

Control of Grid-Forming VSCs: A Perspective of Adaptive Fast/Slow Internal Voltage Source

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Abstract—Grid-forming (GFM) capability requirements are increasingly imposed on grid-connected voltage-source converters (VSCs). Under large grid disturbances, GFM-VSCs need to remain stable while providing GFM services. Yet, such objectives, as pointed out in this article, inherently lead to conflicting requirements on the dynamics of the internal voltage source (IVS) of GFM-VSCs, i.e., the fast IVS dynamics is needed to avoid the loss of synchronism with the grid, whereas the slow IVS dynamics is preferred for maintaining GFM capability. To tackle this challenge, an adaptive fast/slow IVS control is proposed, which switches GFM-VSC between fast and slow IVS dynamics based on system needs. The proposed method enhances the transient stability of GFM-VSC while maximizing its capability of providing GFM service. Further, the approach is robust to different grid strengths and different types of grid disturbances. The experimental results verify the theoretical findings and the effectiveness of the proposed control method.

Index Terms—Grid-forming (GFM), robustness, transient stability, voltage-source converters (VSCs).

I. INTRODUCTION

THE grid-forming (GFM) control is emerging as a promising approach for the massive integration of voltage-source converters (VSCs) into electrical grids [1], [2]. Differing from the legacy grid-following (GFL) control that operates VSC as an *external-voltage-dependent current source*, the GFM-VSC is controlled as a *voltage source behind the impedance*, and hence, its stable operation does not rely on the voltage stiffness of ac grid [3], [4]. It is well documented that GFM-VSCs exhibit superior small-signal stability over GFL-VSCs under weak ac grids [5], [6]. The recent study further shows that with the proper design of the controller, the small-signal stability of GFM-VSC can be guaranteed with a wide variation of grid strength and operating points [7].

On top of the small-signal stability, control of GFM-VSC under large grid disturbances, including voltage sags, phase-angle jumps, high rate of change of frequency (RoCoF), and the combination thereof, is also of concern. Except for current limitation [8], [9], [10], GFM-VSCs should also remain

synchronous with the grid (i.e., transient stability) during and after different large disturbances [11]. Extensive studies are reported to enhance the transient stability of GFM-VSCs, which can, in general, be categorized into the following two groups.

- 1) Guaranteeing the existence of equilibrium points (EPs) during large disturbances, which is typically realized by modifying the active/reactive power references of GFM-VSC [12], [13], [14], and by optimizing the current limitation algorithm [15].
- 2) Optimizing the dynamic response of GFM-VSC to guarantee the system convergence to stable EPs (SEPs), which can be achieved by increasing the equivalent damping of GFM-VSC through shaping the active power control (APC)/reactive power control (RPC) loop [16], [17], [18], [19], or using the mode-adaptive control [20], [21].

While transient stability is an essential requirement, grid codes are evolving with more capability requirements on GFM-VSCs. More specifically, GFM-VSCs are expected to provide adequate services under grid disturbances, including the provisions of active inertia power to alleviate the RoCoF of the power grid, active phase jump power to counteract the step change of phase angle of grid voltage, as well as the fast fault current injection to boost system voltage during grid faults [22]. Those GFM capabilities are crucial for restoring the power system from abnormal events [23]. Hence, many research efforts have also been made to enhance the GFM capability of VSC by optimizing its APC/RPC loops [24], [25], [26].

The state-of-the-art control solutions have made significant progress in enhancing either transient stability or GFM capabilities of VSCs under large grid disturbances. However, few of them address these two requirements at the same time, even though it is demanded in practice [16], [17], [18]. In [16], it is demonstrated that increasing virtual inertia may lead to improved GFM capability in alleviating the RoCoF of the system, but at the cost of degraded transient stability. Subsequently, Xiong et al. [17], [18] proposed different damping solutions to mitigate this conflict. However, these solutions have several limitations.

- 1) They have only been tested under specific grid strength and single type of grid disturbance, namely grid voltage dips.
- 2) The entire analysis relies on a strong assumption that the current limit of the GFM-VSC is not triggered during grid disturbances, which might not hold in practice [16], [17], [18].

To tackle the abovementioned challenges, this article, thus, revisits the underlying control philosophy that guarantees the transient stability and GFM capability of GFM-VSCs, from the

Manuscript received 4 October 2022; revised 14 February 2023; accepted 15 April 2023. Date of publication 19 April 2023; date of current version 21 June 2023. Recommended for publication by Associate Editor G. Seo. (Corresponding author: Xiongfei Wang.)

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Color versions of one or more figures in this article are available at <https://doi.org/10.1109/TPEL.2023.3268374>.

Digital Object Identifier 10.1109/TPEL.2023.3268374

perspective of internal voltage source (IVS) dynamics. *It is, for the first time, revealed that these two control objectives impose conflicting requirements on the IVS dynamics of GFM-VSC.* More specifically, a slow IVS dynamics is demanded to facilitate GFM-VSC to provide GFM services [4], yet on the other hand, a fast IVS dynamics is needed for enhancing the transient stability of GFM-VSCs. *Therefore, existing control solutions that using the fixed slow IVS control for GFM capability enhancement tend to jeopardize the transient stability of the system, and vice versa.* To tackle this challenge, a high-level, implementation-agnostic control framework, named adaptive fast/slow IVS control, is proposed in this work to better coordinate the requirement of GFM capability and transient stability. The approach furnishes GFM-VSCs with slow IVS control when there are sufficient stability and current margins for providing GFM service, yet operates GFM-VSC with fast IVS control when its current limit is reached or it operates with a large power angle in order to prevent the loss of synchronization (LOS). A detailed realization of such adaptive fast/slow IVS control is further put forward, including:

- 1) a control-mode switching criterion that is based on the local output current magnitude of VSC is proposed, which is readily implemented in practice;
- 2) a standard slow APC/RPC scheme is adopted for enabling slow IVS dynamics of the GFM-VSC;
- 3) two widely used control methods for transient stability enhancement, i.e., hybrid-synchronization control (HSC) [12], [27], [28] and voltage magnitude-based active power reference adjustment [13], [14], [29], are revisited from the fast IVS control perspective. It is revealed that they have degraded performance under the weak grid. A fast IVS control that modifies the active power reference based on the output current magnitude is thus added to enhance the transient stability of GFM-VSC under the weak grid.

Finally, experimental tests are performed to corroborate the theoretical analysis and the proposed control approach. The proposed adaptive fast/slow IVS control outperforms the state-of-the-art solutions in [16], [17], and [18] with the following advantages.

- 1) Robustness against various grid strengths (from very weak grid to stiff grid) and different types of grid disturbances, including grid voltage dips, phase angle jumps, high RoCoF, and the combinations thereof.
- 2) The proposed scheme does not rely on any assumptions and remains effective even when the current limit of the GFM-VSC is triggered during grid disturbances.

Moreover, the proposed adaptive fast/slow IVS control is an open framework without any limitations on how fast/slow IVS control should be implemented (although an implementation example is given in this work). Hence, the more advanced fast and/or slow IVS control developed in the future can also be seamlessly incorporate within this control framework for further performance improvement.

II. IMPACT OF FAST AND SLOW IVS CONTROL

A. System Description

There are many GFM control schemes available in the literature [3], [4]. Among others, the GFM-VSC with single-loop

voltage magnitude (SLVM) control and adaptive virtual impedance (VI) based current limitation, as shown in Fig. 1, is adopted as the benchmark in this work [30], [31], [32]. Nevertheless, the core idea of this work is generic and can be easily extended to GFM-VSCs with other control schemes. As shown in Fig. 1, the GFM-VSC is connected to the point of common coupling (PCC) through an LC filter, and Z_g represents the grid impedance. P_o/Q_o and v_o/i_o denote the output active/reactive power and output voltage/current of VSC, while v_{inv} and v_g are the inverter bridge voltage and grid voltage, respectively.

The GFM-VSC synchronizes with the power grid through the APC, in which the active power–frequency ($P-\omega$) droop control as well as the inertial and damping emulation are embedded [33], as shown in Fig. 1. The output of the APC is the angle reference θ_{ref} that is used for the dq transformation. ω_n denotes the nominal angular frequency. D is the $P-\omega$ droop coefficient. K_p and H represent the virtual damping and inertia constant, respectively. It is worth noting that the emulated virtual inertia has the same effect as that of a low-pass filter (LPF) [34], and hence, no additional LPF is needed after the active power measurement.

The voltage magnitude reference of GFM-VSC is regulated by the RPC, e.g., the reactive power–voltage ($Q-V$) droop control shown in Fig. 1 [3]. V_{ref} is the voltage magnitude reference while V_n is the nominal voltage magnitude. K_{RPC} is the $Q-V$ droop coefficient. G_{LPFq} represents a first-order LPF used for the reactive power measurement.

The SLVM control uses an integrator K_{iv}/s to regulate the output voltage magnitude of VSC ($V_{omag} = \sqrt{v_{od}^2 + v_{oq}^2}$) to track V_{ref} [30], and a first-order LPF G_{LPFv} is adopted to filter out the high-frequency noise in V_{omag} . The active damping resistor R_{ad} is added at the output of K_{iv}/s to damp the synchronous resonance introduced by the power control [5]. R_{ad} is typically cascaded with a high-pass filter $G_{HPF} = s/(s + \omega_{HPF})$ to eliminate its impact on the steady-state power control performance [5], and ω_{HPF} represents the cutoff frequency of G_{HPF} .

The adaptive VI is used to limit the current of GFM-VSC under large grid disturbances, the general idea of which is to adjust the value of VI based on the fault current magnitude, as shown in Fig. 1. X_v and R_v represent the adaptive virtual reactor and virtual resistor, respectively, which are given by [31], [32]

$$X_v = \begin{cases} k_X (G_{LPFi} I_{omag} - I_{th}), & \text{if } I_{omag} \geq I_{th} \\ 0, & \text{if } I_{omag} < I_{th} \end{cases}$$

$$R_v = \frac{X_v}{n_{X/R}} \quad (1)$$

where I_{omag} denotes the magnitude of the output current of VSC, and I_{th} is the threshold current beyond which the adaptive VI will be activated. k_X is the proportional gain of the adaptive virtual reactor and $n_{X/R}$ represents the X/R ratio of the adaptive VI. G_{LPFi} is the first-order LPF used for measuring I_{omag} . v_{zd} and v_{zq} represent the fictitious voltage drop across the VI, which is calculated as

$$v_{zd} = i_{od}R_v - i_{oq}X_v$$

$$v_{zq} = i_{oq}R_v + i_{od}X_v. \quad (2)$$

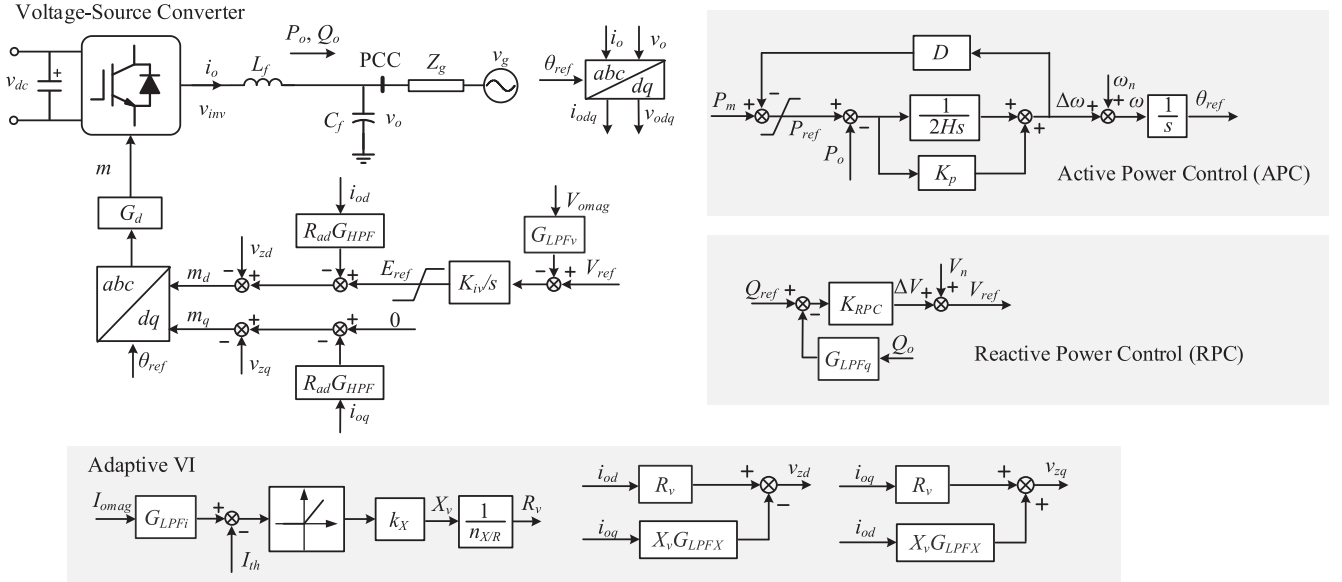


Fig. 1. GFM-VSC with the SLVM control and adaptive VI-based current limitation.

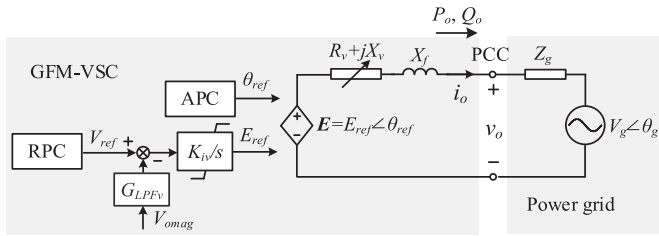


Fig. 2. Equivalent circuit of the VSC-grid system.

The emulation of VI is realized by subtracting the fictitious voltage drop $v_{zd} + jv_{zq}$ from the voltage reference $E_{ref} + j0$, as shown in Fig. 1. G_{LFPX} represents the first-order LFP used for calculating v_{zdq} , whose purpose is to guarantee the small-signal stability when the adaptive VI is activated [32]. For the detailed parameters tuning of the adaptive VI, refer to [32].

Fig. 2 illustrates the equivalent circuit of the VSC-grid system, where GFM-VSC is represented by a controlled voltage source behind the impedance. Since the focused timescale of this work is longer than the fundamental period, the filter capacitor branch in Fig. 1 can be treated as an open circuit due to its large impedance in the low frequency range [5].

B. Fast or Slow IVS Control: Performance Comparison

This section intends to perform a conceptual comparison of GFM-VSC with slow and fast IVS control. For simplicity, the resistive part of the VI, filter impedance, and grid impedance are neglected due to the high X/R ratio in the transmission grid. X_{tot} represents the total reactance, which is calculated as $X_{tot} = X_v + X_f + X_g$. Defining the power angle δ as the phase difference between the internal voltage phasor of GFM-VSC E and grid voltage phasor V_g , i.e., $\delta = \theta_{ref} - \theta_g$, and the output active power of GFM-VSC can be calculated as [unless otherwise mentioned, the per-unit (p.u.) representation is adopted in

this work afterward] [35]

$$P_o = \frac{E_{ref} V_g}{X_{tot}} \sin \delta. \quad (3)$$

Fig. 3 illustrates the P_o - δ curve as well as phasor diagram of GFM-VSC when subjected to a small grid disturbance, e.g., a small phase angle jump of grid voltage. The solid and dashed lines represent phasors before and after grid disturbances, respectively, while variables after the disturbance are represented with the prime symbol, e.g., E' . The GFM-VSC is initially operated at the SEP a with power angle δ_s . By adopting the slow IVS control, the internal voltage phasor E can be kept almost unchanged at the instant of grid phase angle jump, leading to a sudden increase of δ from δ_s to δ'_s , and consequent increase of the output current I_o and output active power P_o , as shown in Fig. 3(a). The fast provision of this additional active power under phase angle jump of the grid voltage (defined as “active phase jump power” in the grid code [22]) has been proven crucial for maintaining the power system stability. Moreover, since the change of the grid frequency finally ends up with the grid phase angle shifts, the GFM-VSC with a slow IVS control is also capable of providing fast active inertia power injection under grid frequency drifts, which is beneficial for alleviating the RoCoF of the power grid [22].

In contrast, the fast IVS control enables a tight regulation of the output active and reactive power of GFM-VSC to follow their references. This is realized by modifying the internal voltage phasor E in a fast manner to “follow” the change of the grid voltage phasor V_g , by which, there is a limit change on δ (also I_o and P_o) under the grid phase angle jump, as shown in Fig. 3(b). In that case, however, the GFM-VSC would have limited responses to grid disturbances, and thus, its benefit in stabilizing the power system is diminished.

While the slow IVS control is crucial for maintaining GFM capability, it risks in destabilizing GFM-VSC itself under large grid disturbances (e.g., 60° phase angle jump required in the

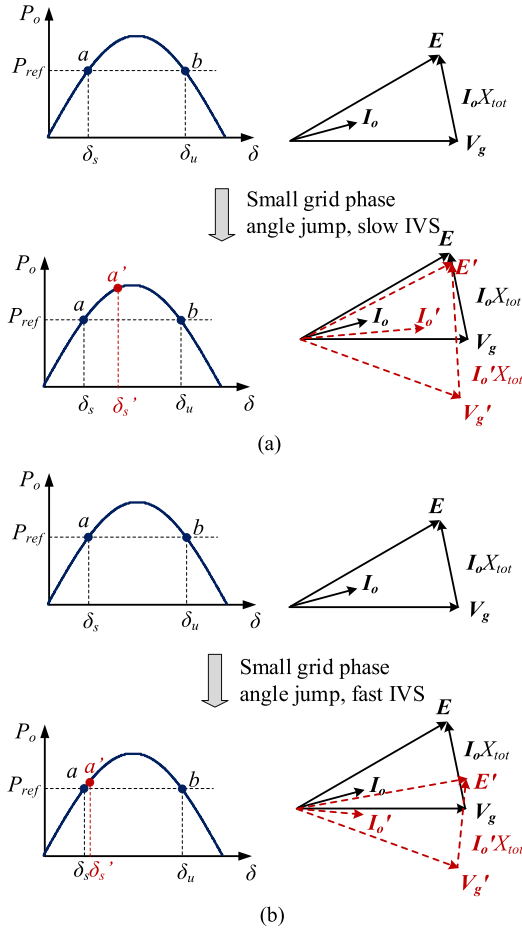


Fig. 3. Phasor diagram of GFM-VSC when subjected to small grid phase jump. The solid and dashed lines represent phasors before and after grid disturbances, respectively, and the prime symbol is used to denote variables after the disturbance. (a) With a slow IVS control, additional active output power is generated. (b) With a fast IVS control, limited or no additional active output power is generated.

grid code [22]). As shown in Fig. 4(a), GFM-VSC with slow IVS control might yield a very large δ under a large phase angle jump, which results in the crossover of the unstable EP (UEP) b . Then, since $P_{ref} > P_o$ at new operating point a' , δ will further increase, and finally, the LOS is resulted [11]. In contrast, the fast IVS control enables the fast modification of internal voltage phasor E to “follow” the change of the grid voltage phasor V_g such that the change of δ is limited even under a large phase angle jump of the power grid, as shown in Fig. 4(b). Hence, the LOS is avoided.

Table I summarizes the performance comparison of GFM-VSC with fast or slow IVS control. It can be seen that the slow IVS control is beneficial for maintaining GFM capability, yet it might jeopardize the transient stability of VSC under severe grid disturbances. The fast IVS control introduces the opposite effect.

It is worth mentioning that even though the performance comparison of GFM-VSC with fast/slow IVS control is made by considering the phase angle jump of the grid voltage, the same conclusions also hold for grid voltage dips (grid faults), which can be easily demonstrated by following the similar analysis procedure and will not be repeated here due to the page limit.

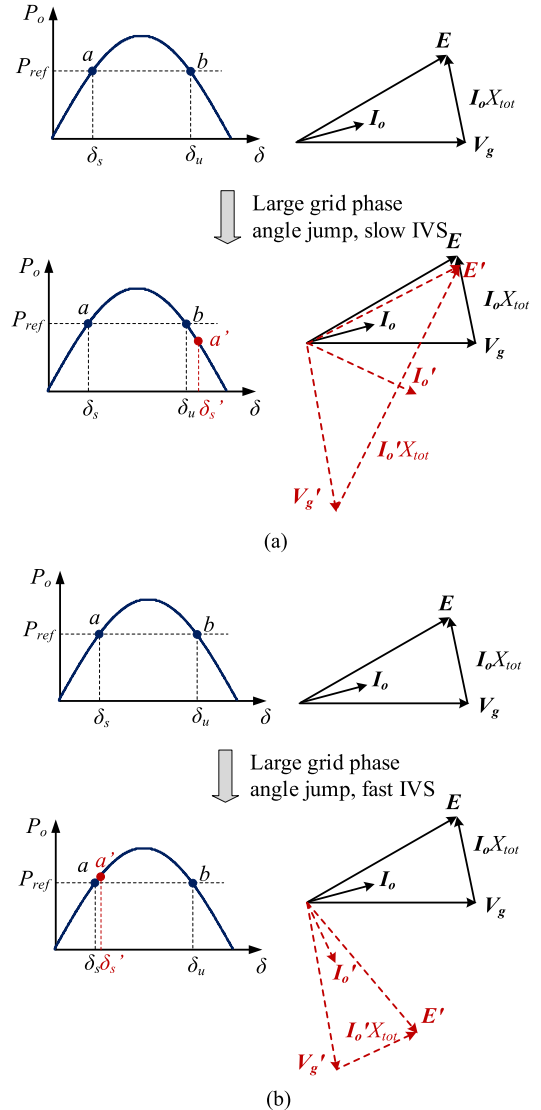


Fig. 4. Phasor diagram of GFM-VSC when subjected to large grid phase jump. The solid and dashed lines represent phasors before and after grid disturbances, respectively, and the prime symbol is used to denote variables after the disturbance. (a) With a slow IVS control, LOS is resulted. (b) With a fast IVS control, LOS is prevented.

TABLE I
PERFORMANCE COMPARISON BETWEEN FAST AND SLOW IVS CONTROL

	Slow IVS control	Fast IVS control
Features	Slow dynamics of internal voltage phasor E	Fast dynamics of internal voltage phasor E
GFM capability	√	×
Large-signal stability	×	√

III. ADAPTIVE FAST/SLOW IVS CONTROL

A. Basic Idea

As pointed out in Section II-B, the GFM-VSC with a slow IVS control can naturally provide GFM service to counteract grid disturbances. Yet, from the transient stability perspective, a fast

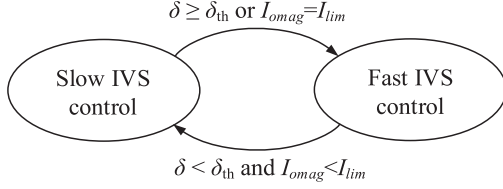


Fig. 5. General idea of the adaptive fast/slow IVS control.

IVS control is preferred to minimize the risk of LOS. These conflicting control requirements make it difficult to simultaneously enhance the transient stability and GFM capability with a fixed control scheme. Therefore, an adaptive fast/slow IVS control is proposed in this work, which switches GFM-VSC between fast and slow IVS control based on its operation conditions, as shown in Fig. 5. The design principles of the adaptive fast/slow IVS control are as follows.

- 1) Since GFM-VSC cannot provide any additional power/current for GFM service after reaching its current limit ($I_{omag} = I_{lim}$), adopting the slow IVS control in this scenario does not make sense. Therefore, GFM-VSC is always operated with the fast IVS control to avoid the LOS under the current limiting mode.
- 2) In the case that the current limit of GFM-VSC is not reached ($I_{omag} < I_{lim}$), the risk of LOS is low when it is operated with small power angle [3]. Consequently, maintaining GFM capability should be prioritized by adopting the slow IVS control. However, the fast IVS control should be used to prevent the LOS when GFM-VSC is operated with large power angle. Hence, the mode switching between fast/slow IVS control can be realized by comparing the power angle δ with a predefined threshold δ_{th} , as shown in Fig. 5. The selection of δ_{th} will be discussed afterward.

Nevertheless, it is known from (3) that the calculation of δ requires the knowledge of grid voltage and of grid impedance [36], which is challenging in practice. Therefore, a switching criterion based on local measurements should be developed for the practical implementation. The selected local variable x should hold a monotonic relationship with δ such that the original switching criterion based on the comparison between δ and δ_{th} can be mapped to comparing x and x_{th} . Moreover, the impact of different short-circuit ratio (SCR) and V_g should also be considered to guarantee the robustness of the switching criterion.

B. I_{omag} -Based Switching Criterion

It is known from Fig. 5 that the local measurement variable I_{omag} is always needed to check whether GFM-VSC is operated under the current limit mode. Therefore, it is interesting to first investigate whether I_{omag} holds a monotonic relationship with δ before reaching the current limitation, such that the δ -based switching criterion can be mapped to the I_{omag} -based switching criterion.

It is known from Fig. 2 that the internal voltage phasor E is aligned with the dq -frame defined by the output phase angle of the APC. Based on Fig. 2, the dq components as well as the

magnitude of the output current can be calculated as

$$I_{od} + jI_{oq} = \frac{E_{ref} + j0 - (V_{gd} + jV_{gq})}{jX_{tot}} \quad (4)$$

$$I_{omag} = \sqrt{I_{od}^2 + I_{oq}^2} \quad (5)$$

where

$$V_{gd} = V_g \cos \delta \quad (6)$$

$$V_{gq} = -V_g \sin \delta \quad (7)$$

$$X_{tot} = X_f + X_g. \quad (8)$$

Substituting (4), (6)–(8), into (5), which yields

$$I_{omag} = \frac{\sqrt{E_{ref}^2 + V_g^2 - 2E_{ref}V_g \cos \delta}}{X_f + X_g}. \quad (9)$$

Substituting $\delta = \delta_{th}$ into (9), which yields

$$I_{omag_th} = \frac{\sqrt{E_{ref}^2 + V_g^2 - 2E_{ref}V_g \cos \delta_{th}}}{X_f + X_g}. \quad (10)$$

It is known from (9) that I_{omag} is monotonously increased with the increase of δ before triggering the current limitation, which yields $I_{omag} < I_{omag_th} \leftrightarrow \delta < \delta_{th}$. Yet, it is clear from (10) that I_{omag_th} is not a constant value for specific δ_{th} , but is affected by two other variables, i.e., grid impedance X_g and grid voltage V_g . Define $I_{omag_th_min}$ is the minimum value of I_{omag_th} considering different X_g and V_g , the sufficient condition for $\delta < \delta_{th}$ becomes $I_{omag} < I_{omag_th_min}$. To calculate $I_{omag_th_min}$, the largest possible value of X_g , i.e., $X_g = 1$ p.u. (corresponding SCR = 1) is considered as X_g appears in the denominator of (10). On the other hand, the value of V_g for calculating $I_{omag_th_min}$ can be obtained by solving

$$\frac{dI_{omag_th}}{dV_g} = \frac{d\left(\sqrt{E_{ref}^2 + V_g^2 - 2E_{ref}V_g \cos \delta_{th}}\right)}{dV_g} = 0 \quad (11)$$

which yields

$$V_g = E_{ref} \cos \delta_{th}. \quad (12)$$

Since V_g cannot be a negative value, the value of V_g that is used for calculating $I_{omag_th_min}$ is given by

$$V_g = \begin{cases} E_{ref} \cos \delta_{th}, & \text{if } \delta_{th} < 90^\circ \\ 0, & \text{if } \delta_{th} \geq 90^\circ \end{cases}. \quad (13)$$

Substituting (13) into (10), $I_{omag_th_min}$ can be calculated as

$$I_{omag_th_min} = \begin{cases} \frac{E_{ref} \sqrt{1 - \cos^2 \delta_{th}}}{X_f + X_g}, & \text{if } \delta_{th} < 90^\circ \\ \frac{E_{ref}}{X_f + X_g}, & \text{if } \delta_{th} \geq 90^\circ \end{cases}. \quad (14)$$

Considering a typical 0.1 p.u. filter reactance, i.e., $X_f = 0.1$ p.u., together with $X_g = 1$ p.u. and $E_{ref} = 1.1$ p.u. (in order to maintain 1 p.u. PCC voltage, E_{ref} is slightly higher than 1 p.u. to compensate the voltage drop across X_f [30]), the $I_{omag_th_min}$ - δ_{th} curve can be plotted based on (14), as shown in Fig. 6. It is clear that the maximum value of $I_{omag_th_min}$ is around 1 p.u., which is lower than current limit of GFM-VSC, e.g., $I_{lim} = 1.5$

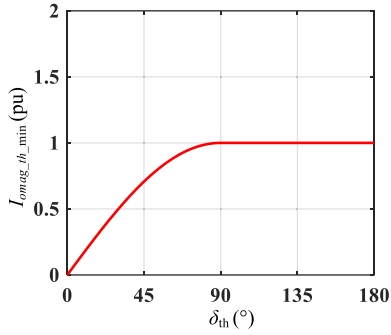


Fig. 6. $I_{omag_th_min}$ - δ_{th} curve.

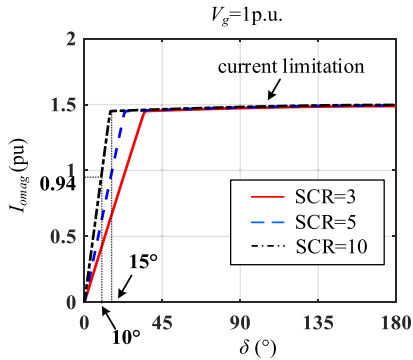


Fig. 7. I_{omag} - δ curve of GFM-VSC. $V_g = 1$ p.u. with different SCR.

p.u. selected in this work. Therefore, $I_{omag} < I_{omag_th_min}$ is the sufficient condition for both $\delta < \delta_{th}$ and $I_{omag} < I_{lim}$. Therefore, two switching criteria given by Fig. 5 can be combined, i.e., the GFM-VSC is operated with a slow IVS control provided $I_{omag} < I_{omag_th_min}$, otherwise it is switched to the fast IVS control.

The value of $I_{omag_th_min}$ is dependent on δ_{th} , which should be selected smaller than δ_u (i.e., the corresponding power angle of the UEP b , see Fig. 4) to avoid the LOS [35]. It is noted that $\delta_u = 90^\circ$ is yielded under the worst case where $SCR = 1$ [3], and hence, $\delta_{th} < 90^\circ$ is required. A smaller δ_{th} can better guarantee the transient stability of GFM-VSC, yet it jeopardizes the GFM capability. Therefore, a tradeoff is needed in practice. In this article, $\delta_{th} = 70^\circ$ selected, which leads to $I_{omag_th_min} = 0.94$ p.u. based on (14).

C. Discussion and Practical Realization

It should be noted that $I_{omag} = 0.94$ p.u. $\leftrightarrow \delta = 70^\circ$ only holds under the worst scenario where $SCR = 1$ and V_g satisfies (13). In other cases, e.g., stiffer grid conditions, I_{omag} may reach 0.94 p.u. with a much smaller δ . As seen from the I_{omag} - δ curve given by Fig. 7, $I_{omag} = 0.94$ p.u. $\leftrightarrow \delta = 10^\circ$ is yielded with $SCR = 10$ and $V_g = 1$ p.u. In this scenario, one might argue that the proposed I_{omag} -based switching criterion may unnecessarily switch GFM-VSC to the fast IVS control when it is operated with a small δ (e.g., 10°). However, it should be noted that the current limitation of GFM-VSC will also be triggered with a small δ under the stiff grid [$I_{omag} = I_{lim}$ (1.5 p.u.) $\leftrightarrow \delta = 15^\circ$ when $SCR = 10$, see Fig. 7]. Therefore, even if the ideal δ -based switching criterion in Fig. 5 can be used,

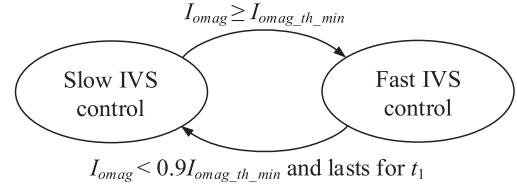


Fig. 8. Practical switching criterion of the proposed adaptive fast/slow IVS control.

the GFM-VSC would still be switched to the fast IVS control with a small δ (e.g., 15°) due to the triggering of the current limitation. Hence, while it is true that the worst-case-based design of the I_{omag} -based switching criterion may jeopardize the GFM capability of VSC under the stiff grid compared with the ideal δ -based switching criterion, the degradation is not significant considering the presence of the current limit control.

Fig. 8 illustrates the practical switching criterion used in this work. A hysteresis comparator and a time delay are added to avoid the frequent switching of control modes caused by the measurement noise. The GFM-VSC is switched to the fast IVS control when $I_{omag} > I_{omag_th_min}$, but can only be switched back to the slow IVS control if $I_{omag} \leq 0.9I_{omag_th_min}$ holds for a given amount of time (t_1). A larger t_1 leads to a better noise immunity of the criterion but it degrades the sensitivity. A compromise is, thus, needed in the practical application. In this work, $t_1 = 0.2$ s is adopted.

IV. FAST IVS CONTROL IMPLEMENTATION

A. Basic Idea

Following the practical switching criterion given in Fig. 8, the detailed implementation of the adaptive slow/fast IVS control should further be investigated. Due to the low control bandwidth of the APC/RPC, the GFM-VSC is inherently a slow IVS when it is operated with the standard APC/RPC given in Fig. 1 [4]. Therefore, only modified control schemes that furnish GFM-VSC with a fast IVS will be discussed in this section. It is worth noting that even though the modifications can be made on both APC/RPC, the modification on RPC is not that effective, as RPC is often bypassed under grid faults, due to the saturation of E_{ref} in Fig. 1. Therefore, the implementation of the fast IVS control would only consider the modification of APC in this work.

The underlying idea of fast IVS control is to retain the power angle δ under grid disturbances to prevent the LOS. This can be realized by modifying θ_{ref} in the APC to guarantee that θ_{ref} could follow θ_g under grid disturbances. In the following, two existing solutions that modify θ_{ref} through ω and P_{ref} of APC are revisited from the perspective of the fast IVS control, and their effectiveness under different grid strengths/disturbances are discussed. To circumvent the drawbacks of the two existing methods, a new fast IVS control that modifies P_{ref} based on the I_{omag} is added.

B. Hybrid-Synchronization Control

Fig. 9 illustrates the block diagram of the HSC [12], [27], [28], in which V_{oq} is feedforwarded to modify ω through a

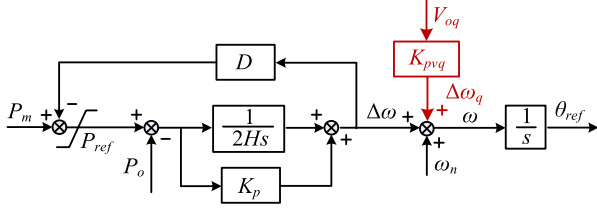


Fig. 9. Block diagram of the HSC.

proportional gain K_{pvq} . It is pointed out in [12] and [27] that the transient stability of GFM-VSC can be improved by adopting the HSC, whose underlying mechanism is revisited here from the perspective of the fast IVS control. For a better illustration, the detailed expression of V_{oq} will be derived first.

It is known from Fig. 2 that

$$V_{od} + jV_{oq} = V_{gd} + jV_{gq} + jX_g (I_{od} + jI_{oq}). \quad (15)$$

Substituting (4), (6)–(8), into (15), which yields

$$V_{oq} = -(1-a)V_g \sin \delta \quad (16)$$

where

$$a = \frac{X_g}{X_{\text{tot}}}. \quad (17)$$

Therefore, $\Delta\omega_q$ in Fig. 9 can be expressed as

$$\Delta\omega_q = K_{pvq}V_{oq} = -K_{pvq}(1-a)V_g \sin \delta. \quad (18)$$

Based on (18), the mechanism of the HSC that operates GFM-VSC as a fast IVS to prevent the LOS can be easily understood. For any disturbances that cause an increase of δ , a more negative $\Delta\omega_q$ is generated via the V_{oq} feedforwarded path [see (18)], which reduces the $\omega(\theta_{\text{ref}})$ of GFM-VSC and, hence, counteracts the effect of δ increase. Yet, with a fixed K_{pvq} , it is also known from (18) that the effect of the V_{oq} feedforward is dependent on two factors: $(1-a)$ and V_g . More specifically:

- 1) V_{oq} feedforward is more effective under the grid phase angle jump with $V_g = 1$ p.u., yet it becomes less effective under grid voltage dip due to the smaller V_g .
- 2) V_{oq} feedforward is more effective under the stiff grid where a is close to 0, yet it becomes less effective under the weak grid where a approaches to 1.

C. V_{omag} -Based P_{ref} Adjustment

Another widely used method of avoiding the LOS is to reduce P_{ref} based on the dip of voltage magnitude V_{omag} . To that end, different implementations are given in [13], [14], and [29]. Among others, the simplest implementation, i.e., $P_{\text{ref}} = P_{\text{ref}0}V_{omag}$, is adopted in this work for illustration. The corresponding control diagram is given in Fig. 10, where V_{omag} can be calculated as

$$V_{omag} = \sqrt{V_{od}^2 + V_{oq}^2}. \quad (19)$$

Substituting (4), (6)–(8), (15) into (19), which yields

$$V_{omag} = \sqrt{(1-a)^2V_g^2 + a^2E_{\text{ref}}^2 + 2a(1-a)E_{\text{ref}}V_g \cos \delta}. \quad (20)$$

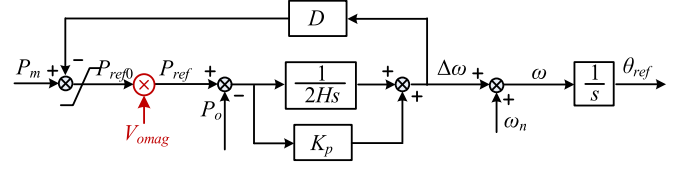
Fig. 10. Control diagram that modifies P_{ref} based on V_{omag} .

TABLE II
PERFORMANCE OF HSC AND V_{omag} -BASED P_{REF} ADJUSTMENT

	Grid voltage dips		Grid phase angle jump/RoCoF	
	Stiff grid	Weak grid	Stiff grid	Weak grid
HSC	Moderate	Low	High	Low
V_{omag} -based P_{ref} adjustment	High	Low	Low	Low

It is clear from (20) that V_{omag} is reduced with the decrease of V_g and the increase of δ . Hence, the V_{omag} -based P_{ref} adjustment essentially operates the GFM-VSC as a fast IVS, which reduces P_{ref} under grid faults or grid phase angle jump. The lower value of P_{ref} helps to reduce $\omega(\theta_{\text{ref}})$ of GFM-VSC, which alleviates the risk of LOS. Nevertheless, it can be seen from (20) that the performance of this approach is affected by the grid strength that is characterized by the factor a . More specifically:

- 1) $V_{omag} \approx V_g$ under the stiff grid where $a \rightarrow 0$, which is independent of δ . Thus, V_{omag} -based P_{ref} adjustment is very effective under the grid voltage dip, but less effective under grid phase angle jump under very stiff grid conditions.
- 2) $V_{omag} \approx E_{\text{ref}}$ under the ultraweak grid where $a \rightarrow 1$, which is independent of both V_g and δ . In this scenario, V_{omag} -based P_{ref} adjustment is ineffective under both grid voltage dip and grid phase angle jump.

Table II summarizes the performances of HSC and V_{omag} -based P_{ref} adjustment with respect to the enhancement of transient stability, considering different grid disturbances and grid strengths. The HSC is more effective under the phase angle jump while V_{omag} -based P_{ref} adjustment is more effective under the voltage dip. Therefore, these two methods are complementary to each other and, thus, can be used at the same time for the performance improvement. Nevertheless, the effectiveness of both methods is degraded under weak grid conditions. This is because both of them manipulate the APC based on the PCC voltage, which deviates significantly from the grid voltage under the weak grid. Therefore, a new fast IVS control that can improve the transient stability of GFM-VSC under weak grid conditions is needed.

D. $P_{\text{ref}}-I_{omag}$ Droop Control

It can be seen from (9) that for any given grid strength (X_g), I_{omag} is always increased with the increase of δ [as the term $\cos \delta$ in (9) is decreased with the increase of δ]. Therefore, reducing P_{ref} based on the increase of I_{omag} (which reflects the increase of δ) is a more robust fast IVS control against grid strength variations, which is named as $P_{\text{ref}}-I_{omag}$ droop control hereafter.

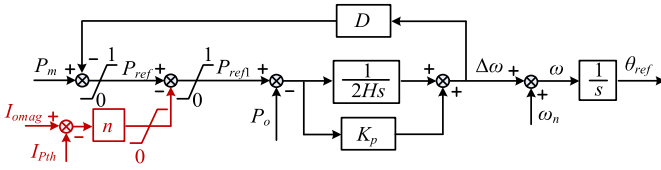
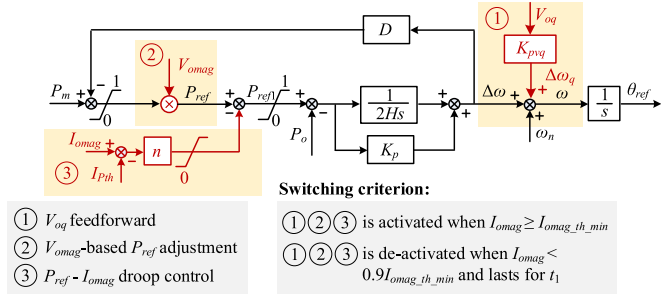
Fig. 11. Block diagram that proposed P_{ref} - I_{omag} droop control.

Fig. 12. Detailed implementation of the proposed adaptive fast/slow IVS control.

Fig. 11 illustrates the control diagram of the proposed method, whose principle can be elaborated as

$$P_{ref1} = \begin{cases} P_{ref}, & \text{if } I_{omag} < I_{Pth} \\ P_{ref} - n(I_{omag} - I_{Pth}), & \text{if } I_{omag} \geq I_{Pth} \end{cases} \quad (21)$$

where n is the droop coefficient, and I_{Pth} is the threshold current beyond which the proposed P_{ref} - I_{omag} droop control is activated. In this work, $I_{Pth} = 1.1$ p.u. is selected to avoid the impact of the proposed method on the steady-state operation of the system.

A larger droop coefficient n indicates more P_{ref} reduction with the same increase of I_{omag} , which is beneficial for system transient stability. Yet, the risk of unnecessary P_{ref} swing due to the measurement noise is also increased. In this work, $n = 10$ p.u. is selected for a good compromise, which indicates that a 0.1 p.u. increase of I_{omag} leads to a 1 p.u. decrease of P_{ref} when $I_{omag} \geq I_{Pth}$. Moreover, to avoid that P_{ref1} becomes a negative value due to the P_{ref} - I_{omag} droop control, a limiter is added to limit P_{ref1} within 0 to 1 p.u.

Fig. 12 illustrates the final implementation of the proposed adaptive fast/slow IVS control. The fast IVS control is implemented by adding the P_{ref} - I_{omag} droop control, V_{omag} -based P_{ref} adjustment, and V_{oq} feedforward on top of the slow IVS control, and is activated/deactivated based on the switching criterion defined in Fig. 8. When the fast IVS control is deactivated, Fig. 12 reduces to the standard control scheme given in Fig. 1, which is a slow IVS control that guarantees the GFM capability of VSC.

E. Small-Signal Stability Analysis

As mentioned, the GFM-VSC is equipped with standard APC/RPC when operated as a slow IVS, whose small-signal stability has been extensively investigated [7], [32], [37]. Hence, the small-signal stability analysis here will focus on the scenario where GFM-VSC is subjected to large grid disturbances

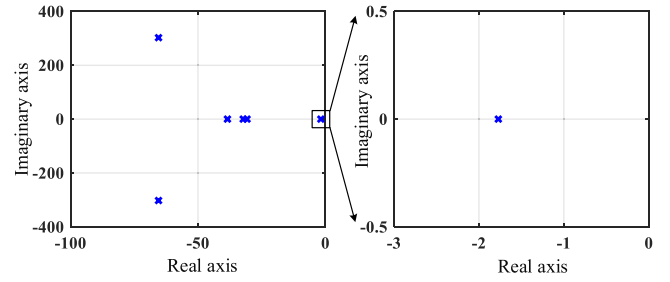


Fig. 13. Pole maps GFM-VSC with fast IVS control activated.

TABLE III
SYSTEM PARAMETERS

SYMBOL	DESCRIPTION	VALUE
V_{PCC}	PCC voltage (RMS value)	50 V
P	Power rating of the VSC	1 kW
f_g	Grid frequency	50 Hz
L_f	Filter inductance	3 mH
C_f	Filter capacitance	20 μ F
SCR	Short circuit ratio	Weak grid: 1.2 Stiff grid: 10
f_{sw}	Switching frequency	10 kHz
T_s	Sampling (control) period	100 μ s
T_d	Time delay in the control loop	1.5 T_s

with fast IVS control, i.e., V_{oq} feedforward, V_{omag} -based P_{ref} adjustment, as well as P_{ref} - I_{omag} droop control, activated. The complete small-signal model of GFM-VSC with fast IVS control is derived in the Appendix, based on which, the closed-loop poles of the system can be calculated from (A.21), as shown in Fig. 13. It can be observed that all poles are located in the left-half plane, indicating that the system is small-signal stable with used controller parameters (see Table IV) in this work.

V. EXPERIMENTAL RESULTS

Experimental tests are carried out to validate the proposed adaptive fast/slow IVS control for the GFM-VSC, and the parameters given in Tables III and IV are adopted. The controller parameters in Table IV are tuned based on [7], [32], [37], [38] to guarantee the small-signal stability of the system. Fig. 14 illustrates the configuration of the experimental setup, where a 45 kVA Chroma 61850 grid simulator is used to generate the grid voltage and emulate different grid disturbances. The control algorithm is implemented in the DS1007 dSPACE system. The DS2102 high-speed D/A board is used to transmit the calculated active power, power angle, current magnitude (I_{omag}), and the enable signal of fast IVS control (FastIVS_en) to the oscilloscope.

A. Verification of Switching Criterion

Experimental tests are carried out to verify the I_{omag} -based switching criterion given in Fig. 8. As shown in Fig. 15, the GFM-VSC is initially operated with slow IVS control (FastIVS_en = 0) when I_{omag} is less than the minimum threshold, i.e., $I_{omag} < I_{omag_th_min} = 0.94$ p.u. When a symmetrical fault occurs with V_g reduced to 0.1 p.u., the GFM-VSC is operated

TABLE IV
CONTROLLER PARAMETERS

SYMBOL	DESCRIPTION	VALUE (P.U.)
$n_{X/R}$	X/R ratio of the adaptive VI	5
k_X	Proportional gain of adaptive virtual reactance	1.45 p.u.
I_{th}	Threshold current of activating adaptive VI	1.1 p.u.
I_{lim}	Current limit	1.5 p.u.
K_{IV}	Integral gain of SLVM control	6.28 p.u.
ω_{LPPX}	Cutoff frequency of G_{LPPX}	0.2 p.u.
R_{ad}	Active damping resistor	0.1 p.u.
ω_{HPF}	Cutoff frequency of G_{HPF}	0.1 p.u.
D	P - ω droop control	50 p.u.
K_p	Proportional gain of APC	0.02 p.u.
H	Inertial time constant of APC	10 p.u.
K_{RPC}	Q - V droop control	0.1 p.u.
ω_q	Cutoff frequency of G_{LPPq}	1 p.u.
$I_{omag_th_min}$	Threshold current for fast/slow IVS control switching	0.94 p.u.
K_q	Proportional gain of HSC	0.34 p.u.
I_{Ph}	Threshold current of activating $P_{ref} - I_{omag}$ droop control	1.1 p.u.
n	Droop coefficient of $P_{ref} - I_{omag}$ droop control	10 p.u.

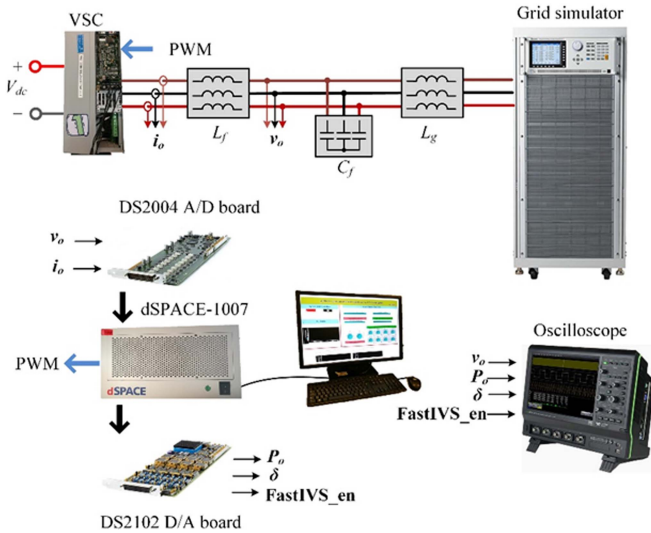


Fig. 14. Configuration of the experimental setup.

under the current limiting mode where I_{omag} exceeds the minimum threshold, i.e., $I_{omag} = 1.5 \text{ p.u.} > I_{omag_th_min}$, and the fast IVS control is thus activated ($\text{FastIVS_en} = 1$). After the fault is cleared, the I_{omag} is reduced to be less than $0.9I_{omag_th_min}$, yet the GFM-VSC is still operated with the fast IVS control, as expected, for 0.2 s before it switches back to the slow IVS control. The experimental results given in Fig. 15 matches well with the proposed switching criterion given in Fig. 8.

B. Verification of GFM Capability

In order to verify the GFM capability of VSC with the proposed adaptive fast/slow IVS control, experimental tests are

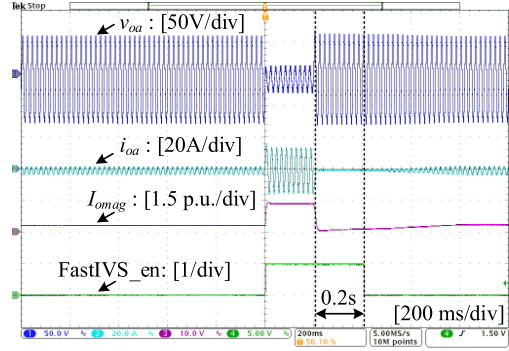


Fig. 15. Dynamic response of GFM-VSC with adaptive fast/slow IVS control during grid faults (V_g drops to 0.1 p.u. and lasts 0.2 s). $\text{SCR} = 10$, $P_m = 0.1 \text{ p.u.}$

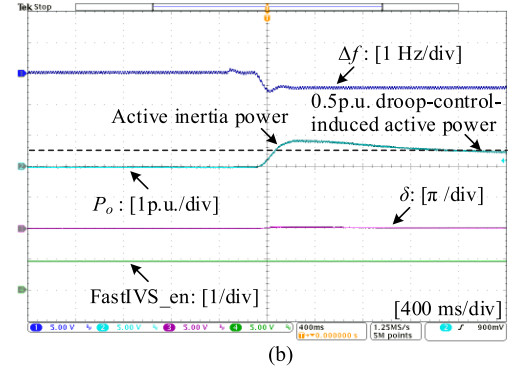
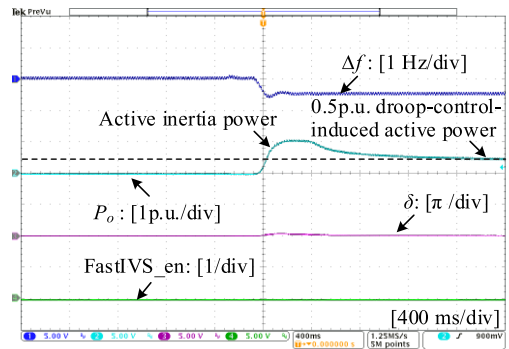


Fig. 16. Dynamic response of GFM-VSC when subjected to -5 Hz/s RoCoF that lasts 0.1 s, $\text{SCR} = 10$, $P_m = 0 \text{ p.u.}$ (a) Adaptive fast/slow IVS control. (b) Fast IVS control.

carried out by operating GFM-VSC under the stiff grid condition ($\text{SCR} = 10$) with zero output power ($P_m = 0 \text{ p.u.}$) before grid disturbances. For better illustration, two types of control schemes are tested and compared.

- 1) Adaptive fast/slow IVS control that corresponds to the control scheme given in Fig. 12.
- 2) Fast IVS control that corresponds to the control scheme given in Fig. 12 with $P_{ref} - I_{omag}$ droop control, V_{omag} -based P_{ref} adjustment, and V_{oq} feedforward always enabled.

Fig. 16 shows the dynamic responses of GFM-VSC when subjected to a -5 Hz/s RoCoF event of the power grid that

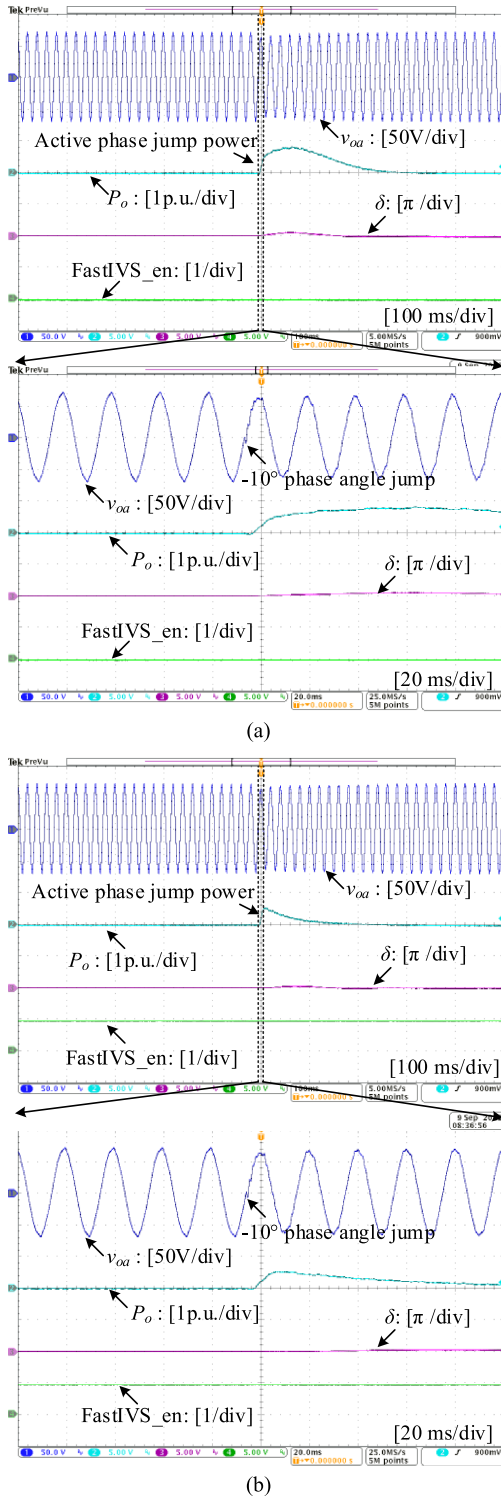


Fig. 17. Dynamic response of GFM-VSC when subjected to -10° grid phase angle jump ($\theta_g = -10^\circ$). SCR = 10, $P_m = 0$ p.u. (a) Adaptive fast/slow IVS control. (b) Fast IVS control.

lasts 0.1 s. Since GFM-VSC is operated with a small power angle before and after grid disturbances without triggering the current limitation, it would always operate with the slow IVS control (FastIVS_en = 0) when the proposed adaptive control

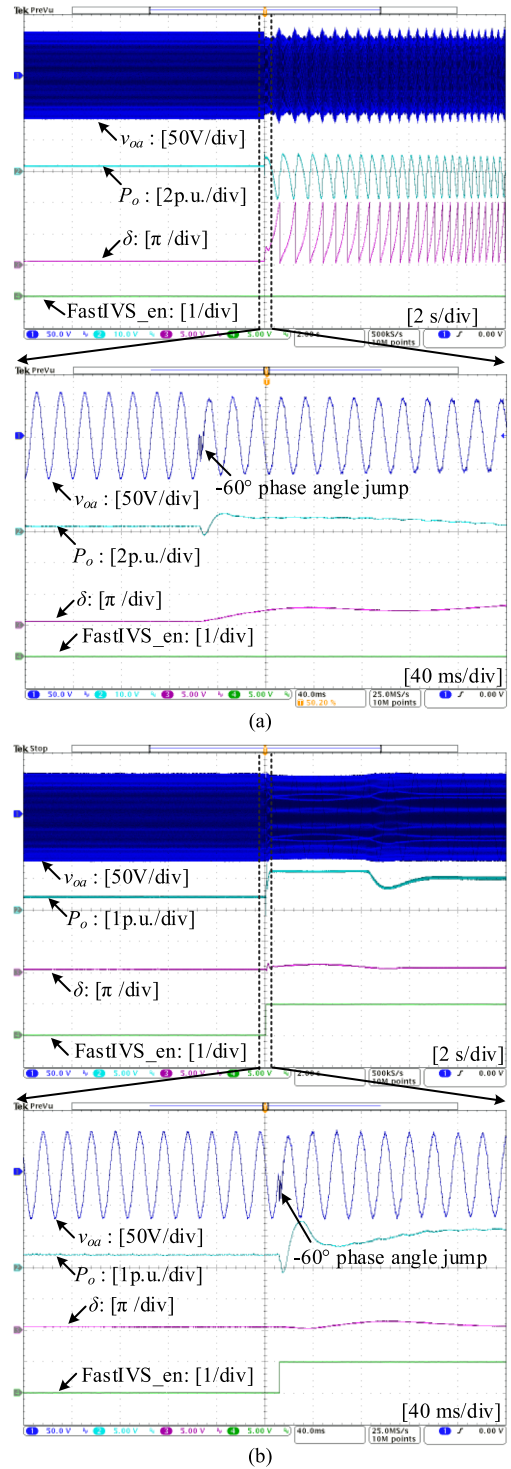


Fig. 18. Dynamic response of GFM-VSC when subjected to -60° grid phase angle jump ($\theta_g = -60^\circ$), together with -5 Hz/s RoCoF that lasts 0.2 s. SCR = 10, $P_m = 0.4$ p.u. (a) Slow IVS control. (b) Adaptive fast/slow IVS control without $P_{ref}-I_{omag}$ droop control.

is adopted. Hence, despite generating 0.5 p.u. droop-control-induced active power due to 0.5 Hz frequency dips, the GFM-VSC is also capable of providing additional active inertia power to counteract the RoCoF, as shown in Fig. 16(a). For comparison, Fig. 16(b) illustrates the dynamics of GFM-VSC with fast IVS

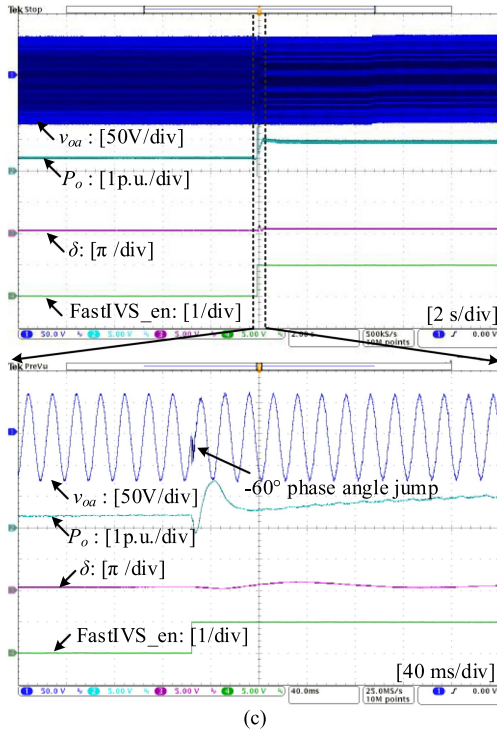


Fig. 18. (Continued) Dynamic response of GFM-VSC when subjected to -60° grid phase angle jump ($\theta_g = -60^\circ$), together with -5 Hz/s RoCoF that lasts 0.2 s. SCR = 10, $P_m = 0.4$ p.u. (c) Adaptive fast/slow IVS control.

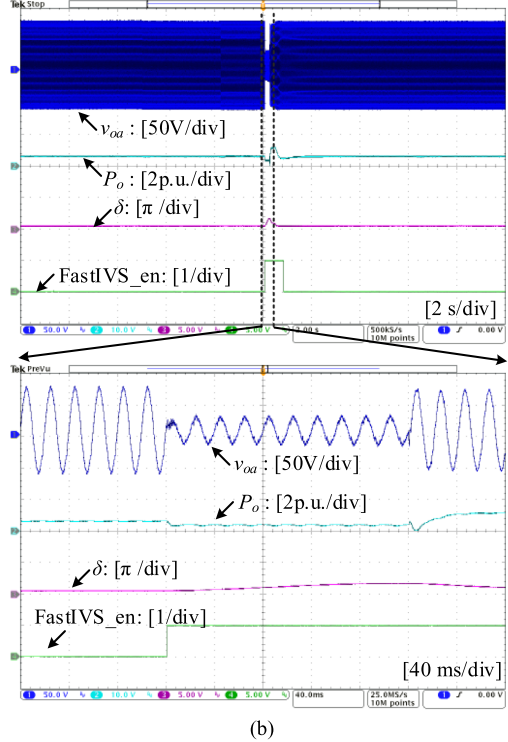
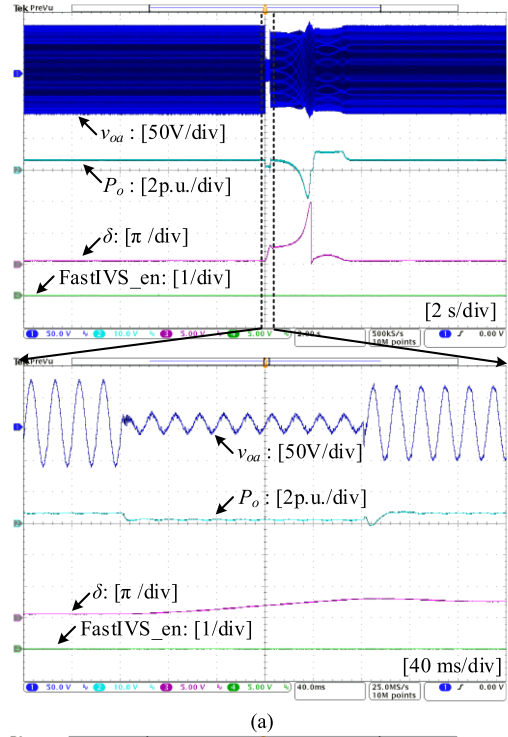


Fig. 20. Dynamic response of GFM-VSC during symmetrical grid faults (V_g drops to 0.2 p.u. and lasts 0.2 s) together with -60° grid phase angle jump ($\theta_g = -60^\circ$). SCR = 10, $P_m = 0.7$ p.u. (a) Slow IVS control. (b) Adaptive fast/slow IVS control without $P_{ref}-I_{omag}$ droop control.

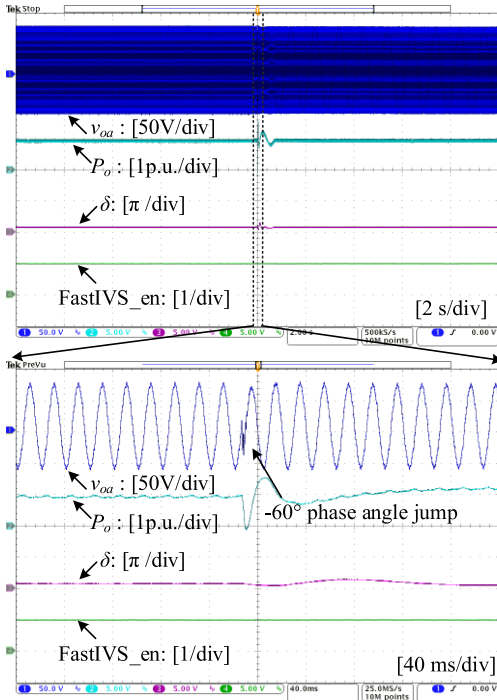


Fig. 19. Dynamic response of GFM-VSC with adaptive fast/slow IVS control when subjected to -60° grid phase angle jump ($\theta_g = -60^\circ$), together with -5 Hz/s RoCoF that lasts 0.2 s. SCR = 10, $P_m = 1$ p.u.

control always enabled (FastIVS_en = 1), it can be seen that the capability of GFM-VSC in providing active inertial power is significantly degraded.

Fig. 17 shows the dynamic responses of GFM-VSC when subjected to -10° phase angle jump of the power grid ($\theta_g = -10^\circ$), and GFM-VSC is operated with small power angle before and

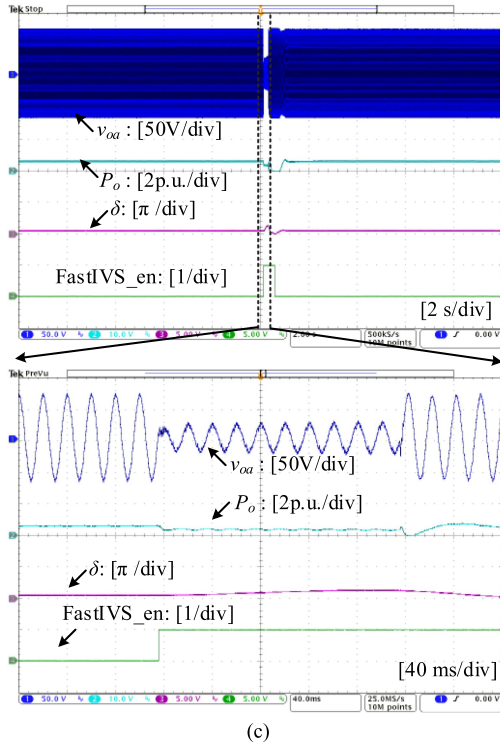


Fig. 20. (Continued) Dynamic response of GFM-VSC during symmetrical grid faults (V_g drops to 0.2 p.u. and lasts 0.2 s) together with -60° grid phase angle jump ($\theta_g = -60^\circ$). SCR = 10, $P_m = 0.7$ p.u. (c) Adaptive fast/slow IVS control.

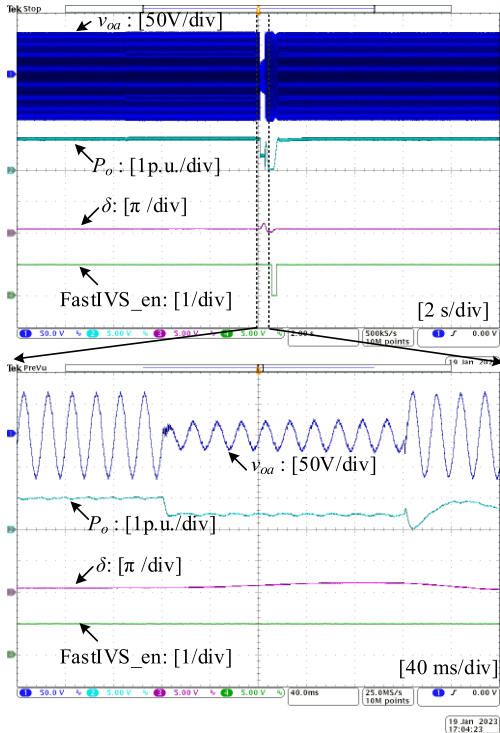


Fig. 21. Dynamic response of GFM-VSC with adaptive fast/slow IVS control during symmetrical grid faults (V_g drops to 0.2 p.u. and lasts 0.2 s) together with -60° grid phase angle jump ($\theta_g = -60^\circ$). SCR = 10, $P_m = 1$ p.u.

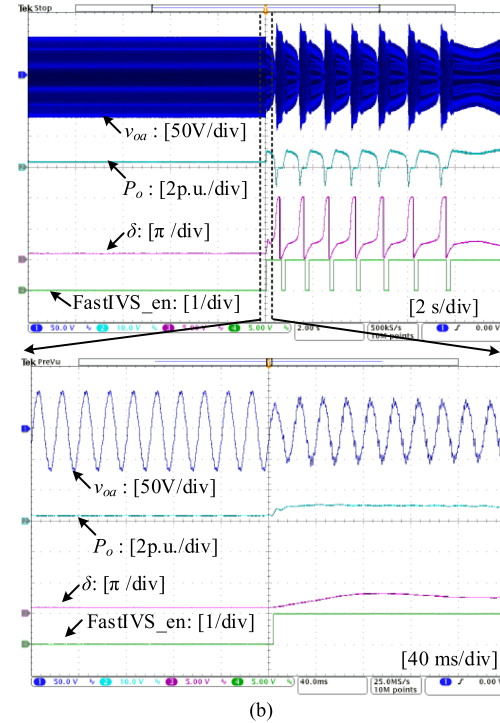
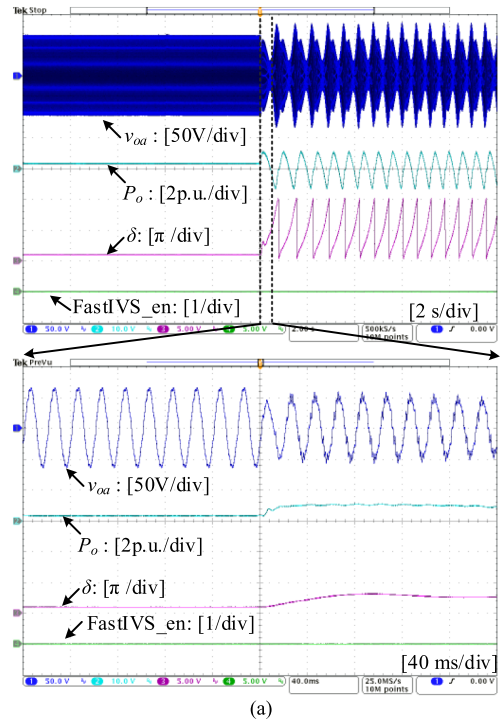


Fig. 22. Dynamic response of GFM-VSC when subjected to -60° grid phase angle jump ($\theta_g = -60^\circ$), together with -5 Hz/s RoCoF that lasts 0.2 s. SCR = 1.2, $P_m = 0.4$ p.u. (a) Slow IVS control. (b) Adaptive fast/slow IVS control without $P_{ref}-I_{omag}$ droop control.

after grid disturbances without triggering the current limitation. By adopting the proposed adaptive control, GFM-VSC would remain operating with slow IVS control (FastIVS_en = 0), which maintains its capability of providing active phase jump power, as shown in Fig. 17(a). In contrast, it can be observed

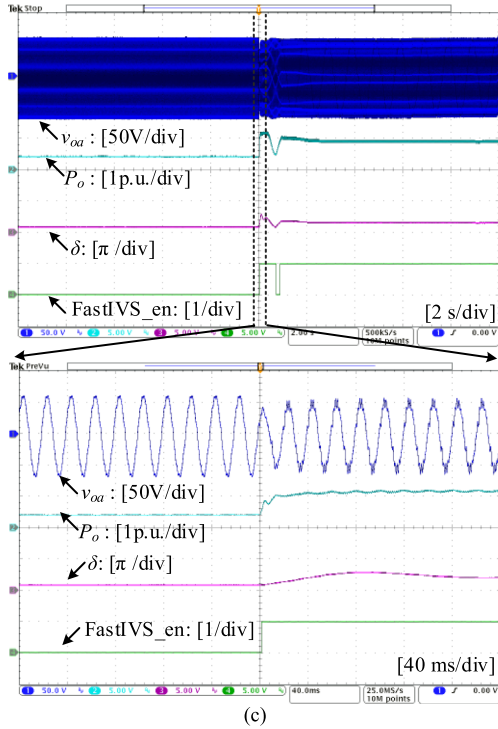


Fig. 22. (Continued) Dynamic response of GFM-VSC when subjected to -60° grid phase angle jump ($\theta_g = -60^\circ$), together with -5 Hz/s RoCoF that lasts 0.2 s. SCR = 1.2, $P_m = 0.4$ p.u. (c) Adaptive fast/slow IVS control.

from Fig. 17(b) that much lower active phase jump power is generated from GFM-VSC under same grid phase angle jump, provided that GFM-VSC is always operated with the fast IVS control (FastIVS_en = 1). The experimental results in Figs. 16 and 17 clearly demonstrate the benefit of the proposed fast/slow IVS control in retaining the GFM capability of VSC.

C. Verification of Transient-Stability Improvement

In this section, more severe grid disturbances are considered to verify the transient stability performance of GFM-VSC with the proposed adaptive fast/slow IVS control. For better illustration, three types of control schemes are tested and compared.

- 1) Slow IVS control: corresponds to the basic GFM control scheme given in Fig. 1.
- 2) Adaptive fast/slow IVS control without $P_{ref}-I_{omag}$ droop: corresponds to the control scheme given in Fig. 12, yet the $P_{ref}-I_{omag}$ droop control is not added.
- 3) Adaptive fast/slow IVS control: corresponds to the control scheme given in Fig. 12.

1) *Stiff Grid (SCR = 10)*: Fig. 18 illustrates the dynamic responses of GFM-VSC under the stiff grid condition (SCR = 10) considering phase angle jump + RoCoF disturbances [-60° phase angle jump ($\theta_g = -60^\circ$) together with -5 Hz/s RoCoF that lasts 0.2 s]. The GFM-VSC is initially operated with $P_m = 0.4$ p.u. It can be seen from Fig. 18(a) that GFM-VSC becomes unstable by adopting the slow IVS control (FastIVS_en = 0), where the oscillation in the output power and power angle can be clearly observed, indicating the LOS of GFM-VSC. In contrast, GFM-VSC can successfully ride through large phase angle jump + RoCoF disturbances by using the adaptive control

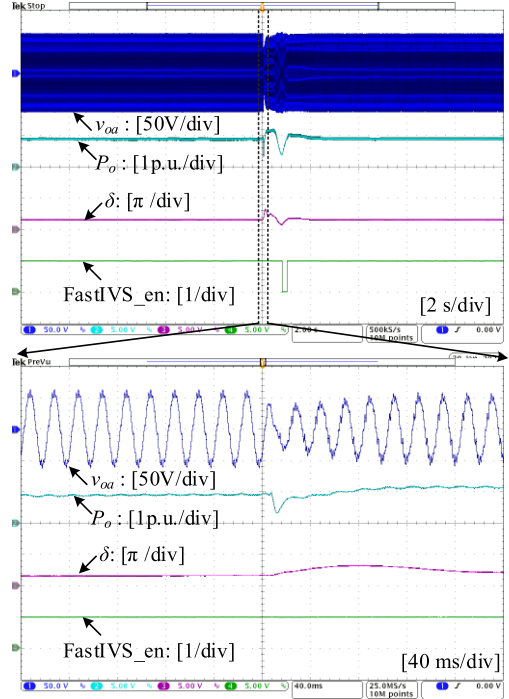


Fig. 23. Dynamic response of GFM-VSC with adaptive fast/slow IVS control when subjected to -60° grid phase angle jump ($\theta_g = -60^\circ$), together with -5 Hz/s RoCoF that lasts 0.2 s. SCR = 1.2, $P_m = 1$ p.u.

with or without $P_{ref}-I_{omag}$ droop. As illustrated in Fig. 18(b) and (c), the adaptive control initially operates GFM-VSC with the slow IVS control (FastIVS_en = 0), but is naturally switched to the fast IVS control (FastIVS_en = 1) under grid disturbances to facilitate the grid synchronization. Moreover, adding $P_{ref}-I_{omag}$ droop control can slightly improve the dynamics of GFM-VSC after grid disturbances, which can be observed by comparing Fig. 18(b) and (c).

Fig. 19 further illustrates that GFM-VSC with the adaptive fast/slow IVS control can stably ride through the combined large phase angle jump + RoCoF disturbances even if P_m is increased to 1 p.u. under the stiff grid condition. The only difference is that GFM-VSC is already operated with the fast IVS control (FastIVS_en = 1) before grid disturbances due to the fact of $I_{omag} > I_{omag_th_min}$.

Fig. 20 illustrates the dynamic responses of GFM-VSC under the stiff grid condition (SCR = 10) considering symmetrical grid faults + phase angle jumps [V_g drops to 0.2 p.u. and lasts for 0.2 s, together with -60° phase angle jump ($\theta_g = -60^\circ$)]. The GFM-VSC is initially operated with $P_m = 0.7$ p.u. It can be seen from Fig. 20(a) that GFM-VSC with slow IVS control (FastIVS_en = 0) loses synchronization with the power grid after the fault clearance, which yields one cycle of oscillation where power angle δ is increased to 360° . Even though GFM-VSC finally resynchronizes with the power grid, the overall performance is not that satisfactory. In contrast, it can be observed from Fig. 20(b) and (c) that the proposed adaptive control operates GFM-VSC with the fast IVS control (FastIVS_en = 1) during grid faults, which enables its direct resynchronization with the power grid after the fault clearance. Moreover, the GFM-VSC is switched back to the slow IVS control (FastIVS_en = 0) when

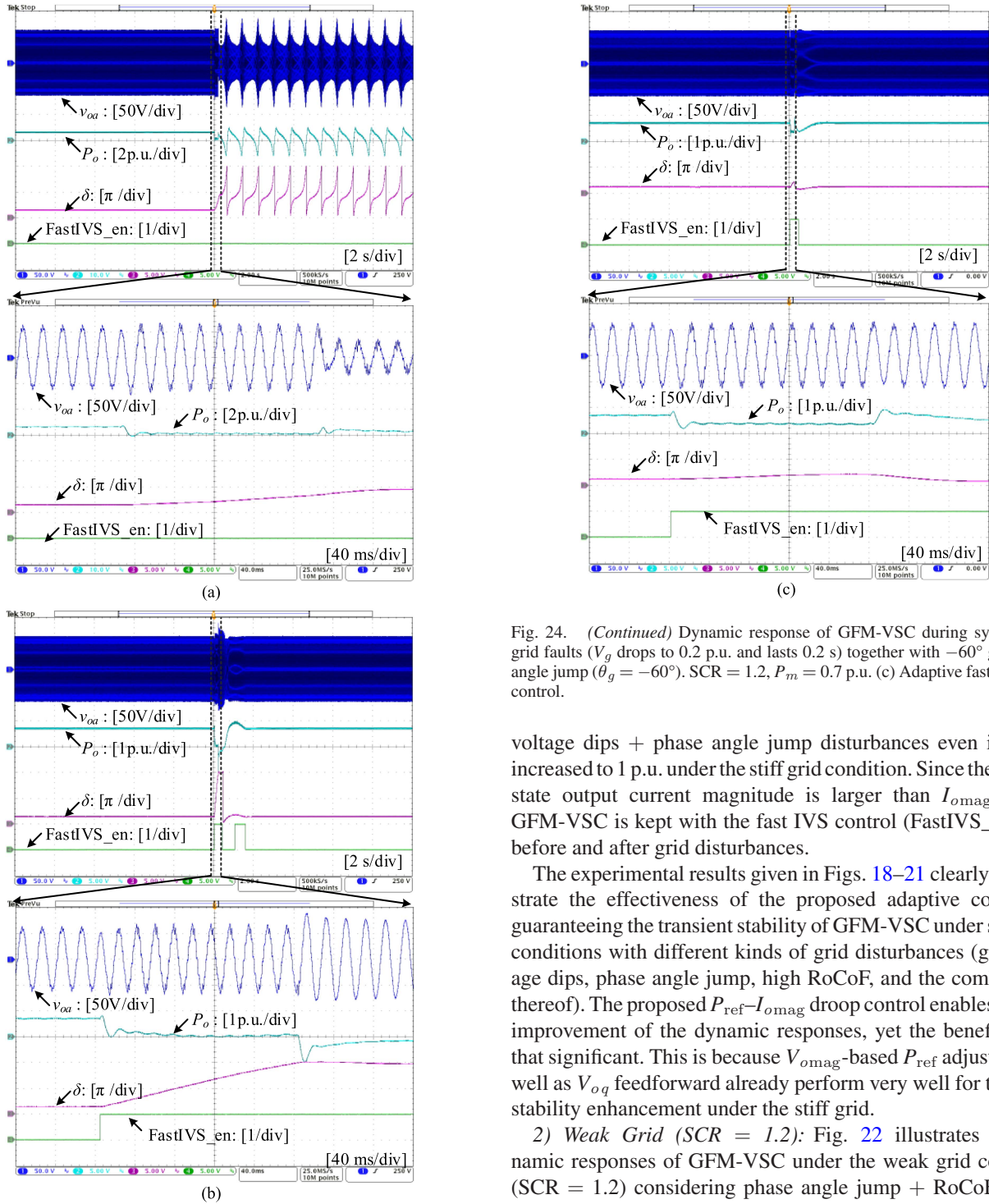


Fig. 24. Dynamic response of GFM-VSC during symmetrical grid faults (V_g drops to 0.2 p.u. and lasts 0.2 s) together with -60° grid phase angle jump ($\theta_g = -60^\circ$). SCR = 1.2, $P_m = 0.7$ p.u. (a) Slow IVS control. (b) Adaptive fast/slow IVS control without $P_{ref}-I_{omag}$ droop control.

it comes to the steady-state operation after the fault clearance, retaining its GFM capability. A further detailed comparison between Fig. 20(b) and (c) indicates that adding $P_{ref}-I_{omag}$ droop control can slightly improve the postfault dynamics of GFM-VSC in this scenario.

Fig. 21 further illustrates that GFM-VSC with the adaptive fast/slow IVS control can stably ride through the combined grid

Fig. 24. (Continued) Dynamic response of GFM-VSC during symmetrical grid faults (V_g drops to 0.2 p.u. and lasts 0.2 s) together with -60° grid phase angle jump ($\theta_g = -60^\circ$). SCR = 1.2, $P_m = 0.7$ p.u. (c) Adaptive fast/slow IVS control.

voltage dips + phase angle jump disturbances even if P_m is increased to 1 p.u. under the stiff grid condition. Since the steady-state output current magnitude is larger than $I_{omag_th_min}$, GFM-VSC is kept with the fast IVS control (FastIVS_en = 1) before and after grid disturbances.

The experimental results given in Figs. 18–21 clearly demonstrate the effectiveness of the proposed adaptive control in guaranteeing the transient stability of GFM-VSC under stiff grid conditions with different kinds of grid disturbances (grid voltage dips, phase angle jump, high RoCoF, and the combination thereof). The proposed $P_{ref}-I_{omag}$ droop control enables a slight improvement of the dynamic responses, yet the benefit is not that significant. This is because V_{omag} -based P_{ref} adjustment as well as V_{oq} feedforward already perform very well for transient stability enhancement under the stiff grid.

2) *Weak Grid (SCR = 1.2)*: Fig. 22 illustrates the dynamic responses of GFM-VSC under the weak grid condition (SCR = 1.2) considering phase angle jump + RoCoF disturbances [-60° phase angle jump ($\theta_g = -60^\circ$) together with -5 Hz/s RoCoF that lasts 0.2 s]. The GFM-VSC is initially operated with $P_m = 0.4$ p.u. It can be seen from Fig. 22(a) that GFM-VSC becomes unstable by adopting the slow IVS control. Yet, it also cannot be stabilized with the adaptive control provided that the $P_{ref}-I_{omag}$ droop is not used, as shown in Fig. 22(b). This is because V_{omag} -based P_{ref} adjustment and V_{oq} feedforward become less effective for transient stability enhancement under the weak grid due to the significant deviations between the PCC voltage and V_g , as pointed out in Section IV. Therefore, only the adaptive control with $P_{ref}-I_{omag}$ droop included can stabilize GFM-VSC in this scenario, as shown in Fig. 22(c).

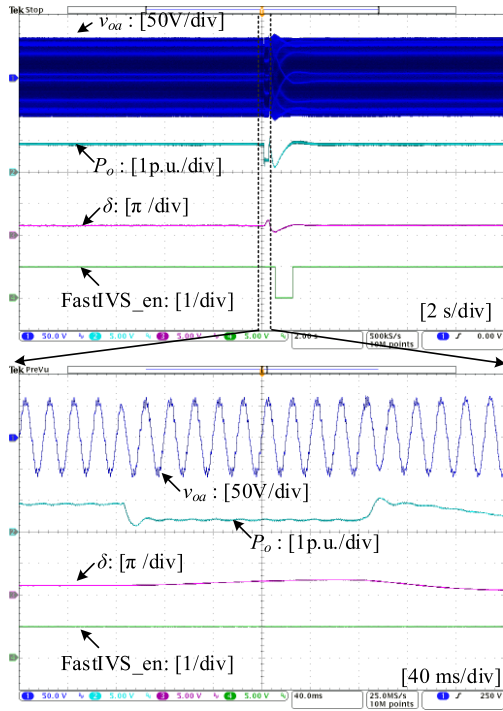


Fig. 25. Dynamic response of GFM-VSC with adaptive fast/slow IVS control during symmetrical grid faults (V_g drops to 0.2 p.u. and lasts 0.2 s) together with -60° grid phase angle jump ($\theta_g = -60^\circ$). SCR = 1.2, $P_m = 1$ p.u.

Fig. 23 further illustrates that GFM-VSC with adaptive fast/slow IVS control can stably ride through the combined large phase angle jump + RoCoF disturbances even if P_m is increased to 1 p.u. under the weak grid condition. The only difference is that GFM-VSC is already operated with fast IVS control (FastIVS_en = 1) before grid disturbances due to the fact of $I_{omag} > I_{omag_th_min}$.

Fig. 24 illustrates the dynamic responses of GFM-VSC under the weak grid condition (SCR = 1.2) considering symmetrical grid faults + phase angle jumps [V_g drops to 0.2 p.u. and lasts for 0.2 s, together with -60° phase angle jump ($\theta_g = -60^\circ$)]. The GFM-VSC is initially operated with $P_m = 0.7$ p.u. It can be seen from Fig. 24(a) that GFM-VSC becomes unstable by adopting the slow IVS control (FastIVS_en = 0). Yet, by adopting the adaptive control without the $P_{ref}-I_{omag}$ droop, the GFM-VSC still suffers from one-cycle of oscillation after the fault clearance before it can resynchronize with the power grid, as shown in Fig. 24(b). This is due to the reduced performance of V_{omag} -based P_{ref} adjustment and V_{oq} feedforward under the weak grid. In contrast, by adopting the adaptive control with $P_{ref}-I_{omag}$ droop included, the GFM-VSC can successfully ride through grid faults and directly resynchronize with the power grid after fault clearance, as shown in Fig. 24(c).

Fig. 25 further illustrates that GFM-VSC with adaptive fast/slow IVS control can stably ride through the combined grid voltage dips + phase angle jump disturbances even if P_m is increased to 1 p.u. under the weak grid condition. Since the steady-state output current magnitude is larger than $I_{omag_th_min}$, GFM-VSC is kept with the fast IVS control (FastIVS_en = 1) before and after grid disturbances.

Figs. 22–25 clearly demonstrate that the proposed adaptive control can also guarantee the transient stability of GFM-VSC under weak grid conditions with different kinds of grid disturbances (grid voltage dips, phase angle jump, high RoCoF, and the combination thereof). Different from stiff grid scenarios, the proposed $P_{ref}-I_{omag}$ droop control is crucial in stabilizing GFM-VSC under the weak grid and should always be included.

3) *Asymmetrical Fault-Ride Through*: Figs. 26 and 27 illustrate the dynamic response of GFM-VSC under single-line-to-ground fault and double-line-to-ground (DLG) fault considering both stiff and weak grid conditions. It can be seen that with the proposed adaptive fast/slow IVS control, GFM-VSC can stably ride through different kinds of asymmetrical faults regardless of grid strength variations. It is not surprising as positive-sequence voltage only drops to 0.33 p.u. even for the most severe asymmetrical faults, i.e., DLG faults [35]. This represents a better case in terms of transient stability compared with symmetrical faults, in which the remaining positive-sequence voltage could be lower than 0.33 p.u.

4) *Compared With Other State-of-the-Art Method*: To further demonstrate the advantage of the proposed adaptive fast/slow IVS control, experimental tests are carried out by comparing the proposed method with the control scheme in [18] that enhances system damping by feedforwarding the frequency in the RPC loop, with which, a good compromise between transient stability and GFM capability can also be achieved. Yet, this method becomes ineffective if GFM-VSC is operated under the current limiting mode where the RPC loop is naturally bypassed. This is demonstrated by experimental results given in Fig. 28(a), where the LOS of GFM-VSC can be observed under large grid disturbances with a current limit triggered, even if the method in [18] is used. In contrast, the proposed adaptive fast/slow IVS control allows GFM-VSC to stably ride through large grid disturbances under the current limiting mode, as shown in Fig. 28(b).

VI. CONCLUSION

With clear physical insights on different IVS dynamic requirements of GFM-VSC for enhancing the transient stability and GFM capability, an adaptive fast/slow IVS control has been proposed in this work. The method not only guarantees the transient stability of GFM-VSC under different grid strengths and different types of grid disturbances (grid voltage dips, phase angle jump, high RoCoF, and the combination thereof), but also retains the GFM capability of VSC when there are sufficient stability and current margins. The effectiveness of the proposed method is verified by experimental tests. The efficacy of the proposed adaptive fast/slow IVS control under the large power network with multiple GFM-VSCs will be analyzed in future work.

APPENDIX

By considering the dynamics of the APC, there are two rotating dq frames of GFM-VSC [5]: one is the *controller-dq* frame that is defined by the output phase angle of the APC, and another is the *system-dq* frame that is aligned with phase angle of the grid voltage. For clarity, superscript s represents the variables in the *system-dq* frame, while the superscript c denotes the variables in the *controller-dq* frame.

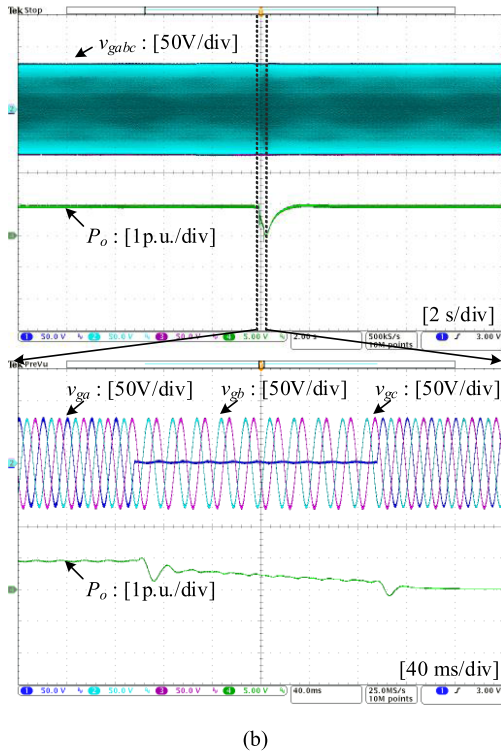
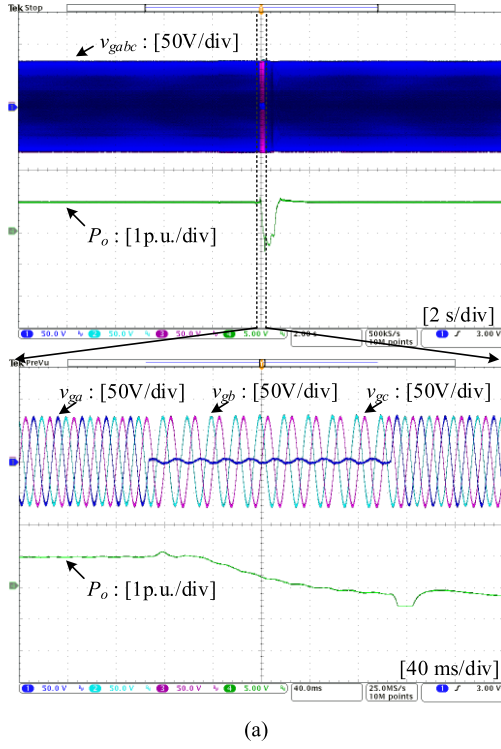


Fig. 26. Dynamic response of GFM-VSC with adaptive fast/slow IVS control during SLG fault. $P_m = 1$ p.u. (a) Stiff grid, SCR = 10. (b) Weak grid, SCR = 1.2.

Define δ as the phase angle difference between the *controller-dq* frame and the *system-dq* frame, i.e., $\delta = \theta_{\text{ref}} - \theta_g$. Then the relationships between the state variables in the *controller-dq* frame and the *system-dq* frame are given by

$$x_{dq}^c = e^{-j\delta} x_{dq}^s. \quad (\text{A.1})$$

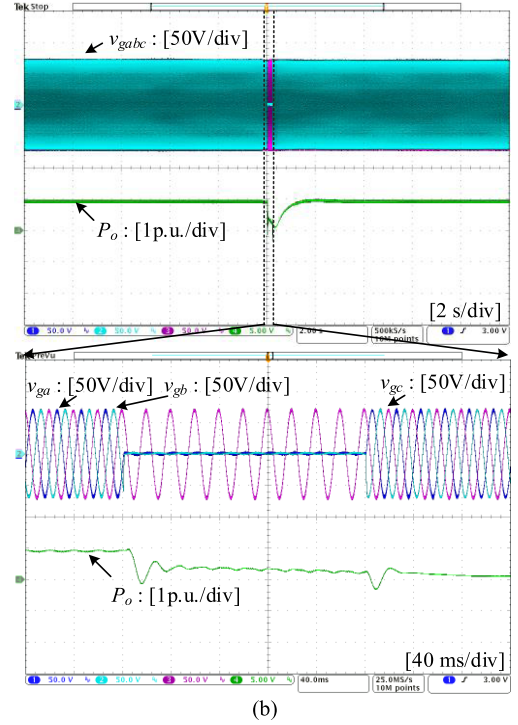
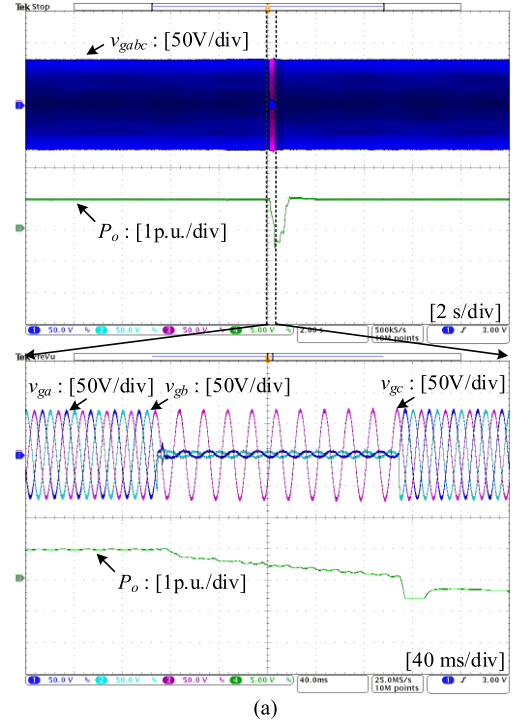


Fig. 27. Dynamic response of GFM-VSC with adaptive fast/slow IVS control during DLG fault. $P_m = 1$ p.u. (a) Stiff grid, SCR = 10. (b) Weak grid, SCR = 1.2.

The small-signal representation of (A.1) is expressed as

$$\hat{x}_{dq}^c = e^{-j\delta_0} \hat{x}_{dq}^s - jX_{dq0}^s e^{-j\delta_0} \hat{\delta} \Leftrightarrow$$

$$\begin{bmatrix} \hat{x}_d^c \\ \hat{x}_q^c \end{bmatrix} = \begin{bmatrix} \cos \delta_0 & \sin \delta_0 \\ -\sin \delta_0 & \cos \delta_0 \end{bmatrix} \begin{bmatrix} \hat{x}_d^s \\ \hat{x}_q^s \end{bmatrix}$$

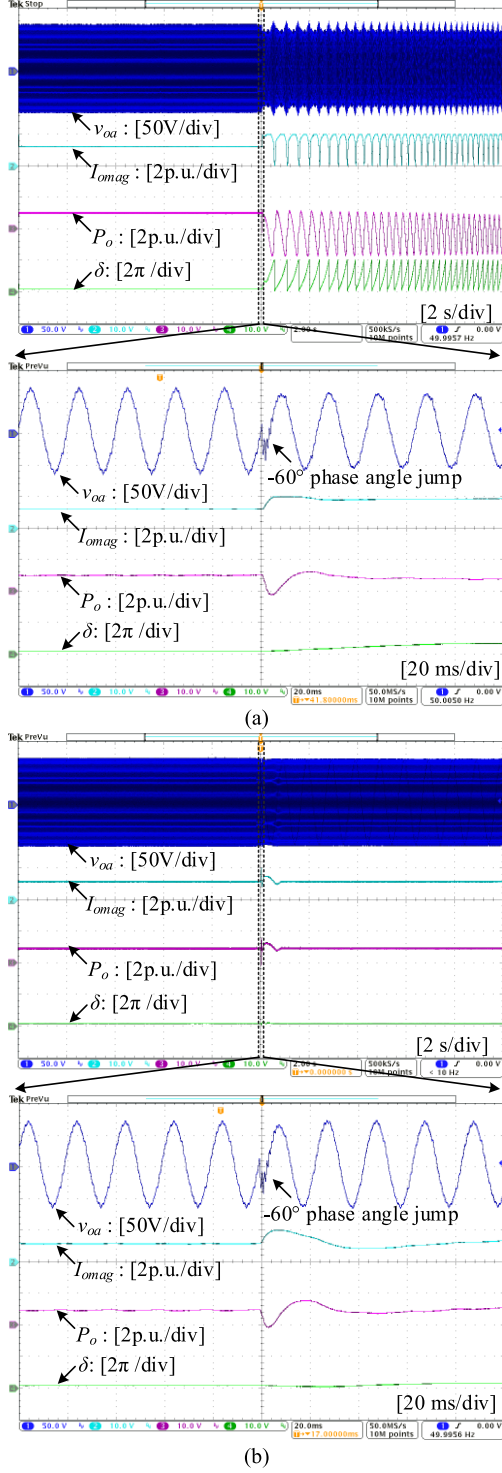


Fig. 28. Dynamic response of GFM-VSC when subjected to -60° grid phase angle jump ($\theta_g = -60^\circ$), together with -5 Hz/s RoCoF that lasts 0.2 s. SCR = 10, $P_m = 1$ p.u. (a) Existing method in [18], unstable. (b) Proposed adaptive fast/slow IVS control, stable.

$$+ \hat{\delta} \begin{bmatrix} \cos \delta_0 & \sin \delta_0 \\ -\sin \delta_0 & \cos \delta_0 \end{bmatrix} \begin{bmatrix} X_{q0}^s \\ -X_{d0}^s \end{bmatrix}. \quad (\text{A.2})$$

It should also be noted that the output of SLVM control, i.e., E_{ref} in Fig. 1, will be saturated during grid disturbances as $V_{omag} \neq V_{\text{ref}}$, which naturally bypasses the RPC loop and the SLVM control [32].

A. Small-Signal Modeling of the Power Plant and Adaptive Virtual Impedance Control

This part has been addressed in authors' previous publication [32], and hence, only final results will be given. Readers are referred to [32] for more details.

The output current in the *system-dq* frame can be expressed as

$$\begin{bmatrix} \hat{i}_{od}^s \\ \hat{i}_{oq}^s \end{bmatrix} = \underbrace{(Z_L + Z_{v_totdq})^{-1} \left(Z_{v_totdq} \begin{bmatrix} -I_{oq0}^s \\ I_{od0}^s \end{bmatrix} + \begin{bmatrix} -V_{invq0}^s \\ V_{invd0}^s \end{bmatrix} \right)}_{\mathbf{G}_{i\delta}} \hat{\delta} \triangleq \begin{bmatrix} m_1 \\ m_2 \end{bmatrix} \hat{\delta}. \quad (\text{A.3})$$

The dynamics of the power plant can be derived as

$$G_{P\delta} = \frac{\hat{p}_o}{\hat{\delta}} = \frac{3}{2} \left([V_{od0}^s \ V_{oq0}^s] + [I_{od0}^s \ I_{oq0}^s] Z_{Lg} \right) \mathbf{G}_{i\delta}. \quad (\text{A.4})$$

B. Small-Signal Modeling of V_{oq} Feedforward

Based on (A.3) and circuit dynamics of GFM-VSC, \hat{v}_{odq}^s can be expressed as

$$\begin{bmatrix} \hat{v}_{od}^s \\ \hat{v}_{oq}^s \end{bmatrix} = \mathbf{Z}_{Lg} \begin{bmatrix} \hat{i}_{od}^s \\ \hat{i}_{oq}^s \end{bmatrix} = \begin{bmatrix} sm_1 L_g & -m_2 X_g \\ m_1 X_g & sm_2 L_g \end{bmatrix} \hat{\delta}. \quad (\text{A.5})$$

Transform (A.5) to *controller-dq* frame based on (A.2), which yields

$$\begin{aligned} \hat{v}_{od}^c &= \underbrace{(n_1 \cos \delta_0 + n_2 \sin \delta_0 + V_{oq0}^c)}_{G_{vd\delta}} \hat{\delta} \\ \hat{v}_{oq}^c &= \underbrace{(-n_1 \sin \delta_0 + n_2 \cos \delta_0 - V_{od0}^c)}_{G_{vq\delta}} \hat{\delta}. \end{aligned} \quad (\text{A.6})$$

Based on Fig. 12, the dynamics of the V_{oq} feedforward is, thus, expressed as

$$\Delta \hat{\omega}_q = K_{pvq} \hat{v}_{oq}^c = K_{pvq} G_{vq\delta} \hat{\delta}. \quad (\text{A.7})$$

C. Small-Signal Modeling of V_{omag} -Based P_{ref} Adjustment

The output voltage magnitude is calculated as

$$V_{omag} = \sqrt{(v_{od}^c)^2 + (v_{oq}^c)^2}. \quad (\text{A.8})$$

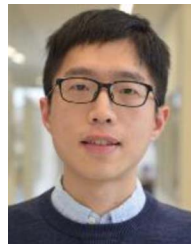
The small-signal representation of (A.8) is given by

$$\begin{aligned} \hat{v}_{omag} &= \frac{\partial V_{omag}}{\partial v_{od}^c} \Big|_{v_{od}^c=V_{od0}^c} \cdot \hat{v}_{od}^c + \frac{\partial V_{omag}}{\partial v_{oq}^c} \Big|_{v_{oq}^c=V_{oq0}^c} \cdot \hat{v}_{oq}^c \\ &= \frac{V_{od0}^c \hat{v}_{od}^c + V_{oq0}^c \hat{v}_{oq}^c}{\sqrt{(V_{od0}^c)^2 + (V_{oq0}^c)^2}} = \frac{V_{od0}^c \hat{v}_{od}^c + V_{oq0}^c \hat{v}_{oq}^c}{V_{omag0}}. \end{aligned} \quad (\text{A.9})$$

It is known from Fig. 12 that by using the V_{omag} -based P_{ref} adjustment, the modified P_{ref} is expressed as

$$P_{\text{ref}} = V_{omag} (P_m - D\Delta\omega). \quad (\text{A.10})$$

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