plots of the grid impedance Z_g and the device impedance Z_{dev} , whose magnitudes intersect and whose phases differ by about 180° at the resonance frequency f_r .

4.3. The s -domain nodal admittance matrix method

The s -domain methodology was first used to analyze power system small-signal stability issues in [69]. In contrast to impedance-based analysis, which primarily focuses on the equipment-side characteristics, the s -domain nodal admittance matrix method offers a grid-side perspective for resonance stability analysis by formulating the entire electrical network directly in the Laplace domain. Network elements, converter port impedances, filters, transmission lines, and other frequency-dependent components are represented by their s -domain admittances and assembled into the nodal admittance matrix [70,71]. Because it characterizes the network as a whole, this method is particularly suited to Type-4 resonance distributed over a multi-converter network and to network-level electrical resonances, identifying not only the resonance frequency and damping but also the buses and devices that dominate each mode.

For an n -node network, the nodal equation is written as:

$$\mathbf{Y}_{\text{node}}(s)\mathbf{V}_{\text{node}}(s) = \mathbf{I}_{\text{node}}(s), \quad (36)$$

where $\mathbf{Y}_{\text{node}}(s)$ is the s -domain nodal admittance matrix, $\mathbf{V}_{\text{node}}(s)$ is the nodal voltage vector, and $\mathbf{I}_{\text{node}}(s)$ is the nodal injection current vector. In general, the diagonal and off-diagonal elements of $\mathbf{Y}_{\text{node}}(s)$ can be expressed as

$$Y_{ii}(s) = \sum_{j \neq i} y_{ij}(s) + y_i^{\text{sh}}(s) + y_i^{\text{dev}}(s), \quad (37)$$

and

$$Y_{ij}(s) = -y_{ij}(s), \quad i \neq j, \quad (38)$$

where $y_{ij}(s)$ is the branch admittance between nodes i and j , $y_i^{\text{sh}}(s)$ is the shunt admittance connected to node i , and $y_i^{\text{dev}}(s)$ denotes the equivalent admittance of the dynamic device connected to node i . For example, if a converter or wind generator is represented by its port impedance $Z_i^{\text{dev}}(s)$, its contribution to the corresponding diagonal element is $y_i^{\text{dev}}(s) = 1/Z_i^{\text{dev}}(s)$.

For natural resonance modes, the external current injection is set to zero. Therefore, a nonzero free voltage response can exist only when the nodal admittance matrix becomes singular at a certain complex frequency. For the k th resonance mode, this condition can be written as

$$\mathbf{Y}_{\text{node}}(s_k)\mathbf{r}_k = \mathbf{0}, \quad \mathbf{r}_k \neq \mathbf{0}, \quad (39)$$

where s_k is the complex resonance root, and

$$\mathbf{r}_k = [r_{1k} \quad r_{2k} \quad \cdots \quad r_{nk}]^T \quad (40)$$

is the nodal voltage mode-shape vector of the k th resonance mode. The element r_{ik} represents the relative magnitude and phase of the voltage at node i under this mode. Since $\mathbf{r}_k$ is a modal vector rather than an absolute voltage vector, it is usually normalized, for example by

$$\max_i |r_{ik}| = 1. \quad (41)$$

Accordingly, nodes with larger $|r_{ik}|$ are more strongly involved in the k th resonance mode and can be regarded as the dominant resonance region.

The existence of the nonzero solution $\mathbf{r}_k$ requires

$$\det[\mathbf{Y}_{\text{node}}(s_k)] = 0. \quad (42)$$

Thus, the resonance stability problem is transformed into solving the zeros of the determinant of the s -domain nodal admittance matrix. Each root can be expressed as

$$s_k = \sigma_k + j\omega_k, \quad (43)$$

where σ_k determines the damping of the resonance mode and ω_k determines its angular resonance frequency. The corresponding resonance frequency is

$$f_k = \frac{\omega_k}{2\pi}. \quad (44)$$

The resonance stability criterion is therefore

$$\sigma_k < 0, \quad \forall k. \quad (45)$$

If any resonance mode satisfies $\sigma_k > 0$, the free component associated with this natural resonance frequency will grow after a disturbance, indicating resonance instability. For a stable but weakly damped resonance mode, the damping ratio can be further expressed as

$$\zeta_k = -\frac{\sigma_k}{\sqrt{\sigma_k^2 + \omega_k^2}}. \quad (46)$$

The modal voltage distribution associated with the k th resonance mode can be approximately expressed as

$$\mathbf{V}_{\text{node}}(s_k) \approx \mathbf{r}_k U_k, \quad (47)$$

where U_k is the scalar modal voltage amplitude. To further describe the participation of nodal current injections in this modal voltage response, the left mode-shape vector $\mathcal{E}_k$ is introduced as

$$\mathcal{E}_k^T \mathbf{Y}_{\text{node}}(s_k) = \mathbf{0}^T. \quad (48)$$

With a proper normalization, such as $\mathcal{E}_k^T \mathbf{r}_k = 1$, the participation factor matrix of the k th resonance mode can be defined as

$$\mathbf{P}_k = \mathbf{r}_k \mathcal{E}_k^T, \quad (49)$$

where the element $p_{ij,k}$ reflects the contribution of the current injection at node j to the voltage response at node i under the k th resonance mode.

In practical large-scale systems, directly solving the characteristic equation associated with $\mathbf{Y}_{\text{node}}(s)$ may be computationally difficult. A practical implementation is to first set all resistive or conductive damping terms to zero and identify the undamped resonance frequencies on the $j\omega$ -axis. Under this condition,

$$\mathbf{Y}_{\text{node}}(j\omega) = j\mathbf{B}_{\text{node}}(j\omega), \quad (50)$$

where $\mathbf{B}_{\text{node}}(j\omega)$ is the nodal susceptance matrix. The undamped resonance frequencies can then be obtained from

$$\det[\mathbf{B}_{\text{node}}(j\omega)] = 0. \quad (51)$$

After restoring all damping terms, the complex resonance root near each undamped frequency can be identified. One effective way is to use a test-signal-based transfer function, such as the shunt-current ratio [71]

$$\eta_{\text{sh}}(s) = \frac{i_{\text{sh}}(s)}{i_k(s)} = y_{\text{sh}}(s) \boldsymbol{\gamma} \mathbf{Y}_{\text{node}}^{-1}(s) \boldsymbol{\beta}, \quad (52)$$

where $i_k(s)$ is the injected test current at the selected node, $i_{\text{sh}}(s)$ is the current through a selected shunt branch, $y_{\text{sh}}(s)$ is the shunt-branch admittance, and $\boldsymbol{\beta}$ and $\boldsymbol{\gamma}$ are incidence vectors determined by the injection node and the observed branch. Near a specific resonance mode, this transfer function can be approximated by a second-order form,

$$\eta_{\text{sh}}(s) \approx \frac{b_2 s^2 + b_1 s + b_0}{s^2 + a_1 s + a_0}, \quad (53)$$

where a_0, a_1, b_0, b_1 , and b_2 are real coefficients identified from frequency-domain responses around the undamped resonance frequency. The roots of the denominator provide the damped resonance mode. In this way, the s -domain nodal admittance matrix method identifies the resonance frequency, damping, nodal voltage mode shape, participation region, and sensitive components from a unified network-level admittance model.

In summary, the s -domain nodal admittance matrix method establishes a grid-side framework for resonance stability analysis by formulating the network directly in the Laplace domain. This formulation enables the resonance structure of large-scale systems to be characterized while allowing frequency-dependent network elements and device port models to be incorporated in a unified manner. Its effectiveness, however, relies on the accuracy of the adopted s -domain models, and computing resonance roots or reduced transfer functions may become increasingly involved as the system scale and modeling detail increase. Compared with the impedance-based method, which focuses on a single device-grid interface, the s -domain nodal admittance method provides a network-wide picture and is therefore better suited to localizing resonance in multi-converter systems.

4.4. Complex torque coefficient method for SSR analysis

The three frameworks of Sections 4.1 to 4.3 are general-purpose: each is tied to a modeling viewpoint and, given an adequate model, is, in principle, applicable across the four resonance types, and each treats the power system as a single uniform object, whether represented in

state-space, impedance, or nodal-admittance form. The complex torque coefficient method takes a different path. Rather than seeking generality, it exploits the characteristic structure of (torsional) subsynchronous resonance, in which the turbine-generator naturally decomposes into a mechanical shaft subsystem and an electrical subsystem coupled only through electromagnetic torque and the rotor angle. This specialization provides direct physical interpretability for the SSR of synchronous-generator systems with series compensation and a frequency-scanning procedure that sidesteps high-order eigenvalue computation, which is why the method remains a fixture of SSR studies alongside the general frameworks [84–86].

On linearization around a steady operating point, the perturbations in the rotor angle $\Delta\delta$ and in the electromagnetic torque ΔT_e become the only two variables shared by the two subsystems. Modeling the shaft as a spring-mass system driven by ΔT_e and neglecting incremental mechanical torque components, the mechanical subsystem yields the transfer relation:

$$\Delta T_e = -k_m(s) \Delta\delta, \quad (54)$$

where $k_m(s)$ embeds the inertias, stiffnesses, and damping coefficients of the shaft and is independent of the network and converter dynamics. From the side of the electrical subsystem, comprising the generator electrical circuit, the rest of the network, and any converter or controller present, the response to a rotor-angle perturbation can be decomposed into components in phase with $\Delta\delta$ and with $\Delta\omega = s \Delta\delta$, giving:

$$\Delta T_e = k_e(s) \Delta\delta, \quad k_e(s) = T_S(s) + s T_D(s), \quad (55)$$

where $T_S(s)$ and $T_D(s)$ are the synchronizing and damping transfer functions of the electrical system. Combining (54) and (55) yields the characteristic equation of the SSR loop:

$$[k_m(s) + k_e(s)] \Delta\delta = 0, \quad (56)$$

whose roots determine its stability.

Rather than computing these roots from a high-order state-space realization, the method evaluates k_m and k_e as functions of frequency by substituting $s = j\omega$ and resolving each into real and imaginary parts:

$$k_m(j\omega) = K_m(\omega) + j\omega D_m(\omega), \quad (57)$$

$$k_e(j\omega) = K_e(\omega) + j\omega D_e(\omega), \quad (58)$$

in which K_m , K_e are the mechanical and electrical synchronizing coefficients and D_m , D_e the corresponding damping coefficients. The natural torsional frequencies of the loop are then the values of ω at which the synchronizing coefficients cancel,

$$K_m(\omega) + K_e(\omega) = 0, \quad (59)$$

and the mode at such a frequency ω_r is poorly damped or unstable when the net damping coefficient is non-positive,

$$D_m(\omega_r) + D_e(\omega_r) \leq 0. \quad (60)$$

The full SSR assessment, therefore, reduces to a one-dimensional sweep of ω over the subsynchronous range and a comparison of two pairs of frequency-domain curves, which can be obtained from impedance and frequency-response data and, crucially, without forming the global state matrix of the system.

In multi-machine settings, the principal effort lies in constructing $k_e(j\omega)$ for the unit under study, since it must absorb the contributions of the rest of the network and of all other generators. The CPCM-based formulation of [84] represents each network element and each SSR damping device as a frequency-domain port-equivalence block and assembles the system by nodal analysis, so that k_e is obtained from a low-order admittance reduction in which the shaft dynamics and rotor-angle interactions of the remaining generators are explicitly retained. The simplified variant in [86] carries this further by deriving an explicit analytical expression for $D_e(\omega)$ of the studied unit, on the basis of

which a screening procedure decides when the shafts of neighboring generators, particularly those sharing close torsional frequencies, must be modeled in detail and when they may be condensed.

The method's appeal is its transparency. It keeps the mechanical and electrical contributions separate, replaces the full-system eigenproblem with a one-dimensional frequency scan, and shows directly which subsystem supplies or absorbs damping at each torsional mode. Its limitations are equally structural. It examines only oscillatory roots, so monotonic instability from real poles goes undetected; when modal damping is not small, it may misplace or miss modes or misjudge their stability; and, being formulated for synchronous-machine torsional dynamics, it does not extend naturally to induction-machine-based resonance [85]. It is therefore best used as a fast, physically transparent first pass for synchronous-generator SSR, with eigenvalue analysis reserved for a definitive classification.

4.5. Harmonic state-space resonance analysis method

The preceding methods are commonly formulated using linear time-invariant small-signal representations about a constant operating point in an appropriate reference frame. Where power electronic converters are involved, their discontinuous switching processes are represented predominantly by averaged-value models, in which the converter behavior is averaged over one switching period. This modeling choice is appropriate for many torsional, electromechanical, and subsynchronous resonance studies, where the oscillation and switching dynamics are sufficiently separated in timescale and the dominant mechanism is the coupling among mechanical, electrical, electromechanical, and control modes. Under standard timescale-separation assumptions, averaging theory provides a reduced small-signal representation whose accuracy generally improves as the separation between the perturbation and switching timescales increases [87]. Practical averaged-value impedance models may additionally retain sampling, modulation, and digital-control delays because these terms strongly influence the phase and passivity properties of converter terminal impedances, particularly toward the high-frequency band.

The averaged LTI description may nevertheless become inadequate when the periodicity of the operating trajectory cannot be eliminated or neglected in the adopted coordinates, or when the associated cross-frequency coupling materially affects the resonance mechanism. Representative situations include single-phase and unbalanced systems, modular multilevel converters (MMCs) whose internal variables contain fundamental- and double-frequency components even in averaged form, thyristor-based devices whose conduction patterns repeat periodically, and converter interactions involving modulation sidebands. In these cases, linearization is performed around the periodic steady-state trajectory rather than around a time-invariant equilibrium, yielding an LTP small-signal model. HSS analysis provides a frequency-domain computational realization of this LTP framework [88,89]. Throughout this subsection, the term “harmonic” refers to the Fourier components of the periodic steady-state trajectory and to the coupled frequency channels of the linearized model. Steady-state harmonic distortion remains a power-quality issue outside the scope of this review. Harmonic instability refers here to an oscillatory instability associated with cross-frequency coupling among harmonic or sideband channels in a periodically operated system; in the converter-dominated cases considered in this review, such phenomena are treated within the broader Type-4 resonance category when this coupling affects small-signal stability [13].

The starting point is the LTP small-signal model

$$\begin{aligned} \Delta \dot{x}(t) &= A(t) \Delta x(t) + B(t) \Delta u(t), \\ \Delta y(t) &= C(t) \Delta x(t) + D(t) \Delta u(t), \\ A(t+T) &= A(t), \quad B(t+T) = B(t), \\ C(t+T) &= C(t), \quad D(t+T) = D(t). \end{aligned} \quad (61)$$

Here, T is the base period of the periodic trajectory, and the periodic coefficient matrices reflect the time-varying local dynamics along that trajectory. Let $\omega_0 = 2\pi/T$. The coefficient matrices are expanded in Fourier series, and the state, input, and output perturbations are sought in exponentially modulated periodic form, for example

$$A(t) = \sum_{k=-\infty}^{\infty} A_k e^{jk\omega_0 t}, \quad \Delta x(t) = e^{st} \sum_{k=-\infty}^{\infty} X_k e^{jk\omega_0 t}, \quad (62)$$

with analogous expansions for $B(t)$, $C(t)$, and $D(t)$ and for the input and output perturbations. Substitution of these expansions into (61) transforms the differential equations into the lifted harmonic state-space relation

$$\begin{aligned} s\mathcal{X} &= (\mathcal{A} - \mathcal{N})\mathcal{X} + \mathcal{B}\mathcal{U}, \\ \mathcal{Y} &= \mathcal{C}\mathcal{X} + \mathcal{D}\mathcal{U}, \\ \mathcal{N} &= \text{diag}(\dots, -j\omega_0 I, 0, j\omega_0 I, \dots), \end{aligned} \quad (63)$$

where $\mathcal{X}$, $\mathcal{U}$, and $\mathcal{Y}$ stack the harmonic components of the state, input, and output, respectively. The matrices $\mathcal{A}$, $\mathcal{B}$, $\mathcal{C}$, and $\mathcal{D}$ are block-Toeplitz matrices formed from the Fourier coefficients of $A(t)$, $B(t)$, $C(t)$, and $D(t)$, while $\mathcal{N}$ is the frequency-shift operator.

Truncating the Fourier expansion at a finite harmonic order h produces an LTI lifted model of dimension $(2h+1)n_x$, where n_x is the dimension of the original state vector. The eigenvalues of the truncated matrix $(\mathcal{A} - \mathcal{N})$ approximate the Floquet exponents of the periodic system, and convergence should therefore be checked by increasing the truncation order. Because Floquet exponents are defined modulo $jk\omega_0$, the lifted spectrum contains repeated harmonic copies shifted along the imaginary axis by integer multiples of $j\omega_0$; for stability interpretation, these repeated copies are usually mapped into one principal strip, for example $\text{Im}(s) \in [-\omega_0/2, \omega_0/2]$.

The input–output behavior of the lifted model is described by the harmonic transfer function

$$\begin{aligned} \mathcal{Y} &= H(s)\mathcal{U}, \\ H(s) &= \mathcal{C} [sI - (\mathcal{A} - \mathcal{N})]^{-1} \mathcal{B} + \mathcal{D}. \end{aligned} \quad (64)$$

The (m, k) block of $H(s)$ maps an input component at frequency $\omega + k\omega_0$ to an output component at frequency $\omega + m\omega_0$. The diagonal blocks describe same-frequency responses, whereas the off-diagonal blocks quantify cross-frequency coupling caused by the periodic variation of the operating trajectory. When the off-diagonal blocks are negligible, the representation reduces to a conventional same-frequency impedance or transfer-function model, such as a scalar, sequence-domain, or dq impedance model.

For a system with a single base periodicity, a perturbation at frequency f may therefore generate responses at $f \pm f_0$, $f \pm 2f_0$, and higher-order shifted frequencies, where $f_0 = \omega_0/(2\pi)$. When carrier or modulation periodicity is explicitly retained and is commensurate with the adopted base period, the same lifted formulation can additionally represent switching-related sidebands. Systems containing several asynchronous or incommensurate periodicities, however, generally require a multi-frequency, quasi-periodic, or generalized harmonic formulation rather than the single-period model in (61). Consequently, sideband interactions among converters with asynchronous carriers should be interpreted through such a multi-frequency extension rather than through a single-period HSS model.

In terminal form, the harmonic transfer function generalizes the impedance concept of Section 4.2 to a frequency-coupled impedance matrix. Such a matrix may be constructed analytically from a white-box periodic model or identified through multi-tone frequency scanning. Subject to the internal stability of the partitioned subsystems and adequate harmonic truncation, resonance stability can be assessed either from the approximate Floquet exponents of the lifted model or by applying a generalized Nyquist criterion to the resulting harmonic loop-gain matrix [13,68,88].

Several strands of the resonance literature rest on this modeling framework. The generalized averaging method of [87] provides a

closely related reduced representation by tracking selected Fourier coefficients, or dynamic phasors, of periodically varying waveforms. It has been applied to the subsynchronous behavior of thyristor-controlled series capacitors, whose apparent impedance is shaped by their firing and conduction patterns and may not be reproduced accurately by a fundamental-frequency average alone [90,91]. HSS models of grid-connected converters expose harmonic and sideband interactions between converter controls and grid dynamics that may be missed by uncoupled LTI models as the frequency of interest increases [89]. Frequency-coupled and multi-frequency formulations have also been used to study sideband interactions among paralleled inverters with asynchronous carriers [92]. For MMCs, whose internal steady state is inherently multi-harmonic, HSS-based impedance models incorporating internal harmonic dynamics reproduce terminal responses in frequency ranges where conventional LTI averaged models may deviate [93]. At the network level, generalized impedance-based formulations extend the same frequency-coupled representation to combined AC/DC systems for harmonic-stability screening [68].

Overall, the HSS framework extends small-signal resonance analysis to systems in which residual periodicity and cross-frequency coupling cannot be neglected, making frequency coupling an explicit and quantifiable object rather than an unmodeled effect. Its price is increased dimensionality and information requirements: the model size grows with the harmonic truncation order, and its construction requires either a white-box periodic model or measured frequency-coupled terminal responses. Multiple asynchronous periodicities further require multi-frequency extensions beyond the standard single-period formulation. HSS therefore complements rather than replaces the methods of Sections 4.1–4.4. It is particularly suitable for MMCs, single-phase and unbalanced systems, and modulation-related sideband interactions. When discrete sampling effects dominate or the relevant frequencies approach the switching or sampling range, sampled-data, exact periodic, or other higher-fidelity models may additionally be required.

4.6. Data-driven and learning-based resonance analysis

All the methods reviewed above rely on an explicit small-signal representation, whether derived from a physical model or obtained from measured frequency responses. A separate strand of the literature infers resonance behavior more directly from measured or simulated data. Its members do not form a sixth method of the same kind, because they occupy two distinct positions relative to Sections 4.1–4.5: one identifies the representation subsequently analyzed by those methods, whereas the other replaces the model-based inference with a learned surrogate mapping. This distinction determines which parts of the preceding interpretive apparatus remain available.

4.6.1. Data-driven identification of resonance models

The first branch is upstream of, not parallel to, the preceding methods: its product is the very object they analyze, so that a white-box model ceases to be a prerequisite for a model-based analysis. This branch is already implicit above. The terminal impedance of Section 4.2 is routinely obtained by frequency scanning rather than by derivation, and the frequency-coupled impedance matrix of Section 4.5 may be identified through multi-tone excitation; naming the branch merely makes explicit a dependence the preceding sections already carry.

On the state-space side, eigensystem realization applied to multi-channel measured responses estimates a reduced-order input–output realization whose poles yield the oscillation modes used in the eigenvalue framework of Section 4.1 [94]. Because the identified state coordinates are generally related to the physical states through an unknown similarity transformation, the poles and input–output modal residues retain direct meaning, whereas state-level participation factors require an additional mapping to physical coordinates. On the terminal side, neural-network regression maps operating conditions to converter impedance; embedding prior knowledge of the converter into

the network structure reduces both the data requirement and the online computational burden relative to an unconstrained fit [95], and transfer learning reuses a model trained on one configuration to characterize another, which is attractive for modular multilevel converters whose impedance must be re-identified as control settings change [96].

When the identified object is a state-space, impedance, nodal-admittance, or harmonic representation, the corresponding analytical criterion of Sections 4.1–4.5 remains applicable to that identified representation. The resulting poles, resonance roots, stability margins, mode shapes, and passivity properties are nevertheless estimates whose reliability depends on excitation bandwidth, measurement noise, selected model order, and coverage of the relevant operating conditions. Identification uncertainty therefore affects the representation supplied to the analytical framework and propagates to its outputs; it does not create a new stability criterion. Coordinate-dependent quantities require additional care, as illustrated above for state-level participation factors.

4.6.2. Learning-based direct stability assessment

The second branch does not reconstruct an explicit dynamical model. Instead, it learns a mapping from operating-condition or measurement data to selected stability descriptors, with model-based analysis or measurements commonly used offline to generate the training labels. For resonance specifically, the descriptor may be chosen to expose modal proximity rather than only a stable–unstable verdict, thereby retaining part of the mechanism emphasized in Section 3. A deep extreme learning machine trained on scenario information and modes identified from historical records predicts the oscillation modes of both the converter and the multi-machine subsystems under an unseen scenario, from which the Type-3 resonance condition is evaluated [94]. A generalized regression neural network trained on scenario data and converter control parameters predicts the boundaries of the resonance area, i.e., the regions of the complex plane occupied by the open-loop modes of the two subsystems of Section 4.1.2, thereby approximating the model-based construction of [97] without reconstructing its underlying system model [98]. Related formulations estimate the stability region of a converter-grid interaction system directly in the space of control parameters [99]. Data-driven source-localization methods have also been developed for forced oscillations amplified under resonance conditions: robust principal component analysis separates a low-rank resonant response from a sparse source component using synchrophasor data [100]. Because this case involves an external forcing frequency rather than coupling between two autonomous system modes, it is treated here as a related monitoring application rather than as one of the four resonance types defined in Section 3.

The gain of this branch is coverage and speed: once trained, it can evaluate a large scenario set at a cost that repeated eigenanalysis or impedance construction cannot match, which enables preventive rather than purely reactive resonance management. Its limits follow from the same property. Unless participation, source, or interface information is explicitly included in the outputs or imposed through physical constraints, the learned mapping generally provides less direct mechanism attribution than the model-based methods. Its accuracy is warranted only within the operating region represented by the training data, extrapolation beyond that region carries no guarantee, and its labels must themselves be obtained from model-based analysis or measurements. The branch therefore relieves the online burden of Sections 4.1–4.5 without dispensing with them offline and is best regarded as a screening, prediction, or monitoring layer rather than a universal substitute for mechanism-based analysis.

4.7. Comparison and method selection

The five model-based methods reviewed in Sections 4.1–4.5 are complementary rather than competing. Table 2 compares their modeling foundations, information requirements, outputs, strengths, limitations, and typical applications. The mapping to resonance types is indicative rather than restrictive, reflecting the model information typically available for each type: state-space methods are commonly used for Type-1 to Type-3, impedance- and nodal-admittance methods for Type-4, and harmonic state-space analysis wherever periodicity or cross-frequency coupling is material. The data-driven approaches of Section 4.6 are included for comparison but positioned separately, because identification supplies an estimated model to the preceding methods, whereas direct learning predicts selected resonance descriptors without retaining such a model.

The four LTI methods of Sections 4.1–4.4 share a common characteristic-root basis despite their different system partitions and interface variables. For a complete state-space realization, the roots satisfy $\det(sI - A) = 0$, with A the state matrix in (1); for the roots visible from a selected interface, the same condition can be represented — after accounting for the poles of the partitioned subsystems and for modes lost through uncontrollability, unobservability, or pole-zero cancellation — by

$$\det(sI - A) = 0 \quad \xLeftrightarrow[\text{interface-visible roots}] \quad \Delta_{\text{int}}(s) = 0,$$

$$\Delta_{\text{int}}(s) = \begin{cases} G(s)H(s) - 1, & \text{open-loop partition,} \\ \det[\mathbf{I} + \mathbf{L}(s)], & \text{impedance partition,} \\ \det[\mathbf{Y}_{\text{node}}(s)], & \text{nodal formulation,} \\ k_m(s) + k_e(s), & \text{torque-angle partition.} \end{cases} \quad (65)$$

Here $\mathbf{L}(s)$ is the minor-loop-gain matrix formed at the chosen interface; for a scalar one-port model, $\det[\mathbf{I} + \mathbf{L}(s)] = 0$ reduces to $1 + L(s) = 0$, the familiar device-grid impedance balance. The equivalence presumes formulations built from the same model and operating point. Beyond it, the methods differ in the model information they require, the analytical representation they adopt, and the modal visibility they afford: state-space analysis returns the complete spectrum of the adopted realization, whereas interface-based formulations may omit or poorly reveal modes that are insufficiently controllable or observable from the selected variables or ports. The impedance formulation uses one device-grid interface, the nodal-admittance formulation extends the port description to a network, and the complex-torque-coefficient formulation specializes it to the rotor-angle–electromagnetic-torque channel; its commonly used real-frequency scan remains an approximation mainly suited to lightly damped torsional modes and does not detect monotonic instability associated with real roots.

The harmonic state-space method is not another algebraically equivalent formulation of the LTI problem: it approximates the Floquet exponents of the periodic model in (61), defined modulo integer shifts of $j\omega_0$, through the eigenvalues of the truncated lifted matrix in (63). In the time-invariant limit, all nonzero-order Fourier coefficients vanish and the lifted matrix becomes block diagonal; after folding its repeated eigenvalue copies into a principal frequency strip, the conventional LTI spectrum is recovered, and with it the common basis of the four LTI methods. This limit is a property of the underlying model; reducing the harmonic truncation order merely omits selected coupling channels without rendering the model time invariant. In terms of model information, the method admits both entry points: constructed from a white-box periodic model, it acts as a state-space framework for periodically operated systems; condensed into frequency-coupled terminal responses, it generalizes the impedance viewpoint. In both forms its distinguishing output is an explicit representation of cross-frequency coupling.

Data-driven methods are likewise outside the strict equivalence of (65). Identification-based methods provide an estimated state-space,

Table 2
Comparison of the resonance-stability analysis methods.

	State-space modal	Impedance-based	<i>s</i> -domain nodal admittance	Complex torque coefficient	Harmonic state-space	Data-driven/learning-based
Modeling foundation	Complete linearized state-space model of the whole system	Terminal small-signal impedance/admittance at the PCC	Network-wide <i>s</i> -domain nodal admittance matrix	Mechanical shaft and electrical subsystems coupled through ΔT_e and $\Delta \delta$	LTP model linearized around a periodic trajectory and lifted into harmonic coordinates	Identified small-signal representation or learned surrogate mapping
Information required	Detailed internal white-box models of all devices	Terminal frequency response only; black-box models admissible	<i>s</i> -domain admittances of all branches and device port models	Shaft mechanical data and electrical-system frequency response	White-box periodic model or measured frequency-coupled terminal responses	Measured or simulated response data with adequate excitation and operating-condition coverage
Analytical viewpoint	System-wide modal/eigenstructure	Device-versus-grid interface	Network-level grid-side resonance	Mechanical-versus-electrical interaction at the generator shaft	Periodic-system stability and cross-frequency coupling	Model identification for the preceding frameworks, or direct inference of selected resonance descriptors
Frequency range	All ranges in principle; limited in practice by model order and availability	Broad; from sub-Hz to several kHz; effective for wideband converter-grid interactions	Broad; network resonances from sub-Hz to kHz	Subsynchronous range	Broad; determined by the periodicities retained, model bandwidth, and harmonic truncation order	Determined by excitation bandwidth and sampling rate
Best-suited resonance	Type-1 to Type-3; Type-4 when white-box converter models are available	Type-4 converter-grid resonance	Type-4 resonance distributed over multi-converter networks	Type-1 synchronous-generator SSR	Resonance of any type when periodicity or cross-frequency coupling is material; especially converter-network, MMC, unbalanced, thyristor-controlled, and modulation-sideband interactions	Any type when models are unavailable, or when many operating scenarios must be screened online
Primary outputs	Eigenvalues, eigenvectors, sensitivities; DDI and PFT in the open-loop form	Minor-loop-gain Nyquist/Bode plots, phase margin, and resonance frequency	Resonance roots, nodal voltage mode shapes, and participation factors	Synchronizing- and damping-coefficient curves; subsynchronous mode frequency and damping	Approximate Floquet exponents, harmonic transfer functions, and frequency-coupled impedances	Identified state-space or impedance models; or predicted modes, resonance areas, and stability regions
Main strengths	Rigorous and complete modal information; reveals interacting modes and mechanisms	Minimal internal information; suitable for proprietary converters and measurement-based analysis	Network-wide localization of resonance and dominant components	Physically transparent damping attribution; avoids the global eigenproblem	Makes cross-frequency coupling explicit and captures periodic effects omitted by uncoupled LTI models	No white-box model required; supports rapid multi-scenario screening and online updating
Main limitations	Requires complete white-box models; computationally demanding; recomputed for each operating point	Single-interface focus; MIMO coupling; depends on impedance-model validity	Requires accurate <i>s</i> -domain models throughout; root finding becomes demanding at scale	Misses monotonic instability; may lose accuracy for strongly damped modes; limited to synchronous-machine SSR	Dimension grows with truncation order; requires periodic models or coupled measurements; asynchronous periodicities require multi-frequency extensions	Identification branch inherits measurement and model-reduction uncertainty; direct-learning branch has limited interpretability and no guarantee outside the training region

impedance, admittance, or harmonic representation to which the corresponding model-based criterion is applied; direct-learning methods instead approximate selected analysis outputs and generally possess no independent characteristic equation. Their reliability therefore depends on identification accuracy and uncertainty characterization in the former case, and on generalization beyond the training domain in the latter.

For practical selection, consistent with the best-suited row of Table 2, state-space or open-loop modal analysis is preferred when detailed models are available and mechanism attribution is required; impedance analysis when only converter terminal behavior is accessible; nodal admittance when a network-wide resonance must be localized; and the complex torque coefficient method for physically transparent torsional-SSR assessment. Harmonic state-space analysis is appropriate when periodicity or cross-frequency coupling cannot be neglected, while sampled-data or higher-fidelity periodic models may be needed near switching or sampling frequencies. Data-driven identification is useful

when white-box models are unavailable but mechanism-level analysis remains necessary, whereas direct learning is most suitable for rapid multi-scenario screening or online prediction.

Because these model-based methods remain linearized, their predictions should be cross-checked against nonlinear switching-level electromagnetic-transient simulation, which captures switching events, saturation and limiting, and large-disturbance behavior beyond the retained small-signal and harmonic-truncation approximations; identified and directly learned results additionally require model-validation and out-of-sample checks.

To facilitate mechanism-oriented reproduction without tying the review to a newly constructed, case-specific simulation, the generic formulations presented above can be instantiated using established benchmark and test systems from the primary literature. For Type-1 resonance, the first system of the IEEE second benchmark model has been used to compare small-signal subsynchronous-resonance predictions with nonlinear time-domain simulations [101]. For Type-2

and Type-3 resonance, the two-area four-machine system offers a widely used benchmark for electromechanical modal interactions: its local and inter-area electromechanical modes form a representative setting for studying Type-2 modal proximity and interaction, while [50] uses the same system to show an excitation-control mode interacting with an inter-area mode near a strong resonance, illustrating Type-3. For Type-4 resonance, the DFIG-weak-grid and VSC-HVDC-AC-grid systems in [25,65], together with the frequency-coupled MMC-HVDC case in [66], provide representative settings for reproducing impedance-based resonance signatures and their simulation-based validation. These systems can be re-implemented in electromagnetic-transient or equation-based environments, including open-source platforms such as OpenModelica, with the model fidelity and parameter definitions following the corresponding primary studies.

5. Control and mitigation strategies for resonance

Mitigation acts mainly through damping injection, impedance reshaping, or modal detuning. In this section, the strategies are organized by resonance type and further distinguished by their implementation route — control-side modification of existing assets or additional device- or network-side intervention — and by the frequency band of the targeted interaction. The implementation route is defined relative to the existing system configuration: modifying the control of an installed STATCOM is control-side, whereas installing a new STATCOM is device-side. Data-driven techniques support the identification, tuning, scheduling, or adaptation of these physical levers. Table 3 summarizes the corresponding frequency ranges, implementation routes, and band-specific design requirements.

5.1. Mitigation of torsional subsynchronous resonance (Type-1)

Type-1 resonance arises when subsynchronous currents in a series-compensated network provide negative damping to turbine-generator shaft modes. Its mitigation therefore targets the identified torsional frequencies by suppressing subsynchronous currents, injecting positive damping torque, or detuning the electrical resonance, while avoiding adverse effects on neighboring torsional modes. The most common implementations are subsynchronous damping controllers and FACTS-based damping devices: SSSC-based schemes estimate the subsynchronous components in the line current and inject proportional subsynchronous voltages to cancel them [102], controlled supersynchronous current injection has been used to damp multimodal torsional interaction [103], and UPFC-based subsynchronous damping controllers superimpose modal damping signals on the inner current-control references of the shunt and series converters [104]. Beyond such dedicated damping controllers, the UPFC's basic series-voltage control modes can themselves mitigate SSR: injecting series real voltage to emulate a positive series resistance raises the damping of the critical torsional mode, while injecting series reactive voltage both reduces the negative damping and shifts the electrical resonance away from the torsional frequencies, thereby detuning the interaction [105]. VSC-based shunt static var generators (SVGs), commonly termed STATCOMs in the FACTS literature, provide another shunt-connected damping resource. For a STATCOM installed at the electrical center of a series-compensated line, an auxiliary subsynchronous damping controller superimposed on its reactive-current control can be designed through damping-torque-based nonlinear optimization over the critical torsional-frequency range, thereby effectively damping the turbine-generator torsional modes [106]. Renewable inverters can also serve as auxiliary damping resources; for example, a PV solar farm may temporarily operate as a PV-STATCOM, modulating its reactive power to damp the torsional modes of nearby turbine-generators [107].

5.2. Mitigation of electromechanical related resonance (Type-2 and Type-3)

Type-2 and Type-3 resonances occur mainly in the low-frequency range of approximately 0.1–2.5 Hz and are mitigated primarily through damping enhancement or modal detuning. The selected control channel should provide appropriate gain and phase characteristics around the target mode, while parameter tuning should avoid moving neighboring electromechanical and control modes toward stronger resonance. For conventional electromechanical oscillations, power system stabilizers (PSSs) remain the most widely used and effective measure, providing supplementary damping to poorly damped local, intra-area, and inter-area modes through the excitation system [49]. Resonance-oriented studies, however, show that PSS tuning cannot be treated as a simple gain-increasing problem: when an electromechanical mode approaches an excitation- or controller-related mode, excessive PSS gain may drive the system toward near-strong modal resonance, where the beneficial damping of the PSS is weakened or even reversed [50]. Recent work, therefore, emphasizes resonance-aware PSS placement and coordinated parameter tuning, in which the effectiveness of a stabilizer depends not only on the participation of its generator in the target mode but also on whether it shifts the interacting modes in a favorable direction, so that an improperly located stabilizer may deteriorate the very mode it is intended to damp [50]. The same concern extends to the supplementary controllers embedded in FACTS and HVDC devices, whose parameters should be coordinated with modal-resonance analysis to avoid altering the electromechanical-to-controller mode interaction unfavorably [51,76]. With the growing penetration of converter-interfaced generation, this coordination has extended from synchronous-machine stabilizers to converter-control parameters: for PMSG-based full-converter wind generation, modal-shift sensitivity and resonance-excitation indices can guide the tuning of PLL and grid-side-converter parameters so as to avoid detrimental modal interaction and enhance resonance-mode damping [56], whereas for VSG-based resources the virtual inertia and damping are selected to keep the VSG modes away from the system electromechanical modes, yielding a prohibited-region-based parameter-design strategy [55]. A further difficulty is that the interacting modes migrate as the operating scenario changes, so a parameter set detuned for one scenario may become resonant in another. The resonance-area formulation confronts this explicitly by mapping the regions of the complex plane that the open-loop modes of the two subsystems of Section 4.1.2 may occupy over a set of anticipated scenarios, and then selecting converter parameters that keep those regions apart [97]. Its data-driven successors remove the need to rebuild the small-signal model for every scenario: a deep extreme learning machine predicts the modes of both subsystems from future scenario information and, when the predicted modes satisfy the resonance condition, supports preventive optimization of the phase-locked-loop parameters before an oscillation event occurs [94]; a generalized regression neural network instead predicts the resonance-area boundaries directly, with reported parameter choices approaching those obtained from the exact model [98]. The lever exercised here remains the classical one, detuning by parameter coordination; the learned predictor contributes the speed required to apply it preventively across a scenario set that repeated model-based evaluation could not cover online.

5.3. Mitigation of electrical-control resonance (Type-4)

Type-4 resonance arises from the interaction between converter controls and the external electrical network and can occur from the subsynchronous to the medium- and high-frequency ranges. Its mitigation is therefore discussed separately for subsynchronous control interaction and medium- or high-frequency converter-network resonance, which differ substantially in actuator bandwidth, frequency selectivity, and robustness requirements.

5.3.1. Subsynchronous control interaction

For DFIG- and PMSG-based renewable systems, SSCI can first be mitigated by retuning sensitive converter parameters and coordinating broader controllable parameters within an explicit multi-parameter SSR stability region [108–110], or, for direct-drive PMSG systems, by embedding a band-pass supplementary damping loop in the PLL and retuning its gain online according to the operating condition [111]. When fixed-gain retuning is insufficient, or robustness across a wide operating range is required, model-based nonlinear control offers a more powerful alternative. Sliding-mode control of the rotor-side converter collapses the problematic rotor dynamics and constrains the rotor currents to their references while preserving decoupled active- and reactive-power control [112]; an adaptive sigmoid-modulated terminal sliding-mode scheme extends this idea by coordinating the rotor- and grid-side converters through an adaptive damping-participation factor, ensuring finite-time convergence while suppressing chattering [113]; and an energy-shaping controller, formulated on a port-controlled Hamiltonian model with an L_2 -gain disturbance-attenuation design, preserves the system nonlinearity and provides wide-range SSCI damping that is robust to parameter uncertainty and external disturbances [114]. The same interaction can also be addressed from the impedance perspective: active-damping or virtual-impedance control reshapes the converter output impedance to remove its adverse interaction with the series-compensated network [115], while STATCOM/BESS-based grid-stiffness enhancement reduces the equivalent grid-impedance seen by the wind farm and suppresses impedance-interaction SSR without relying on the accurate detection of a specific subsynchronous frequency [116]. Although this subsection focuses on DFIG- and PMSG-based SSCI, related SVG/STATCOM-based mitigation has also been reported for wind-farm-related subsynchronous resonance and oscillation. For induction-generator-based wind farms radially connected to series-compensated lines, corresponding to the classical IGE limiting case noted in Section 3.4, a dedicated STATCOM damping algorithm can mitigate resonance caused by both the induction-generator effect and torsional interactions while simultaneously damping power-system oscillations [117]. Even under conventional terminal-voltage control, without a supplementary damping loop, a STATCOM can improve the damping of induction-generator-effect resonance at practical compensation levels, as demonstrated by eigenvalue analysis and electromagnetic-transient validation [118]. For the DFIG-based SSCI considered here, model-free adaptive STATCOM control can replace the model-based subsynchronous damping controller with a data-driven law identified from online input–output measurements, so that the mitigation performance is maintained when the oscillation characteristics vary with the operating condition [119]. It should be noted, however, that the SVG/STATCOM is itself a converter-interfaced device whose control loops add modes of their own to the Type-4 mode population. Therefore, its damping contribution still requires proper coordination of control parameters, as emphasized above.

The recurring difficulty in this band is that the interaction frequency and damping migrate with wind speed, compensation level, and grid strength, so a fixed-gain damping controller tuned for one condition may lose effectiveness in another. Data-driven control addresses this variability without repeatedly re-deriving the physical model. Beyond the model-free adaptive law noted above [119], Koopman-operator lifting constructs a data-driven linear predictor of the converter-network dynamics in an enlarged observable space and supports model-predictive damping control, with lifted-model participation information used to select effective control channels [120]. Deep reinforcement learning has also been used to formulate the supplementary damping controller as a Markov decision process: deviations in active and reactive power and rotor d - and q -axis currents form the state, the actions are additional d - and q -axis voltage damping signals injected into the rotor-side converter, and the reward combines a damping-ratio objective with sensitivity-based electrical terms [121]. The agent is trained offline

over multiple operating conditions and deployed online, while transfer-learning-based source localization selects the controller location in multi-wind-farm cases. Their common price is the absence of an *a priori* stability certificate over a continuous operating region: the resulting controllers are validated over sampled scenarios, so a model-based check of the retained stability margin remains advisable at the design stage.

5.3.2. Medium- and high-frequency resonance

In the higher frequency range, mitigation relies mainly on fast converter-side impedance reshaping or frequency-selective damping. Voltage feedforward and control delay may create a non-passive negative-resistance band, so the relevant measurement and control paths must cover the critical frequency and account for digital delay and frequency coupling. The most direct countermeasure inserts a low-pass filter in the voltage feedforward path to narrow this negative-resistance band and remove the negative damping [25]. Because such a filter improves the high-frequency impedance only at the expense of the mid-frequency band, a more complete impedance-reshaping strategy instead combines a nonlinear feedforward filter with an additional current-loop damping controller, reshaping the converter impedance across the whole band while accounting for its frequency coupling [66]. Because the resonance point migrates by hundreds of hertz with grid topology and strength, an adaptive notch-filter scheme estimates the prevailing resonant frequency online and retunes notch filters in the feedforward loops, adding damping at the captured mode without affecting other frequencies [122]. Finally, narrowband damping injects positive damping only within a narrow band centered on the resonant frequency, avoiding the new negative-damping regions a broadband filter tends to create, and can be replicated as several tuned dampers to suppress multiple simultaneous resonances [123]. Every one of these measures presupposes knowledge of where the negative-damping band lies, which is precisely what moves with grid conditions; the adaptive notch scheme addresses this by estimating the resonant frequency online [122]. The same need motivates learned impedance models. A neural network mapping operating conditions to the converter terminal impedance, with the converter physics embedded in its structure to keep the data requirement and the online burden low, can refresh the impedance model on which a reshaping design depends as the operating point moves [95], and the admissible region of control parameters can likewise be estimated by a learned surrogate instead of by repeated impedance evaluation [99]. Here the data-driven element supplies the model for an unchanged impedance-reshaping lever, which is the identification role described in Section 4.6.1.

6. Future research directions

Building on the mechanism-based framework developed in this review, several theoretical and practical issues remain to be addressed before resonance-stability analysis and mitigation can be applied systematically to large-scale renewable-dominated power systems.

6.1. Classification-aware analysis of coupled resonances

The proposed four-type classification uses the dominant participating modal pair as its organizing principle. In practical systems, however, several modal pairs and subsystems may interact simultaneously, and an observed oscillation may therefore exhibit the characteristics of more than one resonance type. For example, a converter-grid electrical interaction may excite nearby torsional or electromechanical modes, while several converter control loops may participate in the same network resonance. Existing methods commonly isolate one dominant mechanism or divide the system into only two interacting subsystems. Future research should extend modal-interaction analysis to multi-subsystem configurations, develop quantitative indices for evaluating coupling strength among different resonance types, and establish criteria for determining when a reduced single-mechanism model remains adequate and when a coupled multi-timescale representation is necessary.

Table 3

Representative mitigation strategies by resonance type, frequency band, and implementation route.

Resonance type and typical frequency band	Control-side modification of existing assets	Additional device- or network-side intervention	Band-specific acting principle and design requirement	Refs.
Type-1: torsional SSR Subsynchronous, centered on shaft torsional modes	Supplementary subsynchronous damping control on an existing SSSC or UPFC; controlled subsynchronous or supersynchronous current injection; PV-STATCOM operation of an existing solar farm	Installation of a series- or shunt-connected FACTS device or another dedicated damping resource	Suppress harmful subsynchronous currents, inject positive damping torque, or detune the electrical resonance. Damping should target the identified shaft modes while avoiding adverse effects on neighboring torsional modes.	[102–107]
Type-2 and Type-3 Low frequency, typically 0.1–2.5 Hz	Resonance-aware PSS placement and tuning; supplementary control of existing FACTS or HVDC systems; PLL and grid-side-converter parameter coordination; virtual-inertia and virtual-damping coordination; scenario-aware or data-assisted modal detuning	Addition of a suitably located FACTS device or another controllable damping resource when existing actuators provide insufficient modal controllability	Inject damping and separate neighboring electromechanical and control modes. Control gains and phase characteristics should cover the target low-frequency mode without shifting neighboring modes toward stronger resonance.	[49–51,55,56,76,94,97,98]
Type-4: SSCI and related converter-network interaction Subsynchronous, below the fundamental frequency	Converter-gain retuning and stability-region coordination; PLL-based supplementary damping; nonlinear control; active damping and virtual impedance; model-free adaptive STATCOM control; Koopman-based or reinforcement-learning-based damping control	Installation of a STATCOM, BESS, or another grid-stiffening resource; adjustment of the series-compensation level or grid reinforcement	Reshape converter or network impedance, inject damping, or detune the interacting dynamics. Because the critical frequency may migrate with the operating condition, robust or adaptive designs are preferable to fixed-frequency tuning alone.	[108–121]
Type-4: medium- and high-frequency converter-network resonance Hundreds of hertz to the kilohertz range	Voltage-feedforward modification; nonlinear or current-loop impedance reshaping; adaptive notch filtering; narrowband damping; learned-impedance-assisted controller retuning	Not emphasized in the reviewed studies; mitigation is implemented mainly through the controls of existing converters	Remove the non-passive or negative-resistance band and inject damping around the critical resonance frequency. Measurement and control bandwidths must cover the target band, while digital delay and frequency coupling should be considered.	[25,66,95,99,122,123]

6.2. Operating-condition-dependent and probabilistic resonance assessment

Converter-related modes are strongly influenced by controller parameters and may migrate with generation dispatch, network topology, grid strength, converter operating mode, and the connection or disconnection of individual devices. Resonance risk is therefore inherently dependent on operating conditions and cannot always be represented adequately by a limited number of deterministic scenarios. Future work should develop efficient screening and scenario-reduction techniques for large sets of operating conditions, together with probabilistic or risk-based resonance indices for system planning under renewable-generation uncertainty. Online tracking of resonance frequency, damping, and modal participation also deserves further investigation. The coordinated use of wide-area phasor measurements, high-resolution point-on-wave measurements, and converter-terminal data may support early warning and source localization before poorly damped interactions develop into sustained oscillations.

6.3. Data-driven and physics-informed methods

Section 4.6 and the mitigation applications distributed through Section 5 indicate the scope of what such methods already provide: identification of oscillation modes and terminal impedances from measurements, prediction of resonance conditions across operating scenarios, source localization, and adaptive damping control. Their broader application to resonance stability, however, remains restricted by the scarcity of labeled data from rare instability events, changes in data distributions across operating conditions and systems, limited interpretability, and the lack of verifiable stability guarantees. Physics-informed and hybrid model-data methods provide a promising direction by incorporating network equations, modal structures, impedance constraints, passivity properties, or known controller dynamics into the

learning process. Further research is needed on uncertainty quantification, transferability between different systems, explainable source localization, benchmark datasets, and the certification of learning-based mitigation strategies outside the operating conditions represented in the training data.

6.4. Coordinated, adaptive, and certifiable mitigation

Resonance is a property of the interconnected system rather than of a single device. Consequently, mitigation implemented locally in one converter may be insufficient, may shift the instability to another frequency range, or may introduce new interactions with neighboring controllers and damping devices. Future mitigation should therefore coordinate renewable-energy converters, flexible alternating-current transmission devices, energy-storage systems, and high-voltage direct-current links across multiple vendors and control layers. Adaptive or online retuning is also needed to track changes in critical modal frequency, damping, and participation as operating conditions evolve. Beyond achieving satisfactory damping at a single operating point, future designs should provide robust stability margins over prescribed ranges of grid strength, topology, and device composition. These developments should be accompanied by resonance-oriented requirements in grid codes and connection studies, including standardized impedance or passivity specifications at the point of connection and dedicated mitigation concepts for grid-forming converters and systems approaching fully converter-based operation.

Progress in these directions would help move resonance-stability research from offline and case-specific studies toward online, system-level, and verifiable assessment and mitigation for future renewable-dominated power systems.

7. Conclusion

This paper has revisited resonance stability in renewable-dominated power systems from a unified, mechanism-oriented perspective. Resonance phenomena across different frequency ranges were interpreted as manifestations of strong dynamic coupling and energy exchange among mechanical, electrical, electromechanical, and control modes. On the basis of the dominant participating modal pair, a four-type classification was established to place classical torsional resonance, electromechanical modal resonance, electromechanical-control interaction, and converter-network resonance within a common framework. The principal analysis methods were then compared according to their modeling foundations, information requirements, and intended analytical purposes, while mitigation strategies were organized around three common principles: damping injection, impedance reshaping, and modal detuning. The review shows that no single analytical or control method is universally applicable; method selection and mitigation design should instead be matched to the participating modes, available model or measurement information, frequency range, and system scale. For practical application, this framework can be condensed into three steps: classify the dominant interacting modal pair to identify the resonance type; select the analysis method according to the available information and what the analysis is intended to reveal; and apply the mechanism-matched mitigation lever of damping injection, impedance reshaping, or modal detuning. Together, the proposed classification, method-selection framework, mitigation mapping, and research agenda provide a coherent basis for interpreting resonance mechanisms and guiding future resonance-stability studies in increasingly converter-dominated power systems.

CRedit authorship contribution statement

Hao Xu: Writing – original draft, Visualization, Investigation, Formal analysis, Conceptualization. **Robert Dimitrovski:** Writing – review & editing, Project administration. **Aleksandra Lekić:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

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Data availability

No data was used for the research described in the article.

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