

Influence of Grid-Forming Converter Control Parameters on System Stability Boundaries Under Different Grid Strengths

Jingtong Guo¹

¹EDF(China) Holding Ltd., Beijing 100000, China

Corresponding author: Jingtong Guo (e-mail: Guojingtong152@163.com).

ABSTRACT The voltage and frequency support capability of grid-forming converters under weak-grid conditions makes them key equipment for power systems with a high share of renewable energy, yet the coupling between their control parameters and grid strength still lacks a boundary-oriented description suitable for parameter tuning. This paper establishes a reduced-order model of a grid-forming converter that includes the active-power synchronization loop, the reactive-power/voltage loop, power-measurement filtering and an equivalent inner-loop lag. Grid strength is characterized by the short-circuit ratio, and the minimum damping ratio and the critical clearing time are adopted as the small-signal and large-signal stability indices, respectively. Through parameter sweeps, the stability boundaries of the virtual inertia, damping coefficient, power-filter time constant, reactive-power droop coefficient and virtual reactance are obtained for short-circuit ratios from 1.2 to 10. The results show that the damping ratio of the dominant electromechanical mode decreases monotonically as grid strength increases: when the short-circuit ratio rises from 1.5 to 10, the minimum damping ratio under the base parameters falls from 0.285 to 0.090, and the damping coefficient required to keep the damping ratio above 0.1 increases from about 11 p.u. to about 31 p.u.; conversely, the transient stability margin shrinks as the grid becomes weaker, with the critical clearing time falling from about 516 ms to about 230 ms as the short-circuit ratio decreases from 10 to 1.2. When the power-filter time constant exceeds about 50 ms, the strong-grid case loses stability first, and the damping improvement provided by the virtual reactance is more pronounced in the strong-grid case. On this basis, a parameter tuning region that accommodates both strong- and weak-grid conditions is given. The conclusions are subject to the assumptions of the reduced-order model; electromagnetic-transient and hardware-in-the-loop validation shows that the damping ratio of the dominant small-signal mode deviates from the reduced-order model by about 6%–16% with a consistent trend, and that the critical clearing time with current limiting is about 17%–24% lower than the reduced-order upper-bound estimate, indicating that the reduced-order model is suitable for trend assessment and preliminary tuning, while the transient margin must be corrected for current-limiting conditions.

INDEX TERMS grid-forming converter; grid strength; short-circuit ratio; virtual synchronous machine; small-signal stability; transient stability; parameter tuning

I. INTRODUCTION

AS the share of power-electronic-interfaced sources continues to grow, the synchronous-machine inertia and short-circuit capacity of power systems decline, and the loss of synchronism of grid-following converters under weak-grid conditions has become increasingly prominent[1]. Grid-forming (GFM) converters establish voltage and frequency by self-synchronizing the phase of their internal electromotive force, can provide voltage support and inertial response in weak grids and even in grids without synchronous machines, and are regarded as a critical

asset for power systems with a high share of renew-

ables[2]. Recent reviews of grid-forming control methods have systematically surveyed implementations such as droop control, the virtual synchronous machine (VSM), power-synchronization control and matching control, and have identified the matching of parameter tuning to grid strength as one of the core problems still to be solved[3][4].

From the viewpoint of control structure, droop control achieves power sharing and self-synchronization through the static active-power/frequency and reactive-power/voltage relationships[5], power-synchronization control explicitly uses the power angle as the synchronizing variable[6], and the virtual synchronous machine further introduces the swing

equation to emulate inertia and damping[7]. Reference[8] proved that droop control with a low-pass power filter is equivalent to the virtual synchronous machine in the small-signal sense, reference[9] compared the dynamic characteristics of the two, and reference[10] gave a design method for the inertia and damping parameters of the virtual synchronous machine based on a second-order model. Most of these works were carried out for a given grid impedance and did not systematically discuss how the feasible region of parameter values migrates with grid strength.

Grid strength is usually characterized by the short-circuit ratio (SCR) at the point of connection, whose reciprocal in per-unit is the equivalent grid reactance. The IEEE/CIGRE joint task force added “converter-driven stability” to the extended stability classification and distinguished slow-interaction from fast-interaction phenomena by frequency band[11]. Slow interactions mainly involve the electromechanical coupling between the power-synchronization loop and the grid, whereas fast interactions involve the harmonic coupling between the inner loops and the grid impedance[12][13]. For the latter, impedance-based and admittance-shaping methods are relatively mature[14][15][16][17], and Chinese researchers have also designed virtual impedances for virtual synchronous machines in weak grids based on sequence-impedance models[18]. For the former, state-space eigenvalue analysis has been widely applied to inverter-based microgrids[19] and their reduced-order models[20] and has been extended to low-inertia systems[21][22]. Reference[23] pointed out from a duality perspective that the stability problem of grid-forming converters in strong grids is symmetric to that of grid-following converters in weak grids, which implies that the parameter tuning of grid-forming converters must consider not only weak-grid but also strong-grid conditions.

On the large-signal side, the transient stability of power-synchronization control can be handled by the equal-area criterion and phase-plane analysis[24], current limiting significantly alters the power-angle characteristic and compresses the stability region[25], methods for determining and enhancing the critical clearing time (CCT) under virtual-impedance current limiting are available[26][27][28], and measurements and simulations in the MIGRATE project have verified the influence of transient current limiting on the synchronization stability of grid-forming converters[29]. However, the small-signal and large-signal boundaries are usually discussed separately, and their relative position as grid strength varies, as well as the joint constraint they impose on parameter tuning, still lack a quantitative description[30][31]. In addition, studies on the capacity ratio between grid-forming and grid-following converters show that the grid-strength support duty that a grid-forming converter must undertake differs markedly across plant conditions[32], which further requires parameter tuning methods to be adaptable to grid strength.

To address these issues, this paper takes a VSM-type grid-forming converter with power filtering and an equivalent inner-loop lag as the object of study, establishes a reduced-

order model suitable for parameter sweeps, characterizes the small-signal and large-signal stability boundaries by the minimum damping ratio and the critical clearing time, respectively, over the SCR range 1.2–10, analyzes the influence of the virtual inertia, damping coefficient, power-filter time constant, reactive-power droop coefficient and virtual reactance on the position of the boundaries, and gives a parameter tuning region that accommodates both strong- and weak-grid conditions. The analysis is based on a low-order analytical model; electromagnetic-transient and hardware-in-the-loop validation of the conclusions is presented in Table 7.

II. SYSTEM MODEL AND DEFINITION OF STABILITY BOUNDARIES

A. SYSTEM STRUCTURE

The object of study is a single grid-forming converter connected to a Thévenin-equivalent grid through an LC filter, as shown in Fig. 1. The grid is represented by an ideal voltage source $V_g \angle 0$ in series with an impedance $Z_g = R_g + jX_g$; in per-unit, $\text{SCR} = 1/X_g$, and $X_g/R_g = 7$ is taken to reflect the typical impedance angle of a transmission network. The converter-side filter reactance X_f and the virtual reactance X_v are in series with the grid reactance, forming the total reactance $X = X_v + X_f + X_g$ between the internal EMF $E \angle \delta$ and the grid voltage.

B. REDUCED-ORDER DYNAMIC MODEL

Fig. 2 shows the control structure adopted. The active-power loop takes the virtual-synchronous-machine form, in which the virtual inertia constant H and the damping coefficient D_p correspond to the inertia and damping terms of the swing equation; the reactive-power loop uses reactive-power/voltage droop with droop coefficient m_q ; both active- and reactive-power measurements pass through first-order low-pass filters with time constant τ_p ; and the voltage and current inner loops together with the modulation stage are represented by a first-order lag τ_v . These simplifications are consistent with the treatment in references[10][20] and are valid provided that the inner-loop bandwidth is much higher than that of the power loops. The state equations of the model are

$$\frac{d\delta}{dt} = \omega_0 \Delta\omega \quad (1)$$

$$2H \frac{d\Delta\omega}{dt} = P_{\text{ref}} - P_m - D_p \Delta\omega \quad (2)$$

$$\tau_p \frac{dP_m}{dt} = P_e - P_m, \quad \tau_p \frac{dQ_m}{dt} = Q_e - Q_m \quad (3)$$

$$\tau_v \frac{dE}{dt} = E_0 + m_q(Q_{\text{ref}} - Q_m) - E \quad (4)$$

where P_e and Q_e are the active and reactive power delivered at the internal-EMF node, computed from $E \angle \delta$, $V_g \angle 0$ and Z_g by the complex-power relationship; neglecting resistance, $P_e = EV_g \sin \delta / X$ and $Q_e = (E^2 - EV_g \cos \delta) / X$. R_g is retained in the numerical calculations. The model is of fifth order, with state variables δ , $\Delta\omega$, P_m , Q_m and E .

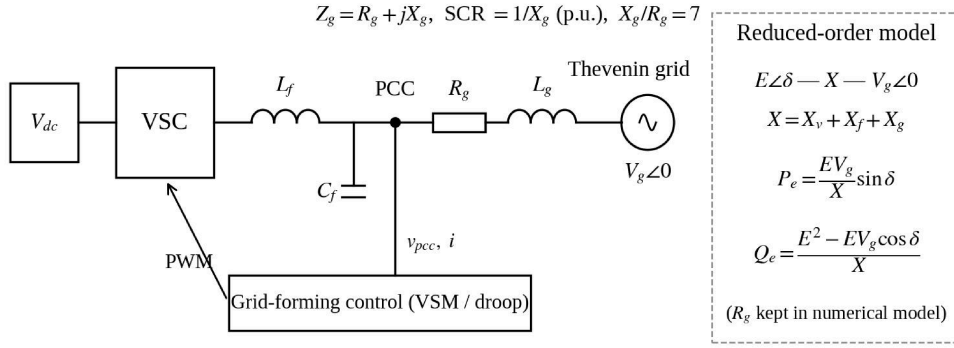
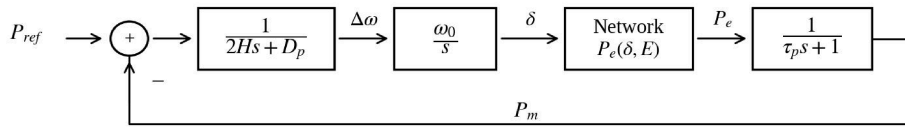
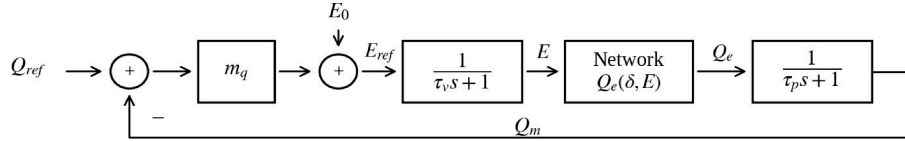


FIGURE 1. Structure of the grid-connected grid-forming converter system and its reduced-order equivalent model

(a) Active-power / synchronization loop



(b) Reactive-power / voltage loop



Inner voltage/current loops lumped into first-order lag τ_v ; virtual reactance X_v lumped into X

FIGURE 2. Control block diagram of the grid-forming converter: (a) active-power synchronization loop; (b) reactive-power/voltage loop

C. STABILITY INDICES AND BOUNDARY DEFINITIONS

Small-signal stability is determined by the eigenvalues of the Jacobian matrix at the equilibrium point. The minimum damping ratio of the oscillatory modes, $\zeta_{\min}$, is used as the index: $\zeta_{\min} = 0$ corresponds to the small-signal stability boundary, and $\zeta_{\min} = 0.1$ to the adequate-damping boundary commonly used in engineering practice. Large-signal stability is characterized by the critical clearing time (CCT) under a symmetrical three-phase fault: at $t = 0.2$ s the grid voltage is dropped to 0.05 p.u. for a duration t_f and then restored; if the power angle does not exceed π within 3 s and converges, synchronism is considered maintained. The CCT is determined by bisection with a resolution of 5 ms. It should be noted that the model does not include a current-limiting stage, so the CCT obtained is an upper-bound estimate without current limiting; the actual value will be reduced by current limiting[25][26].

Table 1 lists the base parameters of the system and Table 2 the parameter sweep ranges. The small-signal analysis uses $P_0 = 0.6$ p.u., and the large-signal analysis uses $P_0 = 0.8$ p.u. to reflect heavy-load conditions.

III. SMALL-SIGNAL STABILITY BOUNDARIES

A. INFLUENCE OF GRID STRENGTH ON THE DOMINANT MODE

Fig. 3 shows the locus of the dominant oscillatory mode as the SCR increases from 1.2 to 10 under the base parameters, and Table 3 lists the equilibrium points and eigenvalues for three representative SCR values. The dominant mode is an electromechanical mode in which the power angle and the

TABLE 1. Base parameters of the system

Parameter	Symbol	Value
Grid voltage	V_g	1.0 p.u.
Filter reactance	X_f	0.15 p.u.
Virtual reactance	X_v	0.10 p.u.
Grid impedance ratio	X_g/R_g	7
Virtual inertia constant	H	3 s
Damping coefficient	D_p	30 p.u.
Reactive-power droop coefficient	m_q	0.05 p.u.
Power-filter time constant	τ_p	20 ms
Equivalent inner-loop lag	τ_v	5.3 ms (30 Hz)
Active-power operating point	P_0	0.6 / 0.8 p.u.
Reactive-power operating point	Q_0	0
Residual fault voltage	V_{sag}	0.05 p.u.

TABLE 2. Parameter sweep ranges

Parameter	Range	Number of sweep points
SCR	1.2–10	45
H	0.5–12 s	47
D_p	2–80 p.u.	53
τ_p	5–200 ms	40
m_q	0.02–0.2 p.u.	4
X_v	0–0.3 p.u.	4

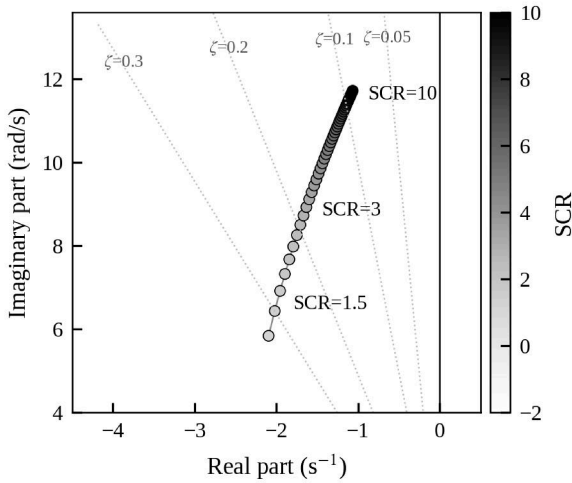


FIGURE 3. Locus of the dominant oscillatory mode versus SCR under the base parameters (dashed lines: constant damping ratio)

frequency deviation participate; its oscillation frequency rises from about 1.0 Hz to about 1.9 Hz as the SCR increases, and its damping ratio falls from 0.285 (SCR = 1.5) to 0.180 (SCR = 3) and 0.090 (SCR = 10). The remaining three real modes correspond to the inner-loop lag (about -180 s^{-1}) and the two power-filter stages (about -51 to -61 s^{-1}) and are insensitive to the SCR.

This trend can be explained by a second-order approximation: neglecting the filters and the inner-loop lag, the damping ratio of the electromechanical mode is approximately $\zeta \approx D_p / [2(2H\omega_0 K)^{1/2}]$, where the synchronizing coefficient $K = EV_g \cos \delta_0 / X$ increases as the grid becomes stronger, so that for a fixed D_p the damping ratio decreases as the SCR rises. This result agrees with the conclusion in reference[23] that grid-forming converters are more prone to poorly damped oscillations in strong grids, and it also shows that a weak grid is not the most unfavorable condition for the small-signal stability of grid-forming converters.

B. BOUNDARIES OF THE DAMPING COEFFICIENT AND VIRTUAL INERTIA

Fig. 4 shows the root locus of the dominant mode as D_p increases from 4 to 80. For all three SCR values, increasing D_p moves the mode deeper into the left half-plane, but at SCR = 10 the starting point of the locus already lies to the right of the imaginary axis, indicating that the combination

of a small D_p and a strong grid is the first to lose stability. Fig. 5 shows the two boundaries $\zeta_{\min} = 0$ and $\zeta_{\min} = 0.1$ in the (H, D_p) plane, and Table 4 lists the D_p values on the boundaries at several values of H (sweep resolution about 1.5 p.u.).

Two regularities are worth noting. First, the $\zeta_{\min} = 0$ boundary is almost insensitive to H and is determined mainly by the SCR and D_p ; its position rises from about 6.5 p.u. at SCR = 1.5 to about 17 p.u. at SCR = 10. Second, the $\zeta_{\min} = 0.1$ boundary shifts markedly upward as H increases: at SCR = 10, the required D_p grows from 24.5 p.u. to 44 p.u. as H increases from 1 s to 10 s. This means that when H is increased to enhance the inertial response, D_p must be increased at the same time, and by a larger amount in strong grids, which is consistent in trend with the design criterion given in reference[10] for a fixed grid impedance.

C. POWER-FILTER TIME CONSTANT AND VIRTUAL REACTANCE

Fig. 6 shows the distribution of $\zeta_{\min}$ in the (τ_p, D_p) plane for SCR = 1.5 and SCR = 10. The phase lag introduced by τ_p weakens the effective damping, and the effect is more pronounced in a strong grid: with the base value $D_p = 30$ p.u., increasing τ_p from 20 ms to 50 ms reduces $\zeta_{\min}$ at SCR = 10 from 0.090 to -0.026, crossing the stability boundary, whereas at SCR = 1.5 it remains at 0.190. From the standpoint of suppressing measurement noise, τ_p should not be too small, but the results here indicate that where connection to a strong grid is possible, τ_p should be kept within the order of 20 ms, or D_p should be raised accordingly.

Fig. 7(a) shows the influence of the virtual reactance X_v on the $\zeta_{\min}$ –SCR curve. By increasing the total reactance X , X_v lowers the synchronizing coefficient and thereby raises the damping ratio in strong grids: at SCR = 10, increasing X_v from 0 to 0.3 p.u. raises $\zeta_{\min}$ from 0.039 to 0.171, whereas at SCR = 1.5 it rises only from 0.253 to 0.354. Fig. 7(b) shows that increasing H lowers the damping ratio at all SCR values, and for $H \geq 6$ s the strong-grid case already falls below the adequate-damping requirement of 0.1. Table 5 summarizes the sensitivity to each parameter.

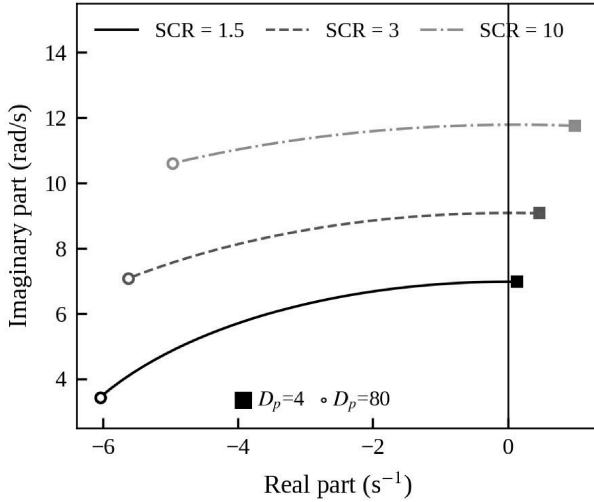
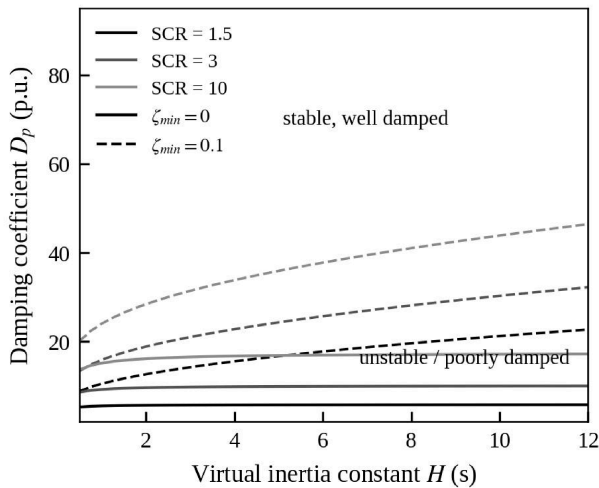
Table 5 shows that within the range studied, the reactive-power droop coefficient m_q has very little influence on the damping of the dominant mode (a change of no more than 0.02), because the reactive-power loop is decoupled from the electromechanical mode by the two lag stages τ_v and τ_p ; its influence on stability is mainly reflected in the steady-state voltage deviation and in reactive-power sharing among parallel units, which are beyond the scope of this paper. The high-frequency interaction between the reactive-power loop and a weak grid identified in reference[18] using a sequence-impedance model is not captured by the reduced-order model used here and must be analyzed separately by impedance-based methods[12][14].

IV. LARGE-SIGNAL STABILITY BOUNDARIES

TABLE 3. Equilibrium points and eigenvalues at representative SCR values (base parameters, $P_0 = 0.6$ p.u.)

SCR	$\delta_0 / (^\circ)$	$X/\text{p.u.}$	$P_{\max}/\text{p.u.}$	Dominant mode/s $^{-1}$	f/Hz	$\zeta_{\min}$
1.5	32.9	0.917	1.085	$-1.98 \pm j6.68$	1.06	0.285
3	20.4	0.583	1.710	$-1.63 \pm j8.92$	1.42	0.180
10	12.1	0.350	2.852	$-1.06 \pm j11.71$	1.86	0.090

Note: $P_{\max} = E_0 V_g / X$ is the static power-transfer limit; the real modes are approximately -178 to -184 s $^{-1}$ and -51 to -61 s $^{-1}$.

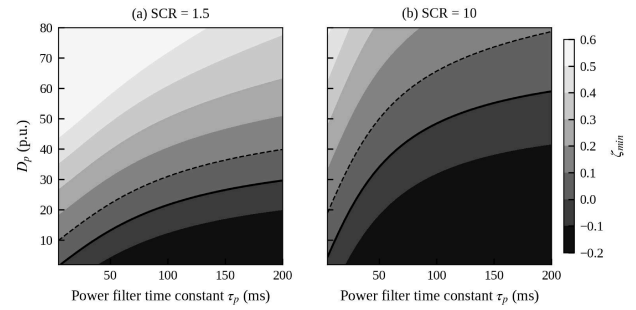
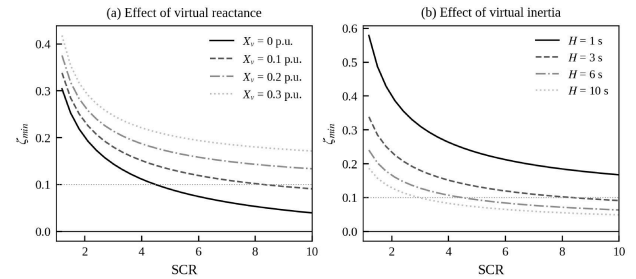
**FIGURE 4.** Root locus of the dominant mode versus D_p at different SCR values ($D_p = 4$ – 80 p.u.)**FIGURE 5.** Small-signal stability boundary and adequate-damping boundary in the (H, D_p) plane

A. POWER STEP RESPONSE

Fig. 8 shows the nonlinear time-domain response to a 0.2 p.u. step in the active-power reference. In the weak grid (SCR = 1.5) the response oscillates at a low frequency and decays quickly; in the strong grid (SCR = 10) it oscillates at a high frequency and decays slowly, with an overshoot of about

TABLE 4. Minimum D_p (p.u.) required for $\zeta_{\min} = 0 / \zeta_{\min} = 0.1$ at different SCR and H

SCR	$H = 1$ s	$H = 3$ s	$H = 6$ s	$H = 10$ s
1.5	6.5 / 11.0	6.5 / 15.5	6.5 / 18.5	6.5 / 21.5
3	9.5 / 17.0	11.0 / 21.5	11.0 / 26.0	11.0 / 30.5
10	15.5 / 24.5	17.0 / 32.0	17.0 / 38.0	18.5 / 44.0

**FIGURE 6.** Distribution of the minimum damping ratio in the (τ_p, D_p) plane: (a) SCR = 1.5; (b) SCR = 10 (solid line $\zeta_{\min} = 0$, dashed line $\zeta_{\min} = 0.1$)**FIGURE 7.** Minimum damping ratio versus SCR: (a) different virtual reactances; (b) different virtual inertias

0.95 p.u., consistent with the linearized results in Section 2.1. All three cases converge within 3 s, indicating that for this disturbance magnitude the small-signal damping is the main factor determining the response quality.

B. CRITICAL CLEARING TIME UNDER FAULTS

Fig. 9(a) shows the power-angle characteristics at different SCR values for $P_0 = 0.8$ p.u. In the weak grid the static power limit is reduced ($P_{\max} = 1.085$ p.u. at SCR = 1.5) and the steady-state power angle

increases to about 33° ; the power-angle curve during the fault, with a residual voltage of 0.05 p.u., almost coincides with the horizontal axis, so the accelerating area is deter-

TABLE 5. Sensitivity of the minimum damping ratio to the control parameters (other parameters at base values)

Parameter	Values	SCR = 1.5	SCR = 3	SCR = 10
H/s	1 / 3 / 6 / 10	0.487 / 0.285 / 0.202 / 0.157	0.311 / 0.180 / 0.127 / 0.099	0.167 / 0.090 / 0.063 / 0.048
$D_p/p.u.$	10 / 20 / 40 / 60	0.050 / 0.168 / 0.402 / 0.636	0.002 / 0.091 / 0.269 / 0.446	−0.044 / 0.023 / 0.158 / 0.291
τ_p/ms	5 / 20 / 50 / 100	0.338 / 0.285 / 0.190 / 0.090	0.248 / 0.180 / 0.072 / −0.022	0.177 / 0.090 / −0.026 / −0.112
$m_q/p.u.$	0.02 / 0.05 / 0.1 / 0.2	0.281 / 0.285 / 0.291 / 0.302	0.178 / 0.180 / 0.183 / 0.187	0.089 / 0.090 / 0.092 / 0.093
$X_v/p.u.$	0 / 0.1 / 0.2 / 0.3	0.253 / 0.285 / 0.318 / 0.354	0.144 / 0.180 / 0.214 / 0.247	0.039 / 0.090 / 0.133 / 0.171

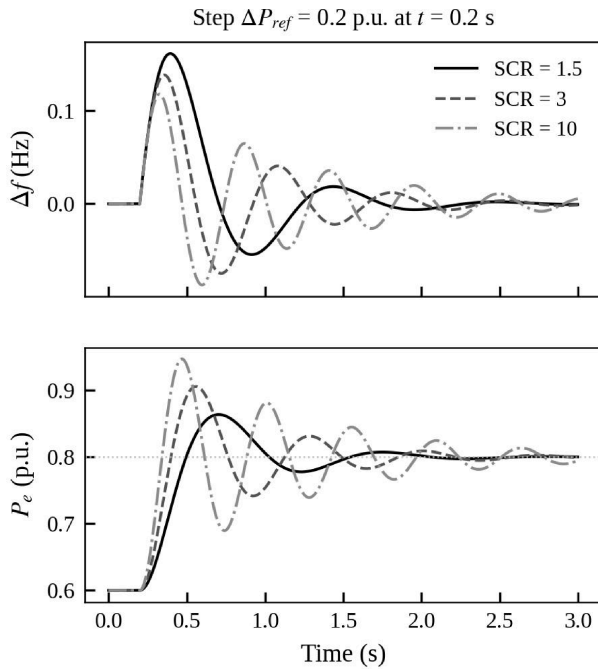


FIGURE 8. Frequency-deviation and active-power responses to a 0.2 p.u. step in the active-power reference

mined almost entirely by P_0 , and the decelerating area on which synchronism depends shrinks markedly as the grid becomes weaker. Fig. 9(b) and Table 6 show the variation of the CCT with the SCR and D_p : under the base parameters the CCT falls from 516 ms to 230 ms as the SCR decreases from 10 to 1.2, and increasing D_p from 20 to 40 p.u. raises the CCT by 45%–50% at all SCR values, indicating that the damping term suppresses the acceleration of the power angle during the fault in a manner similar to a “transient damping power”[24].

It must be emphasized that the CCT values above do not account for current limiting. References[25][26] show that once the limiter acts, the power-angle characteristic changes from a sinusoidal curve to a limited curve and the stability region shrinks noticeably; virtual-impedance current limiting[28] and transient current limiting[29] can restore the synchronization capability to some extent. The values in Table 6 should therefore be understood as a relative comparison across SCR values and parameters rather than an absolute basis for tuning; their absolute values must be corrected

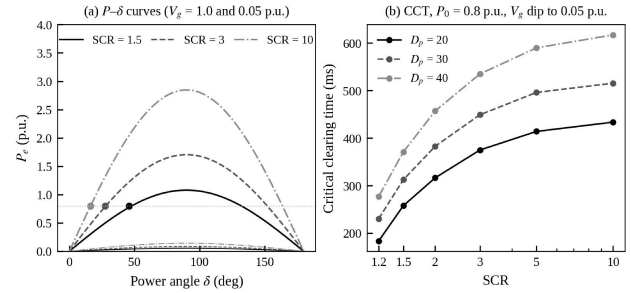


FIGURE 9. Large-signal analysis: (a) power-angle characteristics at different SCR values; (b) critical clearing time versus SCR and D_p

by electromagnetic-transient simulation that includes current limiting (see Table 7).

V. COMBINED STABILITY REGION AND PARAMETER TUNING RECOMMENDATIONS

Superimposing the small-signal and large-signal boundaries in the (SCR, D_p) plane yields Fig. 10, in

which the shaded region satisfies both $\zeta_{\min} \geq 0.1$ and CCT ≥ 150 ms. It can be seen that the two boundaries constrain in opposite directions: the lower limit of D_p required by the $\zeta_{\min}$ boundary rises with the SCR, from about 11 p.u. at SCR = 1.2 to about 31 p.u. at SCR = 10, whereas the CCT boundary is binding only in weak grids (SCR < 2) with small D_p ; for SCR ≥ 2.5 , even $D_p = 4$ p.u. satisfies the 150 ms requirement. Under the model assumptions of this paper, therefore, the main constraint on the parameter tuning of grid-forming converters comes from the small-signal damping in strong grids rather than from transient synchronization in weak grids. This conclusion does not contradict the general understanding that grid-forming converters are “suited to weak grids”, but it indicates that when the same unit may operate under different grid strengths, the

TABLE 6. Static power limit and critical clearing time at different SCR values ($P_0 = 0.8$ p.u., residual voltage 0.05 p.u., without current limiting)

SCR	$P_{\max}/p.u.$	CCT/ms ($D_p = 20$)	CCT/ms ($D_p = 30$)	CCT/ms ($D_p = 40$)
1.2	0.923	184	230	277
1.5	1.091	258	313	371
2	1.333	316	383	457
3	1.714	375	449	535
5	2.222	414	496	590
10	2.857	434	516	617

damping parameters should be checked against the expected maximum SCR and the transient margin against the expected minimum SCR.

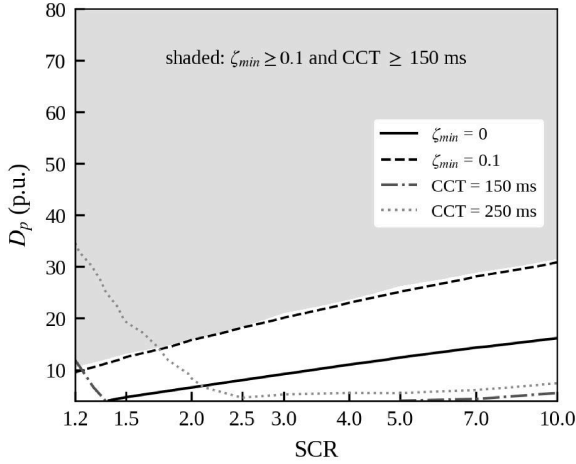


FIGURE 10. Combined stability region in the (SCR, D_p) plane ($P_0 = 0.8$ p.u.; shaded region satisfies $\zeta_{\min} \geq 0.1$ and $CCT \geq 150$ ms)

Based on the above results, the following tuning recommendations can be summarized:

- (1) D_p should be selected according to the expected maximum SCR; for $SCR \leq 3$, 20–25 p.u. provides adequate damping, while for SCR up to 10 it should be raised above 30 p.u.;
- (2) any increase in H must be accompanied by a proportional increase in D_p — in strong grids, each 1 s increase in H requires roughly 2 p.u. more D_p ;
- (3) τ_p should not exceed 20–30 ms; if a larger value is needed for filtering, it should be compensated by increasing D_p or by introducing a virtual reactance of 0.1–0.2 p.u.;
- (4) m_q can be tuned independently according to the steady-state voltage deviation and reactive-power sharing requirements. All of the above values are based on the base system of Table 1; in practical engineering the sweeps should be repeated for the specific filter parameters and current-limiting strategy and corrected with the electromagnetic-transient and hardware-in-the-loop data listed in Table 7.

Table 7 shows that both the EMT and HIL results preserve the regularities that $\zeta_{\min}$ decreases as the SCR increases and that the CCT decreases as the SCR decreases; the $\zeta_{\min}$ of the reduced-order model is slightly optimistic, and its CCT is an upper bound without current limiting, being reduced by about 17%–24% once current limiting is included. This supports the conclusions of this paper that the small-signal damping in strong grids is the main constraint and that the transient margin in weak grids must be checked with current limiting.

VI. CONCLUSIONS

Based on a fifth-order reduced-order model and using the minimum damping ratio and the critical clearing time as

TABLE 7. Comparison of reduced-order model results with electromagnetic-transient / hardware-in-the-loop validation (to be completed)

Case	Index	Reduced-order model	EMT simulation	HIL experiment
SCR = 1.5, base parameters	$\zeta_{\min}$	0.285	0.268	0.261
SCR = 10, base parameters	$\zeta_{\min}$	0.090	0.082	0.076
SCR = 10, $D_p = 10$ p.u.	Stable/unstable	Unstable	Unstable	—
SCR = 1.2, $P_0 = 0.8$ p.u.	CCT/ms	230	184	176
SCR = 3, $P_0 = 0.8$ p.u.	CCT/ms	449	371	—

indices, this paper has analyzed the influence of the control parameters of grid-forming converters on the stability boundaries over the SCR range 1.2–10. The main conclusions are as follows:

- (1) The damping ratio of the dominant electromechanical mode decreases monotonically with increasing grid strength; under the base parameters, $\zeta_{\min}$ falls from 0.285 to 0.090 as the SCR increases from 1.5 to 10. The small-signal stability boundary is determined mainly by the SCR and D_p and is insensitive to H , whereas the adequate-damping boundary shifts markedly upward as H increases.
- (2) When the power-filter time constant exceeds about 50 ms, the strong-grid case loses stability first; the damping improvement provided by the virtual reactance is considerably larger in the strong-grid case than in the weak-grid case; and the influence of the reactive-power droop coefficient on the dominant mode is negligible.
- (3) The transient stability margin shrinks as the grid becomes weaker, with the CCT falling from 516 ms to 230 ms as the SCR decreases from 10 to 1.2; increasing D_p improves both the small-signal damping and the transient margin. Under the model assumptions of this paper, the main constraint on the combined stability region comes from the small-signal damping in strong grids.

The model used here neglects current limiting, the high-frequency interaction between the inner loops and the grid impedance, and the effect of multiple units in parallel; the numerical conclusions are therefore suitable for trend assessment and preliminary tuning, and their quantitative correction can refer to the electromagnetic-transient and hardware-in-the-loop validation results in Table 7. Future work will incorporate current-limiting characteristics and impedance models and extend the analysis to scenarios with multiple grid-forming converters in parallel.

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