

Impact and Mitigation of Current Saturation Algorithms in Grid-Forming Inverters on Power Swing Detection

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Abstract—Conventional power swing detection schemes generally rely on the assumption that the apparent impedance trajectory observed by a distance relay varies slowly and continuously during a power swing. However, this assumption may no longer hold when a grid-forming (GFM) inverter-based resource (IBR) enters current saturation. This paper theoretically derives the conditions for entering and exiting current saturation under circular, d-axis priority, and q-axis priority current saturation algorithms (CSAs), and analyses the corresponding full-cycle apparent impedance trajectories. The analysis reveals that the CSAs fundamentally reshape the impedance trajectories observed by protective relays, leading to behaviours that are qualitatively different from those of synchronous generator (SG)-based systems. Moreover, it is demonstrated that the conventional power swing detection scheme may lose functionality due to the rapid movement of the trajectory. To mitigate this issue, a current vector angle holding strategy is proposed to maintain the continuity of the apparent impedance trajectory during the transition into current saturation. The theoretical findings and the effectiveness of the proposed strategy are validated through MATLAB/Simulink simulations using a simplified grid-connected GFM IBR system and a modified IEEE 9-bus system.

Index Terms—grid-forming control, current limiter, current saturation algorithm, power swing detection.

I. INTRODUCTION

TO achieve the net-zero commitment, inverter-based resources (IBRs) driven by renewable energy, such as wind and solar, are gradually replacing synchronous generators (SGs) powered by fossil fuels in power systems [1]. The increasing penetration of IBRs also changes the fault and transient characteristics of power systems, creating new challenges for conventional protection schemes [2]. Although grid-following (GFL) remains the predominant control method for IBRs, grid-forming (GFM) more accurately mimics the rotor dynamic response of synchronous generators (SGs) [3], on which conventional protection schemes are based. Therefore, compared to GFL IBRs, GFM IBRs are considered more

effective in alleviating the potential risk of malfunctions in power swing detection functions as the penetration of IBRs increases [4]. However, differing from SGs, the external response of GFM IBRs is governed by control loops [5], lacking a rigid rotor body to provide inherent inertia. Moreover, the current limiter in the control loop restricts the current reference to protect the power electronic components. Consequently, how GFM IBRs influence power swing detection functions remains an unsolved mystery [4, 6], and further research is required to investigate the underlying mechanisms.

Power swing detection serves two primary functions: power swing blocking (PSB) and out-of-step tripping (OST). The PSB function aims to discriminate between a fault and a power swing, blocking the distance protection to prevent unnecessary tripping in a power swing event [7]. The objective of the OST function is to distinguish between stable and unstable power swings, separating the system at pre-determined network locations to prevent further cascading faults in an unstable power swing event [8, 9]. Mature power swing detection methods include traditional approaches based on the rate of change of impedance or resistance, as well as non-traditional techniques developed for microprocessor-based relays [8–11]. Among them, those utilising the rate of change of apparent impedance remain the most widely implemented in commercial relays, with blinder-based schemes being the predominant realisation [12–15]. In practice, three sets of blinders, including inner, middle, and outer, are commonly applied [13, 16], enabling the simultaneous implementation of both PSB and OST functions. However, the effectiveness of this method for power swing detection in power systems dominated by GFM IBRs requires further investigation.

To prevent overcurrent from causing damage to the power electronic components in GFM IBRs, current saturation algorithms (CSAs) and virtual impedance (VI) methods are widely applied to limit the current [17–19]. This paper focuses on three typical CSAs: circular CSA, d-axis priority CSA, and q-axis priority CSA. Limited research has investigated the conditions for exiting the current saturation mode. The authors in [18] assume that the current exits the saturation mode at the intersection point of the $P - \delta$ curves under saturated and unsaturated modes. Although the simulation-based case studies in [18] seem to verify this assumption, a theoretical analysis is lacking to prove it. The fault recovery process under the constant CSA has been analysed in [20], revealing different conditions for transitions between the normal operating mode and the current saturation mode. However, further theoretical

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analysis and a closed-form expression are not provided. It is highlighted in [21–23] that IBRs can potentially fall into saturated stable equilibrium points (SSEPs) during fault recovery, and the conditions for exiting the current saturation mode are also derived. However, the analysis only addresses the user-defined current angle in constant CSA, without considering the other three types of CSAs. The exiting conditions under other different CSAs, which remain not well understood, may significantly impact the apparent impedance trajectories.

Some research has preliminarily explored the impact of replacing SGs with renewable energy resources or IBRs on power swing detection. The influence of Type III wind turbine generators on power swing detection was investigated in [16], and the scope was further extended to more general IBRs in [24]. However, these analyses are based solely on simulations, without providing theoretical explanations. Methods for distinguishing faults from power swings were proposed in [25, 26]. Nevertheless, the former is limited to Type III wind turbine generators, while the latter is specifically developed for GFL IBR-connected transmission lines. Simulations presented in [27] demonstrate that the rate of change of apparent impedance during stable and unstable power swings is significantly faster in GFL IBR-based systems than in systems with only SGs. This rapid rate of change poses a risk of PSB and OST malfunctions. From a more theoretical perspective, a dynamic model is developed in [28] to illustrate that the DC-link voltage-control dynamics can significantly amplify the rate of impedance change [29]. The authors of [30] and [31] conducted a detailed theoretical analysis of power swing trajectories caused by IBRs and qualitatively investigated the influence of control parameters. An intuitive analytical framework was developed in [32], in which the influence of IBR current injection on the measured apparent impedance is represented as an additional impedance component. However, the analyses in [27–32] mainly focus on GFL IBRs and do not address the CSA-based modelling of GFM IBRs.

Although power swing characteristics have been studied for GFL IBR-based systems, the corresponding conclusions cannot be directly extended to GFM IBRs equipped with CSAs. In GFL IBRs, the converter synchronises with the grid through a PLL, and the injected current is regulated according to current references prescribed by the adopted control strategy. In contrast, a GFM IBR behaves as a voltage source converter before current saturation, and its current reference is generated by the internal voltage control loop and GFM synchronisation dynamics. Therefore, even after the current magnitude is limited by a CSA, the saturation entry and exit conditions require separate analysis.

GFM IBRs are considered in [33]; however, the role of the current limiter is not accounted for. The influence of GFM IBR penetration levels and power synchronisation loop parameters on power swing dynamics and the performance of PSB and OST functions was investigated in [34]; however, specific current-limiting algorithms were not systematically examined. The full cycle power swing trajectories under variable and adaptive virtual impedance (VI) current limiting strategies were theoretically investigated in [35], revealing distinct tra-

jectory shapes and potential PSB and OST malfunctions. Nevertheless, VI-based strategies employ a fundamentally different current limiting mechanism from CSAs. The power swing characteristics of inertial and non-inertial GFM IBR systems under circular current limitation were investigated in [36], where the impedance trajectory was shown to be governed by a control-dependent angle. However, this study considers only the circular current limiter and does not compare the saturation conditions and full cycle trajectories introduced by different CSA implementations. To the best of the authors' knowledge, no previous study has systematically analysed and compared the saturation entry and saturation exit conditions and the corresponding full-cycle power swing trajectories of GFM IBRs under circular, d-axis priority, and q-axis priority CSAs.

To fill this gap, the apparent impedance trajectories of the GFM IBR during power swings under three types of CSA are analysed in this paper. Furthermore, the impact of these trajectories on legacy power swing detection protection is investigated. The main contributions of this paper are:

- The conditions for entering and exiting the current saturation mode are derived for three types of CSAs: circular, d-axis priority, and q-axis priority. The analysis reveals that the entering and exiting angle sets are not complementary to each other.
- The full-cycle power swing trajectories under these three CSA strategies are examined. The analysis highlights their distinct characteristics compared to those of conventional SG-based systems.
- A current vector angle holding strategy is proposed to improve the reliability of legacy power swing detection by ensuring that the impedance trajectory moves continuously during the transition from the unsaturated to the saturated mode.

The theoretical analysis and the effectiveness of the proposed strategy are validated through simulation models implemented on the MATLAB/Simulink platform, including a simplified grid-connected GFM IBR system and a modified IEEE 9-bus system.

The paper is organised as follows. In Section II, the system model is presented. In Section III, three typical CSAs are introduced, and the conditions for entering and exiting current saturation are derived. Section IV analyses the apparent impedance trajectories under the three CSAs. The proposed current vector angle holding mitigation strategy is presented in Section V. Section VI presents simulation case studies using the simplified test system. Extended validation on the modified IEEE 9-bus system is provided in Section VII. Section VIII discusses the practical considerations of the proposed strategy. Finally, Section IX concludes the paper.

II. SYSTEM MODEL

Fig. 1(a) shows the system configuration of a grid-connected GFM IBR system. The DC source is connected to the grid through an inverter, an LC filter, a step-up transformer Z_{tr} , and a power line Z_l . The grid is modeled as a Thevenin equivalent voltage source $V_g \angle \theta_g$ in series with an impedance Z_g . The

low-voltage side of the transformer is considered as the point of common coupling (PCC). Thus, the total impedance between the PCC and the Thevenin equivalent voltage source of the grid is $Z_{tr} + Z_l + Z_g = Z_T \angle \phi = R_T + jX_T$. The voltage phasor angle of the GFM IBR, θ , is generated by the active power controller (APC) in the virtual synchronous machine control scheme to emulate the swing equations of the SGs; while the voltage set point of the GFM IBR should be determined by the reactive power controller (RPC). However, as RPC is not the focus of this paper, the voltage set point is assumed to be $\hat{V}^{\text{ref}} = v_d^{\text{ref}} + jv_q^{\text{ref}} = 1 + j0$. With the local voltage reference of the GFM IBR aligned along the d-axis, where $\theta = 0$, the power angle between the IBR and the grid is defined by $\delta = \theta - \theta_g$, i.e., $\delta = -\theta_g$. A distance protection relay is installed at the power line terminal near the transformer, equipped with both three-zone mho-type distance protection and power swing detection functions.

A typical voltage-current dual-loop cascaded control structure is implemented in this paper, as illustrated in Fig. 1(b). To prevent overcurrent in any abnormal operating condition from damaging the power electronic components in the inverter, a CSA is essential. It limits the magnitude of the current reference output from the voltage controller to the maximum allowable value $I_{\max}$, generating a new current reference as the input to the current controller. To prevent integrator windup, the clamping anti-windup technique is employed within the voltage PI controllers to limit the magnitude of the PI output to $u_{\max}$. The CSA can be implemented by prioritising the current vector angle, d-axis current and q-axis current, as presented in Fig. 2. These different algorithms have distinct conditions for exiting current saturation, which are reflected in different apparent impedance trajectories and will be investigated in the next sections.

III. CURRENT SATURATION ALGORITHM

In this section, the condition for entering current saturation is derived, followed by the analysis of the conditions for exiting saturation under different CSAs. When a CSA is activated, the GFM IBR enters a current-limited operating mode and can no longer fully maintain its voltage source behaviour.

A. Condition for Entering Current Saturation

Independent of the specific CSA employed, the condition for entering current saturation remains consistent and can be expressed as:

$$i_{sd}^2 + i_{sq}^2 > I_{\max}^2. \quad (1)$$

Based on (1) and Kirchhoff's voltage law, the GFM IBR enters current saturation [37], if

$$\cos \delta < \frac{(v_d^{\text{ref}})^2 + (V_g)^2 - (|Z_T| I_{\max})^2}{2v_d^{\text{ref}} V_g}. \quad (2)$$

The power angle at the critical condition where the current transitions from unsaturated to saturated is defined as

$$\delta_{\text{enter}} = \arccos \left[\frac{(v_d^{\text{ref}})^2 + (V_g)^2 - (|Z_T| I_{\max})^2}{2v_d^{\text{ref}} V_g} \right]. \quad (3)$$

Thus, when

$$\delta \in [\delta_{\text{enter}}, 2\pi - \delta_{\text{enter}}], \quad (4)$$

the power angle satisfies the condition for current saturation.

B. Conditions for Exiting Current Saturation

The conditions for exiting current saturation are not inherently complementary to those for entering saturation. Instead, they depend on the CSAs, as will be elaborated in the following discussion.

1) *Circular Current Saturation Algorithm*: Fig. 2(a) illustrates the priority of the current angle, referred to as the circular CSA, which limits the magnitude to $I_{\max}$ while maintaining the angle consistent with the unsaturated current reference before the current limiter. Under this algorithm, the generated d-axis and q-axis current references are

$$\bar{i}_{sd}^{\text{ref}} = \frac{i_{sd}^{\text{ref}}}{|i_{sd}^{\text{ref}}|} \times \min \left(|i_{sd}^{\text{ref}}|, |i_{sd}^{\text{ref}}| \times \frac{I_{\max}}{\sqrt{(i_{sd}^{\text{ref}})^2 + (i_{sq}^{\text{ref}})^2}} \right), \quad (5)$$

$$\bar{i}_{sq}^{\text{ref}} = \frac{i_{sq}^{\text{ref}}}{|i_{sq}^{\text{ref}}|} \times \min \left(|i_{sq}^{\text{ref}}|, |i_{sq}^{\text{ref}}| \times \frac{I_{\max}}{\sqrt{(i_{sd}^{\text{ref}})^2 + (i_{sq}^{\text{ref}})^2}} \right). \quad (6)$$

When the current enters the saturation mode, v_d and v_q cannot track their references, causing the rapid clamping of the PI controllers in the voltage control loops. Thus, the current references for the d-axis and q-axis before the CSA are

$$\bar{i}_{sd}^{\text{ref}} = \text{sgn}(u_d) u_{\max} + \bar{i}_{sd}, \quad (7)$$

$$\bar{i}_{sq}^{\text{ref}} = \text{sgn}(u_q) u_{\max} + \bar{i}_{sq}, \quad (8)$$

where $\bar{i}_{sd} = \bar{i}_d - v_q \omega C_f$ and $\bar{i}_{sq} = \bar{i}_q + v_d \omega C_f$. Assuming that the response of the current controller is fast enough to accurately track the references, i.e., $\bar{i}_{sdq} = \bar{i}_{sdq}^{\text{ref}}$, it can be derived that

$$\left(\frac{1}{k} - 1 \right) \bar{i}_{sd}^{\text{ref}} = \text{sgn}(u_d) u_{\max}, \quad (9)$$

$$\left(\frac{1}{k} - 1 \right) \bar{i}_{sq}^{\text{ref}} = \text{sgn}(u_q) u_{\max}, \quad (10)$$

where $k = I_{\max} / \sqrt{(i_{sd}^{\text{ref}})^2 + (i_{sq}^{\text{ref}})^2}$. The sign of u_d depends on the sign of $(v_d^{\text{ref}} - v_d)$, according to the voltage control loop in Fig. 1(b); similarly, the sign of u_q depends on the sign of $(v_q^{\text{ref}} - v_q)$, where v_d and v_q refer to the d-axis and q-axis components of the PCC voltage, denoted as

$$v_d = V_g \cos \delta + |Z_T| (\bar{i}_{sd} \cos \phi - \bar{i}_{sq} \sin \phi), \quad (11)$$

$$v_q = -V_g \sin \delta + |Z_T| (\bar{i}_{sd} \sin \phi + \bar{i}_{sq} \cos \phi). \quad (12)$$

Since $k \leq 1$ under the saturation mode, the magnitude of the d-axis and q-axis currents satisfy

$$|\bar{i}_{sd}| = |\bar{i}_{sq}| = \frac{\sqrt{2}}{2} I_{\max}. \quad (13)$$

The signs of $\bar{i}_{sd}$ and $\bar{i}_{sq}$ are consistent with those of u_d and u_q , respectively. Therefore, when the current has not exited saturation, that is, when v_d and v_q fail to simultaneously track their respective references, the signs of $\bar{i}_{sd}$ or $\bar{i}_{sq}$ may change

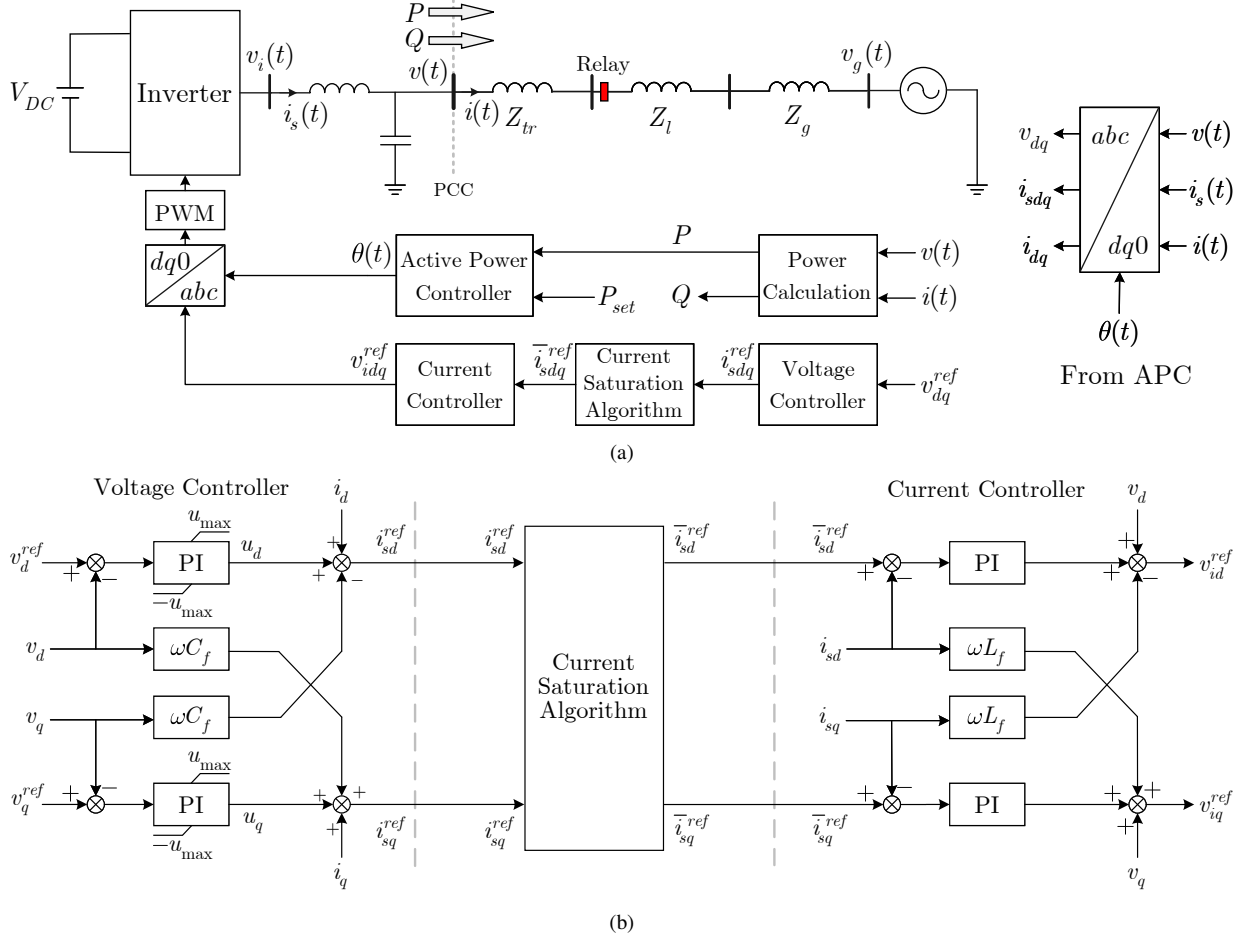


Fig. 1: Grid-connected GFM IBR system. (a) System model and control structure. (b) Control block diagram.

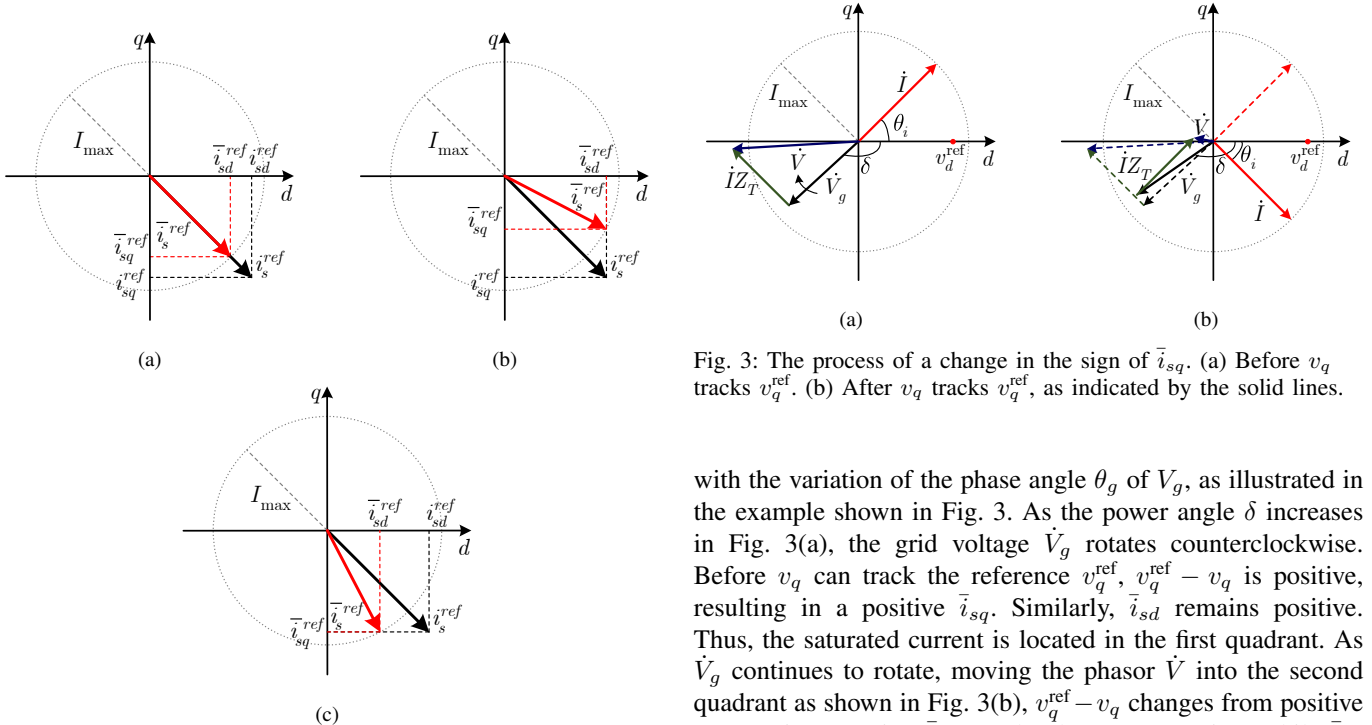


Fig. 2: The new current references generated by the CSAs. (a) Circular. (b) D-axis priority. (c) Q-axis priority.

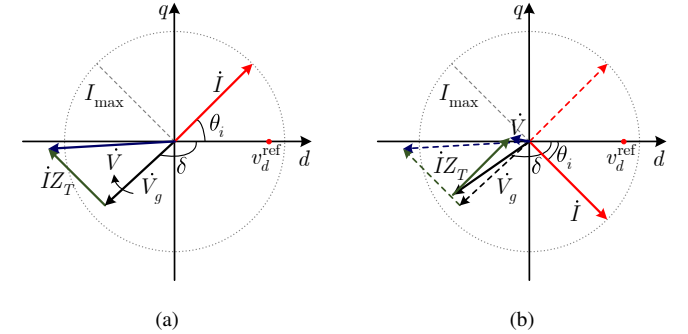


Fig. 3: The process of a change in the sign of $\bar{i}_{sq}$. (a) Before v_q tracks v_q^{ref} . (b) After v_q tracks v_q^{ref} , as indicated by the solid lines.

with the variation of the phase angle θ_g of V_g , as illustrated in the example shown in Fig. 3. As the power angle δ increases in Fig. 3(a), the grid voltage $\dot{V}_g$ rotates counterclockwise. Before v_q can track the reference v_q^{ref} , $v_q^{ref} - v_q$ is positive, resulting in a positive $\bar{i}_{sq}$. Similarly, $\bar{i}_{sd}$ remains positive. Thus, the saturated current is located in the first quadrant. As $\dot{V}_g$ continues to rotate, moving the phasor $\dot{V}$ into the second quadrant as shown in Fig. 3(b), $v_q^{ref} - v_q$ changes from positive to negative, causing $\bar{i}_{sq}$ to also become negative, while $\bar{i}_{sd}$ remains positive. Consequently, the saturated current rapidly changes from the first quadrant to the fourth quadrant. This

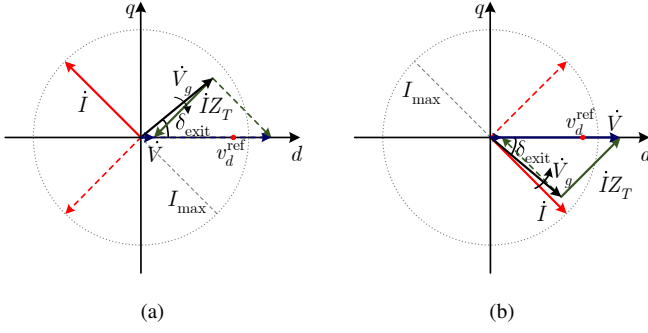


Fig. 4: Two scenarios for current exiting saturation under circular CSA control. The dashed lines represent the moment just before v_q tracks v_q^{ref} , while the solid lines represent the moment just after v_q tracks v_q^{ref} . (a) $\dot{V}_g$ rotates clockwise. (b) $\dot{V}_g$ rotates counterclockwise.

change in the current leads to a significant reduction in the magnitude of $\dot{V}$, as shown by the change in $\dot{V}$ from Fig. 3(a) to Fig. 3(b).

Since the saturated current exhibits a rapid change before and after the d-axis or q-axis voltage successfully reaches its reference, only two possible scenarios exist under circular CSA control where both d-axis and q-axis voltages simultaneously reach their respective references, as shown in Fig. 4. Just before v_q reaches v_q^{ref} , the saturated current $\dot{I}$ and the PCC voltage $\dot{V}$ are located at the positions indicated by the red dashed line and the blue dashed line in Fig. 4, respectively. Once v_q successfully reaches v_q^{ref} , the sign of $\bar{i}_{sq}$ changes, resulting in $\dot{I}$ and $\dot{V}$ rapidly shifting to the positions marked by the red solid line and the blue solid line. During this transition, $\dot{V}$ passes through the PCC voltage set point v_{dq}^{ref} , thereby satisfying the exit condition and enabling the current to exit saturation. The clockwise and counterclockwise variations of δ shown in the figure share the same exit condition, which is

$$-V_g \sin \delta + \frac{\sqrt{2}}{2} I_{\max} |Z_T| \cos \phi + \frac{\sqrt{2}}{2} I_{\max} |Z_T| \sin \phi = v_q^{\text{ref}} = 0. \quad (14)$$

Defining

$$\delta_{\text{exit}}^{\text{circular}} = \arcsin \left[\frac{\sqrt{2} I_{\max} |Z_T| (\cos \phi + \sin \phi)}{2 V_g} \right], \quad (15)$$

the set of power angles δ that enable the current to exit the saturation mode under circular CSA control is given by

$$\delta \in [0, \delta_{\text{exit}}^{\text{circular}}] \cup [2\pi - \delta_{\text{exit}}^{\text{circular}}, 2\pi]. \quad (16)$$

2) *D-Axis Priority Current Saturation Algorithm*: With the d-axis priority current saturation algorithm shown in Fig. 2(b), the d-axis and q-axis current references are as follows.

$$\bar{i}_{sd}^{\text{ref}} = \frac{i_{sd}^{\text{ref}}}{|i_{sd}^{\text{ref}}|} \times \min(|i_{sd}^{\text{ref}}|, I_{\max}) \quad (17)$$

$$\bar{i}_{sq}^{\text{ref}} = \frac{i_{sq}^{\text{ref}}}{|i_{sq}^{\text{ref}}|} \times \min(|i_{sq}^{\text{ref}}|, \sqrt{(I_{\max})^2 - (\bar{i}_{sd}^{\text{ref}})^2}). \quad (18)$$

After the current is limited, the GFM IBR can exit the saturation mode, if

$$(\bar{i}_{sd}^{\text{ref}})^2 + (\bar{i}_{sq}^{\text{ref}})^2 < I_{\max}^2, \quad (19)$$

where i_{sd}^{ref} and i_{sq}^{ref} are expressed as (7) and (8). With the saturation of the current, the voltages on the d-axis and q-axis cannot track their respective voltage references. Consequently, the integrators within the PI controllers of the voltage loops, as shown in Fig. 1(b), will clamp promptly, reaching their maximum output, $u_{\max}$. Thus, the condition for exiting the saturation has the expression as

$$[\text{sgn}(u_d) u_{\max} + \text{sgn}(\bar{i}_{sd}) I_{\max}]^2 + [\text{sgn}(u_q) u_{\max}]^2 < I_{\max}^2. \quad (20)$$

In the voltage controller, $u_{\max}$ denotes the output saturation limit of the PI controller and is set much smaller than the converter current limit. Assuming that $u_{\max} \ll I_{\max}$, it is derived that

$$\text{sgn}(u_d) \text{sgn}(\bar{i}_{sd}) < 0. \quad (21)$$

There are two cases that can address the above inequality.

$$\text{Case 1: } u_d < 0, \bar{i}_{sd} = +I_{\max}; \quad (22)$$

$$\text{Case 2: } u_d > 0, \bar{i}_{sd} = -I_{\max}. \quad (23)$$

In Case 2, the solution does not exist; therefore, the solution in Case 1 yields a unique exit condition, which is

$$\cos \delta > \frac{v_d^{\text{ref}} - |Z_T| I_{\max} \cos \phi}{V_g}. \quad (24)$$

Defining

$$\delta_{\text{exit}}^{\text{d-axis}} = \arccos \left[\frac{v_d^{\text{ref}} - |Z_T| I_{\max} \cos \phi}{V_g} \right], \quad (25)$$

the power angle set of exiting the current saturation with d-axis priority CSA is

$$\delta \in [0, \delta_{\text{exit}}^{\text{d-axis}}] \cup [2\pi - \delta_{\text{exit}}^{\text{d-axis}}, 2\pi]. \quad (26)$$

3) *Q-Axis Priority Current Saturation Algorithm*: If the q-axis current reference is prioritised for current limiting, as shown in Fig. 2(c), the d-axis and q-axis references generated by the current limiter are

$$\bar{i}_{sd}^{\text{ref}} = \frac{i_{sd}^{\text{ref}}}{|i_{sd}^{\text{ref}}|} \times \min(|i_{sd}^{\text{ref}}|, \sqrt{(I_{\max})^2 - (\bar{i}_{sq}^{\text{ref}})^2}), \quad (27)$$

$$\bar{i}_{sq}^{\text{ref}} = \frac{i_{sq}^{\text{ref}}}{|i_{sq}^{\text{ref}}|} \times \min(|i_{sq}^{\text{ref}}|, I_{\max}). \quad (28)$$

The condition for current exiting saturation under q-axis priority CSA control is similar to that under d-axis priority. At the moment of exiting saturation, the signs of u_q and $\bar{i}_{sq}$ satisfy the relationship

$$\text{sgn}(u_q) \text{sgn}(\bar{i}_{sq}) < 0. \quad (29)$$

It can be discussed in two cases:

$$\text{Case 1: } u_q < 0, \bar{i}_{sq} = +I_{\max}; \quad (30)$$

$$\text{Case 2: } u_q > 0, \bar{i}_{sq} = -I_{\max}. \quad (31)$$

The solutions corresponding to the two cases are

$$\sin \delta > -\frac{|Z_T| I_{\max} \cos \phi}{V_g} \quad (32)$$

and

$$\sin \delta < \frac{|Z_T| I_{\max} \cos \phi}{V_g}, \quad (33)$$

respectively. Defining

$$\delta_{\text{exit}}^{\text{q-axis}} = \arcsin \left[\frac{|Z_T| I_{\max} \cos \phi}{V_g} \right], \quad (34)$$

the current can exit the saturation mode, if the power angle belongs to the set

$$\delta \in [0, \delta_{\text{exit}}^{\text{q-axis}}] \cup [\pi - \delta_{\text{exit}}^{\text{q-axis}}, \pi + \delta_{\text{exit}}^{\text{q-axis}}] \cup [2\pi - \delta_{\text{exit}}^{\text{q-axis}}, 2\pi]. \quad (35)$$

However, it is worth noting that the exit angle set $\delta \in [\pi - \delta_{\text{exit}}^{\text{q-axis}}, \pi + \delta_{\text{exit}}^{\text{q-axis}}]$ also belongs to the saturation angle set. When the power angle is within this set, both the entering and the exiting saturation conditions are simultaneously satisfied, causing the IBR to oscillate between the two modes, which negatively impacts system stability. To eliminate the oscillation, within this subset, forced saturation is implemented as follows.

$$\bar{i}_{sq} = +I_{\max}, \quad \text{if } \delta \in [\pi - \delta_{\text{exit}}^{\text{q-axis}}, \pi]; \quad (36)$$

$$\bar{i}_{sq} = -I_{\max}, \quad \text{if } \delta \in [\pi, \pi + \delta_{\text{exit}}^{\text{q-axis}}]. \quad (37)$$

Therefore, the set of power angles for exiting saturation under q-axis priority CSA control is

$$\delta \in [0, \delta_{\text{exit}}^{\text{q-axis}}] \cup [2\pi - \delta_{\text{exit}}^{\text{q-axis}}, 2\pi]. \quad (38)$$

IV. ANALYSIS OF POWER SWING TRAJECTORIES

The power swing trajectories can be affected by different CSAs. In this section, the trajectory in the absence of current saturation is introduced, followed by a discussion of the trajectories under the three types of CSAs. The analysis in this section is based on the model in Fig. 5, which is the equivalent model shown in Fig. 1(a).

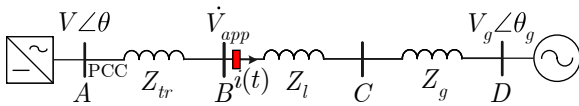


Fig. 5: Single machine GFM IBR grid-connected system.

A. Current Unsaturation

Under the assumptions that there is no current limitation in the control loops and that $|\dot{V}| = |\dot{V}_g|$, the apparent impedance observed by the relay near Bus B, marked in red in Fig. 5, is consistent with that in an SG-based system, as derived in [38]:

$$Z_{\text{app}} = \left(Z_l + Z_g - \frac{1}{2} Z_T \right) - j \frac{1}{2} Z_T \cot \frac{\delta}{2}. \quad (39)$$

Accordingly, with point B as the origin, the trajectory of the apparent impedance on the impedance plane is shown in Fig. 6. The green vector $\overrightarrow{BP}$ represents the apparent impedance measured by the relay, and $\angle APD$ reflects the power angle δ between the GFM IBR and the grid. As δ increases from 0 to 2π , the apparent impedance endpoint P moves along OO' from right to left. The trajectory OO' is the perpendicular

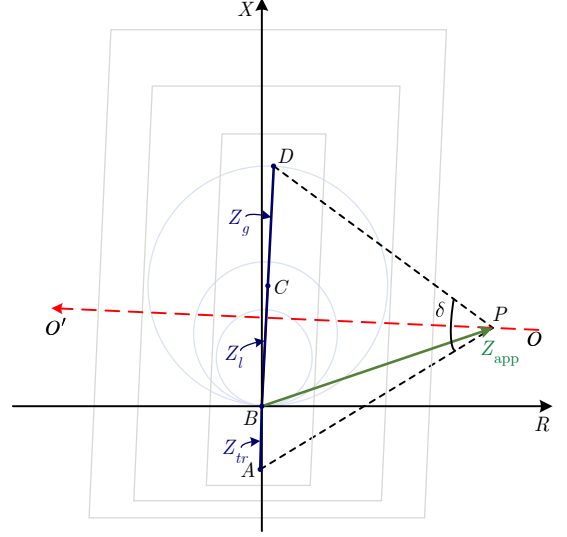


Fig. 6: Power swing trajectory in the absence of current limitation.

bisector of the line segment AD , which represents the total impedance between the PCC and the equivalent voltage source of the grid. Therefore, $|DP| = |AP|$. The figure illustrates that the apparent impedance $\overrightarrow{BP}$ is uniquely mapped to the power angle δ , and this relationship can be effectively represented on the impedance plane. The conventional power swing detection scheme is based on this well-established property.

The straight line trajectory in (39) is obtained under the assumption that $|\dot{V}| = |\dot{V}_g|$. When the two voltage magnitudes are unequal, the apparent impedance trajectory becomes circular [38]. For $|\dot{V}| > |\dot{V}_g|$, the circle centre is located on the upper extension of AD , whereas for $|\dot{V}| < |\dot{V}_g|$, it is located on the lower extension. Accordingly, the impedance trajectory is displaced upward or downward, respectively.

B. Current Saturation with CSAs

Under the influence of CSAs in the control loops, the apparent impedance in the current saturation mode is

$$Z_{\text{app}} = \frac{(Z_l + Z_g) I \angle \theta_i + V_g \angle -\delta}{I \angle \theta_i} \quad (40)$$

$$= (Z_l + Z_g) + \frac{V_g}{I} \angle (-\delta - \theta_i), \quad (41)$$

where θ_i represents the phase angle of the saturated current. The apparent impedance trajectory on the impedance plane forms a circle centred at point D , which is the endpoint of the vector $(Z_l + Z_g)$, with a radius $r = V_g / I_{\max}$, i.e., DQ , as shown in Fig. 7. When the current does not reach the overcurrent limitation $I_{\max}$ and remains in the unsaturated mode, the apparent impedance trajectory still follows the line described in the previous subsection, moving along either OM or NO' . Both OM and NO' , as well as their extensions, are perpendicular bisectors of the line segment AD . As δ gradually increases to δ_{enter} , which is $\angle AMD$, the current reaches the critical saturation state, and the trajectory moves to point M . With further increase in δ , the current enters the

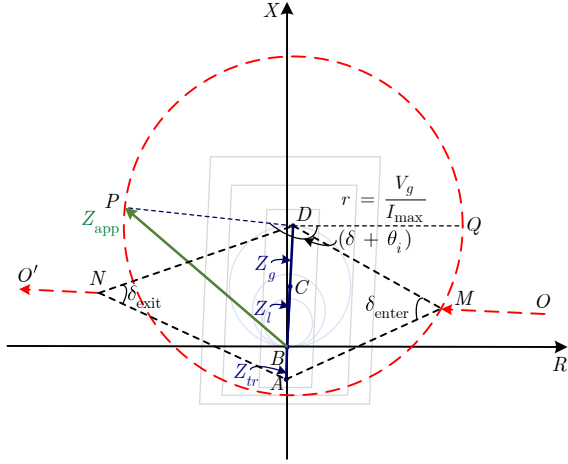


Fig. 7: Power swing trajectory under the CSAs.

saturation mode, and the trajectory follows the circular path where point M is located.

The process by which the trajectory transitions from the critical saturation point M to the saturation trajectory on the circle varies depending on the CSAs.

1) *Circular CSA*: Once the d-axis and q-axis voltages fail to track their references, the integrators in the voltage PI controllers will clamp soon, as discussed in Section III-B. Consequently, the magnitudes of $\bar{i}_{sd}$ and $\bar{i}_{sq}$ become equal; however, their signs depend on the system parameters, which determine the value of θ_i . As reflected in the impedance plane, the trajectory will quickly move from point M along the circular path to a specific point on the circle, characterised by a central angle of $\angle QDP = \delta_{\text{enter}} + \theta_i$. Subsequently, it moves clockwise along the circular path as δ increases. During saturation, due to the presence of anti-windup, $\bar{i}_{sd}$ and $\bar{i}_{sq}$ may change signs, resulting in a change in θ_i in a short time on the apparent impedance trajectory.

2) *D-Axis Priority CSA*: After entering the saturation mode, θ_i undergoes a transient process to reach 0° . Subsequently, θ_i remains at 0° until the GFM IBR exits the saturation mode.

3) *Q-Axis Priority CSA*: During forced saturation, the q-axis voltage may reach the reference value, resulting in a change in the sign of $\bar{i}_{sq}$. This results in a 180° shift in θ_i , which is reflected in the impedance trajectory as a change with a central angle of 180° along the circular path.

V. CURRENT VECTOR ANGLE HOLDING MITIGATION STRATEGY

This section proposes a mitigation strategy based on current vector angle holding to suppress rapid changes in the apparent impedance trajectory during power swings and thereby reduce the risk of power swing detection malfunction. The continuous trajectory condition is first derived, followed by a description of the operating principle and implementation of the proposed strategy.

A. Derivation of the Continuous-Trajectory Condition

The three typical CSAs may lead to rapid changes in power swing trajectories. If such rapidly changing trajectories pass

through the blinders, there is a potential risk of malfunction in power swing detection. To mitigate this risk, a current vector angle holding strategy based on a constant current saturation angle is proposed in this section.

The user-defined constant CSA is used to determine the current saturation angle β , represented by θ_i in (41). The current saturation angle β governs the starting point of the trajectory once the current enters saturation during a power swing. The condition for maintaining trajectory continuity is illustrated in Fig. 8. When the starting point of the saturated

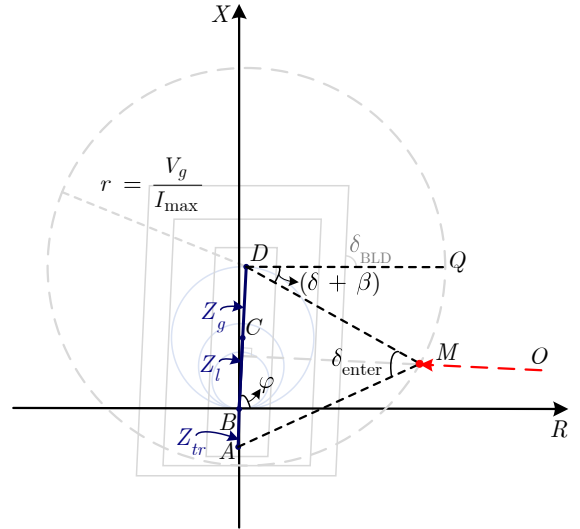


Fig. 8: Condition for maintaining continuity of the power swing trajectory at point M .

trajectory is located at the critical position, i.e., point M in Fig. 8, the power swing follows a continuous trajectory rather than exhibiting a rapid change. Therefore, point M represents the required starting point of the saturated trajectory. Since $\angle QDM = \delta + \beta$, the saturation angle that ensures trajectory continuity satisfies

$$(\delta_{\text{enter}} + \beta) + \varphi + (90^\circ - \frac{\delta_{\text{enter}}}{2}) = 180^\circ, \quad (42)$$

where the impedance angle of $(Z_l + Z_g)$ is approximated by φ . Accordingly, the current vector angle required for a continuous transition is

$$\beta_c = 90^\circ - \varphi - \frac{\delta_{\text{enter}}}{2}. \quad (43)$$

Maintaining the current vector angle at its saturation entry value preserves the continuity of the apparent impedance trajectory and reduces the risk of power swing detection malfunction caused by the rapid trajectory variations introduced by conventional CSAs.

B. Principle and Implementation of the Proposed Strategy

The proposed mitigation strategy can be implemented using only locally available current reference signals within the GFM IBR control system. The magnitude of the unsaturated current reference is first calculated as

$$I_s^{\text{ref}} = \sqrt{(i_{sd}^{\text{ref}})^2 + (i_{sq}^{\text{ref}})^2}. \quad (44)$$

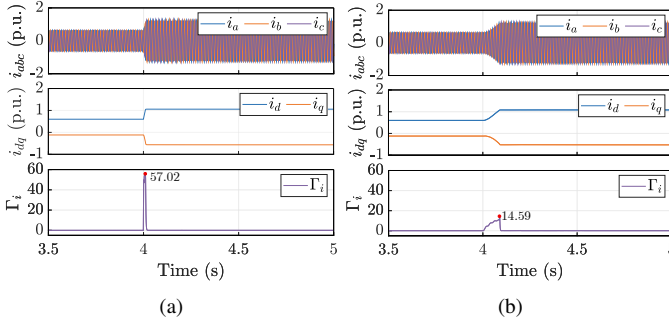


Fig. 9: Comparison of current variation under fault and power swing events. (a) Fault event. (b) Power swing event.

When I_s^{ref} reaches I_{max} , the GFM IBR enters the current saturation mode. However, current saturation may be triggered by either a fault or a power swing. Since the proposed strategy is intended to mitigate the rapid impedance trajectory variation during power swings, these two types of events should be distinguished before the current vector angle holding function is activated. Current variations caused by faults are generally much faster than those associated with power swings. Therefore, the variation rate of the current reference vector is employed as a local discrimination index, defined as

$$\Gamma_i = \sqrt{\left(\frac{d\bar{i}_{sd}^{\text{ref}}}{dt}\right)^2 + \left(\frac{d\bar{i}_{sq}^{\text{ref}}}{dt}\right)^2}. \quad (45)$$

The discrimination index Γ_i in (45) is used to distinguish fault-triggered current saturation from power swing-related current saturation. As shown in Fig. 9, the index Γ_i is first evaluated under a representative fault event and the fastest power swing event. For the power swing event, the GFM parameters are set to $H = 1$ s and $D_p = 0.25$. For the fault event, a bolted three-phase short-circuit fault is applied at 0% of the protected line. The results show a clear difference between the values of Γ_i under the power swing and fault events. The threshold is then set as

$$\Gamma_{\text{th}} = k_{\Gamma} \Gamma_{i,\text{ps}}^{\text{max}}, \quad (46)$$

where $\Gamma_{i,\text{ps}}^{\text{max}}$ is the maximum value of Γ_i under the fast power swing, which is 14.59 in this case, as shown in Fig. 9(b). A security factor k_{Γ} in the range of 1.5–2.5 may be selected to preserve a sufficient discrimination margin between power-swing and fault events. In this study, $k_{\Gamma} = 2.5$ is adopted, resulting in $\Gamma_{\text{th}} = 14.59 \times 2.5 = 36.48$, which remains lower than the value of Γ_i under the fault event shown in Fig. 9(a). When $I_s^{\text{ref}} \geq I_{\text{max}}$ and $\Gamma_i > \Gamma_{\text{th}}$, the event is identified as a fault event, and the proposed strategy is not activated. Otherwise, the event is identified as a power swing event, and the proposed strategy is activated. To further evaluate the effectiveness of the proposed discrimination criterion over a range of operating conditions, a parametric study is conducted, as shown in Fig. 10. For the power swing cases, the inertia constant H and damping coefficient D_p are varied, and the value of Γ_i in each case is recorded. For the fault cases, the fault location and fault resistance are varied, and the corresponding value of Γ_i is obtained. As shown in Fig. 10, the values of Γ_i under all investigated power swing conditions remain

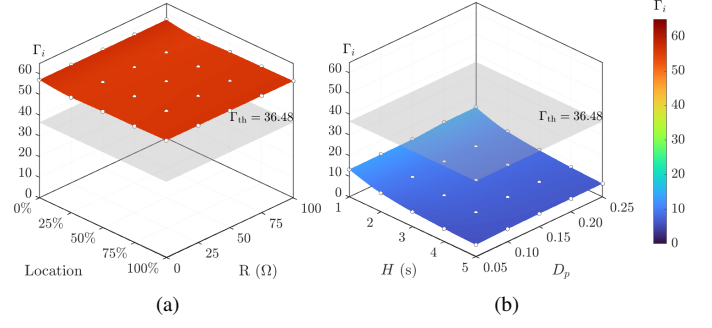


Fig. 10: Variation of the index Γ_i under different operating conditions. (a) Fault events with different fault locations and fault resistances. (b) Power swing events with different values of H and D_p .

clearly lower than those under the investigated fault conditions, providing a clear discrimination margin and demonstrating that the selected threshold remains effective over the investigated operating conditions.

When the angle holding strategy is enabled, the current vector angle is recorded as

$$\beta_h = \text{atan2} [\bar{i}_{sq}^{\text{ref}}(t_h), \bar{i}_{sd}^{\text{ref}}(t_h)], \quad (47)$$

where t_h denotes the activation instant. Since t_h corresponds to the saturation entry point during a power swing, the recorded angle β_h is consistent with the continuous trajectory angle β_c derived in Section V-A. However, unlike β_c , β_h is obtained directly from local current reference signals and does not require external network parameters. The saturated current references are then generated as

$$\bar{i}_{sd}^{\text{ref}} = I_{\text{max}} \cos \beta_h; \quad (48)$$

$$\bar{i}_{sq}^{\text{ref}} = I_{\text{max}} \sin \beta_h. \quad (49)$$

Thus, the magnitude of the current reference is limited to I_{max} , while its angle is maintained at the value corresponding to the saturation entry point. This prevents the rapid change in the saturated current angle introduced by conventional priority-based CSAs and maintains continuity of the apparent impedance trajectory when the GFM IBR enters current saturation.

When the GFM IBR exits the current saturation mode, the angle holding strategy is deactivated, and the current references are restored to the outputs of the voltage controller. A hysteresis margin and a short confirmation time can be incorporated into the entry and exit logic to prevent repeated transitions between the unsaturated and angle holding modes.

The proposed current vector angle holding strategy is implemented within the local control loop of the GFM IBR. It only requires the locally available current reference components $\bar{i}_{sd}^{\text{ref}}$ and $\bar{i}_{sq}^{\text{ref}}$, the current limit I_{max} , and the local variation rate index Γ_i . Therefore, the implementation does not require communication with external protection devices or online estimation of the external network equivalent. This makes the strategy suitable as a local control-side mitigation method.

VI. SIMULATION CASE STUDIES IN THE SIMPLIFIED TEST SYSTEM

In this section, the simplified grid-connected GFM IBR system is first used to verify the theoretical analysis and illustrate the CSA-induced trajectory distortion mechanism. The impacts of CSAs on power swing detection functions and power system transient stability are then investigated.

A. System Configuration

A grid-connected GFM IBR model, as shown in Fig. 1, is developed using the MATLAB/Simulink platform to validate the theoretical analysis. The relay, highlighted in red in the figure, employs the conventional three-zone mho characteristics in distance protection, which are shown as the orange circles in Fig. 11. In the figure, the three sets of blinders

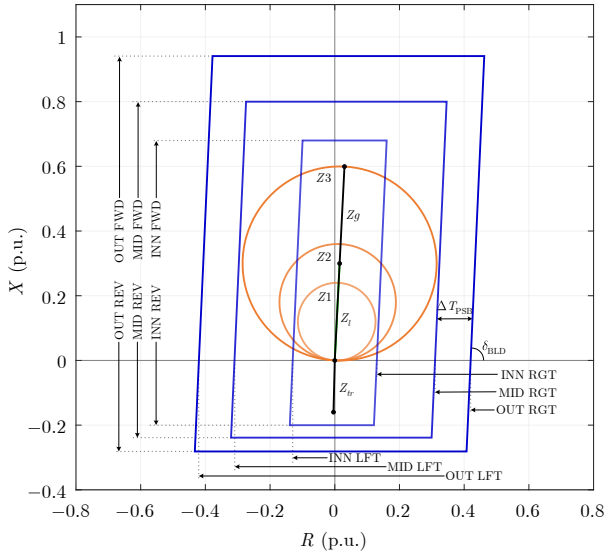


Fig. 11: Three-zone mho characteristics in distance protection and three sets of blinders in power swing detection.

(inner, middle, and outer), represented in blue, achieve both PSB and OST functionalities. The parameters of the system and the protection setting are shown in TABLE I.

The power swing detection characteristics are configured to operate across all three distance protection zones, corresponding to 80%, 120%, and 200% of Z_l . The detection process begins when the impedance trajectory intersects the outer blinder, at which point a timer is initiated. Once the trajectory reaches the middle blinder, the timer stops, and the elapsed time interval ΔT is compared with the reference threshold ΔT_{PSB} . This threshold should be determined from transient stability analysis to reliably distinguish between the fastest stable power swings and faults. If $\Delta T < \Delta T_{PSB}$, it indicates a fault. Otherwise, if $\Delta T > \Delta T_{PSB}$, it indicates a power swing, and the PSB function is subsequently activated to block distance protection and prevent unintended tripping. To ensure that the PSB function covers all distance protection zones, the middle blinders should encompass the largest zone, while the outer blinders should be set based on transient stability analysis to avoid overlapping with maximum load impedance. If a power swing is detected and the trajectory intersects the

TABLE I: Parameters of the test system and settings for distance protection and power swing detection

Parameters	Description	Value
System Configuration		
P_0	Active power set point	0.6 p.u.
f_n	Nominal frequency	60 Hz
v_d^{ref}	PCC voltage set point	1 p.u.
Z_g	Impedance of the generator	$0.3 \angle 87.14$ p.u.
Z_l	Impedance of the line	$0.3 \angle 87.14$ p.u.
Z_{tr}	Impedance of the transformer	$0.16 \angle 88.57$ p.u.
$\angle \phi$	Impedance angle of Z_T	87.44°
I_{max}	Overcurrent limitation	1.2 p.u.
u_{max}	Maximum magnitude of the output from the voltage PI controllers	0.063 p.u.
Distance Protection Setting		
Z1	80% of Z_l	$0.24 \angle 87.14$ p.u.
TD1	Zone1 time delay	0 s
Z2	120% of Z_l	$0.36 \angle 87.14$ p.u.
TD2	Zone2 time delay	0.5 s
Z3	200% of Z_l	$0.6 \angle 87.14$ p.u.
TD3	Zone3 time delay	1 s
Power Swing Detection Setting		
OUT RGT	Outer right blinder	0.42 p.u.
OUT LFT	Outer left blinder	-0.42 p.u.
MID RGT	Middle right blinder	0.31 p.u.
MID LFT	Middle left blinder	-0.31 p.u.
INN RGT	Inner right blinder	0.13 p.u.
INN LFT	Inner left blinder	-0.13 p.u.
OUT FWD	Outer forward reach	0.94 p.u.
OUT REV	Outer reverse reach	-0.28 p.u.
MID FWD	Middle forward reach	0.80 p.u.
MID REV	Middle reverse reach	-0.24 p.u.
INN FWD	Inner forward reach	0.68 p.u.
INN REV	Inner reverse reach	-0.20 p.u.
δ_{BLD}	The angles of right and left blinders	87.14°
ΔT_{PSB}	Power swing detection time threshold	0.033 s

inner blinder, the OST function is triggered. The system will initiate separation at the pre-determined location. Therefore, the inner blinder should be set to allow only unstable swings to pass through. The blinder angles should also align with the characteristic angle of the mho element.

B. Verification of Full-Cycle Impedance Trajectories

To verify the full-cycle impedance trajectories derived in Section IV, four simulation cases (A, B, C, and D) are established, with detailed event descriptions provided in TABLE II. The system configuration and other settings are

TABLE II: The event settings for Cases A, B, C, and D

	Case A	Case B	Case C	Case D
CSA	No CSA	Circular	D-Priority	Q-Priority
Event	A three-phase-to-ground fault occurs at the terminal of the PCC at $t = 4$ s and is cleared 150 ms later.			

identical to those listed in TABLE I. The relay-observed apparent impedance trajectories throughout an entire swing cycle are illustrated in Fig. 12. The subfigures correspond to the cases without the CSA strategy, with circular, d-axis priority, and q-axis priority CSA, respectively. After the fault is cleared, all four cases experience unstable power swings. In Fig. 12(a), the trajectory of the case without CSA is the same as that of the SG-based system, which is a straight line. The simulation results are consistent with the theoretical analysis. In Fig. 12(b), (c), and (d), the trajectories during the

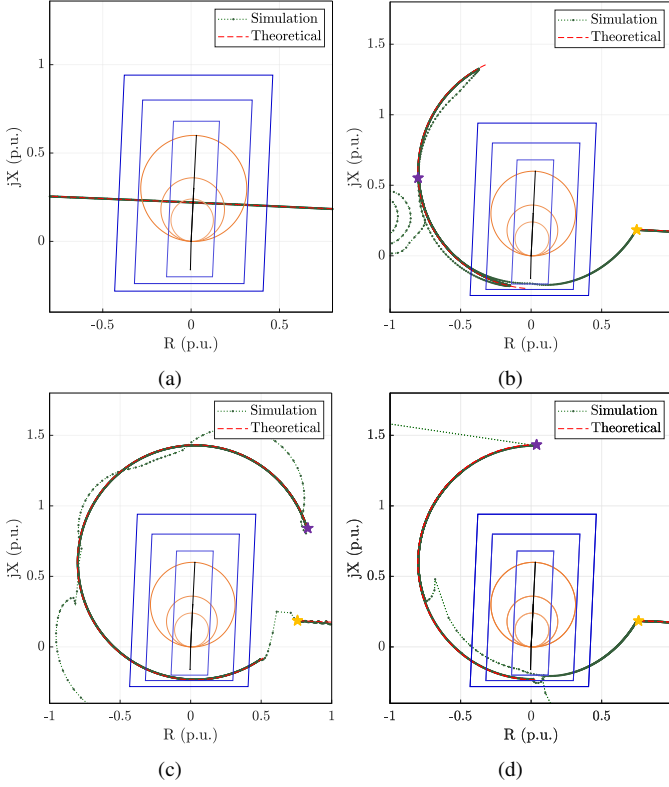


Fig. 12: The apparent impedance trajectories for Cases A, B, C, and D. The yellow stars indicate the critical points where the current enters saturation, while the purple stars mark where it exits saturation. (a) Case A: Without CSA. (b) Case B: Circular CSA. (c) Case C: D-axis priority CSA. (d) Case D: Q-axis priority CSA.

current saturation mode are on the circle, which is consistent with the theoretical analysis in Section IV. Cases B, C, and D also demonstrate that under different CSAs, the saturation exiting angles are distinct. These differences are reflected on the impedance plane as variations in the specific points where the trajectories exit the circular path. The locations of these exit points are determined by both δ_{exit} and θ_i . The theoretical saturation entry and exit angles, along with their corresponding simulation results as illustrated in the trajectories of Fig. 12, are presented in Table III. The yellow stars in Fig. 12 indicate the points where the GFM-IBR enters the saturation mode, while the purple stars indicate where it exits the saturation mode. The theoretical values show good agreement with the simulation results. Furthermore, the results in Fig. 12(b), (c),

TABLE III: Critical angles for entering and exiting saturation under different CSAs in Cases B to D

Unit: deg ($^\circ$)	Circular	D-Axis Priority	Q-Axis Priority
Theoretical Values			
δ_{enter}	54.26	54.26	54.26
δ_{exit}	± 42.30	± 16.41	± 2.34
$\delta_{\text{exit}} + \theta_i$	182.70	343.59	267.77
Simulation Results			
δ_{enter}	54.44	54.66	54.94
δ_{exit}	316.40	342.90	357.50
$\delta_{\text{exit}} + \theta_i$	179.10	343.80	269.80

and (d) verify that the rapid changes in the trajectory are caused by variations in the current phasor angle, which are

in turn triggered by sign changes in the i_d or i_q .

C. The Impact of CSAs on Power Swing Detection

The new features of apparent impedance trajectories introduced by CSAs can cause power swing detection to malfunction under certain conditions. Cases E and F illustrate two typical scenarios.

- Case E: D-axis priority CSA. $Z_g = 0.2$ p.u.; $Z_l = 0.2$ p.u. A three-phase-to-ground fault occurs at $t = 4$ s and then is cleared 150 ms later. The power swing detection settings are adjusted following the guidelines outlined in Section VI.A.
- Case F: D-axis priority CSA. $P_0 = 0.1$ p.u.; $I_{\text{max}} = 1.5$ p.u. Phase jump of -78.49° at $t = 4$ s.

The other conditions and settings remain consistent with those in TABLE I. Fig. 13(a) shows the apparent impedance trajectory of Case E. It can be observed that the full-cycle trajectory remains outside the three sets of blinders, meaning that neither stable nor unstable power swings can be correctly detected, resulting in the failure of both PSB and OST. Fig. 13(b) shows the apparent impedance trajectory in Case F. Under the conditions of Case F, the event is a stable power swing. However, due to the rapid changes in d-axis and q-axis currents caused by the transition process at the early stage of saturation, the time interval for the trajectory passing through the outer and middle blinders is $\Delta T = 0.0056$ s, which is shorter than $\Delta T_{\text{PSB}} = 0.033$ s. Consequently, the PSB misidentifies the power swing event as a fault event, leading to a malfunction.

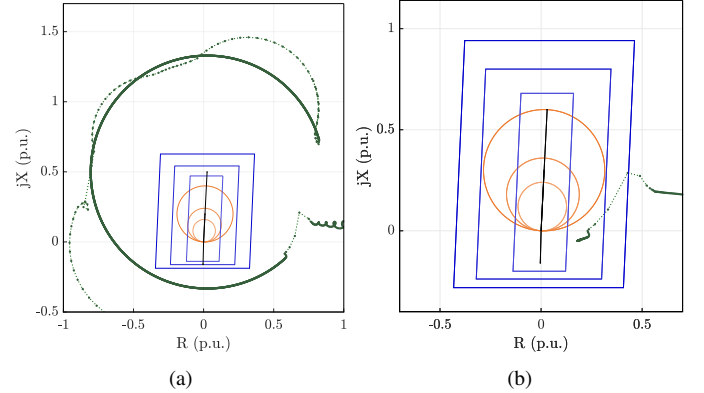


Fig. 13: The apparent impedance trajectories of Case E and Case F. (a) Case E. (b) Case F.

D. Current-Vector Angle-Holding Strategy to Prevent Malfunction

The proposed current vector angle holding strategy is designed to maintain continuity of the apparent impedance trajectory when the GFM IBR enters current saturation during a power swing. To verify its effectiveness, Case G-I and Case G-II are presented as follows.

- Case G-I: D-axis priority CSA. $Z_g = 0.2$ p.u.; $Z_l = 0.5$ p.u. $\Delta P_0 = +0.5$ at $t = 4$ s. The power swing detection settings are adjusted accordingly.

- Case G-II: Proposed current vector angle holding strategy. Under the system conditions of this case, the continuous-trajectory condition gives $\beta_c = -32.31^\circ$. Accordingly, the current vector angle at the saturation entry instant is recorded and maintained throughout the saturation period. The other system configuration and protection settings are the same as those in Case G-I.

The results of Cases G-I and G-II are shown in Fig. 14. Fig. 14(a) shows a rapid change in the trajectory when the current enters the saturation mode. The time duration during which the trajectory passes through the blinders is $\Delta t = 0.0054$ s. Fig. 14(b), with the proposed current vector angle holding strategy, exhibits a continuous trajectory. The duration of the trajectory passing through the blinders is $\Delta t = 0.043$ s, which is greater than the setting threshold $\Delta T_{PSB} = 0.033$ s for PSB operation.

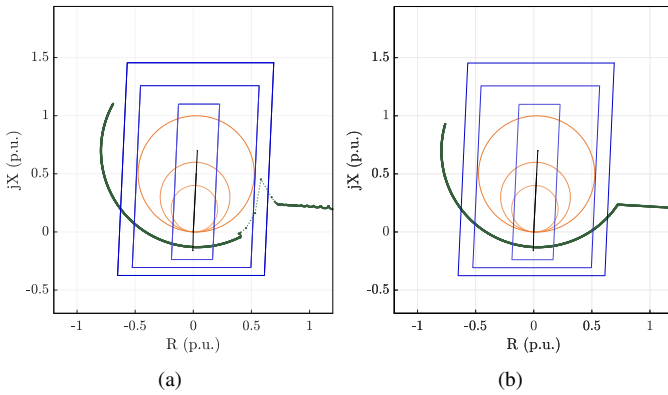


Fig. 14: The apparent impedance trajectories of Case G. (a) Case G-I. (b) Case G-II.

E. The Risk of Being Unable to Exit Saturation

Different CSAs lead to variations in the $P - \delta$ curve. For instance, the $P - \delta$ curve of the d-axis priority CSA is presented in Fig. 15. The $P - \delta$ curve affects not only the transient stability but also the steady-state behaviour of the system. As shown in Fig. 15, the point D indicates an SSEP, at which the system remains stable while the current is saturated. During the fault recovery process, the GFM IBR may become trapped at this SSEP, preventing successful recovery and leading to an undesirable outcome. This scenario is simulated in Case H, with the conditions described as follows.

- Case H: D-axis priority CSA. Phase jump of -216.76° at $t = 4$ s.

The other conditions remain consistent with those in TABLE I. Fig. 16 illustrates the results of Case H. The active power curve in Fig. 16(a) shows that the GFM IBR can output the expected active power. However, the power angle fails to return to the original SEP but instead settles at a new SSEP. The apparent impedance trajectory, shown in Fig. 16(b), oscillates along the circular path before eventually stabilising at a point on the circle. This phenomenon is a unique feature introduced by the CSAs of the GFM IBR and is not present in the conventional SG-based power swing model considered here.

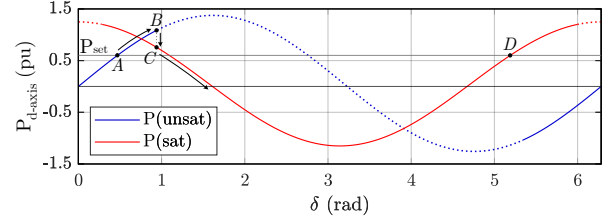


Fig. 15: $P - \delta$ curves for the d-axis priority CSA. The point D indicates an SSEP.

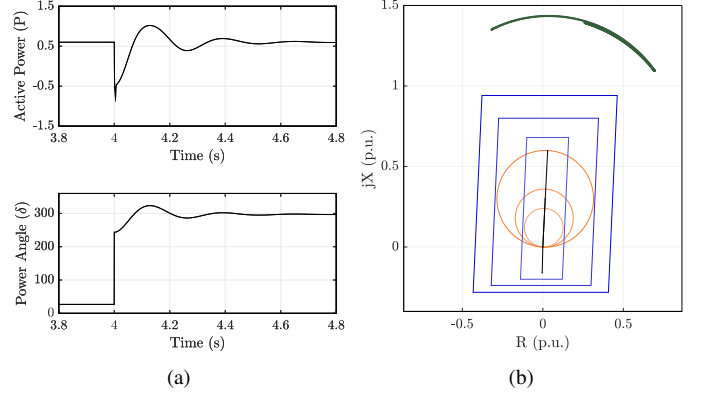


Fig. 16: The results of Case H. (a) The curves of active power (p.u.) and power angle (unit: degrees) variations over time. (b) The apparent impedance trajectory.

VII. EXTENDED VALIDATION ON A MODIFIED IEEE 9-BUS SYSTEM

To further validate the derived CSA-induced power swing trajectories and the effectiveness of the proposed mitigation strategy, extended case studies under varying operating conditions are conducted on a modified IEEE 9-bus system.

A. Modified IEEE 9-Bus Test System

Fig. 17 shows the topology of the modified IEEE 9-bus test system, and the corresponding system parameters are listed in Table IV.

B. Verification on the Modified IEEE 9-Bus System

To further validate the derived apparent impedance trajectories and evaluate the effectiveness of the proposed current vector angle holding strategy under different network topologies and operating conditions, simulations are conducted using the modified IEEE 9-bus system introduced in Section VII-A. One representative N-1 contingency and one representative N-2 contingency are considered. For each contingency, the post-fault apparent impedance trajectories obtained using the d-axis priority CSA and the proposed current vector angle holding strategy are compared. When a power swing-related saturation process is identified, the current vector angle at the saturation entry instant is recorded and maintained throughout the saturation period.

1) *N-1 Contingency*: Under the N-1 contingency, a three-phase-to-ground fault is applied to Line 8-9. Following fault clearance, the line is isolated by the circuit breakers at both terminals upon operation of relays R_{8-9} and R_{9-8} , thereby forming the corresponding N-1 post-fault network topology.

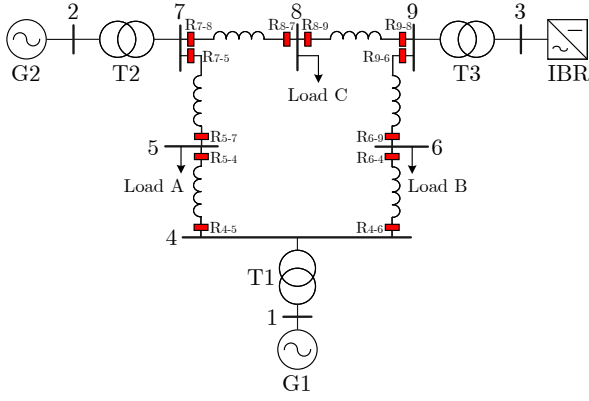


Fig. 17: Modified IEEE 9-bus system.

TABLE IV: Parameters of the modified IEEE 9-bus system

Component	Parameter	Value
System Base Values		
Power Base	S_{base}	100 MVA
Nominal Frequency	f_n	60 Hz
Voltage Level	V_{base}	230 kV
Generation and Load Parameters		
G1 at Bus 1	$V_{G1,base}$	16.5 kV
G2 at Bus 2	$V_{G2,base}, P_{G2}$	18 kV, 163 MW
G2 at Bus 2	Short-circuit level	900 MVA
G2 at Bus 2	X/R ratio	15
GFM IBR at Bus 3	$V_{IBR,base}, P_{IBR}$	13.8 kV, 85 MW
Load A at Bus 5	$P + jQ$	125 MW + j50 Mvar
Load B at Bus 6	$P + jQ$	90 MW + j30 Mvar
Load C at Bus 8	$P + jQ$	100 MW + j35 Mvar
GFM IBR Control Parameters		
Voltage controller	K_{pv}, K_{iv}	8, 10
Current controller	K_{pi}, K_{ii}	1.5, 10
Inertia constant	H	2 s
Damping coefficient	D_p	0.05
Current limit	I_{max}	1.2 p.u.
Transformer Parameters		
T1: Bus 1–4	Ratio, X	16.5/230 kV, 0.0576 p.u.
T2: Bus 2–7	Ratio, X	18/230 kV, 0.0625 p.u.
T3: Bus 3–9	Ratio, X	13.8/230 kV, 0.0800 p.u.
Transmission Line Parameters (p.u.)		
Line 4–5	R, X, B	0.0100, 0.0850, 0.1760
Line 4–6	R, X, B	0.0170, 0.0920, 0.1580
Line 5–7	R, X, B	0.0320, 0.1610, 0.3060
Line 6–9	R, X, B	0.0975, 0.4250, 0.8950
Line 7–8	R, X, B	0.0085, 0.0720, 0.1490
Line 8–9	R, X, B	0.0357, 0.3024, 0.6270

The fault and subsequent line outage disturb the power balance of the system and initiate a post-fault power swing. Under this operating condition, the current vector angle satisfying the continuous trajectory condition is theoretically calculated as $\beta_c \approx -6.192^\circ$ based on the equivalent network parameters. At the saturation entry instant, the current reference components are recorded as $i_{sd}^{ref} = 1.195$ p.u. and $i_{sq}^{ref} = -0.114$ p.u. According to (47), these values give the held current vector angle $\beta_h \approx -5.449^\circ$, which agrees closely with the theoretical value β_c . The angle β_h is then maintained throughout the saturation period. Fig. 18(a) and Fig. 18(b) show the post-fault apparent impedance trajectories measured at relay R_{9-6} using the d-axis priority CSA and the proposed current vector angle holding strategy, respectively. As shown in Fig. 18(a), under the d-axis priority CSA, the apparent impedance trajectory rapidly transitions from the unsaturated trajectory to the saturated

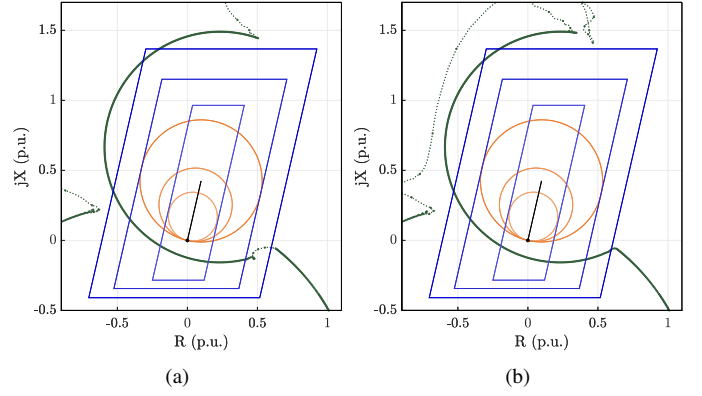


Fig. 18: Apparent impedance trajectories for N-1 contingency in the modified IEEE 9-bus system. (a) D-axis priority. (b) Proposed strategy.

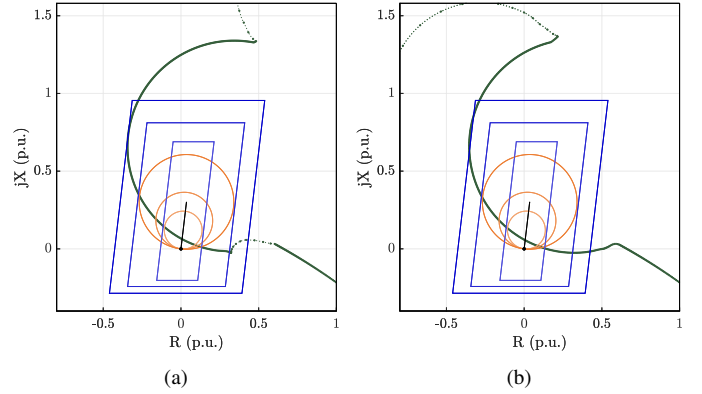


Fig. 19: Apparent impedance trajectories for N-2 contingency in the modified IEEE 9-bus system. (a) D-axis priority. (b) Proposed strategy.

circular trajectory, resulting in a noticeable discontinuity at the saturation entry point. This discontinuity occurs because the saturated current angle rapidly approaches 0° once the GFM IBR enters current saturation. In contrast, as shown in Fig. 18(b), the proposed current vector angle holding strategy maintains the recorded angle β_h , which closely matches the theoretical continuous-trajectory angle β_c . Consequently, the saturated trajectory starts from the critical saturation point of the unsaturated trajectory, thereby preserving trajectory continuity and reducing the risk of power swing detection malfunction.

2) *N-2 Contingency*: Under the N-2 contingency, G2 is assumed to be out of service for maintenance, while a three-phase-to-ground fault occurs on Line 6–9. Following fault clearance, Line 6–9 is isolated, forming the corresponding post-fault network topology. Under this operating condition, the theoretical continuous trajectory angle is $\beta_c \approx -13.672^\circ$. Using the same angle holding procedure introduced in Section V-B, the current reference components recorded at the saturation entry instant are $i_{sd}^{ref} = 1.174$ p.u. and $i_{sq}^{ref} = -0.268$ p.u., yielding $\beta_h \approx -12.859^\circ$. The obtained β_h agrees closely with β_c and is maintained throughout the saturation period. As shown in Fig. 19(a), the d-axis priority CSA causes a rapid transition of the apparent impedance trajectory at saturation

entry. In contrast, Fig. 19(b) shows that the proposed current vector angle holding strategy preserves trajectory continuity by maintaining β_h , further demonstrating the adaptability of the proposed strategy to different network topologies and conditions.

VIII. DISCUSSION AND PRACTICAL CONSIDERATIONS

This section provides further discussion on the dynamic performance and practical considerations associated with the analysis and mitigation strategy presented in this paper. The discussion also identifies aspects that require further investigation in future work.

A. The Impact of CSAs on Power System Stability

The presence of CSAs introduces new characteristics of the $P - \delta$ curve under the current saturation mode. Fig. 20 illustrates the $P - \delta$ curves for both unsaturated and saturated modes under different current limiting strategies. Specifically, Fig. 20(a)–(d) correspond to the circular CSA, d-axis priority CSA, q-axis priority CSA, and proposed strategy, respectively. The blue curves represent the $P - \delta$ characteristics in the unsaturated mode, while the red curves represent the corresponding characteristics in the current saturated mode. The solid parts of the curves indicate the actual $P - \delta$ trajectory followed by the system in the corresponding operating mode. The dashed blue parts are the theoretical extensions of the unsaturated $P - \delta$ curve after the current limit has been reached, and therefore are not followed because the IBR has entered current saturation. The dashed red parts denote the extensions of the saturated mode $P - \delta$ curves outside the corresponding current saturated operating region.

Taking Fig. 20(a) as an example, the system initially operates at point A, where the current is unsaturated and the output active power is balanced with the active power set point. After a disturbance, the power angle δ increases, and the active power follows the blue unsaturated $P - \delta$ curve until point B, where the current reaches its limit, and the IBR enters the current saturation mode. Once the circular CSA is activated, the active power characteristic changes from the blue unsaturated curve to the red saturated curve. Since the power angle δ cannot change instantaneously, the operating point moves rapidly from point B to point C, resulting in an abrupt change in active power. As δ continues to increase, the active power then evolves along the red saturated $P - \delta$ curve. Similar transitions can be observed under the d-axis priority and q-axis priority CSAs in Fig. 20(b) and (c), respectively. In Fig. 20(d), the proposed strategy avoids the active power jump at the saturation entry point. The operating point enters the saturated mode $P - \delta$ curve continuously. These CSA-induced changes in the $P - \delta$ curve modify the accelerating and decelerating areas during the current limiting period, thereby adversely affecting the transient angle stability margin. In comparison, the proposed strategy provides a smoother transition at saturation entry and retains a larger decelerating area, indicating a less severe impact on transient angle stability.

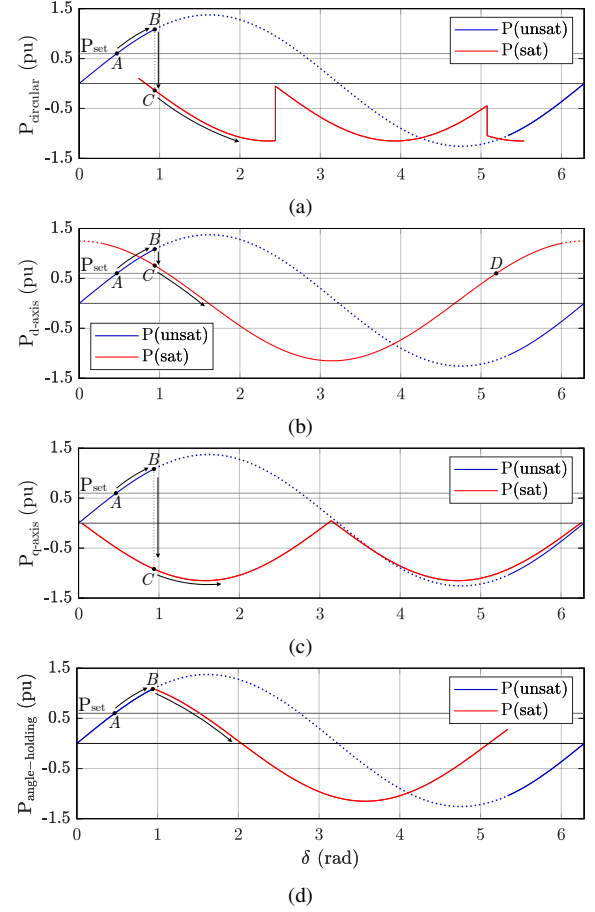


Fig. 20: $P - \delta$ curves for the four types of CSAs. (a) Circular. (b) D-axis priority. (c) Q-axis priority. (d) Proposed current vector angle-holding strategy.

To provide a quantitative comparison, the active power area above the power set point is calculated. The corresponding power-area index is defined as

$$A_P = \int_{\delta_c}^{\delta_e} \max [P_{\text{act}}(\delta) - P_{\text{set}}, 0] d\delta, \quad (50)$$

where $P_{\text{act}}(\delta)$ accounts for both $P(\text{unsat})$ and $P(\text{sat})$, δ_c denotes the angle of point A in Fig. 20 and δ_e denotes the end of the interval. This formulation includes both the unsaturated and saturated portions of the active power trajectory, while only the area above P_{set} is accumulated. Under the same fault and operating conditions, a larger A_P indicates that a greater active power contribution above the set point is maintained during the post-fault response, implying a more favourable power angle recovery characteristic. For the quantitative comparison, the active power areas are calculated under the grid condition of $P_{\text{set}} = 0.6$ p.u. and total impedance $Z_T = 0.76$ p.u. Under this operating condition, the initial stable power angle is 26.85° , and the positive critical angle for entering current saturation is 54.26° . The same grid parameters are applied to all CSAs to ensure a consistent comparison. The calculated power area indices under different current saturation algorithms are summarised in Table V. The proposed strategy produces the largest active power area above P_{set} , confirming

TABLE V: Active power area above P_{set} under different CSAs

A_P (p.u.·rad)	Circular	D-priority	Q-priority	Proposed
	0.1249	0.1360	0.1249	0.2793

that the proposed strategy has a less adverse effect on the power angle recovery process.

Under normal unsaturated operating conditions, the CSA is inactive and does not alter the small-signal model around the normal operating point. The small-signal stability impact of different CSA mechanisms is beyond the main scope of this paper.

B. SSEP Risk and Practical Mitigation

The $P - \delta$ curves in Fig. 20 provide a comparison of the SSEP risk under different CSAs. Among the three conventional CSAs considered in this paper, the SSEP trapping risk is observed under the d-axis priority CSA. As shown in Fig. 20(b), the intersection between the red saturation mode $P - \delta$ curve and the active power set point introduces a stable equilibrium point D that can keep the GFM IBR in the current saturation mode. In contrast, the saturated $P - \delta$ curves of the circular CSA and the q-axis priority CSA do not intersect the active power set point within the saturation operating region; therefore, no SSEP trapping is observed for these two CSAs. The proposed current vector angle holding strategy, which is designed to mitigate power swing detection malfunction by maintaining apparent impedance trajectory continuity, also does not introduce SSEP trapping in the presented results.

Avoiding trapping in the saturated state generally requires a stability-oriented current limiting design. A practical approach is to tune the saturated current angle, or modify the current limiting logic, so that the current saturated equilibrium point lies outside the region in which the converter can remain in current saturation. For example, the saturated current angle can be optimised by considering the current saturated equilibrium point together with the entering and returning angle sets [39].

C. Future Research Direction

The proposed current vector angle holding strategy mitigates the problem from the control side by reducing apparent impedance trajectory discontinuities. It is therefore complementary to improved protection schemes, rather than a replacement for them. For IBR-dominated systems, future protection schemes may need to incorporate additional trajectory features to improve their robustness under non-conventional impedance trajectories.

The proposed strategy is activated only when current saturation is caused by a power swing. If it is not activated, the original GFM IBR control remains unchanged, and other network performance aspects are not affected. Its small-signal stability impact under current saturation mode will be considered in future work. In addition, although the proposed strategy has been validated through electromagnetic transient simulations, further experimental validation, such as hardware-in-the-loop tests, would provide additional evidence of its practical implementation performance. These aspects will be investigated in future work.

IX. CONCLUSION

This paper provides a theoretical analysis of the conditions for entering and exiting current saturation under different CSA-based current limiting strategies. Additionally, it investigates how CSAs affect the apparent impedance trajectories, in comparison with those in conventional SG-based systems. The conclusions are summarised as follows.

1) The sets of angles over which circular, d-axis priority, and q-axis priority CSAs enter and exit the current saturation mode are not complementary. They enter saturation under the same angular conditions, but the criteria for exiting saturation differ among the three CSA strategies.

2) Under certain conditions, the circular power swing trajectory introduced by the circular, d-axis priority, and q-axis priority CSAs may cause both PSB and OST to fail, as the trajectory might bypass the blinders during the power swing. Furthermore, the rapid trajectory variations during the transient process of entering current saturation may also lead to malfunction of the PSB.

3) By holding the current vector angle at its saturation entry value, the proposed strategy maintains continuity of the apparent impedance trajectory during the transition from the unsaturated to the saturated mode. This avoids the rapid trajectory transition introduced by conventional CSAs and thereby reduces the risk of power swing detection malfunction.

4) The d-axis priority CSA may cause the GFM IBR to become trapped in an SSEP. In this scenario, the current cannot exit saturation, leading the apparent impedance trajectory to stabilise at a point on the circular path. This is a unique feature introduced by the CSA-based current limiting strategy.

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