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# An Improved Synchronization Stability Method of Virtual Synchronous Generators Based on Frequency Feedforward on Reactive Power Control Loop

Xiaoling Xiong, *Member*, *IEEE*, Chao Wu, *Member*, *IEEE*, Donghua Pan, *Member*, *IEEE* and Frede Blaabjerg, *Fellow*, *IEEE*

*Abstract* — **The synchronization stability of the virtual synchronous generator (VSG) under grid fault is an important issue for maintaining stable operation in the power system. Existing work has pointed out a low pass filter (LPF) with a sufficiently low cutoff frequency in the reactive power control loop (RPCL) can improve the transient stability. Yet, the underlying mechanism was unknown. Moreover, as a key index of VSG and precondition of synchronization stability, the frequency response is rarely studied. In this paper, based on the linearized model for qualitative analysis, combined with the nonlinear model for quantitative analysis, the underlying mechanism of improving synchronization stability using an LPF in the RPCL is revealed. Furthermore, to avoid increasing the system order and solve the conflict between transient stability and frequency response, an improved synchronization stability method is proposed by feedforwarding the frequency difference between the VSG and grid to the RPCL. The frequency response is also acquired based on the combined linearized and nonlinear model, which shows that the frequency feedforward method can further enhance the frequency stability. How to design the coefficient of the frequency feedforward path with different inertia requirements is also presented. Finally, this method is verified by experimental results.**

***Index Terms*—Virtual synchronous generators, synchronization stability, frequency stability, reactive power control loop, virtual inertia.**

## I. Introduction

The penetration of distributed energy resources (DERs) connected to the electric power system (EPS) by voltage source converters (VSCs) is growing quickly [1]-[3]. As a result, the EPS becomes weaker as the ratio of synchronous generators (SGs) based generation decreases, indicating that the inertia of the power grid is reduced [4]. The decrease of inertia will jeopardize the frequency stability from two aspects: frequency deviation and the rate of change of frequency (RoCoF). Firstly, lower inertia leads to a large frequency deviation during the disturbances, which is harmful to both SGs and loads. Besides, lower inertia will cause a high RoCoF, which might trip the generators and lead to cascading failure [5]-[7]. Thus, to avoid the adverse effects of the low inertia characteristic, it is necessary to investigate optimized control strategies that can equip the VSCs with inertia.

The basic idea is to control the VSCs to mimic actual SGs by using the swing equation [8]-[17]. The inertia emulating methods can generally be divided into two categories. The first one is virtual synchronous generators (VSGs) [8]-[10], also called virtual synchronous machines (VISMA) [11] or synchroconverter [12], which directly imitate the mechanical toque equation in the active power control loop (APCL). Another category is the generalized droop control, which implements the inertia by adding a low-pass filter (LPF) in the APCL [13], [14]. It has been proved that these two methods are equivalent to the inertia response [15], [16]. Furthermore, an adaptive inertia and damping method are proposed to further increase the frequency stability by employing different inertia during the frequency deviation and recovery process [17], [18].

Even though the VSGs can support the system inertia and improve frequency stability, it still suffers from other stability problems during different kinds of disturbances. Substantial research efforts have been devoted to the modeling and stability analysis under different grid conditions [19]-[21], [24]-[32]. However, most of them are concentrated on the small-signal stability analysis [19], [20], which are generally assessed by linearizing the system around a steady-state operating point. The linearized small-signal model is simple and can provide a clear physical insight into the stability issues. However, much dynamic information was missing during the linearizing procedure, especially for the nonlinear behaviors during large disturbances. Thus, the linearized model cannot be directly extended to analyze the synchronization stability of the VSGs during grid faults, such as grid voltage sag, as it is a large-signal nonlinear dynamic response [21]. Dynamic voltage restorers (DVRs) is an effective method to restore the load voltage during

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the grid voltage sag [22]. However, it can only support the voltage for a very short time due to the limited capacity of the energy storage system [23]. On the other hand, the additional space and equipment are very costly. Thus, the DVR is usually installed for sensitive load, not in all general applications. Therefore, the DVRs are not concerned in this paper, which mainly focuses on improving the control method of VSG to ride through the grid fault, i.e., synchronization stability. Recently, the synchronization stability, which describes the ability of the VSG to maintain synchronization with the grid during grid fault, has received much research interest [24]-[32].

The transient dynamics of VSC with grid-forming control are analyzed in [24]. It has been found that there were no synchronization stability problems when the system with power synchronous control has equilibrium points after grid fault [24], [25], due to a first-order response of the APCL. However, due to the non-inertia contribution, the RoCoF was very high, which means that the frequency changes sharply during the transient process. In [26], [27], the transient stability of VSGs can be enhanced by reducing the active power reference and/or increasing the reactive power reference during grid voltage sag. These methods are easily implemented by just changing the power reference according to the faulty voltage. However, the disadvantage is that the steady-state performance is changed. According to the IEEE standard 1547-2018 [28], it requires the VSGs to operate normally for 10 s without decreasing the active power when the grid voltage drops to 0.5 p.u-0.8 p.u.. In order to avoid the change of power reference, there are also some works aimed at changing the control structure to enhance the transient stability. In [29], [30], an adaptive inertia method is proposed to decrease the frequency deviation during the transient period, which is dependent on detecting the frequency and RoCoF. The adaptive inertia is changed based on the direction of frequency variation and RoCoF variation, which is complicated to implement, especially the differentiation element. In [31], an additional damping control method is proposed based on Lyapunov's direct method, but the design method for the additional damping coefficient is absent. In [32], a mode-switching control method is presented for riding through even without an equilibrium point by changing VSG mode during the grid faults. However, the mode detection block is complicated based on combining the variation of frequency and active power, especially when the differentiation element is used. In [21], it has been found there is a conflict between the frequency response and the transient stability, indicating that large inertia may drive the VSG to crossover the unstable equilibrium point (UEP). However, the frequency response is a key index and requirement for the VSG. The precondition for synchronization stability enhancement is that frequency stability should be firstly guaranteed.

In order to keep a high inertia contribution, using an LPF with a sufficiently low cutoff frequency in the RPCL can enhance transient stability. However, the underlying mechanism is not analyzed in details in [21]. Despite this, this method will decrease the dynamic performance of RPCL and increase the system order.

This paper is going to solve the above problems. Also, it aims to investigate an improved control method to enhance transient stability and not to deteriorate frequency stability simultaneously. Therefore, the contributions of this paper can be summarized as,

1. An analytical method of combining linearized and nonlinear model is employed to study synchronization stability and frequency stability. The linearized model is used for qualitative analysis to provide physical meaning, while the nonlinear model is adopted for quantitative analysis and stability assessment.

2. The underlying mechanism of improving synchronization stability using an LPF in the RPCL is revealed. The added LPF introduces a dominant closed-loop pole to damp the power angle oscillation during the transient process. However, the system order is increased, and the dominant pole might jeopardize the VSG's small-signal stability.

3. In order to avoid the LPF with very low bandwidth in the RPCL, a frequency feedforward path is added in the RPCL to improve the synchronization stability without increasing the system order and not affecting the small-signal stability.

4. The synchronization stability and frequency response are studied based on the combined model, demonstrating that the frequency feedforward method can improve not only the synchronization stability but also the frequency stability during grid faults.

This paper is organized as follows. The configuration and the basic mathematical model of the VSG are presented in Section II. In Section III, using the linearized method for qualitative analysis and the state space trajectories of the nonlinear system for the quantitative analysis, the effect of LPF in RPCL on the synchronization stability is studied and revealed. Section IV proposes an improved method by adding a frequency feedforward path to the RPCL to enhance synchronization stability. Meanwhile, the frequency response is also derived based on the combined model. Detailed parameter design guidelines of the coefficient parameters for the additional path are also presented. The theoretical analysis is verified in Section V by experimental results, and the conclusions are drawn in Section VI.

## II. Configuration and Mathematical Model

The configuration of a three-phase grid-connected VSG is shown in Fig. 1. The grid is modeled as an infinite voltage in series with an impedance, which includes an inductance $L_g$ and a resistance $R_g$. Here, $\mathbf{V_g}=V_g e^{j\omega_g t}$ and $\mathbf{V_{pcc}}=V_{pcc}e^{j\theta_{pcc}}$ represent the space vectors of the grid voltage and the PCC voltage, respectively. Usually, $\omega_g$ is equal to the synchronous angular frequency $\omega_0$ in a strong grid, but it varies when connected to a weak grid. Inductor $L_f$ represents the output filter of the VSG, and $\mathbf{I}_g$ is the current vector of the injected current to the grid. $P$ and $Q$ represent the active and reactive power transferred from PCC to the grid, respectively. In practice, to make an inertia contribution, a large capacitor is added on the dc side, which is controlled by the front-end converter, or the energy storage is generally employed where the dc-link voltage is regulated by an energy storage converter [33], [34]. Hence, the dc voltage can be assumed to be constant when analyzing the synchronization issues between the VSG and the power grid [16], [21], [24-27].

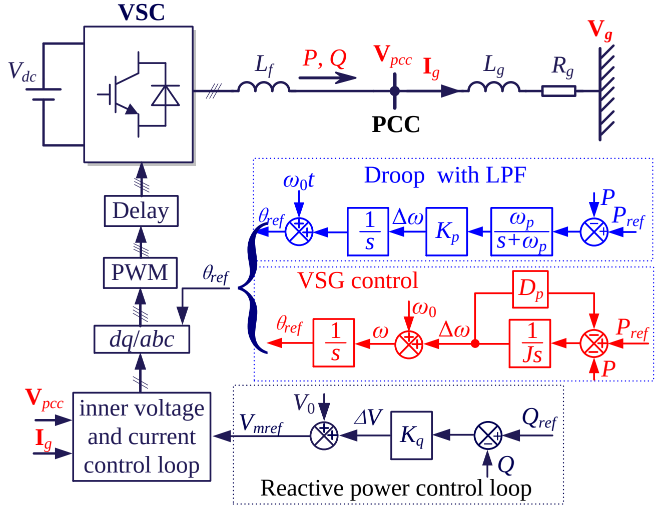


Fig. 1. The configuration of a three-phase grid-connected VSG.

As shown in Fig. 1, $P_{ref}$ and $Q_{ref}$ are active and reactive power references, respectively. The outer power control loops generate the PCC voltage vector reference, i.e., $\mathbf{V}_{ref}=V_{mref}e^{j\theta_{ref}}$, where $\theta_{ref}$ and $V_{mref}$ are the phase and the voltage amplitude reference, respectively. An inner voltage and current control loop are adopted to regulate $\mathbf{V}_{pcc}$ to track $\mathbf{V}_{ref}$ and limit the overcurrent. In practice, the responses of the outer power control loops are very slow, which determines the synchronization stability. Meanwhile, the inner loop bandwidth is much higher, and the delay term mainly affects the performance of high frequency [35], [36]. Therefore, the inner control loop and delay can be regarded as one with an ideal PCC voltage reference tracking when analyzing the synchronization stability [21], [24]-[27]. Thus, $V_{pcc} = V_{mref}$, $\theta_{pcc} = \theta_{ref}$ can be obtained.

The droop control with an LPF can be used to emulate the VSG control, where $K_p$ is the proportional gain, $\omega_p$ is the cutoff angular frequency of LPF, which is added to provide virtual inertia. The commonly used VSG control scheme is also shown in Fig. 1, where $J$ and $D_p$ are the virtual inertia and the gain of frequency governor, respectively. The two control methods are equivalent when

$$J = 1\big/\left(K_p\omega_p\right) \quad , \quad D_p = 1\big/K_p \tag{1}$$

The droop control with an LPF is adopted in this paper to compare with the results in [21] directly. The APCL is to emulate the swing equation of a SG, given as

$$d\omega\big/dt = K_p\omega_p\left(P_{ref}-P\right)-\omega_p\left(\omega-\omega_0\right) \tag{2}$$

The $Q$-$V$ droop control is employed to adjust $V_{mref}$, the transfer function of which is given by

$$V_{mref} = V_0 + K_q\cdot\left(Q_{ref}-Q\right) \tag{3}$$

where $K_q$ is the proportional gain.

Defining $\delta$ as the power angle, which is the phase difference between $\mathbf{V}_{pcc}$ and $\mathbf{V}_g$, i.e., $\delta = \theta_{pcc} - \theta_g = \theta_{ref} - \omega_g t$. Thus, $P$ and $Q$ can be derived as

$$P = \frac{3}{2}\cdot\frac{\left(V_{pcc}^2 - V_{pcc}V_g\cos\delta\right)R_g + X_g V_{pcc}V_g\sin\delta}{R_g^2 + X_g^2} \tag{4}$$

$$Q = \frac{3}{2}\cdot\frac{\left(V_{pcc}^2 - V_{pcc}V_g\cos\delta\right)X_g - R_g V_{pcc}V_g\sin\delta}{R_g^2 + X_g^2} \tag{5}$$

It can be found $P$ and $Q$ are coupled with each other, which gives the inspiration to provide damping from the RPCL. It will be discussed in details in Section IV.

## III. Synchronization Stability Analysis

### A. *Types of the Synchronization Problems*

Substituting (5) to (3) and considering $V_{pcc} = V_{mref}$, $V_{pcc}$ can be solved. $V_{pcc}$ is then substituted into (4), $P$-$\delta$ relationship can thus be obtained in (6), as shown at the bottom of this page, where

$$k_1 = X_g\big/\left(R_g^2 + X_g^2\right) \quad k_2 = R_g\big/\left(R_g^2 + X_g^2\right) \tag{7}$$

Accordingly, the $P-\delta$ curves, with different grid voltage sags and different $R_g$, are plotted in Fig. 2. Assuming $\omega_g = \omega_0$ holds after a disturbance for simplifying the illustration. In Fig. 2(a), as shown by the solid line, the VSG initially operates at point a. After the disturbance occurs, there are two types of transient problems, i.e., the equilibrium point exists or not after the grid fault. According to IEEE Standards 1547-2018 [28], it can be known that the VSG should continue to supply power at least for 10 s when the grid voltage drops to 0.5-0.8 p.u.. 10 s is undoubtedly larger than the critical clearing time (CCT) of VSG, which indicates that the VSG should keep working normally during the fault for a long time. Therefore, this paper aims to optimize the control algorithm to ride through the grid fault when the equilibrium point exists, as shown with the dashed red line. The points $b$ and $b_1$ are the stable equilibrium point (SEP), and the UEP after disturbance, respectively. The corresponding power angles are denoted as $\delta_e$ and $\delta_{ce}$. During the transient period, if the system goes across $b_1$, $\delta$ will

$$P = \frac{3}{2}\cdot\frac{V_g\sin\delta}{X_g}\cdot\frac{1.5k_1K_qV_g\cos\delta + 1.5k_2K_qV_g\sin\delta - 1 + \sqrt{\left(1.5k_1K_qV_g\cos\delta + 1.5k_2K_qV_g\sin\delta - 1\right)^2 + 6k_1K_q(V_0 + K_qQ_{ref})}}{3K_qk_1} \tag{6}$$

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exceed $\delta_{ce}$ and then go to infinite, causing the loss of synchronization (LOS). Thus, $\delta_{ce}$ is called the critical power angle. In contrast, if the power angle was controlled smaller than $\delta_{ce}$ during the transient period, the system finally can operate stably at $b$.

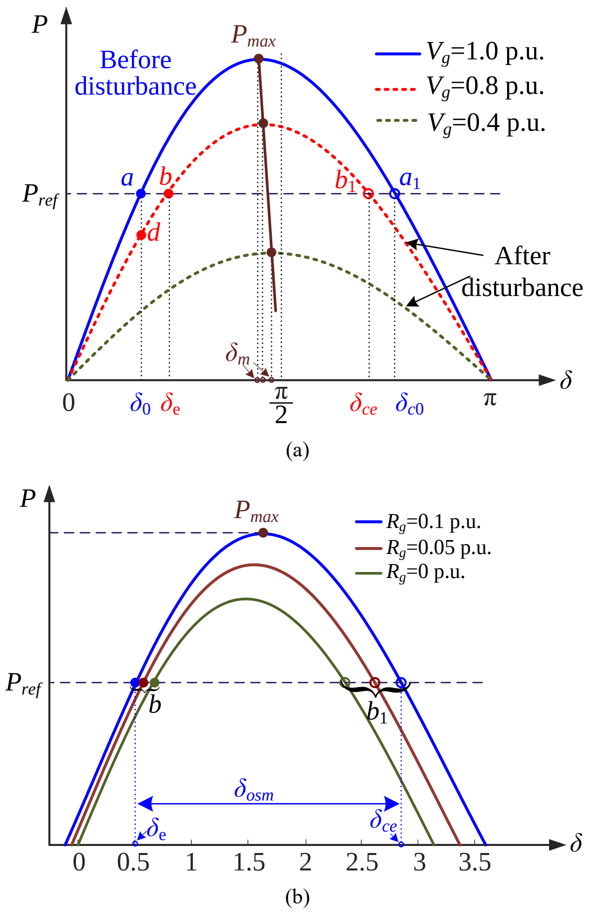


Fig. 2. *P*-*δ* curves with (a) different grid voltage sags and (b) different grid resistances $R_g$.

The other type of no equilibrium point after the fault, shown as the dashed green line, is not of concern here since it cannot continue supplying power normally.

From Fig. 2(b), it can be seen that the power transfer capability of the VSG varies with different $R_g$. The maximum power $P_{max}$ that can be transmitted becomes higher with a larger $R_g$. Meanwhile, the allowed variation range of the power angle $\delta$, i.e., $\delta_{osm}$, is much wider with a larger $R_g$, which can benefit the synchronization stability during grid fault. Thus, the worst condition is $R_g$ =0, which is focused on in this manuscript.

### B. Effects of the LPF in the Reactive Power Control Loop

As shown in Fig. 2, after the grid fault, the SEP $b$ is small-signal stable; thus, all the trajectories of the state variables in the neighborhood are attracted to $b$. However, how large the neighborhood is unknown. The severe grid faults might be out of the neighborhood, resulting in the small-signal stability analysis method is not accurate enough to investigate transient stability. However, the linearized model can provide clear physical insight and intuitive explanation of stability issues, which is thus considered to be used for a better understanding. Before that, the connections between the linearized model and the nonlinear model should be established. Suppose the VSG is large-signal stable. In that case, it will finally be attracted to the neighborhood of $b$ (see Fig. 2), so the trajectory for the original nonlinear system has the same response trend as the linearized system. For example, a larger damping ratio leads to a smaller overshoot for a linear second-order system, which is also applicable to the nonlinear system. Therefore, the linearized system can be used for qualitative analysis during the grid faults, such as analyzing the overshoot and the damping ratio for the power angle response.

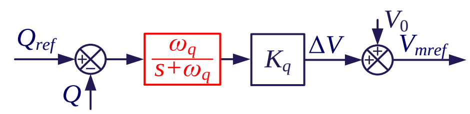


Fig. 3. An LPF is added in RPCL in [21] to enhance the transient stability.

In [21], it has been revealed that adding an LPF in the RPCL, as shown in Fig. 3, with a very low cutoff frequency $\omega_q$ can enhance transient stability. However, the underlying mechanism is not addressed, and this paper will give a thorough qualitative analysis based on the linearized method and quantitative analysis with the nonlinear system.

According to the previous description, the dynamics of the system is a third-order nonlinear system, which can be represented in the standard form as

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\end{bmatrix}=\begin{bmatrix} x_2+\omega_0-\omega_g \\ -\omega_p x_2-\dfrac{3\omega_p K_p V_g x_3}{2X_g}\sin x_1+\omega_p K_p P_{ref} \\ \omega_q\left(V_0-x_3\right)+\omega_q K_q\left(Q_{ref}-\dfrac{3}{2}\cdot\dfrac{x_3{}^2-V_g x_3\cos x_1}{X_g}\right)\end{bmatrix} \tag{8}$$

where dot $(\cdot)$ denotes time derivative, $\boldsymbol{x}=[x_1, x_2, x_3]^T=[\delta, \Delta\omega, V_{pcc}]^T$ is the state variable vector, superscript $T$ represents the transposition of a matrix or vector.

By setting all the differential items in (8) to zero, the two equilibrium points $\boldsymbol{x_e}=[\delta_e, \Delta\omega_e\ V_{pcce}]^T$ and $\boldsymbol{x_{ce}}=[\delta_{ce}, \Delta\omega_{ce}\ V_{pccce}]^T$ can be obtained. This implies $\Delta\omega_e=\Delta\omega_{ce}=\omega_g-\omega_0$, $\delta_e$ ($\delta_{ce}$) and $V_{pcce}$ ($V_{pccce}$) should satisfy,

$$\begin{cases}\dfrac{3}{2}\cdot\dfrac{V_g V_{pcc}\sin\delta}{X_g}=P_{ref}-\dfrac{\omega_g-\omega_0}{K_p}\\ V_{pcc}=V_0+K_q\left(Q_{ref}-\dfrac{3}{2}\cdot\dfrac{V_{pcc}^2-V_{pcc}V_g\cos\delta}{X_g}\right)\end{cases} \tag{9}$$

By solving (9), $V_{pcce}=V_{pccce}$, and two angle values in $[0, 2\pi]$ for $\delta$ can be obtained. Among them, the smaller one is $\delta_e$, and the other larger one is $\delta_{ce}$. The equilibrium points are the same as the second-order system without LPFs.

To linearize the third-order system around the equilibrium point, the Jacobian $\boldsymbol{J}(\boldsymbol{x_e})$ is calculated as

$$\boldsymbol{J}(\boldsymbol{x}_e)=\begin{bmatrix} 0 & 1 & 0 \\ -\dfrac{3\omega_p K_p V_g V_{pcce}\cos\delta_e}{2X_g} & -\omega_p & -\dfrac{3\omega_p K_p V_g \sin\delta_e}{2X_g} \\ -\dfrac{3\omega_q K_q V_g V_{pcce}\sin\delta_e}{2X_g} & 0 & J_{33} \end{bmatrix} \quad (10)$$

where $J_{33}$ is

$$J_{33}=\frac{-2X_g\omega_q-3\omega_q K_q(2V_{pcce}-V_g\cos\delta_e)}{2X_g} \quad (11)$$

Suppose the eigenvalues (also called the closed-loop poles) of $\boldsymbol{J}(\boldsymbol{x}_e)$ include a real and a pair of conjugate eigenvalues. In that case, the system is decomposed into a first- and second-order dynamics. Thus the response consists of an exponential curve and a damped sinusoidal curve. For a stable third-order system, if one pole is much closer to the imaginary axis than the other poles, it is called the dominant pole since this pole will determine the transient response and decay slowest.

To obtain the closed-loop poles, we can solve the characteristic equation for $\boldsymbol{J}(\boldsymbol{x}_e)$, i.e., $\det[\lambda\boldsymbol{I} - \boldsymbol{J}(\boldsymbol{x}_e)] = 0$. Suppose $\lambda_1$ is the pole for the first-order system, and $\lambda_{2,3}$ are the second-order system's conjugate eigenvalues, respectively. $\beta$ denotes the ratio of the real parts of the poles, defined as $\beta = \mathrm{Real}(\lambda_{2,3})/\lambda_1$. A large $\beta$ helps to dampen the oscillation of the second-order system, thus reducing the overshoot of the power angle and improving the synchronization stability. In contrast, if $\beta$ is too small, i.e., $\beta < 0.1$, the system is dominated by the second-order system, and the impact of $\lambda_1$ is so little that it can be neglected. If $\beta$ is sufficiently large, $\lambda_1$ is the dominant pole, and the approximated system can be a first-order one. To conclude, introducing an LPF in the RPCL means introducing a closed-loop pole $\lambda_1$, which can enhance the transient stability if it is close enough to the imaginary axis.

Numerical calculations are performed with $\omega_q$ decreasing from 4π rad/s to 0.1π rad/s when $V_g = 0.6$ p.u. and $\omega_p = 0.6\pi$ rad/s, the other parameters in Table III in section V are adopted. The corresponding loci for eigenvalues are plotted in Fig. 4, and the typical scenario for the variation of the eigenvalues are shown in Table I. It can be found that $\omega_q$ mainly determines the real pole and has a little effect on the pair of conjugate eigenvalues. Smaller $\omega_q$, such as $\omega_q < 0.4\pi$ rad/s, can make $\lambda_1$ closer to the imaginary axis, indicating the first-order system dominates the system response in this case. Thus, smaller $\omega_q$ induces a larger $\beta$ to damp the power angle overshoot, which can enhance the synchronization stability. As $\omega_q$ increases, the impact of $\lambda_1$ is reduced, and if $\omega_q \geq 2.6\pi$ rad/s, the impact can be ignored. Although these conclusions are summarized with the linearized system, it can be applied to qualitatively evaluate the influences of the LPF in the RPCL for the nonlinear system.

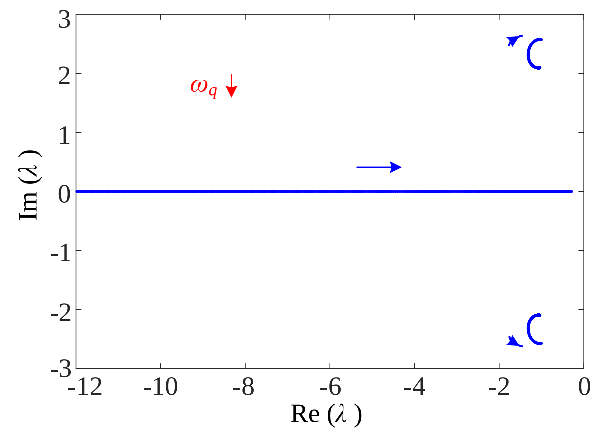


Fig. 4. Loci of eigenvalues with $\omega_q$ is decreasing from 4π rad/s to 0.1π rad/s ($\omega_p$ = 0.6π rad/s and $V_g$ = 0.6 p.u.).

TABLE I
EIGENVALUES FOR INCREASING $\omega_q$ OF THE SYSTEM IN TABLE III

| $\omega_q$ (rad/s) | Eigenvalues ($\lambda_1$, $\lambda_{2,3}$) | $\beta$ |
|---|---|---|
| 0.1π | −0.2910, −1.0033 ± *j*2.5724 | 3.4478 |
| 0.2π | −0.5716, −1.0694 ± *j*2.5728 | 1.8709 |
| 0.4π | −1.1354, −1.2001 ± *j*2.5250 | 1.0570 |
| 0.44π | −1.2541, −1.2234 ± *j*2.5075 | 1.0251 |
| 0.6π | −1.7729, −1.2941 ± *j*2.4153 | 0.9755 |
| π | −3.4718, −1.2700 ± *j*2.1857 | 0.3658 |
| 2π | −7.9490, −1.0948 ± *j*2.0937 | 0.1377 |
| 2.6π | −10.5049, −1.0549 ± *j*2.0924 | 0.1004 |
| 20π | −82.5118, −0.9552 ± *j*2.1131 | 0.0116 |

To further investigate the impacts of $\omega_q$ and to obtain more accurate results, the state-space trajectories based on the original nonlinear system in (8) can be plotted, as shown in Fig. 5(a). To provide a more clear visual support, one of the projections, i.e., $\Delta\omega-\delta$ curves, is replotted in Fig. 5(b), where the second-order system's unstable curve without LPF in the RPCL is also given to make a comparison. The power angle overshoot, denoted as $\delta_p$, is the maximum difference between the transient power angle and $\delta_e$, as shown in Fig. 5(b).

From Fig. 5, it can be found that a smaller $\omega_q$ damps more power angle overshoot, leading to better transient stability. If $\omega_q$ is small enough, as $\omega_q = 0.1\pi$ rad/s, indicating $\lambda_1$ is the dominant closed-loop pole, so the dynamic response behaves similarly as a first-order system in the neighborhood. If $\omega_q$ increases over 2.6π rad/s, the impacts of $\omega_q$ can be almost ignored. The responses of the nonlinear system agree with the qualitative analysis in Fig. 4 based on the linearized system.

However, only reducing $\omega_q$, is not able to achieve an overdamped system during the grid fault. Take $\omega_q = 0.1\pi$ rad/s in Fig. 5 as an example. Although $\omega_q$ is small enough, the overshoot of $\delta$ still exists when the grid voltage drops from 1 p.u. to 0.6 p.u.. Meanwhile, a sufficiently small $\omega_q$ can enhance transient stability but reducing the small-signal stability margin, as $\lambda_1$ is too close to the imaginary axis.

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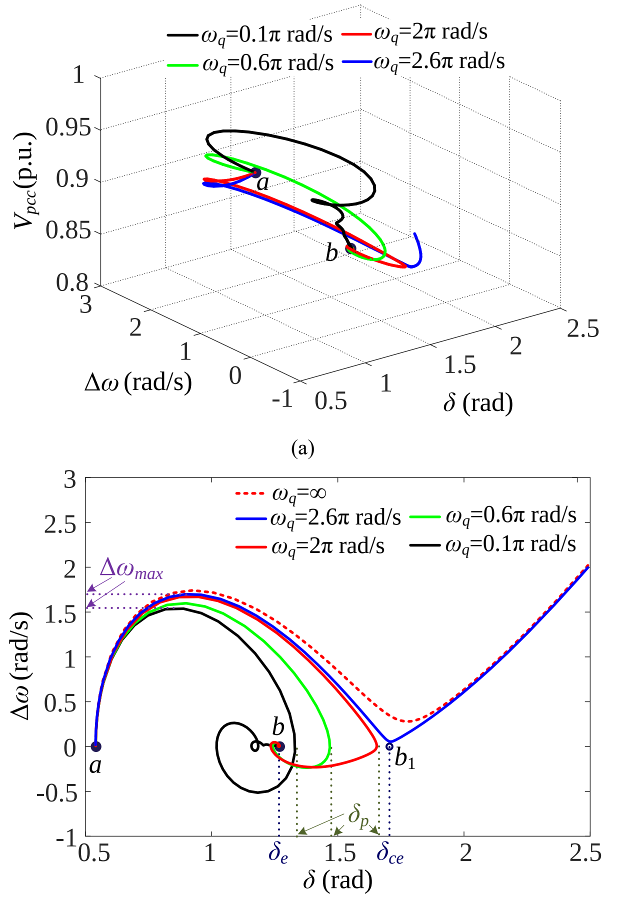


Fig. 5. The state-space trajectories of the nonlinear system in (8) with different $\omega_q$. (a) The corresponding trajectories of the third-order system. (b) The projection of $\Delta\omega$−$\delta$ plane to provide visual support. ($\omega_p$ = 0.6π rad/s and $V_g$ = 1→ 0.6 p.u.).

Moreover, the LPF is usually employed for *Q-V* droop control to filter the high-frequency harmonics and noises [8], [13], [14], $\omega_q$ is at least higher than 10 Hz, i.e., 1000 rad/s is used in [8]. Thus, the effect of this kind of LPF can be generally ignored when studying the synchronization stability issues due to the decoupled timescales. Here, the LPF is employed to simultaneously enhance the synchronization stability, $\omega_q$ needs to be set very low, such as lower than 2π rad/s. In this case, the effects of LPF cannot be ignored when analyzing the synchronization stability. Thus, the dynamics of the system is increased to third-order. Unlike in the linearized second-order system, the underlying mechanism and the performance can be analyzed using an explicit mathematical approach rather than a numerical analysis. Therefore, in order to avoid these negative effects of too small $\omega_q$, adding frequency feedforward to the RPCL is proposed to enhance the synchronization stability in Section IV.

## IV. Frequency Feedforward to the RPCL

In order to keep the desired original steady-state characteristics and not to deteriorate the frequency performance, a synchronization stability enhancement method is proposed, as shown in Fig. 6. The additional path, by feedforwarding the frequency difference between the VSG and grid, is introduced into the RPCL. Since $\omega$ is equal to $\omega_g$ at the steady-state, the additional path does not influence the steady-state characteristics.

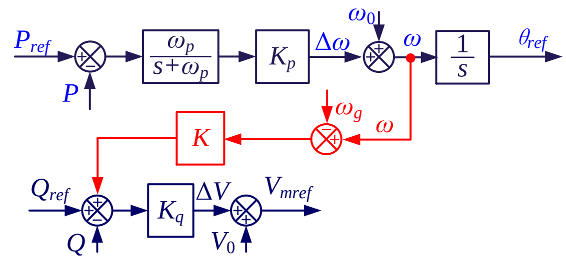


Fig. 6. Diagram of the enhanced method for synchronization stability by frequency feedforward to RPCL.

From Fig. 6, it can be seen that the reactive power control law is different from (3), and it is given as

$$V_{mref} = V_0 + K_q\left(Q_{ref} - Q\right) + K_q K\left(\Delta\omega + \omega_0 - \omega_g\right) \tag{12}$$

Substituting (5) into (12), combining with $V_{pcc} = V_{mref}$ and $R_g$ = 0, the relationship between $V_{pcc}$ and $\delta$, $\Delta\omega$, i.e., $V_{pcc}(\delta, \Delta\omega)$, can be solved, as given in (13) at the top of next page. Since the added term in (12) is zero at steady-state, the additional path will not affect the steady-state characteristics.

### A. *Qualitative Analysis Based on the Linearized System*

The dynamic representation of the system is a second-order state equation, derived as

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix} = \begin{bmatrix} x_2 + \omega_0 - \omega_g \\ -\omega_p x_2 - \dfrac{3\omega_p K_p V_g}{2X_g}F(x_1, x_2) + \omega_p K_p P_{ref}\end{bmatrix} \tag{14}$$

where $F(x_1, x_2)$ is

$$F(\delta, \Delta\omega) = V_{pcc}\left(\delta, \Delta\omega\right)\sin\delta \tag{15}$$

By setting the differential of $\boldsymbol{x}$ in (14) to zero, the two equilibrium points $\boldsymbol{x_e} = [\delta_e, \Delta\omega_e]^T$ and $\boldsymbol{x_{ce}} = [\delta_{ce}, \Delta\omega_{ce}]^T$ are obtained, which are the SEP *b* and UEP $b_1$, respectively. To linearize the nonlinear system at $\boldsymbol{x_e}$, the Jacobian $\boldsymbol{J}(\boldsymbol{x_e})$ is evaluated as

$$\boldsymbol{J}(\boldsymbol{x_e}) = \begin{bmatrix} 0 & 1 \\ J_{21} & -\omega_p + J_{22}\end{bmatrix} \tag{16}$$

where $J_{21}$ and $J_{22}$ are expressed as

$$J_{21} = -\frac{3\omega_p K_p V_g}{2X_g}F'\left(\delta_e\right) \tag{17}$$

$$J_{22} = -\frac{3\omega_p K_p V_g}{2X_g}F'\left(\Delta\omega_e\right) \tag{18}$$

From (13) and (15), the values of the functions $F'(\delta)$ and

$$V_{pcc}\left(\delta,\Delta\omega\right)=\frac{1.5K_qV_g\cos\delta-X_g+\sqrt{\left(X_g-1.5K_qV_g\cos\delta\right)^2+6K_qX_g\left(V_0+K_qQ_{ref}+K_qK\left(\Delta\omega+\omega_0-\omega_g\right)\right)}}{3K_q} \tag{13}$$

$F'(\Delta\omega)$ around $\boldsymbol{x_e}$, i.e., $F'(\delta_e)$ and $F'(\Delta\omega_e)$, can be derived as

$$F'\left(\delta_e\right)=V_{pcce}\cos\delta_e-\frac{3K_qV_gV_{pcce}\sin\delta_e\cdot\sin\delta_e}{2X_g+3K_q\left(2V_{pcce}-V_g\cos\delta_e\right)} \tag{19}$$

$$F'\left(\Delta\omega_e\right)=\frac{2X_gK_qK\sin\delta_e}{2X_g+3K_q\left(2V_{pcce}-V_g\cos\delta_e\right)} \tag{20}$$

Solving the characteristic equation, i.e., $\det[\lambda\boldsymbol{I}-\boldsymbol{J}(\boldsymbol{x_e})]=0$, the eigenvalues are calculated as

$$\lambda_{1,2}=\frac{-\omega_p+J_{22}\pm\sqrt{\left(-\omega_p+J_{22}\right)^2+4J_{21}}}{2} \tag{21}$$

Therefore, the damping ratio of the second-order system can be derived as

$$\begin{aligned}\zeta&=\frac{\omega_p-J_{22}}{2\sqrt{-J_{21}}}\\&=\sqrt{\frac{X_g\omega_p}{6V_gK_pF'\left(\delta_e\right)}}+F'\left(\Delta\omega\right)\sqrt{\frac{3\omega_pK_pV_g}{8X_gF'\left(\delta_e\right)}}\end{aligned} \tag{22}$$

Here, the sign of $F'(\delta_e)$ and $F'(\Delta\omega_e)$ need to be first illustrated. Suppose when $\delta=\delta_m$, $P(\delta_m)=P_{max}$ in Fig. 2(a), and thus $\frac{dP}{d\delta}|_{\delta_m}=0$. According to (4) and (15), $F'\left(\delta_m\right)=0$ is derived. As $P$ is monotonically increasing with $\delta$ when $\delta<\delta_m$. Therefore, when $\delta<\delta_m$, $\frac{dP}{d\delta}>0$, then $F'\left(\delta_e\right)>0$ is obtained. Meanwhile, due to $V_{pcc}\approx V_g$ in steady-state, then $F'(\Delta\omega)>0$ always holds, and it becomes larger with the increase of $K$.

According to (22), it can be clearly seen that $\zeta$ is related to the system parameters and controller parameters. For a given condition, the system parameters are constant. Controller parameters $K_p$ and $\omega_p$ are related to the inertia and frequency governor, which also should be fixed. Without the additional path, the original damping ratio can be derived similarly, which is the first term in (22). Obviously, the damping ratio can be increased with the additional path, and a larger $K$ leads to a larger damping ratio. Moreover, numerical calculations of the eigenvalues are performed with various $K$. The corresponding loci are plotted in Fig. 7. As shown in Fig. 7, the damping ratio increases while $K$ becomes larger, and even an overdamped dynamics can be achieved with a sufficiently large $K$.

To analyze the frequency response in the s-domain, the active power $P$ should be linearized firstly around $b$, given as

$$\begin{aligned}&\hat{P}=\frac{3V_g}{2X_g}\left(F'\left(\delta_e\right)\cdot\hat{\delta}+F'\left(\Delta\omega_e\right)\cdot\Delta\hat{\omega}\right)\\&\overset{define}{\Rightarrow}G_1=\frac{3V_g}{2X_g}F'\left(\delta_e\right)\quad G_2=\frac{3V_g}{2X_g}F'\left(\Delta\omega_e\right)\end{aligned} \tag{23}$$

where cap (^) represents the small variations, $G_1$ and $G_2$ are the approximate gains between $P$ and $\delta$, $P$ and $\Delta\omega$ evaluated at $b$, respectively.

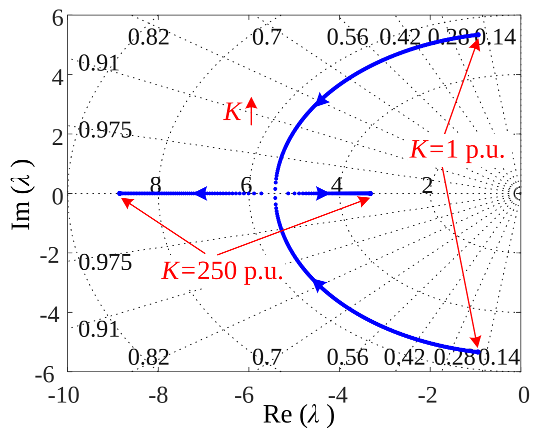


Fig. 7. Loci of eigenvalues for the second-order system in (16) with $K$ increasing from 1 p.u. to 250 p.u. ($\omega_p=0.6\pi$ rad/s and $V_g=0.6$ p.u.).

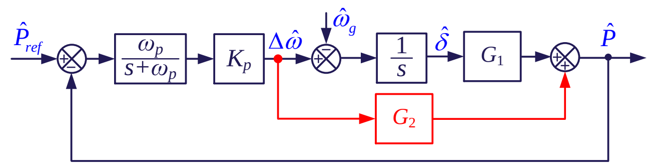


Fig. 8. The control block diagram of the VSG system with the frequency feedforward path.

Combining (23) and Fig.1, the control block diagram is derived as in Fig. 8, where the effects of RPCL and the frequency feedforward path are equivalently substituted into APCL. From there, the dynamics of $\delta$ and $\Delta\omega$, can be described in the $s$-domain as

$$\frac{\hat{\delta}}{\hat{P}_{ref}}=\frac{K_p\omega_p}{s^2+\left(\omega_p+\omega_pK_pG_2\right)s+K_p\omega_pG_1} \tag{24}$$

$$\frac{\Delta\hat{\omega}}{\hat{P}_{ref}}=\frac{K_p\omega_ps}{s^2+\left(\omega_p+\omega_pK_pG_2\right)s+K_p\omega_pG_1} \tag{25}$$

The damping ratio can also be deduced from (24) and (25), which is the same as that in (22).

Assuming that the power reference has a step change, the Laplace form is 1/s. Thus, according to (25), the response of the frequency variation in the s-domain can be deduced as,

$$\Delta\hat{\omega}=\frac{K_p\omega_p}{s^2+\left(\omega_p+\omega_pK_pG_2\right)s+K_p\omega_pG_1} \tag{26}$$

Rewrite (26) in the standard form of the second-order system, expressed as,

$$\Delta\hat{\omega}=\frac{\omega_n^2/G_1}{s^2+2\zeta\omega_ns+\omega_n^2} \tag{27}$$

where $\omega_n^2=K_p\omega_pG_1$, $2\zeta\omega_n=\omega_p+\omega_pK_pG_2$.

Thus, the response of frequency variation in the time-

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domain can be derived as,

$$\Delta\hat{\omega} = \frac{1}{G_1}\frac{\omega_n^2}{\sqrt{1-\zeta^2}} e^{-\zeta\omega_n t}\sin\left(\sqrt{1-\zeta^2}\,\omega_n t\right) \tag{28}$$

The RoCoF is the change rate of frequency, which can be deduced as,

$$\begin{aligned}\text{RoCoF} &= \frac{d\omega}{dt} = \frac{d\Delta\omega}{dt} \\ &= \frac{1}{G_1}\frac{\omega_n^2}{\sqrt{1-\zeta^2}} e^{-\zeta\omega_n t}\sin\left(\beta - \sqrt{1-\zeta^2}\,\omega_n t\right)\end{aligned} \tag{29}$$

where $\sin\beta = \sqrt{1-\zeta^2}$.

The maximum RoCoF is achieved when $t$=0, which is calculated as,

$$\text{RoCoF}\big|_{\max} = \frac{1}{G_1}\frac{\omega_n^2}{\sqrt{1-\zeta^2}}\sin(\beta) = K_p\omega_p = \frac{1}{J} \tag{30}$$

It can be found that the inertia $J$ determines the maximum RoCoF, which has no relationship with $K$, indicating the additional path does not influence the maximum RoCoF. Furthermore, the inertia $J$ should be large enough to maintain the maximum RoCoF in the acceptable range according to the grid code [8].

When the derivative of frequency is equal to zero, the maximum frequency variation can be obtained, given as,

$$\Delta\hat{\omega}\big|_{\max} = \omega_n e^{-\frac{\zeta}{\sqrt{1-\zeta^2}}\arcsin\left(\sqrt{1-\zeta^2}\right)} \approx \sqrt{\frac{G_1}{J}}e^{-\zeta} \tag{31}$$

As can be seen from (31), the maximum frequency deviation is an inverse ratio of $J$ and $\zeta$. Increasing $J$ is unexpected from the perspective of synchronization stability [21]. Thus, increasing $\zeta$ can effectively decrease the frequency deviation during the transient period, which perfectly avoids the conflict between frequency stability and synchronization stability.

Therefore, the additional frequency feedforward path with a larger $K$, leading to a larger damping ratio, which enhances synchronization stability and simultaneously benefits frequency stability during grid fault.

### B. *Quantitative Analysis Based on the Nonlinear System*

The influence of the proposed method on exact transient behaviors is examined in Fig. 9 based on the nonlinear system in (14). It can be observed that without the additional path, a LOS occurs when the grid voltage drops from 1 p.u. to 0.6 p.u. with $\omega_p$ = 0.6π rad/s, due to the low damping dynamics. Increasing $\omega_p$ to 1.2π rad/s (the virtual inertia $J$ is decreased) can remove the instability due to an increased ζ.

However, the frequency response becomes worse, i.e., a larger $\Delta\omega_{max}$ and higher RoCoF are observed, resulting from smaller inertia. The frequency feedforward method can also remove the instability with a large $K$. It can be seen that the overshoot of $\delta$ can be reduced with a larger $K$ due to the increased ζ. Even an overdamped response can be achieved by a sufficiently large $K$, i.e., $K$ = 200 p.u.. Moreover, $\Delta\omega_{max}$ decreases with the increase of $K$, which is also helpful to frequency stability. Therefore, a larger $K$ is expected to increase the damping ratio, thus improving the synchronization stability and frequency stability. Otherwise, instability can occur if $K$ is not large enough, i.e., $K$ = 10 p.u.. The system suffers from poorly damped dynamics, which causes $\delta$ to exceed $\delta_{ce}$.

A larger $K$ is expected from the above analysis, but an extensive $K$ is also not practical. Thus, the minimum required $K$ according to different inertia requirements should be found. This is also handy design information for engineers to identify how far or close the system is from the LOS region. As only if

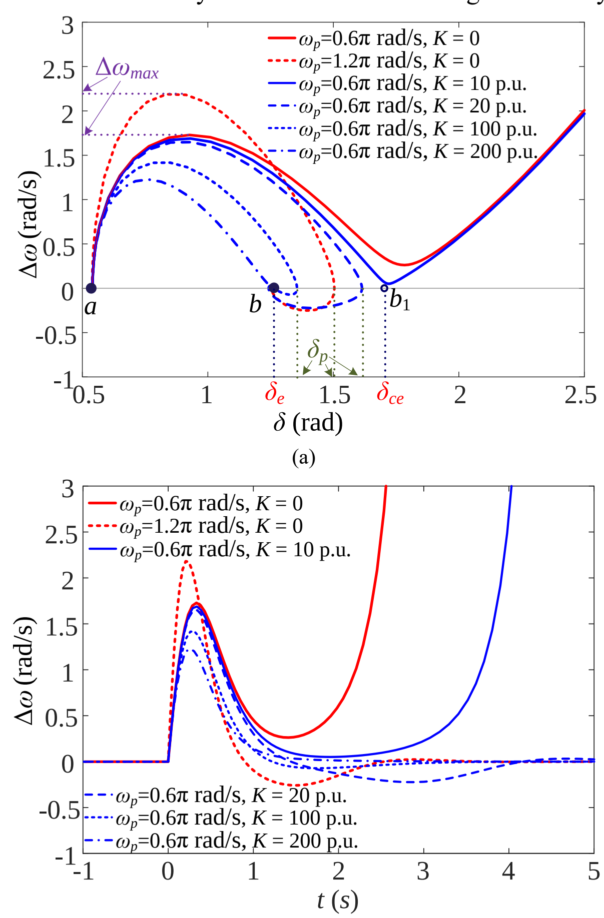


Fig. 9. The VSG responses with different $K$ in the frequency feedforward path when $V_g$= 1→ 0.6 p.u.. (a) The trajectories of the nonlinear system in the phase plane and (b) the frequency response in the time-domain.

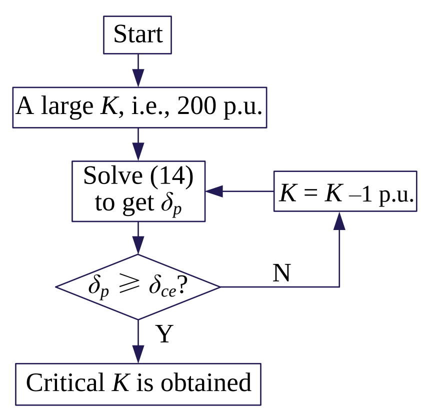


Fig. 10. Iterative calculation procedure of the critical value of $K$ for a specific $\omega_p$.

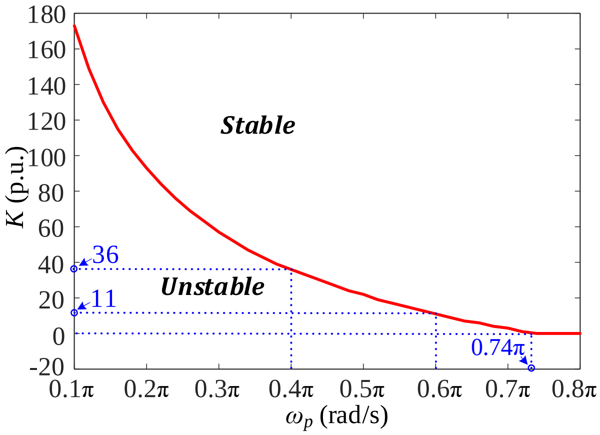


Fig. 11. The minimum required $K$ according to different inertia requirements (different $\omega_p$) when $V_g = 1 \rightarrow 0.6$ p.u..

$\delta$ exceeds $\delta_{ce}$, LOS can occur. Thus, as long as $\delta_p$ does not exceed $\delta_{ce}$, the synchronization stability can be guaranteed. According to this, the critical value of $K$ for each specified $\omega_p$ can be calculated using the procedure in Fig. 10, which is plotted in Fig. 11. In Fig. 11, the stable and unstable operation regions are located above and below the boundary line, respectively. From them, it can be found that smaller $\omega_p$ (larger $J$), the minimum required $K$ for the stable operation increases. For example, with $\omega_p = 0.6\pi$ rad/s, it is sufficient when $K > 11$ p.u., but if $\omega_p = 0.4\pi$ rad/s, then $K > 36$ p.u. must be adopted. Hence, using the frequency feedforward to the RPCL method with a larger $K$, higher inertia becomes viable.

Combining with the analysis in Section IV-A, a larger $J$ can reduce RoCoF of the system. Meanwhile, a larger $K$ increases the damping ratio, which reduces the power angle overshoot and frequency deviation during the transient period. Therefore, by adjusting $J$ and $K$ together, both the transient stability and frequency stability can be improved.

### *C. Comparison of Transient Stability Enhancement Methods*

Different transient stability enhancement methods have distinct performance, a comparison of which is listed in Table II from different perspectives. Four indicators are selected to compare: steady-state performance, enhancement of synchronization stability, enhancement of frequency stability, and implementation complexity.

- Steady-state performance: changing the steady-state performance does not satisfy the IEEE standard 1547-2018. Thus, whether affecting the steady-state performance is a significant index during riding through the grid faults.
- Enhancement of synchronization stability: all the enhancement methods can improve synchronization stability when the VSG has an equilibrium point. However, just [32] can damp the oscillation within a small bounded range even without an equilibrium point, which can be regarded as a good performance of improving synchronization stability.
- Enhancement of frequency stability: if the method can decrease the RoCoF and maximum frequency deviation simultaneously, it can be classified as a good frequency stability performance.
- Implementation complexity: if the method contains differential detecting elements during the transient process, it may reduce the anti-interference performance. This kind of method is classified as having a high implementation complexity.

Based on these four indexes, it can be seen that the frequency feedforward method proposed in this paper is a compromise between the synchronization stability and implementation complexity.

It should be noted that although only a grid voltage sag has been considered in this paper, the analytical method and the proposed method to enhance synchronization stability can be similarly also applied to other types of fault, such as grid impedance jumps. Since the synchronization stability of the grid-forming converters is ongoing work, more analyzing methodologies and the synchronization stability enhancement methods for the multi-inverter system will be studied in the future.

## V. Experimental Verification

To verify the theoretical analysis and the effectiveness of the proposed frequency feedforward method, an experimental setup is established in the lab, as shown in Fig. 12. The dc voltage is provided by another rectifier. A Chroma 61850 grid simulator

TABLE II
METHODS TO IMPROVE THE TRANSIENT STABILITY OF THE VIRTUAL SYNCHRONOUS GENERATOR

| Methods | Affecting the steady-state performance | Enhancement of synchronization stability | Enhancement of frequency stability | Implementation complexity |
|---|---|---|---|---|
| Change active and reactive power references [26] [27] | Yes | Good | Poor | Low |
| Adaptive inertia [29][30] | No | Medium | Good | Medium |
| Additional damping control [31] | No | Medium | Medium | Medium |
| Mode-switching control [32] | No | Good | Not discussed | High |
| Decrease the bandwidth of LPF in RPCL [21] | No | Poor | Not discussed | Low |
| Frequency feedforward added on RPCL | No | Medium | Good | Low |

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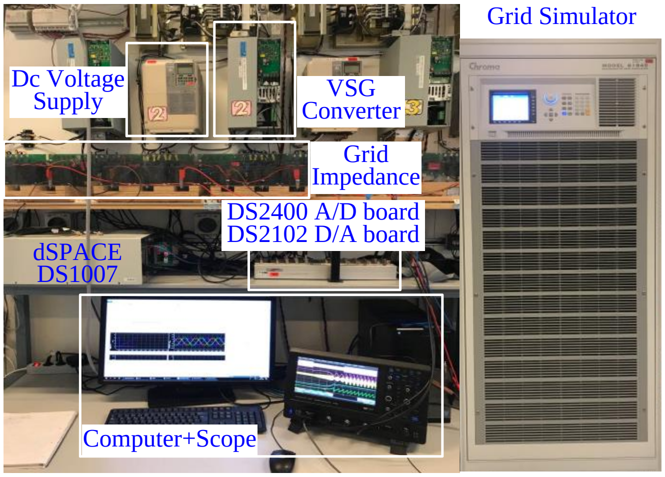



Fig. 12. The experimental setup.

TABLE III
MAIN PARAMETERS OF THE VSG SYSTEM USED IN THE EXPERIMENTS

| Parameters | Description | Value | p.u. |
|---|---|---|---|
| $P_{ref}$ | Rated active power | 2 kW | 1.0 |
| $Q_{ref}$ | Rated reactive power | 0 | 0 |
| $V_0$ | Rated voltage | 100 V | 1.0 |
| $V_g$ | Normal grid voltage | 100 V | 1.0 |
| $\omega_0$ | Grid angular frequency | 314 rad/s | |
| $L_g$ | Grid inductance | 12 mH | 0.5 |
| $K_p$ | *P-f* droop gain | $0.04\omega_0/P_{\max}$ | 0.04 |
| $K_q$ | *Q-V* droop gain | $0.1V_0/Q_{\max}$ | 0.1 |
| $K$ | Additional coefficient | $1\ Q_{\max}/V_0$ | 1 |

connected in series with a three-phase inductor is employed to emulate the weak power grid. The voltage and current are measured by the dSPACE DS2004 A/D board and then sent to the dSPACE DS1007 platform, where the control strategies are implemented. The calculated $P$, $\delta$, and the signal $\Delta\omega$ are transmitted to the oscilloscope through the DS2102 D/A board

The VSG's main parameters are given in Table III, where $K_p$ and $K_q$ are chosen according to their droop functions demanded in grid codes like in [20], [21]. The transient performances of the VSG under the grid voltage dropping from 1 p.u. to 0.6 p.u. are evaluated. In order to perform a comparative verification, three types of scenarios with different sets of $\omega_p$ and $K$ are examined, as shown in Table IV. The corresponding experimental results are shown in Fig.13 ~ Fig.15. From top to bottom in each figure, the displayed waveforms are the phase to phase voltage $V_{gab}$, the active power $P$, the line current of phase a, i.e., $I_{ga}$, the deviation of frequency $\Delta\omega$ and power angle $\delta$, respectively.

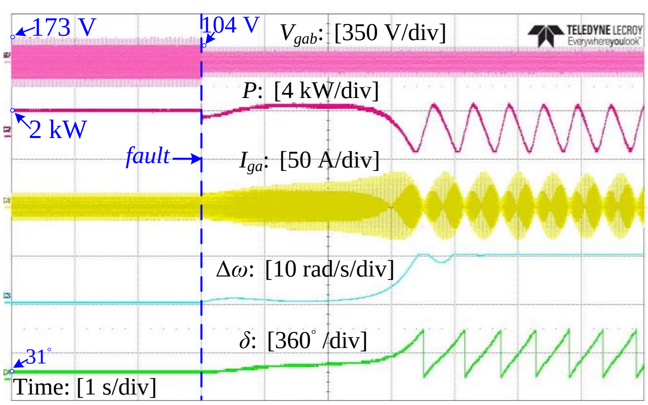
TABLE IV
DIFFERENT SETS OF CONTROL PARAMETERS USED IN THE EXPERIMENTS

| Parameter | Scenario A | | Scenario B | | | | Scenario C | |
|---|---|---|---|---|---|---|---|---|
| | I | II | I | II | III | IV | I | II |
| $\omega_p$ (π rad/s) | 0.6 | 1.2 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 |
| $K$ (p.u.) | 0 | 0 | 10 | 20 | 100 | 200 | 0 | 20 |

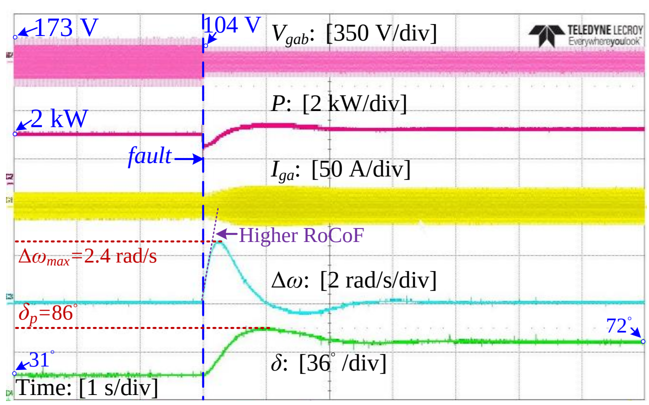
In Fig. 13, the original system without the additional frequency feedforward path is tested. In Fig. 13(a), an instability occurs when $V_g$ drops from 1 p.u. to 0.6 p.u. due to a small $\omega_p$ leading to a small damping ratio for the power angle. This instability can be removed by increasing $\omega_p$, i.e. $\omega_p$ is increased to 1.2π rad/s, as shown in Fig. 13(b). However, a larger $\omega_p$ implies smaller virtual inertia. Thereby, a larger $\Delta\omega_{max}$ and higher RoCoF are observed in Fig. 13(b). These experimental results verify the theoretical analysis on the frequency response, as the red lines are shown in Fig. 9.

Then, the proposed frequency feedforward path was added to the RPCL with different parameter settings. The experimental results are shown in Fig. 14. It can be seen that the grid voltage sag can also trigger a LOS due to the poor damping dynamics with a small $K$, i.e., $K$ = 10 p.u.. Increasing $K$, the system can be stabilized, and the overshoot of $\delta$ declines due to the damping ratio increases. The power angle overshoot can be completely damped with large enough $K$, i.e., $K$ = 200 p.u.. These results agree with the theoretical analysis in Section IV.

Moreover, it can be seen that the additional frequency feedforward path with a large $K$ not only reduces the overshoot of $\delta$ during the fault but also reduces $\Delta\omega_{max}$. These experimental results validate the analyzed theoretical results, confirming the effectiveness of the proposed frequency feedforward method. Therefore, this method can enhance the synchronization stability of the VSG without degrading the frequency stability.




(a)




(b)

Fig. 13. Experimental results of the VSG without the frequency feedforward path ($K_2$ = 0) when $V_g$ drops from 1 p.u. to 0.6 p.u. The Scenario A in Table IV is tested, as (a) Case I: $\omega_p$ = 0.6π rad/s and (b) Case II: $\omega_p$ = 1.2π rad/s.

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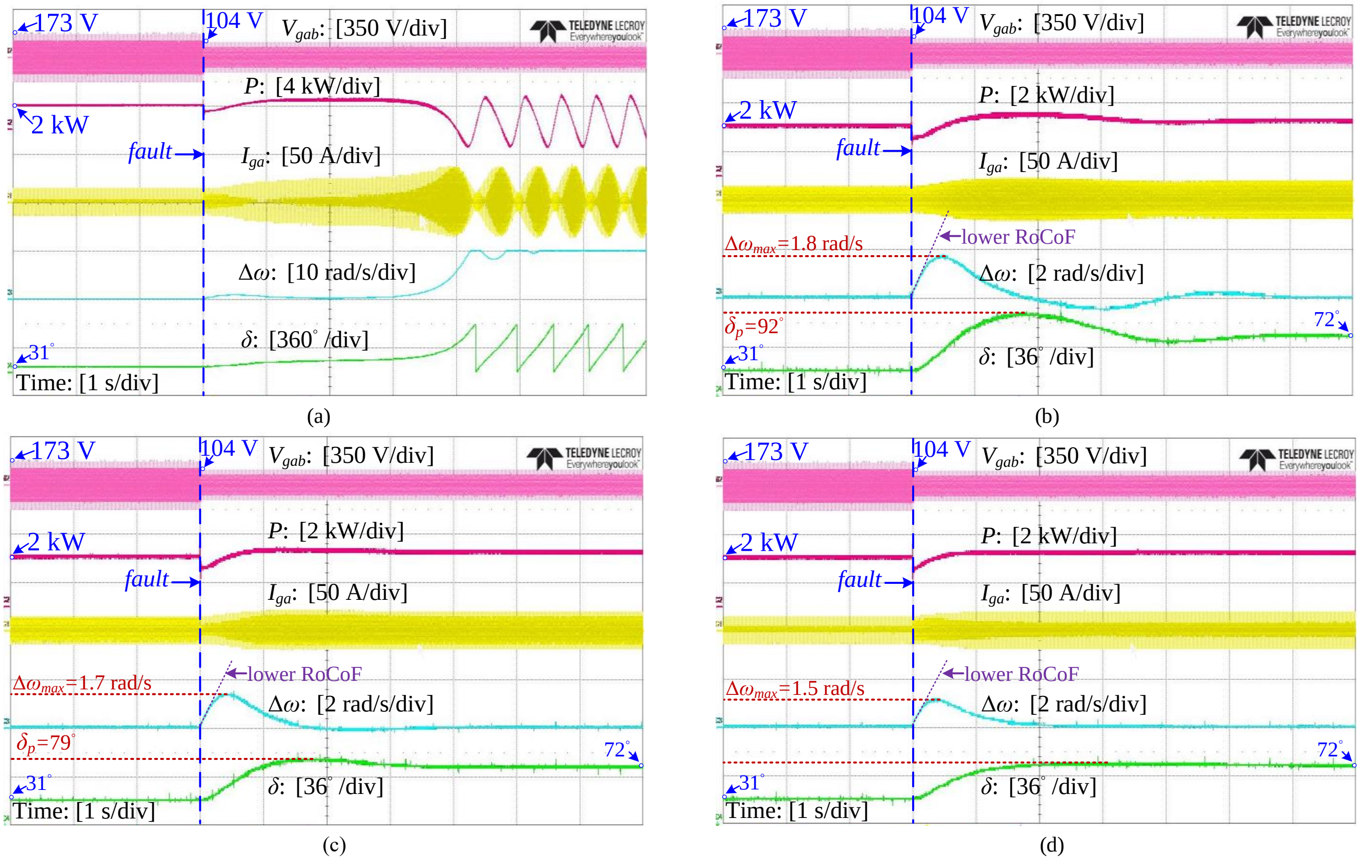


Fig. 14. Experimental results of the VSG with the addtional frequency feedforward path in the RPCL when $V_g$ drops from 1 p.u. to 0.6 p.u. The Scenario B in Table IV is tested, as (a) Case I: $K$ = 10 p.u., (b) Case II: $K$ = 20 p.u., (c) Case III:$K$ = 100 p.u., (d) Case IV: $K$ = 200 p.u.. $\omega_p$ = 0.6π rad/s is used for te fore cases.

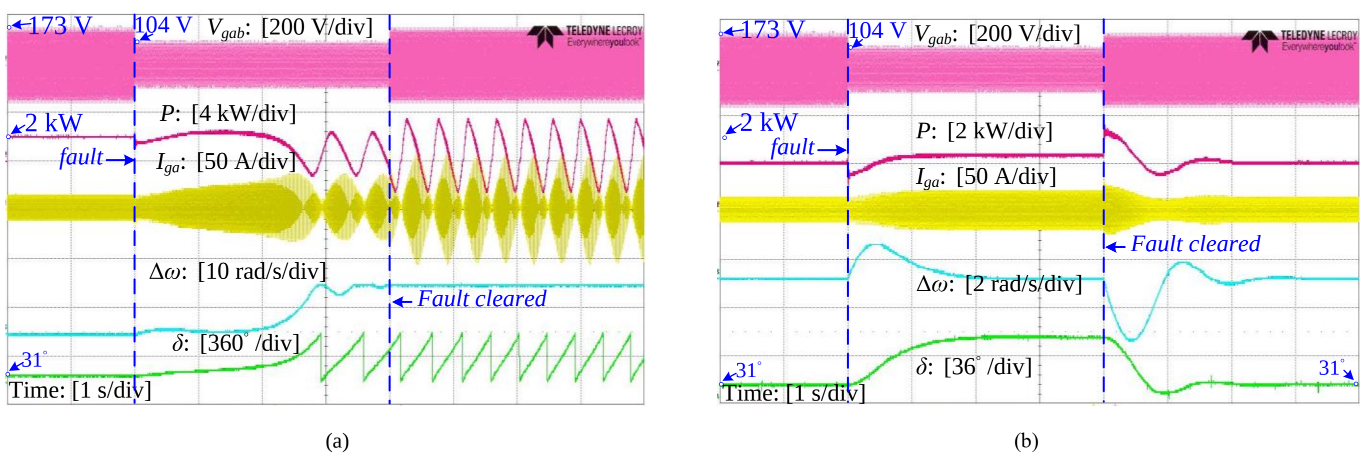


Fig. 15. Experimental results of the VSG with $\omega_p$ = 0.6π rad/s when $V_g$ drops from 1 p.u. to 0.6 p.u. and recoveries after 4s. The Scenario C in Table IV is tested, as (a) Case I: $K$ = 0 p.u., (b) Case II: $K$ = 20 p.u..

According to IEEE Standards 1547-2018 [28], the VSG should continue to supply power at least for 10 s when the grid voltage drops to 0.6 p.u.. Thus, the fault is not cleared in Fig. 13 and Fig. 14, since riding-through the low voltage is more severe than the period of grid voltage coming back to normal. Thus, as long as the VSG is controlled stable during the fault, the synchronization stability can be guaranteed when the fault is cleared after 10s. To prove this, Fig. 15 gives the experimental results of clearing the fault after 4s (for convenience of displaying). From there, it can be seen that if a LOS occurs during the fault, the system can not return to stable operation after the fault is cleared. However, when the additional frequency feedforward path is added to improve the stability during the fault, i.e., $K$ =20 in Fig. 15(b), the system can remain stable after the fault is cleared.

## VI. Conclusion

Firstly, a combined linearized and nonlinear model is employed to analyze synchronization stability. The linearized model is used for qualitative analysis, while quantitative analysis is according to the nonlinear model. Secondly, base on the combined model, the mechanism of employing LPF in the RPCL to enhance synchronization stability is revealed. It indicates that an LPF with a sufficiently low cutoff frequency introduces a dominant closed-loop pole for the original second-order dynamic system and can damp the power angle overshoot oscillation, leading to a better transient power angle response. Thirdly, an improved synchronization method is proposed by feedforwarding the frequency to RPCL, which can avoid the slow dynamic LPF in RPCL. Parameter design guidelines are given to enhance the synchronization stability with different inertia requirements, which indicates a larger coefficient of the feedforward path is expected with larger inertia. Fourthly, the frequency response is also deduced based on the combined model, demonstrating that the improved synchronization methods can further improve the frequency stability during grid faults. Finally, experimental results have verified the effectiveness of the theoretical analysis and the proposed method.

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