Tuning method of a grid-following converter for the extremely-weak-grid connection

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***Abstract*—This paper proves that a grid-following converter can stably connect to a weak grid even short-circuit ratio (SCR) is 1. Root instability causes of this grid-following control are identified including fast control response, insufficient damping, and slow voltage support. A simple and effective tuning method is proposed to stabilize this connection. Three control modes are considered in this tuning method including current control, active power and voltage (PV) control, and active power and reactive power (PQ) control. The switching model of a two-level converter is used for the simulation validation.**

I. Introduction

Voltage source converters (VSC) using grid-following control based on the phase-locked loop (PLL) risk the instability due to weak-grid connection. In [1], a significant contributions have been made to study the coupling between the current control and the PLL to further enhance the stability at SCR=2. [2] indicates that the connection to a weak grid of SCR $<$ 1.3 is hardly stabilized for rated power injection after extensive tuning attempts. A very weak grid is normally defined as SCR$<$2. For distinction, an extremely weak grid refers to SCR=1. For stabilizing such an extremely-weak-grid connection SCR=1, additional stabilization controls are deemed necessary. Besides, it is also found that these controls' responses are slowed to some extent. Outer loop compensation is an effective way to achieve the desired connection; many methods have been proposed, including outer loop decoupling [3], AC voltage compensation [4], and power compensation [5] by suppressing voltage impact on the outer power loop. Virtually advancing the PLL's tracking point is another feasible way to achieve this extremely-weak-grid connection [6].

However, relying on these stabilization controls makes the overall grid-following control more intricate and still risks instability without proper tuning of the whole grid-following control.

In this paper, a tuning method is proposed for grid-following converters to enable the extremely-weak-grid connection even SCR=1, without the need of any additional stabilization controls. This method comprehensively works for current control, PV control, and PQ control. To provide a deep understanding of the extremely-weak-grid instability, the root instability causes of these controls are identified and eventually tackled via this method.

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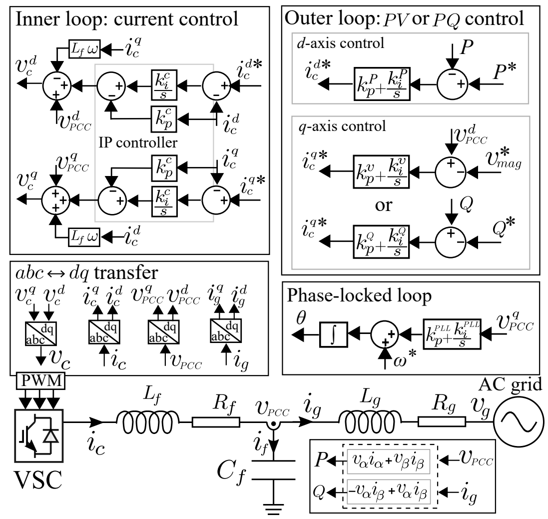


Fig. 1. A grid-following VSC connecting to the AC grid.

II. Tuning method for current control

When connecting to a extremely-weak grid, the PLL-based current control, as shown in Fig. 1, contains two root instability causes, which impact significantly on the voltage of the point of common coupling (PCC):

- high natural frequency of PLL
- insufficient damping of the current control

Only if both the above instability causes are solved, the converter can work stably with an extremely weak grid with SCR=1. Therefore, to tackle all the above root causes, a tuning method is proposed to systematically design the current control and PLL based on the small-signal analysis.

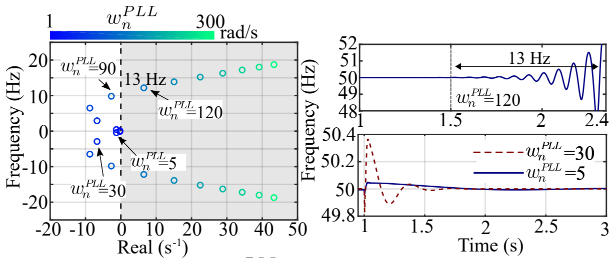
A. PLL tuning

The tuning of PLL is commonly based on the equation below:

$$\theta = \frac{k_p^{PLL} s + k_i^{PLL}}{s^2 + \underbrace{k_p^{PLL}}_{2\zeta^{PLL}\omega_n^{PLL}} s + \underbrace{k_i^{PLL}}_{\omega_n^{PLL2}}} \theta_{PCC}, \quad (1)$$

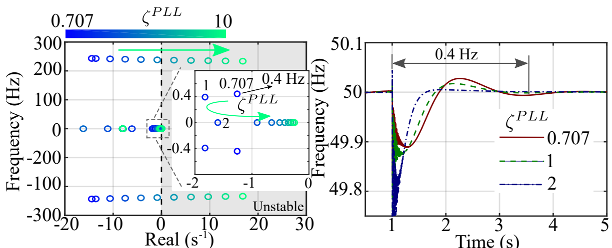
where θ_{PCC} is the voltage phase at the point of common coupling (PCC), θ is the tracked phase, $v_{PCC}^q \approx (\theta_{PCC} - \theta)$, ω_n^{PLL} and ζ^{PLL} are natural frequency and damping ratio respectively and are used for the PLL tuning.

For analyzing the stability impact of this PLL tuning, the full small-signal model of the current-controlled grid-following converter is derived based on [7]. As shown in



(a) Stability analysis of w_n^{PLL} (b) Simulation validation

Fig. 2. Reducing ω_n^{PLL} for the extremely-weak-grid stabilization at SCR=1.



(a) Stability analysis of ζ^{PLL} (b) Simulation validation

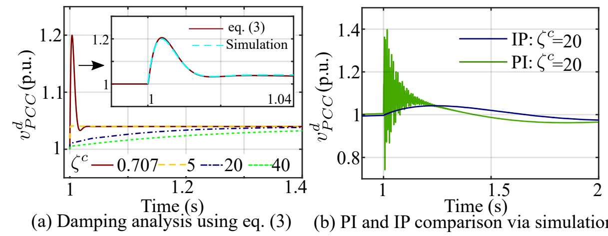
Fig. 3. Damping ratio analysis of PLL at SCR=1.

Fig. 2(a), it is found that high natural frequency ω_n^{PLL} of PLL results in instability. By slowing the PLL (equivalently reducing its natural frequency ω_n^{PLL} to 90), the converter can effectively be stabilized. The simulation validation is shown in Fig. 2(b), when ω_n^{PLL}=120, the converter becomes unstable and the resonant frequency matches the analyzed frequency 13 Hz in Fig. 2(a). When selecting the proper ω_n^{PLL} within the stable range of < 90, ω_n^{PLL}= 5 is recommanded because of its high damping capability (low y-axis value in Fig. 2(a)), and the simulation result in Fig. 2(b) also proves this.

The stability impact of PLL's damping ratio ζ^{PLL} on the converter is shown in Fig. 3(a). It is found that excessive ζ^{PLL} enhancement, which could cause the instability, should be avoided. A proper ζ^{PLL} enhancement, such as increasing ζ^{PLL} from 0.707 to 2, can further reduce the oscillation risk. As shown in the inset figure of Fig. 3(a), when ζ^{PLL}=0.707, a 0.4 Hz oscillation may occur. While the oscillation is mitigated when ζ^{PLL}=2. A simulation study also proves the analyzed result. As shown in Fig. 3(b), a phase jump $\pi/10$ occurs at 1 s. A 0.4 Hz oscillation occurs during frequency recovery with ζ^{PLL}=0.707. ζ^{PLL}=2 effectively damps the oscillation.

B. Current control tuning

When an extremely weak grid is connected, current regulation results in a severe voltage fluctuation due to a lack of voltage support. Enhancing its damping capability is an effective way [8] to suppress this fluctuation and stabilize the converter. It is found that restructuring proportional-integral (PI) controllers as IP controllers for the current control would be more effective for the stabilization [9]. It is because that the IP controller overcomes the inherent drawback that k_p of the conventional PI controller cannot balance the grid voltage impact and damping capability especially in a extremely weak grid.



(a) Damping analysis using eq. (3) (b) PI and IP comparison via simulation

Fig. 4. Damping enhancement for current control at SCR=1.

The relation of the current control is shown below:

$$\mathbf{i}_c = \frac{k_i^c/L_f}{s^2 + \underbrace{[(R_f + k_p^c)/L_f]}_{2\zeta^c\omega_n^c} s + \underbrace{k_i^c/L_f}_{\omega_n^{c\,2}}}\mathbf{i}_c^*, \tag{2}$$

where bold $\mathbf{i}_c$ is a matrix contains dq components $[i_c^d; i_c^q]$.

The relation between PCC voltage and IP-based current control is yielded:

$$\mathbf{v}_f = \frac{(L_g s + R_g)k_i^c/L_f}{s^2 + \underbrace{[(R_f + k_p^c)/L_f]}_{2\zeta^c\omega_n^c} s + \underbrace{k_i^c/L_f}_{\omega_n^{c\,2}}}\mathbf{i}_c^* \tag{3}$$

Based on (3), enhancing the damping ratio ζ^c could effectively reduce the voltage fluctuation during current regulation, as shown in Fig. 4(a). $\zeta^c = 20$ is suggested for low PCC voltage impact. With the same damping ratio $\zeta^c = 20$, the IP controller causes much lower voltage fluctuation than that of the PI controller, as shown in Fig. 4(b). The stability analysis of Fig. 5(a) shows that $\zeta^c = 20$ enables the converter to be stable with a wide w_c^n range up to 2000, which means that the current control can be tuned for a fast response such as 50 ms, as shown in Fig. 5(b).

C. Switching model validation

A double second-order generalized integrator (SOGI) PLL [10], which is more practical for positive sequence tracking than the PLL, is also applied for a current-controlled grid-following converter.

As shown in Fig. 6, it is found that by following the above tuning method of reducing the PLL's ω_n^{PLL} and enhancing the current control's ζ_c, a two-level VSC can connect to an extremely weak grid (SCR=1) with rated power injection. The converter using a double SOGI-PLL has almost the same performance as the converter using PLL. The only difference is that the double SOGI-PLL filters the frequency harmonics more powerfully, as shown in Fig. 6.

III. Tuning method for PV and PQ control

An outer loop can be added to form the PV control or PQ control, as shown in Fig. 1. For a converter increasing its active power, the increased ΔP is shown below:

$$\Delta P \approx I_g^d \Delta v_{PCC}^d + V_{PCC}^d \Delta i_g^d. \tag{4}$$

In an extremely weak grid, if the voltage support at q-axis is not fast enough, Δi_g^d results in a significant voltage drop

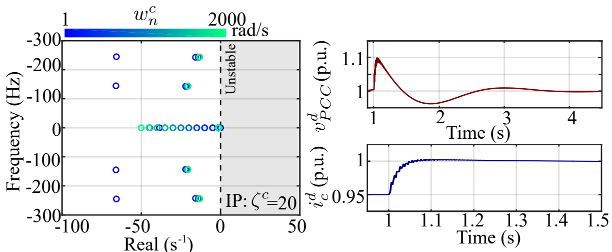


Fig. 5. ω_n^c analysis for current control at SCR=1 (PLL: $\omega_n^{PLL} = 5$).

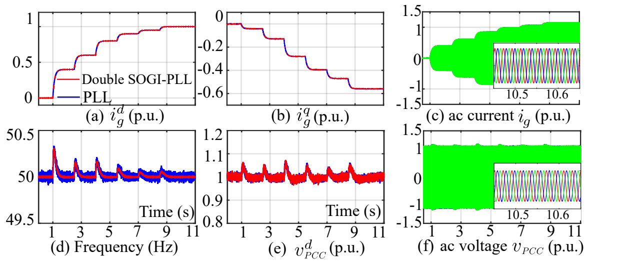


Fig. 6. Rated power injection of a two-level VSC with the proposed tuning method when connecting to an extremely-weak with SCR=1 (Current control: $w_n^c = 320$, $\zeta^c = 20$; PLL: $w_n^{PLL} = 5$, $\zeta^{PLL} = 2$).

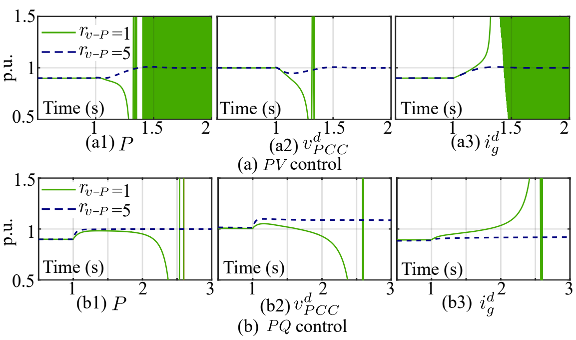


Fig. 7. Effectiveness of fast voltage support on both PV and PQ controls when the converter connects to an extremely-weak grid with SCR=1.

$-\Delta v_{PCC}^d$, which causes $\Delta P < 0$ based on (4). This conflicts with the control target: increasing the active power.

In sum, for a extremely-weak-grid connection, both PV and PQ controls are of two same root instability causes, as shown below:

- slow voltage support, which happens to outer loop: PV or PQ control. In an extremely weak grid, the fact that voltage drops with increasing current may conflict with the active power control. Slow voltage support via q-axis V control or Q control worsens this conflict.
- high natural frequencies of PLL and inner current control;

To tackle all the above root causes, a tuning method based on the small-signal analysis is proposed to systematically design the PLL, the current control, and the PQ/PV control, which indeed stabilizes the converter with rated power injection at SCR=1.

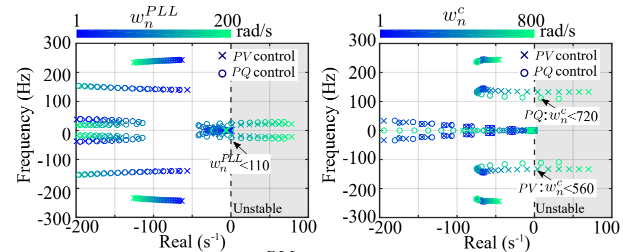


Fig. 8. Effectiveness of w_n reduction for both PLL and current control on the extremely-weak-grid stabilization at SCR=1 ($r_{v-P} = 5$).

A. Outer loop: PV and PQ control tuning

The outer loop leads references of the inner current loop to achieve the desired PV or PQ control, as shown in Fig. 1, which determines that the voltage support from V control or Q control is based on the q-axis current.

A slope ratio r_c^{dq} is defined to describe the impacts of i_g^d and i_g^q on the PCC voltage, which is shown below:

$$r_c^{dq} = \frac{\partial v_{PCC}^d / \partial i_g^d}{\partial v_{PCC}^d / \partial i_g^q}. \tag{5}$$

If both i_g^d and v_{PCC}^d are 1 p.u. at SCR=1, (5) results in $r_c^{dq} = 2$, which indicates that the impact of i_g^d on the PCC voltage drop is 2 times faster than that of i_g^q. Therefore, the voltage support via q-axis current must be speeded up 2 times more than the d-axis power control in order to compensate the voltage drop caused by i_g^d.

To tune the outer loop based on the above analysis, r_{v-P} ($>$2) is defined as the speed-up coefficient to ensure the voltage support via V control or Q control are faster enough to compensate the voltage drop caused by the P control, the following PI relations are defined:

$$k_p^P + \frac{k_i^P}{s} = k_o(k_p^c + \frac{k_i^c}{s}), \tag{6}$$

$$k_p^v + \frac{k_i^v}{s} \text{ or } k_p^Q + \frac{k_i^Q}{s} = r_{v-P} k_o(k_p^c + \frac{k_i^c}{s}), \tag{7}$$

where k_o (such as =0.1) is the coefficient to ensure that the outer loop is slow enough to work well with the inner loop.

Based on the analysis of (5), a sufficient fast voltage support tuning is applied with $r_{v-P} = 5$ for both PV and PQ controls. As shown in Fig. 7, the converter stably connects to the weak grid at SCR=1, while slow voltage support $r_{v-P} = 1$ does cause the instability for both controls.

B. PLL and current control tuning

PLL and current control tuning relies on the stability analysis, as shown in Fig. 8. Slowing both PLL and inner current control, which equivalently reduces w_n of (1-2), helps to stabilize the converter. PLL's w_n^{PLL} reduction has the same stabilization effectiveness for both PV and PQ controls and must be limited within 110. Because of the outer loop, this inner current control does not require the high damping capability as described in Section II-B, $\zeta^c = 0.707$ is applied. The inner current control's w_n^c reduction has the slightly different stabilization effectiveness for PV and PQ controls, and must be limited within 560 and 720 respectively. For a proper stability margin and response speed, $w_n^c = 320$ are selected for both controls.

As analyzed in Section II-A, low w_n^{PLL} (<90) of the PLL helps for stable operation, such as $w_n^{PLL} = 5$ being suggested. For the PV and PQ controls, $w_n^{PLL} = 5$ and 20 are applied respectively with $\zeta^{PLL} = 2$.

C. Switching model validation

By following the above tuning method of speeding up the voltage support ($r_{v-P} = 5$), and slowing PLL and current control ($w_n^{PLL} = 5$ or 20, $w_n^c = 320$), a two-level VSC can connect to an extremely weak grid (SCR=1) with rated power injection using PLL-based PQ control or PV control, as shown in Fig. 9.

As shown in Fig. 9, it is validated at SCR=10 that the proposed tuning method works well of a strong grid. It should be noticed that the PLL-current control is also validated with a strong grid, which does not be presented in the letter.

To present the transient performance of a grid-following converter under a weak grid (SCR=1), a phase jump of the grid is applied at 1 s. This converter is under the PLL-based PV control. As shown in Fig. 10, the converter has a smooth and stable recovery process after the phase jump occurs, which proves the effectiveness of the proposed tuning method.

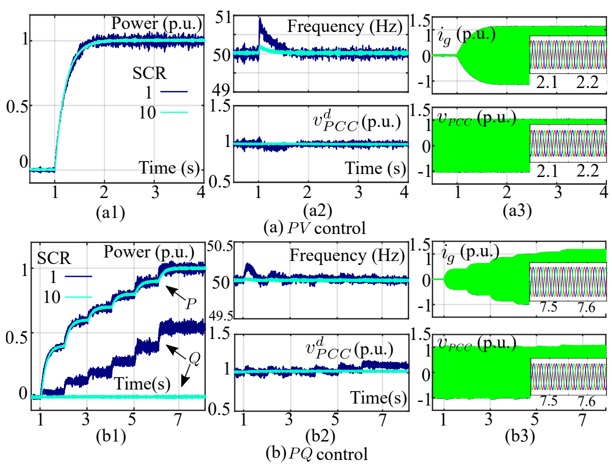


Fig. 9. Rated power injection of a two-level VSC with the proposed tuning method when connecting to an extremely-weak grid with SCR=1 (Current control: $w_n^c = 320$, $\zeta^c = 0.707$; PLL: $w_n^{PLL} = 5\&20$, $\zeta^{PLL} = 2$, Outer loop: $r_{v-P} = 5$, $k_o = 0.1$).

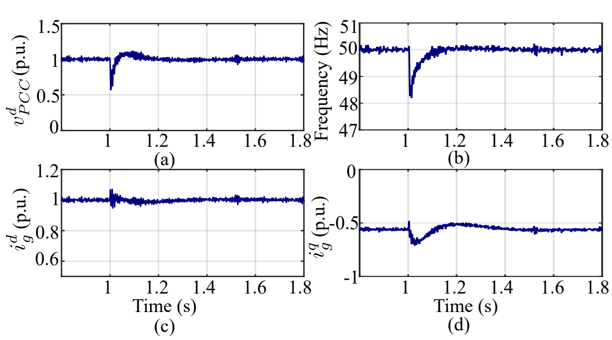


Fig. 10. Transient response with a phase jump of $\pi/10$ from the grid.

IV. Conclusion

The proposed systemic tuning method, for the grid-following control including current control, PQ and PV control, has been validated the simulation test with a switching two-level converter, which enables the grid-following converter to work stably with an extremely-weak grid even SCR=1.

This tuning method is specially designed for an extremely-weak grid at SCR=1, which leads to a slow response of the control. Therefore, for sudden current changes, the current control speed may not be quick enough to deal with.

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