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LETTER

Fourth static stability regarding novel power systems with high shares of renewables and power electronics

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Dear Editor,

Although the classical and extended classification of power system stability has been provided through IEEE/CICRE, it is not suitable for novel power systems with high shares of renewables and power electronics to explain the broadband oscillation. Therefore, a new perspective named as "impedance angle stability" is proposed to explain this issue. This method can be considered parallel to rotor angle stability, voltage stability, and frequency stability as defined by IEEE/CIGRE. To this end, this impedance angle stability is referred to as the fourth stability in the context of novel power systems. This perspective transforms the stability issue into an analysis of whether harmonic reactive power is in balance. It highlights the dynamic process of system instability and explains the reasons for system instability.

With the growing demand for electric energy, a high proportion of renewable energy integrated into the grid through power electronic devices has become a key element in the development of the novel power system.[1] The increasing penetration of renewable energy and power electronics in the grid significantly raises the risk of broadband oscillation problems, posing serious threats to the secure operation of power systems and the safety of people lives and property.

The integration of a high proportion of renewable energy sources and power electronic devices extends the temporal scale of power system stability to the "electromagnetic" scale. In contrast, classical stability analysis methods, as illustrated in the left half of Figure 1A, primarily address relatively slow "electromechanical" phenomena typically observed in power systems dominated by synchronous machine.[2] Furthermore, the rotor angle, voltage, and frequency defined in classical stability refer to those of the fundamental wave component, implying that the definition does not explicitly account for components of other frequencies.[3] Consequently, the new stability issues which manifest as broadband oscillations in the novel power system fall beyond the scope of classical stability research. In 2020, the IEEE/CIGRE released a technical report titled "Stability definitions and characterization of dynamic behavior in systems with high penetration of power electronic interfaced technologies",[3] which introduces two new stability branches: "converter-driven stability" and "resonance stability", as shown in the right half of Figure 1A. While these new categories consider the dynamic effects of inverter-based generation on the system, some issues remain. Compared with the stability classification on the left,[2] the new classification does not adhere to the same standards and fails to provide an accurate system variable responsible for instability. Moreover, resonance stability may be caused by converters, making it indistinguishable from converter-driven stability. Neither of these new branches adequately explain the fundamental causes of instability in novel power systems.

To explain this issue, a new perspective named as "impedance angle stability" is proposed. The analysis results reveal that the stability and instability regions can be delineated using the impedance angle. As an inherent system variable, the impedance angle can stand alongside rotor angle, voltage and frequency as a fundamental concept, effectively explaining the root causes of system instability. Therefore, this perspective proposes that impedance angle stability can be a new stability analysis method for the novel power system, succeeding classical stability approaches.

The specific analysis is as follows:

The schematic diagram of the grid-connected inverter (GCI) is shown as Figure 1B. The system is highly prone to instability when the equivalent impedance of the inverter exhibits negative impedance characteristics.[4,5] In contrast, the traditional power system typically does not possess this feature, as their equivalent impedance is usually positive.[6] This causes the phase of the system synthesized impedance (i.e., the sum of source-side and load-side impedance) to extend from the range of traditional $[-\pi/2, \pi/2]$ to $[-\pi, \pi]$. Meanwhile, the equivalent impedance magnitude of the GCI increases with increasing voltage, while the phase remains unchanged.[7] Therefore, this perspective aims to analyze the instability mechanism of the GCI based on these two characteristics.

According to Figure 1B, the harmonic apparent power generated by external disturbance can be expressed as:

$$\begin{aligned} S(s) &= \left(\frac{\Delta V_g(s)}{Z_g(s)+Z_1(s)}\right)^* * \Delta V_g(s) \\ &= \frac{(\Delta V_g(s))^2}{|Z(s)|} * (\cos(\theta(s)) + j\sin(\theta(s))) \end{aligned} \tag{1}$$

where $\Delta V_g(s)$ is the external disturbance, $Z(s)$ is the sum of the GCI impedance $Z_1(s)$ and line impedance $Z_g(s)$.

$$\theta(s) = angle(Z(s)) \tag{2}$$

where $\theta(s)$ is the angle of $Z(s)$ and also the impedance angle in subsequent impedance angle stability analysis.

Then, the harmonic reactive power expression is obtained as:

$$Q(s) = \frac{(\Delta V_g(s))^2}{|Z(s)|} \sin(\theta(s)) \tag{3}$$

This perspective uses the interval $[0, \pi/2]$ as an example to illustrate the specific process of analyzing system stability based on impedance angle. Assuming the system is disturbed by a frequency of ω_1.

When $\theta(\omega_1) \in [0, \theta_1(\omega_1)+\pi]$: due to disturbance causing an increase in voltage, the magnitude of $Z_1(\omega_1)$ will increase while the phase remains unchanged. According to the vector synthesis relationship as shown in Figure 1C, the change in $Z_1(\omega_1)$ will lead to a simultaneous decrease in both magnitude of $Z(\omega_1)$ and $\theta(\omega_1)$. Due to the decrease in the magnitude of $Z(\omega_1)$, the curve of reactive power shifts from solid line to dashed line with the variation of $\theta(\omega_1)$. At this point, to rebalance $Q(\omega_1)$, $\theta(\omega_1)$ needs to decrease, which is consistent with the actual change in $\theta(\omega_1)$. This means that the harmonic reactive power can reach balance again. Furthermore, the reactive power at this harmonic frequency, when added to the fundamental frequency reactive power, will not further affect the voltage stability. Similarly, when the voltage decreases due to external disturbance, the same analysis result can be obtained. Therefore, the system is stable when $\theta(\omega_1) \in [0, \theta_1(\omega_1)+\pi]$.

When $\theta(\omega_1) \in [\theta_1(\omega_1)+\pi, \pi/2]$: due to disturbance causing an increase in voltage, the magnitude of $Z_1(\omega_1)$ will increase while the phase remains unchanged. According to the vector synthesis relationship as shown in Figure 1C, the change in $Z_1(\omega_1)$ will lead to a decrease in the magnitude of $Z(\omega_1)$ and an increase in $\theta(\omega_1)$. As shown in Figure 1C, the decrease in the magnitude of $Z(\omega_1)$ results in the reactive power curve shifting from solid line to dashed line with the change in $\theta(\omega_1)$. At this point, to rebalance $Q(\omega_1)$, $\theta(\omega_1)$ needs to decrease, which contradicts with the actual change. This means that the harmonic reactive power cannot restore balance. The reactive power generated by the disturbance will cause oscillation, when added to

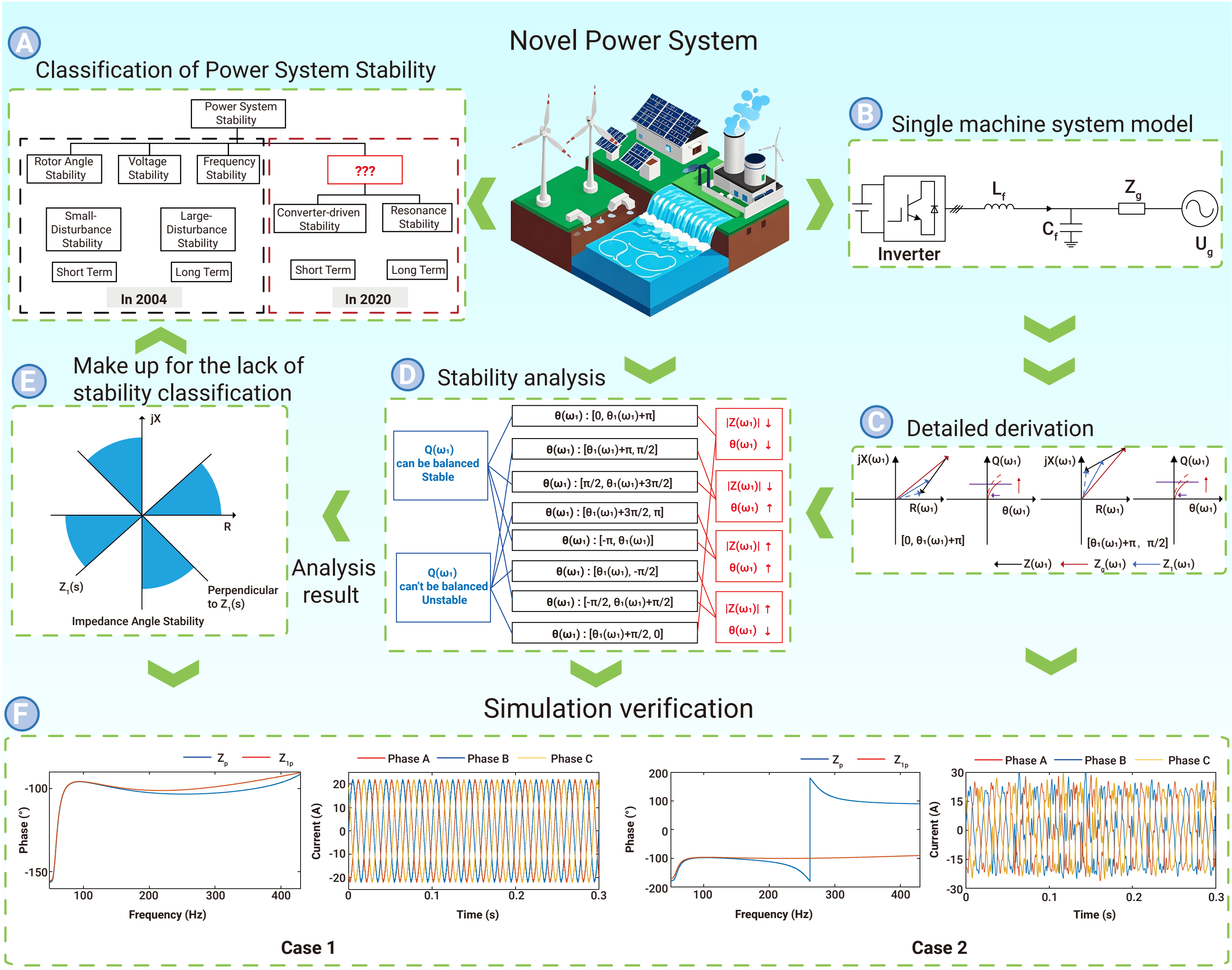

Figure 1. Fourth stability regarding the novel power system (A) Classification of power system stability in 2020. (B) Topology scheme of the GCI. (C) Schematic diagram of $Z(\omega_1)$ and $Q(\omega_1)$ changing with voltage. (D) The detail stability analysis process. (E) The stability discrimination interval based on the impedance angle: the blue region is stable and the remaining is unstable. (F) The simulation results.

the fundamental reactive power, will affect the system voltage. At this point, the system will enter a vicious cycle, resulting in broadband oscillation. When the voltage decreases due to external disturbance, the same analysis result can be obtained. Therefore, the system is unstable when $\theta(\omega_1) \in [\theta_1(\omega_1)+\pi, \pi/2]$.

Similarly, the stability analysis process of impedance angle can be obtained for other intervals, as shown in Figure 1D. The impedance angle can be utilized to divide stability and instability intervals, which is termed as "impedance angle stability." The stability discrimination intervals based on the impedance angle of the GCI grid-connected system are further obtained, as shown in Figure 1E. The dividing lines are the vertical lines corresponding to $Z_1(s)$ and $Z_1(s)$, respectively. When $\theta(s)$ lies in the blue region, the system will remain stable; on the contrary, the system will be destabilized.

In summary, based on the expression of reactive power and system impedance angle, this perspective analyzes whether the system can suppress power oscillations and maintain power stability when a small power disturbance occurs at the operating point, thereby achieving system stability analysis. This perspective holds that there are two conditions when instability occurs in the new power system: one is the equivalent negative impedance of the inverter; and the other is the variability of the equivalent impedance. Among them, equivalent negative impedance is the fundamental condition for system instability, while the variability of equivalent impedance serves as the triggering condition for system instability. When subjected to a small disturbance, the voltage changes, affecting the equivalent impedance of the GCI. Since the magnitude of GCI impedance changes, it inevitably affects the synthesized impedance angle, leading to an imbalance in reactive power under harmonics. The harmonic signal superimposes on the fundamental frequency signal, causing an imbalance in the system transmitted reactive power. Based on the relationship between reactive power and voltage, this imbalance further leads to voltage imbalance, creating a vicious cycle that results in instability.

This perspective effectively addresses the limitations of present stability classifications, filling the gap shown in Figure 1A. Converter-driven stability primarily describes the multi-scale interactions in the control process of converter-interfaced devices, while resonance stability characterizes the interactions between generating units and series-compensated transmission lines. For example, "resonance between the equivalent impedance of an inverter and line capacitance" is classified as "converter-driven stability", whereas "resonance between the equivalent impedance of a wind farm and series capacitance" is categorized as "resonance stability". However, in essence, both instability issues originate from the interaction between converter devices and grid impedance. Furthermore, both two are associated with the system's equivalent negative impedance, which continuously varies. The impedance angle stability proposed is derived based on the interaction between converter impedance and grid impedance[8], as well as the variability of negative impedance. Moreover, as an observable system variable in the novel power system, the impedance angle can effectively characterize such stability issues. It explains the broadband oscillation, that classical stability theories struggle to analyze. This fundamentally reveals the instability mechanism of the novel power system. The impedance angle can serve as a complementary factor alongside rotor angle, voltage, and frequency in classical stability classifications. Therefore, the impedance angle stability consolidates "converter-driven stability" and "resonance stability", and emerges as the fourth category of stability following classical stability.

The simulation results are shown in Figure 1F. In case 1, the line impedance is 1mH. It can be found that the synthesized impedance angle θ always remains below the equivalent impedance phase of the GCI, which falls within the stable interval $[-\pi, \theta_1]$, so the system will remain stable. In case 2, the line impedance is 13mH. It can be found that the synthesized impedance angle θ enters the unstable range $[\theta_1 + 3\pi/2, \pi]$ in the high frequency band. In this case, the system is inevitably unstable. The simulation results verify the correctness of the theoretical analysis.

This perspective follows the internal logic of classical stability classification methods, resolving the inconsistencies between the two newly added stability types in 2020 and the classical stability types. It highlights the essential characteristics of stability issues in the novel power system and demonstrates better adaptability to such system.

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DECLARATION OF INTERESTS

The authors declare no competing interests.