Small-Signal Stability Analysis of Grid-Connected Equipment in Renewable Energy Power Systems (II): Derivation Mechanism and Stability Classification

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Abstract

The first part of this paper proposes qualitative principles and quantitative evaluation metrics for assessing the adaptability of stability analysis methods/criteria from three perspectives: stability equivalence, nominality, and robustness. The second part further examines typical equipment including synchronous machines, converters, and doubly-fed induction generator (DFIG) units to analyze the applicability of existing stability criteria and the validity of their corresponding physical interpretations of instability, and explores classification methods for stability issues from the perspective of dominant output variables. First, the proposed evaluation metrics are employed to validate the reasonableness of existing stability analysis methods and physical interpretations for low-frequency oscillations of synchronous machines and subsynchronous oscillations/resonance. Second, these metrics are utilized to analyze oscillation problems in converters and DFIG units, investigating their applicable stability criteria, underlying mechanisms, and dominant output variables. Finally, a novel classification approach for equipment stability is proposed based on physical mechanisms and dominant output variables, which from a vector perspective categorizes equipment stability into three types: angle-dominant synchronous stability, amplitude-dominant voltage stability, and electrical resonance arising from their special combination. Additionally, the paper discusses concepts such as wide-band oscillations, the relationship between equipment stability and system stability, and the extensibility of the stability classification.

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Small-Signal Stability Analysis of Grid-Connected Equipment in Renewable Energy Power Systems (Part II): Discussion on Mechanism Derivation and Stability Classification

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Abstract

From the perspectives of stability equivalence, nominal performance, and robustness, Part I of this paper proposed qualitative principles and quantitative evaluation indices for the adaptability of stability analysis methods/criteria. Part II further examines typical equipment such as synchronous machines, converters, and doubly-fed induction generators (DFIGs) to analyze the applicability of existing stability criteria and the physical interpretation of instability corresponding to suitable criteria. Firstly, using the proposed evaluation index, the rationality of existing stability analysis methods and physical interpretations for low-frequency oscillation and subsynchronous oscillation/resonance (SSO/SSR) of synchronous machines is verified. Secondly, the proposed evaluation index is applied to analyze oscillations in converters and DFIGs, and the suitable stability criteria, derivation mechanisms, and dominant output variables are further discussed. Finally, a novel concept for equipment stability classification based on physical mechanisms and dominant output variables is proposed, which categorizes equipment stability from the vector perspective into three types: phase-dominated synchronization stability, amplitude-dominated voltage stability, and electrical resonance formed by their special combination. Issues such as the concept of wide-band oscillation, the distinction between equipment stability and system stability, and the extensibility of their classification are further explored.

Keywords: synchronous machine; converter; doubly-fed induction generator; stability mechanism; stability classification

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1 Selection of Equipment Stability Criteria and Mechanism Derivation Process

A series of new instability phenomena have emerged in renewable energy power systems, characterized by large time-scale spans and complex stability mechanisms. Understanding these stability mechanisms is critical for ensuring safe and stable operation. The research in Part I of this paper indicates that different stability criteria adopt different physical perspectives, resulting in varying applicability to stability problems. Although multiple criteria can correctly determine system stability, only by selecting an appropriate perspective/criterion can the stability mechanism be clarified and the key factors determining system stability be identified, thereby enabling targeted control measures. Based on in-depth understanding of physical mechanisms, stability issues in conventional power systems have been traditionally classified into three categories: angle, voltage, and frequency stability. For example, synchronous machine rotor swing issues belong to angle stability, and based on this physical mechanism, the damping torque method has been identified as an effective approach for analyzing and solving such problems.

However, for the various new stability issues emerging in renewable energy power systems, the academic community has not yet reached a unified, widely accepted conclusion regarding their mechanisms. Existing classifications are often based on time-domain morphology or time scales. Differences in understanding stability mechanisms have also led to diverse control measures. Taking converter oscillation issues as an example: Reference [7] proposes an oscillation suppression scheme based on the equivalent impedance criterion by adding virtual positive resistance; Reference [8] proposes an instability mitigation method based on the sequence impedance criterion by increasing admittance; yet Reference [9] finds that increasing the real part of converter admittance can sometimes deteriorate system stability, leading to a proposal for admittance "shaping" based on modal power. Since these references adopt different system observation perspectives, the identified critical links causing instability and the physical mechanisms differ, resulting in varying effectiveness and applicability of the proposed instability/oscillation control measures. In fact, only by correctly identifying the key variables and instability mechanisms dominating the stability problem can effective control solutions be found.

Therefore, Part II of this paper applies the stability criteria/mechanism models and their evaluation methods to single-machine infinite-bus systems for typical equipment such as synchronous machines, converters, and DFIGs. For specific stability issues of each equipment type, the paper explores suitable stability criteria and their physical interpretations. Furthermore, by extending conventional power system models from phasor-based to vector-based representations, the paper investigates the common instability characteristics and derivation mechanisms of equipment such as synchronous machines, converters, and DFIGs in renewable energy power systems, and discusses vector stability classification methods from the perspective of dominant output variables and derivation mechanisms.

The specific organization is as follows: First, based on the evaluation methods proposed in Part I, the paper assesses the applicability of criteria and derives equipment instability mechanisms. The process is divided into two main steps: determining the stability criterion set and analyzing the applicability of stability criteria along with mechanism derivation.

1.1 Determination of Stability Criterion Set

The process of forming a criterion set consists of two steps: 1) Establish the mathematical model of the equipment and divide the main physical or control components according to the equipment' s physical and control characteristics; 2) Treat each physical or control component as the dominant link, eliminate other irrelevant variables, and form corresponding criteria.

Figure 1 illustrates the approach for selecting stability criteria based on physical meaning. The equipment is an n-input n-output system containing loop 1 from input u_1 to output y_1, ···, loop i from input u_i to output y_i, ···, and loop n from input u_n to output y_n. If the physical meaning of loop i is clear, retaining the stability criterion formed by u_i/y_i can serve as an alternative criterion in the criterion set.

It should be noted that criteria with similar physical meanings have similar applicable scopes and corresponding mechanism essences. For example, for converter synchronization issues, there are synchronization loop criteria focusing on PLL output state θ_{pll} [11], generalized impedance criteria focusing on port voltage/current phase angle [9], and generalized torque coefficient criteria focusing on electrical inertia [12], etc. They reflect consistent physical mechanisms, with the difference being that some criteria select state variables as outputs while others select related output variables. This paper does not further distinguish between criteria with similar physical essences.

1.2 Applicability Analysis of Stability Criteria and Mechanism Derivation

Focusing on single-equipment infinite-bus systems, where stability issues and mechanisms are dominated by the dynamic characteristics of a single piece of equipment, this paper refers to them as equipment stability issues for convenience, and discusses the distinction and connection between equipment stability and system stability in Section 6.

Since different stability criteria are proposed based on different mechanism understandings, instability mechanism interpretations correspond one-to-one with criteria, as shown in Figure 2(a). If the selected stability criterion and analysis method are appropriate, the underlying mechanism understanding should also be reasonable, and the derived dominant output variables, derivation mechanisms, and main influencing factors of instability should be reasonable as well.

Therefore, based on applicability analysis of criteria, one can trace back or verify whether the understanding of instability mechanisms is reasonable, and further derive critical links and dominant output variables for instability, facilitating stability control.

The process of deriving equipment stability mechanisms and classification includes: 1) Select appropriate stability criteria based on whether each criterion in the criterion set satisfies the principles of stability equivalence, nominal performance, and robustness (discussed in detail in Part I); 2) Obtain the dominant output variables that determine instability, and combine them with equipment physical characteristics to derive the mechanism interpretation of instability, i.e., the derivation mechanism, and perform stability classification based on dominant output variables.

In summary, Figure 2(b) presents the flowchart for equipment stability criterion selection and mechanism derivation. For equipment with clear mechanisms like synchronous machines, the above process can verify the rationality of conventional stability mechanism understanding. For equipment with unclear mechanisms like converters, it can derive instability mechanism interpretations.

2 Synchronous Machine Stability Analysis

2.1 Stability Criterion Set for Synchronous Machine Oscillations

2.1.1 Stability Criterion Set for Low-Frequency Oscillation of Synchronous Machines The analysis model for low-frequency oscillation of a synchronous machine infinite-bus system is shown in Figure 3. The system has multiple input-output variables: $\Delta\omega$, $\Delta\delta$, ΔE_f, ΔP_e, and ΔU_t. At the electromechanical time scale, it mainly includes rotor and electromagnetic (including excitation) components, with the former dominating the phase-angle characteristics and the latter dominating the terminal voltage characteristics.

1) Damping Torque Method

The classical analysis method for synchronous machine low-frequency oscillation is the damping torque method that extracts rotor dynamics [6,13]. It obtains an equivalent model by retaining $\Delta\delta$ and ΔP_e (the blue part in Figure 3 as the dominant loop), essentially preserving phase-angle synchronization characteristics. The corresponding characteristic equation is:

$$1 + L_D(s) = 0 \tag{1}$$

where the open-loop transfer function $L_D(s) = G_D(s)H_D(s)$ is expressed as:

$$\begin{cases} G_D(s) = \frac{k_2}{D+k_1G_3(s)} \\ H_D(s) = \frac{k_3k_4G_E(s)+k_5k_6}{1+k_3G_E(s)} \end{cases} \tag{2}$$

where $G_3(s) = \frac{k_3}{k_3 s+1}$; $G_E(s) = \frac{k_E}{T_E s+1}$ is the excitation transfer function. Variable definitions can be found in reference [13]. It is worth noting that applying the Nyquist criterion to the open-loop transfer function in the characteristic equation (1) yields stability criteria for the equivalent system, which are consistent with the damping criteria of the damping torque method under weak damping conditions.

2) Excitation-Dominated Stability Criterion
When retaining excitation input/output ($\Delta U_t/\Delta E_f$) and using the shaded part in Figure 3 as the dominant loop, the corresponding characteristic equation is:

$$1 + L_E(s) = 0 \tag{3}$$

where the open-loop transfer function $L_E(s) = G_E(s)H_E(s)$ is expressed as:

$$\begin{cases} G_E(s) = \frac{k_E}{T_E s+1} \\ H_E(s) = \frac{k_3 k_4 + k_5 k_6 G_D(s)}{1+k_3 G_D(s)} \end{cases} \tag{4}$$

Equations (1) and (3) are the characteristic equations dominated by rotor dynamics and excitation loop, respectively, forming the criterion set for synchronous machine low-frequency oscillation.

2.1.2 Stability Criterion Set for Subsynchronous Oscillation of Synchronous Machines Subsynchronous oscillation (SSO) issues include subsynchronous resonance (SSR) and device-induced SSO. SSR typically includes three manifestations [13]: induction generator effect, torsional interaction, and transient torque amplification.

Subsynchronous oscillation involves generator rotor shaft dynamics and circuit dynamics considering series compensation at the electromagnetic transient time scale. The state variables are [13]: $\Delta\omega$, $\Delta\delta$, ΔE_f, $\Delta\Phi$, $\Delta U_{C,dq}$. Classical frequency-domain methods include the complex torque coefficient method and equivalent impedance analysis method [13], corresponding to stability criteria formed by focusing on the synchronous machine shaft system and equivalent circuit model. To demonstrate the completeness of the criterion set, this paper supplements an excitation-dominated criterion for comparative analysis.

1) Complex Torque Coefficient Method
For shaft-dominated subsynchronous oscillation of synchronous machines, the classical analysis method is the complex torque coefficient method [13]. Let the i-th torsional mode s_i be the weakly damped oscillation mode being excited. When the synchronous machine electrical rotor angle $\Delta\delta_k$ oscillates at mode $s_0 = \sigma_0 + j\omega_0$ close to torsional mode s_i, the i-th shaft loop dominates the dynamic characteristics, and its characteristic equation is:

$$1 + L_\delta(s) = 0 \tag{5}$$

where $L_\delta(s) = G_e(s)G_m(s)$ is the system open-loop transfer function, as referenced in [14]. Reference [14] further points out that the complex torque coefficient method is equivalent to the Nyquist-based criterion.

This equivalent model describes the voltage phase-angle dynamics of the system shaft system, belonging to a shaft-dominated equivalent model.

2) Equivalent Impedance Analysis Method
For series-compensation-dominated subsynchronous oscillation, analysis is typically based on equivalent circuits [13], as shown in Figure 4(a). According to [13], when the grid resonance subsynchronous frequency ω_{er} is lower than the rotor frequency ω_0, the synchronous machine exhibits an "induction generator effect" with "negative resistance" characteristics, leading to sustained oscillations. Based on the system resonance impedance condition $Z_l(s) + Z_{SG}(s) = 0$, the system characteristic equation is:

$$1 + \frac{Z_l(s)}{Z_{SG}(s)} = 0 \tag{6}$$

The equivalent circuit model' s transfer function model can be represented by Figure 4(b). This model describes the impedance resonance of the synchronous machine equivalent circuit.

3) Excitation-Dominated Stability Criterion
Based on the synchronous machine electromagnetic transient model, retaining excitation system input/output $(\Delta U_t/\Delta E_f)$ yields an equivalent model reflecting terminal voltage characteristics at the electromagnetic transient scale. Its characteristic equation is:

$$1 + L_{EE}(s) = 0 \tag{7}$$

where $L_{EE}(s)$ is the open-loop transfer function, with derivation provided in Appendix A.

Equations (5), (6), and (8) are the characteristic equations with rotor shaft system, equivalent circuit, and excitation as dominant loops, respectively, forming the complete criterion set.

2.2 Applicability Analysis and Mechanism Derivation for Synchronous Machine Criteria

2.2.1 Applicability Analysis and Mechanism Derivation for Low-Frequency Oscillation Criteria Based on the single-machine infinite-bus system parameters in Appendix Table B1, the damping torque method and excitation-dominated criterion for synchronous machine low-frequency oscillation from Section 2.1.1 are compared and evaluated, with results shown in Table 1.

Table 1. Adaptation Analysis of Two Stability Criteria for Low-Frequency Oscillation

Applicability Evaluation	Damping Torque Method	Excitation-Dominated Criterion
Loop Gain Sensitivity	$4.503\angle 124.2°$	$14038.9\angle 134.7°$
Stability Equivalence Principle	Satisfied	Satisfied
Nominal Performance Principle	Satisfied	Satisfied
Robustness Principle	Better robustness	Poor robustness

According to Table 1, both criteria satisfy the stability equivalence and nominal performance principles. However, the damping torque method has a smaller loop gain sensitivity magnitude and better robustness, making it more suitable for explaining the low-frequency oscillation mechanism. The damping torque method extracts the torque-angle dynamic relationship, describing power-angle synchronization characteristics. Therefore, the dominant output variable for low-frequency oscillation is the power angle (which can also be viewed as the internal voltage phase angle). This conclusion is consistent with conventional understanding of low-frequency oscillation mechanisms and also verifies the rationality of the proposed applicability analysis and mechanism derivation method.

2.2.2 Applicability Analysis and Mechanism Derivation for Subsynchronous Oscillation Criteria Based on the parameters in Appendix B Table B2, the three SSO/SSR analysis methods—complex torque coefficient method, equivalent circuit method, and excitation-dominated criterion—are compared and evaluated for synchronous machines, with results shown in Table 2.

Table 2. Adaptation Analysis of Three Stability Criteria for Subsynchronous Oscillation

Oscillation Mode s_0	Applicability Evaluation	Complex Torque Coefficient	Equivalent Impedance	Excitation Criterion
$-0.05 \pm j65.76$ (shaft-dominated)	Loop Gain Sensitivity	$0.101\angle 174.9°$	$1.382\angle 126.0°$	$0.313\angle 131.6°$

Oscillation Mode s_0	Applicability Evaluation	Complex Torque Coefficient	Equivalent Impedance	Excitation Criterion
	Stability Equivalence Principle	Satisfied	Satisfied	Satisfied
	Nominal Performance Principle	Satisfied	Satisfied	Satisfied
	Robustness Principle	Better robustness	Moderate robustness	Poor robustness
$-0.03 \pm j107.59$ (compensation-dominated)	Loop Gain Sensitivity	$0.138\angle 147.7°$	$0.037\angle 104.3°$	$0.037\angle 121.2°$
	Stability Equivalence Principle	Satisfied	Satisfied	Satisfied
	Nominal Performance Principle	Satisfied	Satisfied	Satisfied
	Robustness Principle	Moderate robustness	Better robustness	Poor robustness

For shaft-dominated oscillation, all three criteria satisfy the stability equivalence and nominal performance principles. However, the complex torque coefficient method has a smaller loop gain sensitivity magnitude and better robustness, making it more suitable for analyzing and explaining such oscillations. This criterion retains shaft rotor angle variables, describing generator shaft system dynamics. Its derivation mechanism is: phase-angle swing and torsional vibration of shaft system mass blocks cause generator terminal voltage phase-angle oscillation, degrading system synchronization characteristics. The dominant output variable is voltage phase angle, which aligns with conventional mechanism understanding.

For series-compensation-induced oscillation, all three criteria satisfy the stability equivalence and nominal performance principles. However, the equivalent circuit method has a smaller loop gain sensitivity magnitude and better robustness, making it more suitable for this mode. Based on equivalent impedance analysis and its physical meaning, the instability mechanism can be explained by circuit impedance resonance: the synchronous machine exhibits negative equivalent resistance in the subsynchronous frequency band, causing system non-power-frequency resonance/oscillation. The dominant output variable is the voltage vector as a whole $\Delta(Ue^{j\delta})$. This oscillation mechanism is also consistent with conventional understanding of compensation-dominated SSR [14-15], where "negative resistance" from the induction generator effect in the subsynchronous band causes system instability.

In summary, the applicable criteria and derivation mechanisms for synchronous machine SSO/SSR are summarized in Table 4, with corresponding oscillation modes detailed in Section 5.1. It is worth noting that shaft-dominated SSO caused by other equipment has been studied, showing that the complex torque coefficient method is also applicable with mechanisms similar to shaft torsional vibration. The method proposed in this paper can also demonstrate this, but is omitted here due to space limitations. Additionally, synchronous machine SSR mechanisms are related to series compensation degree. Shaft-dominated issues generally occur at low compensation degrees, while high compensation degrees or when external circuits exhibit significant capacitive effects near torsional complementary frequencies result in stability problems co-dominated by voltage phase angle and amplitude.

3 Converter Stability Criteria and Mechanism Derivation

3.1 Stability Criterion Set for Multi-Time-Scale Oscillation of Converters

Photovoltaic, direct-drive wind turbine, and flexible DC transmission systems can be modeled as grid-connected converter systems with multi-time-scale characteristics, exhibiting wide-frequency instability phenomena [3,4]. Based on converter control system division, three types of loops can be identified: outer-loop-dominated, PLL-dominated, and inner-loop/feedforward-dominated, generating three categories of criteria.

1) DC Voltage Stability Criterion (Outer-Loop-Dominated)
Analysis methods focusing on the outer loop include: methods retaining DC voltage dynamics [16]; inertia and damping criteria establishing relationships between internal voltage and power [17]. This paper collectively refers to similar criteria as DC voltage stability criteria.

2) Phase-Angle Stability Criterion (PLL-Dominated)
Criteria focusing on the PLL include: stability criteria extracting PLL-dominated loops [11]; generalized impedance criteria extracting phase-angle impedance; generalized torque coefficient criteria extracting electrical inertia [12]. This paper collectively refers to similar criteria as phase-angle stability criteria.

3) Sequence Impedance Criterion (Inner-Loop/Feedforward-Dominated)
Due to the negative resistance effect of converter inner loops/feedforward, criteria focusing on these components mainly refer to sequence impedance [18] or modified sequence impedance criteria [19] that take network physical characteristics as the starting point.

Detailed derivations and expressions of the above three stability criteria are provided in this paper.

3.2 Applicability Analysis and Mechanism Derivation for Converter Criteria

Based on the applicability analysis examples in Part I, converter stability issues can be divided into three categories:

1) Outer-Loop-Dominated Instability
Generally concentrated in the low/medium frequency band or zero-frequency band within the outer-loop bandwidth, including two instability forms: weakly damped low-frequency oscillation and voltage collapse [16]. The applicable criterion is the DC voltage stability criterion. The output variable is ΔU_{dc}. Combined with equipment characteristics, the derivation mechanism is: converter DC voltage oscillation or monotonic instability causes output power/AC current amplitude instability, leading to voltage instability [2,16]. The dominant variable is the state variable DC voltage, or from the system-side output variable perspective, AC current amplitude.

Additionally, conventional DC voltage instability has internal state variable DC current instability, externally manifested as system AC voltage instability. Asynchronous machine stalling causes internal state variable slip instability, with equivalent impedance dropping sharply, leading to voltage/current amplitude instability [20]. Both share similar instability characteristics with converter outer-loop-dominated instability and are not elaborated further here.

2) PLL-Dominated Oscillation
This instability manifests as sub/super-synchronous oscillations within the PLL bandwidth, commonly occurring in weak grid scenarios with low short-circuit ratios [16,21]. Phase-angle stability criteria are applicable in these frequency bands. The derivation mechanism is: phase-angle impedance resonance between converter and grid, with dominant output variable being current phase angle. Therefore, PLL instability can be suppressed by increasing grid strength or phase-angle damping [11], while increasing admittance real part is not necessarily effective [9]. Moreover, since power synchronization loops or virtual synchronous control are also synchronization control components, their instability characteristics are similar to PLL and belong to generalized synchronization stability issues [21-22]. References [21] and [23] refer to this type of stability problem as "virtual power angle" stability.

3) Inner-Loop/Feedforward-Dominated Oscillation
Inner loops, feedforward, or digital/sampling delay components are fast dynamic elements of converters. Their instability issues are concentrated in the medium/high frequency band outside the PLL bandwidth, where sequence impedance criteria are suitable. The derivation mechanism is: mismatch between converter equivalent sequence impedance and grid sequence impedance, where inner loops or feedforward exhibit "negative resistance" characteristics

in the medium/high frequency band, causing circuit resonance. The dominant output variable is the current vector. This conclusion is also consistent with existing research, where "negative resistance" effects from digital/sampling delay cause converter medium/high-frequency oscillations, which can be suppressed by adding equivalent positive resistance in the resonance band [24,25].

4 Stability Criteria and Mechanism Derivation for DFIGs

4.1 Stability Criterion Set for Subsynchronous Oscillation of DFIGs

DFIGs include rotor-side and grid-side converters. This section focuses on subsynchronous oscillation phenomena dominated by the rotor-side converter [26], while grid-side converter stability is similar to the converter grid-connected stability discussed in the previous section. Based on the physical and control characteristics of DFIGs in the subsynchronous band, two categories of stability criteria can be identified: PLL-dominated and inner-loop-dominated.

1) Phase-Angle Stability Criterion (PLL-Dominated)
PLL-dominated stability criteria mainly include generalized impedance criteria focusing on PLL and complex torque coefficient method [27], collectively referred to as phase-angle stability criteria. These criteria establish impedance models based on phase-angle dynamics, retaining PLL-dominated phase-angle loop dynamics. The characteristic equation is:

$$1 + L_{PLL}(s) = 0 \tag{9}$$

where L_{PLL} is the phase-angle open-loop transfer function, detailed in [27].

2) Sequence Impedance Stability Criterion (Inner-Loop-Dominated)
Inner-loop-dominated stability criteria mainly refer to sequence impedance criteria for DFIGs that focus on motor-external circuit resonance, considering positive/negative sequence coupling [26]. The characteristic equation is:

$$L_{p/p}(s) = 0 \tag{10}$$

where $L_{p/m}$ represents positive/negative sequence impedance criteria, detailed in [26].

4.2 Applicability Analysis and Mechanism Derivation for DFIG Criteria

DFIGs mainly exhibit two oscillation modes in the sub/super-synchronous band: 1) oscillations with high PLL participation; 2) oscillations from coupling between line series compensation capacitors and machine equivalent inductance (compensation-dominated).

Based on the DFIG grid-connected model system parameters shown in Appendix Table B3, the two criteria from Section 4.1 are compared and evaluated for both oscillation modes, with results shown in Table 3.

Table 3. Adaptation Analysis of Two Stability Criteria for DFIG

Oscillation Mode s_0	Applicability Evaluation	Phase-Angle Criterion	Sequence Impedance Criterion
$-13.17 \pm j54.07$ (PLL)	Loop Gain Sensitivity	$0.101\angle 174.9°$	$1.382\angle 126.0°$
	Stability Equivalence Principle	Satisfied	Satisfied
	Nominal Performance Principle	Satisfied	Satisfied
	Robustness Principle	Better robustness	Poor robustness
$-2.57 \pm j251.80$ (Compensation 1)	Loop Gain Sensitivity 1	$0.313\angle 131.6°$	$0.037\angle 104.3°$
$-8.57 \pm j375.17$ (Compensation 2)	Loop Gain Sensitivity 2	$0.138\angle 147.7°$	$0.037\angle 121.2°$
	Stability Equivalence Principle	Satisfied	Satisfied
	Nominal Performance Principle	Satisfied	Satisfied
	Robustness Principle	Poor robustness	Better robustness

Oscillations with high PLL participation generally manifest as sub/super-synchronous oscillations. In this case, both criteria satisfy the stability equivalence and nominal performance principles, but the phase-angle criterion has a smaller loop gain sensitivity magnitude and better robustness. Therefore, generalized impedance criteria or complex torque coefficient methods [27] are more applicable for PLL-induced oscillations. Both criteria are obtained by retaining phase-angle dynamics. The derivation mechanism is: insufficient phase-angle damping of DFIG leads to loss of synchronization with the system, with dominant output variable being current phase angle.

For compensation-dominated oscillations, the oscillations caused by series compensation capacitors are highly related to capacitor voltage and rotor or stator flux, generally manifesting as subsynchronous oscillations. In this case, both criteria satisfy the stability equivalence and nominal performance principles, but the sequence impedance criterion has a smaller loop gain sensitivity magnitude and better robustness. Based on sequence impedance analysis and its physical meaning, the instability mechanism of DFIGs in the subsynchronous band is: negative resistance in the equivalent sequence circuit causes instability [26], with dominant output variable being current vector sequence components. Virtual equivalent resistance can be introduced to suppress oscillations.

It is worth noting that after thoroughly understanding equipment stability mechanisms, equipment stability modeling, analysis, and control can be standardized and normalized, including: 1) Extracting key variables to establish mechanism models; 2) Deriving applicable criteria based on mechanism models; 3) Designing stability control methods targeting critical links and dominant variables. For example, for synchronous machine low-frequency oscillation analysis, first establish the Heffron-Phillips model describing the rotor torque-angle relationship; second, form the damping torque method; finally, propose power system stabilizer (PSS) installation as a control strategy. Table 4 summarizes the stability phenomena, mechanism interpretations, dominant output variables, and recommended criteria for power system equipment.

Table 4. Stability Phenomenon, Mechanism, and Criterion for Power System Equipment

Equipment	Stability Phenomenon	Mechanism Interpretation	Dominant Output Variable	Recommended Criterion
Synchronous Machine	Low-frequency oscillation	Insufficient damping torque causing generator angle swing relative to system	Voltage phase angle	Damping torque method
Synchronous Machine	Shaft-dominated SSO/SSR	Torsional vibration of shaft mass blocks causing internal voltage phase-angle oscillation	Voltage phase angle	Complex torque coefficient method

Equipment	Stability Phenomenon	Mechanism Interpretation	Dominant Output Variable	Recommended Criterion
Synchronous Machine + Series Compensation	Compensation-dominated SSO/SSR	Equivalent negative resistance in subsynchronous band causing circuit resonance	Voltage vector	Equivalent impedance analysis
Conventional DC	Voltage instability	Internal DC current instability causing AC voltage monotonic instability	Voltage amplitude	DC voltage criterion
Asynchronous Machine	Voltage instability	Slip instability causing voltage/current amplitude instability	Current amplitude	Equivalent impedance analysis
Converter	Outer-loop-dominated instability	DC voltage instability causing AC current amplitude instability	Current amplitude	DC voltage criterion
Converter	PLL-dominated oscillation	Phase-angle impedance resonance causing loss of synchronization	Current phase angle	Phase-angle stability criterion (generalized impedance)
Converter	Inner-loop/feedforward-dominated oscillation	Equivalent negative resistance in medium/high frequency causing circuit resonance	Current vector	Modified sequence impedance criterion

Equipment	Stability Phenomenon	Mechanism Interpretation	Dominant Output Variable	Recommended Criterion
DFIG + Series Compensation	Compensation-dominated oscillation	Equivalent negative resistance in subsynchronous band causing circuit resonance	Current vector	Modified sequence impedance criterion
DFIG	PLL-dominated oscillation	Insufficient phase-angle damping causing loss of synchronization	Current phase angle	Phase-angle stability criterion (generalized impedance)

5 Unified Vector-Based Stability Classification

5.1 Unified Vector-Based Modeling Analysis and Classification Approach

This section attempts to summarize and classify the equipment stability discussed in Table 4. Observing this table reveals that the stability mechanisms of typical equipment such as synchronous machines, converters, and DFIGs differ significantly, making it difficult to find common characteristics: 1) The variables involved in equipment derivation mechanisms include both phasors and vectors, making it difficult to find common features from the perspective of equipment electrical quantities; 2) The dominant links and other elements of equipment instability issues vary greatly, making it difficult to find common physical characteristics. Therefore, organizations such as IEEE currently treat stability issues caused by renewable energy equipment as a separate category, as shown in Figure 6(a) [1].

To address this problem, this paper extends the modeling objects in conventional power systems from phasor-based to instantaneous-value vector-based models, drawing on the space vector concept from electrical machine theory. The analysis results based on vectors can also be compatible with phasor-based analysis results [28]. Since both magnitude/phase of phasors and vectors can be represented by vector magnitude/angle in mathematics, the synchronous machine and renewable energy equipment models/stability issues in Table 4 can be unified as instantaneous-value vector models/stability issues. At this point, the physical and mathematical meanings of electrical quantity magnitude and phase angle are consistent, laying the modeling foundation for integrating conventional and renewable energy power system stability issues.

Based on vector models and analysis methods, the dynamic characteristics of each equipment can be described through electrical vectors, expressed as:

$$\mathbf{y}(t) = Y(t)e^{j[\omega_0 t+\varphi(t)]} \tag{11}$$

The unified vector modeling and analysis method overcomes the obstacle of inconsistent physical meanings of dominant variables across different equipment. Based on this, stability issues of equipment such as synchronous machines and renewable energy devices can all be analyzed from the electrical vector perspective. The dominant output variables in Table 4 can be considered as electrical vectors.

Combining Table 4, the dominant output variables and derivation mechanisms of common equipment such as synchronous machines, DFIGs, converters, and conventional DC can all be described in polar coordinates from the dimensions of magnitude-dominated, phase-angle-dominated, and vector-as-a-whole-dominated. That is, stability issues can be divided into three categories, hereafter referred to as voltage (magnitude) stability, synchronization (phase-angle) stability, and electrical resonance, respectively. Since these stability issues are described based on electrical vectors, they can be called vector stability.

Figure 5 shows the three typical directions of electrical vector $\mathbf{Y}(t)$ in polar coordinates: 1) magnitude direction (radial direction); 2) phase-angle direction (angular direction); 3) vector-as-a-whole change direction. To intuitively illustrate the characteristics of these vector stability types, Table 5 provides features of phase-angle oscillation, magnitude oscillation, and electrical resonance from the small-signal perspective. Magnitude and phase-angle oscillations can be understood as "periodic fluctuations" in the magnitude and phase of electrical vectors. Electrical resonance is special, understood as "periodic fluctuations" in both magnitude and phase simultaneously, with equal amplitudes and $\pi/2$ phase difference, with proof provided in Appendix C. Appendix C of Part I also presents typical time-domain simulation features of these three oscillation types.

Table 5. Vector Characteristics of Electrical Quantity Oscillation in Polar Coordinates

Oscillation Type	Vector Expression	Features
Phase-angle oscillation	$\mathbf{Y}_p(t) \approx Y_R e^{j[\omega_0 t+\varphi_0]} + j\alpha Y_R e^{j[\omega_0 t+\varphi_0]} e^{j\omega_R t}$	Phase-angle periodic fluctuation
Magnitude oscillation	$\mathbf{Y}_m(t) = Y_R[1+\alpha e^{j\omega_R t}]e^{j[\omega_0 t+\varphi_0]}$	Magnitude periodic fluctuation
Electrical resonance	$\mathbf{Y}_c(t) = Y_R e^{j[\omega_0 t+\varphi_0]} + \alpha Y_R e^{j[(\omega_0+\omega_R)t+\varphi_0]}$	Vector-as-a-whole oscillation

5.2 Vector Stability Classification Method Based on Dominant Output Variables

The stability mechanisms of synchronous machines and renewable energy equipment differ greatly, making it difficult to explain their physical commonalities from a mechanism perspective. Therefore, this paper draws on the formation approach of conventional power system voltage stability to unify various stability mechanisms from the perspective of dominant output variables and derivation mechanisms. The specific approach is as follows:

In conventional power system classification, voltage stability can be viewed as being summarized from the perspective of dominant output variables, unifying instability problems with different mechanisms. For example, AC voltage collapse induced by asynchronous machines and conventional DC are caused by different state variable instabilities, but both are ultimately magnitude-dominated and thus unified as voltage stability. The advantage is that equipment stability problems with different mechanisms can be classified together, and the means to improve such stability also have commonality.

Inspired by this, this paper extends this concept to stability classification of equipment such as synchronous machines and renewable energy devices, i.e., reclassifying various instability mechanisms physically based on dominant output variables. Instability can be interpreted as: equipment dominant state instability causing dominant output variable instability. For example, converter DC capacitor voltage state variable instability causing AC current amplitude instability, and asynchronous machine internal state-induced voltage amplitude instability, both have dominant output variables in the magnitude dimension of electrical quantities, thus can be unified as magnitude stability problems. Converter PLL-induced stability issues and synchronous machine synchronization instability have dominant output variables in the phase-angle dimension, thus can be unified as phase-angle stability problems. Circuit resonance-induced stability issues have dominant output variables as the non-power-frequency vector as a whole, with mechanisms explainable by equivalent circuits.

Furthermore, to maintain consistency with conventional power system stability classification terminology, stability problems with dominant output variables being electrical vector magnitude and phase angle are also referred to as voltage stability and synchronization stability, respectively. Stability problems dominated by the vector as a whole are called electrical resonance.

5.3 Equipment Vector Stability Classification Results

Based on the above classification approach using derivation mechanisms and dominant output variables, the stability issues of equipment such as synchronous machines, DFIGs, and converters in Table 4 are classified, resulting in the equipment vector stability classification shown in Figure 6(b), which is extended to system stability as shown in Figure 6(c) in Section 6. The main categories include:

1) Synchronization Stability (Phase-Angle Stability)
Refers to the stability of electrical quantity phase-angle components, reflecting equipment synchronization performance with the system. The dominant output variable is also the dominant state variable, such as synchronous machine power angle, virtual synchronous machine virtual power angle, etc., thus sometimes also called state synchronization stability. Additionally, synchronous machine shaft-dominated SSO/SSR and converter PLL instability are caused by internal state instabilities such as shaft rotor angle and PLL angle, which then excite output voltage/current phase-angle instability. Synchronization stability belongs to electrical quantity phase-angle-dominated stability in the vector stability spectrum, with included issues shown in Figure 6(d).

2) Voltage Stability (Magnitude Stability)
Refers to the stability of electrical vector magnitude components, reflecting the ability to maintain bus voltage. The instability cause is generally output voltage/current magnitude instability induced by internal state quantity instability [2,20], where AC current magnitude instability ultimately manifests as voltage magnitude instability. Therefore, they can also be considered voltage stability. For example, asynchronous machine slip, converter outer loop, conventional DC outer loop, and other component-dominated stability problems all have corresponding unstable internal states that lead to terminal output voltage/current magnitude instability. Voltage stability belongs to electrical quantity magnitude-dominated stability in the vector stability spectrum, with included issues shown in Figure 6(d).

3) Electrical Resonance
Refers to the stability of the electrical vector as a whole, reflecting equivalent circuit resonance characteristics. The instability cause is output voltage/current vector-as-a-whole-dominated stability induced by equipment (including network elements) state variables. In the vector stability spectrum, it belongs to electrical quantity vector-as-a-whole-dominated stability, with included issues shown in Figure 6(d).

It should be particularly noted that in IEEE' s 2020 new stability classification, the equivalent circuit resonance problem of series compensation capacitors and induction generator effect is classified as "electrical resonance" under resonance stability [1]. This paper borrows the term electrical resonance to refer to vector-as-a-whole-dominated stability problems because: electrical resonance includes stability problems caused by motors with series compensation, consistent with the problems discussed in this paper, where instability mechanisms are equivalent circuit negative resistance and dominant output variables are the vector as a whole. Based on this, this paper expands the connotation of this stability problem and further points out its characteristics: strong coupling exists between magnitude and phase of electrical vectors. When observed in polar coordinates and removing steady-state components, there exist oscillation components with equal amplitude but $\pi/2$ phase difference in both magnitude and phase. This is not a new stability problem—it also exists in conventional power systems, such as synchronous machine SSO caused by series compensation and LC resonance in electrical networks—but holds a non-negligible position in renewable energy power systems.

Based on the above discussion, comparing Figures 6(a) and 6(b) reveals that this paper retains some terms from IEEE stability classification and further clarifies and expands their meanings, enabling previously difficult-to-integrate stability problems such as converter-driven issues to be well incorporated into these stability types. After further considering frequency stability, the recommended stability classification for renewable energy power systems can be formed as shown in Figure 6(c), with extended content detailed in Section 6.

Figure 6. Stability Classification of Renewable Energy Power Systems

6 Further Discussion

1) Discussion 1: Classification of Wide-Band Oscillation Based on Mechanisms

Distinguishing stability issues through time-domain waveforms or oscillation frequency characteristics generally fails to reflect mechanisms. Even within the same frequency band, diverse equipment may experience different types of instability such as synchronization instability, voltage instability, and electrical resonance instability. For example, converter PLL-dominated oscillation and DFIG-plus-series-compensation-induced oscillation have similar oscillation frequencies but essentially belong to synchronization stability and electrical resonance, respectively.

This paper analyzes multi-time-scale oscillations of common equipment and finds that although their oscillation frequencies cover a wide range, they can still be classified according to their respective derivation mechanisms/dominant output variables. Furthermore, the industry and academia often refer to the wide frequency distribution of power electronic equipment oscillations as "wide-band oscillation" and consider it a new stability problem. This view is questionable and 不利于深入理解和解决该问题.

2) Discussion 2: Stability Classification Based on Dominant Output Variables

This paper's stability classification is based on dominant output variables. Power system equipment instability is generally caused by equipment state variable instability and is essentially determined by a certain dominant state variable. However, since state variable instability can generally be reflected in corresponding output variables [21], stability can be classified from the dominant output variable perspective.

In conventional power system stability classification, angle/synchronization stability is summarized from the state synchronization perspective, while voltage stability is summarized from the dominant output variable perspective. Voltage stability based on dominant output variables can encompass stability problems under various instability mechanisms. For example, AC voltage collapse induced by asynchronous machines and conventional DC are caused by different state variable instabilities but are ultimately magnitude-dominated, thus unified as voltage stability. To better organize and accommodate existing and future power system stability classifications, this paper extends this concept to define and classify synchronization stability and electrical resonance also from the dominant output variable perspective, thereby unifying diverse equipment stability problems.

3) Discussion 3: Small-Signal vs. Large-Disturbance Stability

Small-signal stability is derived from linearized models, but large-disturbance trajectories near hyperbolic equilibrium points are topologically homeomorphic to small-signal trajectories. Therefore, a small-signal instability generally corresponds to a large-disturbance instability. Consequently, the classification into synchronization, voltage, and electrical resonance is not limited to periodic oscillatory instability but can be extended to non-periodic monotonic instability. For example, voltage collapse dominated by converter outer loops can still be classified as magnitude stability. Furthermore, considering nonlinearity, large-disturbance instability mechanisms related to physical variables such as magnitude/phase should be included, requiring future research and discussion.

4) Discussion 4: Equipment Stability vs. System Stability

Although this paper focuses on stability characteristics of single-equipment grid-connected systems, the research results have important reference value for stability mechanisms and classification of multi-equipment systems. For example, based on the generalized short-circuit ratio derivation approach, stability modes of isomorphic multi-machine systems can be approximated as the union of multiple equivalent single-machine stability modes [29], establishing a one-to-one correspondence between single-machine and multi-machine stability problems and mechanisms. In this case, multi-machine system stability problems can also be classified with reference to equipment stability problems.

Second, equipment stability and system stability should sometimes be distinguished by impact. Although single-equipment or equipment group instability results from equipment-grid interaction, when equipment capacity is small or system impact is minor, the issue is still considered an equipment stability problem. For example, voltage fluctuations caused by small-capacity asynchronous machine stalling are excluded from system voltage stability. This is why this paper adopts the term "equipment stability." Conversely, when single-equipment instability has significant system impact, although instability is mainly determined by equipment characteristics, the issue is also classified as system stability. For example, stability problems caused by large-capacity conventional DC can be viewed as both equipment and system stability issues of concern.

Additionally, equipment stability is derived from single-equipment infinite-bus system models, ignoring grid frequency variations. However, when analyzing synchronization issues in power systems with multiple equipment, synchronization reaches a common-mode component reflecting system frequency characteristics [30]. Therefore, when considering power imbalance in the system, frequency limit violations or instability issues may also occur, so system stability also includes frequency stability.

In summary, the equipment stability classification results discussed earlier should also exist in the system. System stability includes at least the four categories shown in Figure 6(c): synchronization stability, voltage stability, electrical resonance, and frequency stability. Equipment stability is a subset of system stability, and extending equipment stability classification to a complete system stability classification requires further research.

Using the stability criterion applicability analysis method proposed in Part I, this paper analyzes the criterion rationality, derivation mechanisms, and dominant output variables for multi-time-scale stability issues of equipment such as synchronous machines, converters, and DFIGs based on typical parameters. The findings indicate that these equipment stability problems can be classified from three dimensions of electrical vectors: phase angle, magnitude, and vector as a whole. Specifically: synchronous machine low-frequency oscillation, shaft-dominated SSO/SSR, and converter/DFIG PLL-induced oscillations can be classified as phase-angle-dominated synchronization stability; converter outer-loop, conventional DC outer-loop, and asynchronous machine-induced instabilities can be classified as magnitude-dominated voltage stability; LC circuit resonance, synchronous machine or DFIG with series compensation-induced SSO/SSR, and converter inner-loop/feedforward-induced medium/high-frequency oscillations can be classified as electrical resonance. The proposed vector stability classification integrates renewable energy wide-band/multi-time-scale oscillation problems with conventional power system stability issues, providing a theoretical foundation for analyzing and solving stability problems in high-penetration renewable energy power systems. The basic models, analysis, and control methods for each stability category require further in-depth research.

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Appendix A: Derivation of Excitation Transfer Function Model for Synchronous Machine Subsynchronous Oscillation

Based on the synchronous machine electromagnetic model in reference [13], linearization yields the excitation system transfer function $G_{EE}(s)$. The excitation model is:

$$\begin{cases} \Delta U_d = G_d(s)\Delta I_d - R_a \Delta I_q \\ \Delta U_q = G_q(s)\Delta I_q - R_a \Delta I_d - \Delta E_f \end{cases} \tag{A1}$$

The generator uses a six-mass elastic shaft system model:

$$\begin{cases} \Delta T_m - \Delta T_e = Hs\Delta\omega + D\Delta\omega \\ \Delta\omega = s\Delta\delta \end{cases} \tag{A2}$$

The network-side model considering series compensation capacitors, inductors, and resistors is:

$$\begin{cases} \Delta U_{C,xy} = Z_{net,xy}(s)\Delta I_{xy} \\ \Delta I_{C,xy} = sC\Delta U_{C,xy} \end{cases} \tag{A3}$$

Through xy-dq coordinate transformation, equation (A3) is transformed to the synchronous reference frame. Combined with (A2), the synchronous machine transfer function model with excitation system as the dominant loop is obtained, with the characteristic equation shown in equation (9), where the feedback transfer function $H_{EE}(s)$ is:

$$H_{EE}(s) = \frac{U_{q0} - R_a I_{d0} + I_{q0} Z_{net,dq}(s)}{U_{d0} - R_a I_{q0} + I_{d0} Z_{net,dq}(s)} \tag{A4}$$

where $L_{EE}(s) = G_{EE}(s)H_{EE}(s)$. Symbol definitions are provided in reference [13].

Appendix B: Model Parameters for Case Studies

Table B1. Parameters for Low-Frequency Oscillation of Synchronous Machine

Parameter	Value
Rotor inertia H, damping D	8, 0.8 pu
Synchronous reactance X_d, X_q	1.2, 0.9 pu
d-axis transient reactance X'_d	0.2 pu
d-axis open-circuit transient time constant T'_{d0}	0.35 pu
Line reactance X_{line}	100/(1+0.1s) pu
Excitation system transfer function $G_E(s)$	100/(1+0.1s)

Table B2. Parameters for Subsynchronous Oscillation of Synchronous Machine

Parameter	Shaft-Dominated	Compensation-Dominated
Shaft inertias H_{1-6} (pu)	2.08, 2.08, 2.08, 2.08, 1.38, 0.05	2.08, 2.08, 2.08, 2.08, 1.38, 0.05
Shaft dampings D_{1-6} (pu)	0.05, 0.12, 0.12, 0.12, 0.12, 0.12	0.05, 0.15, 0.15, 0.15, 0.15, 0.15
Shaft spring constants K_{12-56} (pu)	10.5, 18.9, 26.3, 57.8, 5.2	10.5, 18.9, 26.3, 57.8, 5.2
Equivalent internal resistance R_a	0.05 pu	0.05 pu
Synchronous reactance X_d, X_q	1.75, 1.35 pu	1.75, 1.35 pu
Transient reactance X'_d, X'_q	0.32, 0.85 pu	0.32, 0.85 pu
Subtransient reactance X''_d, X''_q	0.25, 0.25 pu	0.25, 0.25 pu

Parameter	Shaft-Dominated	Compensation-Dominated
Open-circuit transient time constants T'_{d0}, T'_{q0} (s)	6.5, 1.5	6.5, 1.5
Open-circuit subtransient time constants T''_{d0}, T''_{q0} (s)	0.05, 0.03	0.05, 0.03
Mechanical torque T_m	0.05 pu	0.05 pu
Line parameters R, L, C (pu)	0.12, 0.6, 5.6	0.05, 0.25, 5.71
Voltage regulator $G_{AVR}(s)$	200/(1+0.15s)	200/(1+0.15s)
Excitation system $G_E(s)$	200/(1+0.15s)	200/(1+0.15s)
Excitation voltage feedback $G_F(s)$	0.02s/(1+0.5s)	0.02s/(1+0.5s)

Table B3. Parameters of Grid-Connected DFIG System

Parameter	Value
Base capacity S_b, voltage U_b, DC voltage U_{bdc}	1.5 MVA, 690 V, 1150 V
DC capacitance C_{dc}	0.038 pu
Line inductance L_g, resistance R_g, series compensation C_g	0.45, 0.05, 10 pu
DC voltage loop $H_{dc}(s)$	0.8 + 6/s
Power outer loop $H_{PQ}(s)$	5 + 30/s
Current loop $H_i(s)$	2 + 15/s
PLL transfer function $G_{PLL}(s)$	(30 + 3200/s)/s
Voltage feedforward filter $G_{FF}(s)$	1/(1 + 0.002/s)
Machine mutual inductance L_m	1.9 pu

Appendix C: Relationship Between Electrical Resonance and Phase/Magnitude Oscillations

Under small disturbances, electrical resonance has the following relationship with phase-angle and magnitude oscillations:

Based on the phase-angle oscillation expression in Table 5, its first-order linear approximation is:

$$\mathbf{Y}_p(t) \approx Y_R e^{j[\omega_0 t+\varphi_0]} + j\alpha Y_R e^{j[\omega_0 t+\varphi_0]} e^{j\omega_R t} \tag{C1}$$

where $\mathbf{Y}_p$ is the first-order linear approximation of Y_p. According to equation (C1), the space vector decomposition of phase-angle oscillation is shown in Figure C1.

With initial phase of $\pi/2$, the magnitude oscillation expression in Table 5 can be transformed to equation (C2), as shown in Figure C1:

$$\mathbf{Y}_m(t) = Y_R e^{j[\omega_0 t+\varphi_0]} + \alpha Y_R e^{j[\omega_0 t+\varphi_0]} e^{j\omega_R t} \tag{C2}$$

Superimposing the two yields the electrical resonance expression:

$$\mathbf{Y}_c(t) = Y_R e^{j[\omega_0 t+\varphi_0]} + \alpha Y_R e^{j[(\omega_0+\omega_R)t+\varphi_0]} \tag{C3}$$

According to equation (C3), electrical resonance has two characteristics: 1) The electrical vector as a whole oscillates, which in polar coordinates can be decomposed into superposition of magnitude and phase-angle oscillations, and in the stationary reference frame is power-frequency signal superimposed with non-power-frequency components; 2) When decomposed into magnitude and phase-angle oscillations in polar coordinates, the magnitude oscillation component leads the phase-angle oscillation component by $\pi/2$, with equal amplitudes.

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Note: Figure translations are in progress. See original paper for figures.