Safe Control of Grid-Following Inverters using CLF-CBF with Stability Guarantees

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01 Background & Motivation

Inverter-based resources are rapidly replacing synchronous generators, making the safety of inverter current control increasingly critical to grid reliability.

- **IEEE 1547** limits injected current to 1.1 pu of rated value, yet conventional controllers routinely violate this during faults and voltage sags [1].
- **PI Controllers** are simple and widely used but they overshoot during transients and rely on saturation blocks as a post-hoc fix [2].
- **LQR** improves dynamic response but still lacks explicit current limit enforcement [3].
- **Conventional Safety Measures:-** saturation blocks, heuristic clamps, conservative tuning are reactive and not guaranteed

02 The Gap we Fill

CLF-CBF safe control has been applied to power systems but only at the outer loop (slow voltage and frequency timescales). It is non-trivial to address the inner current control loop, where:

- Transients develop in milliseconds
- The controller must be compatible with high-frequency PWM
- Reference currents may temporarily exceed safe limits during sags, creating a direct conflict between tracking and safety

03 Study System

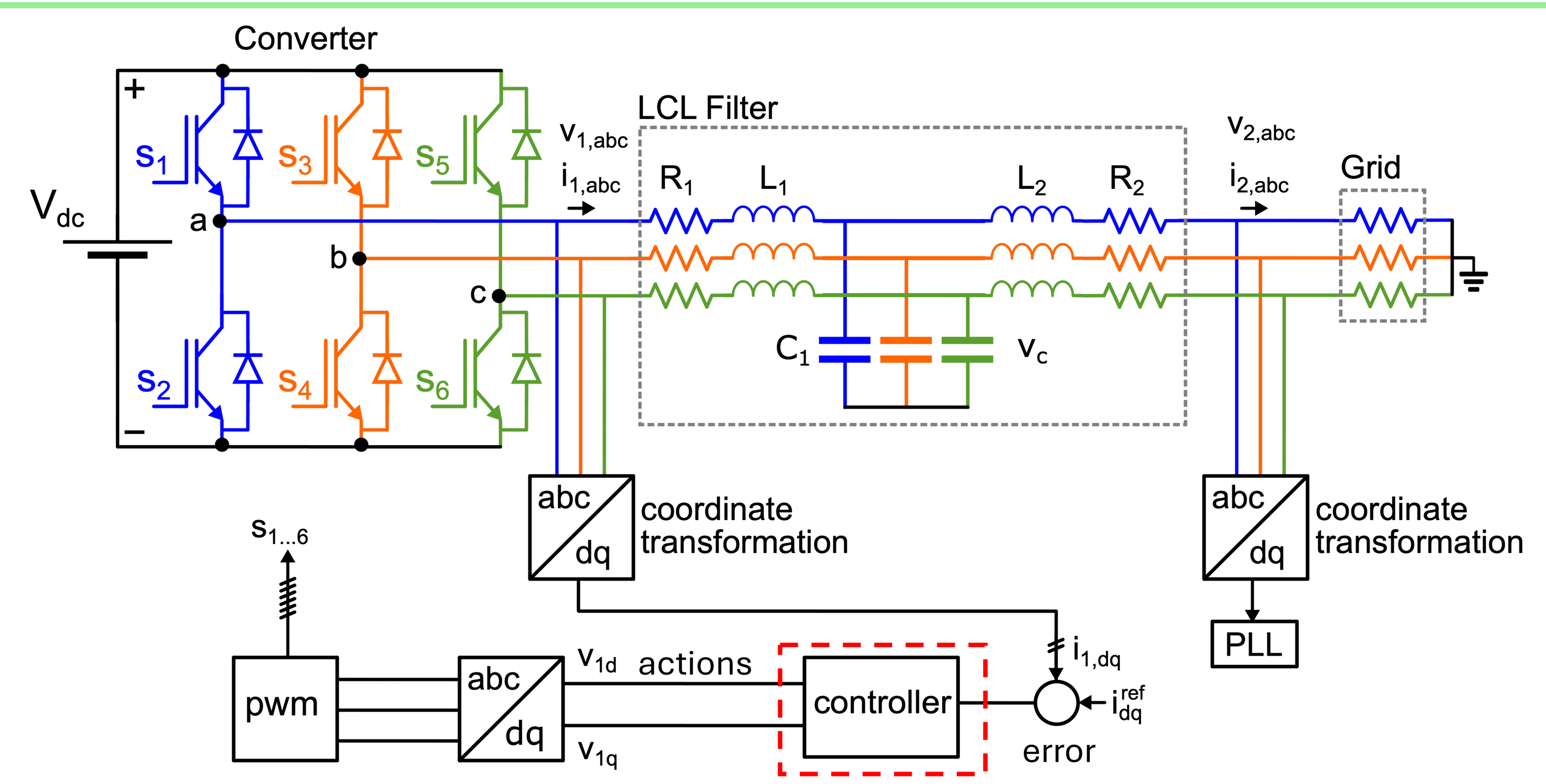

Fig. 1 – Three-phase grid-following inverter with LCL filter. State vector $x = [i_{1d}, i_{1q}, i_{2d}, i_{2q}, v_{cd}, v_{cq}]^T$. Known dynamics: $\dot{x} = Ax + Bu$

SAFE CURRENT LIMIT (IEEE 1547)

$$I^{max} = \sqrt{\frac{2}{3}}\frac{1.1S}{V_{LL,rms}} = 224.5 \text{ A}$$

04 Simulation Parameters

Parameter	Value
Rated Power S	100 kVA
DC-Link Voltage V_{dc}	1500 V
Grid Voltage V_{LL}	400 V
Grid Frequency f	60 Hz
Switching Frequency f_s	10 kHz
Max d-axis Current	224.5 A
CBF Gain $\gamma_d = \gamma_q$	6000

05 Control Lyapunov Function

The CLF is built from the LQR Riccati solution, guaranteeing asymptotic convergence of inverter currents to their reference:

CLF DEFINITION

$$v(x) = \left(x - x^{ref}\right)^T P(x - x^{ref})$$
$$A^T P + PA - PBR^{-1}B^T P + Q = 0$$
$$\dot{v}(x) = 2\left(x - x^{ref}\right)^T PBu$$

P is the unique positive-definite solution to the algebraic Riccati equation. Minimizing $\dot{v}(x,u)$ drives the fastest descent toward the reference

06 Control Barrier Functions

Separate CBFs enforce d- and q-axis current limits, making the safe set **forward invariant:**

BARRIER FUNCTIONS

$$h_d(x) = i_d^{max} - i_{1d} \geq 0$$
$$h_q(x) = i_q^{max} - i_{1q} \geq 0$$

FORWARD INVARIANCE CONDITION [4]

$$\nabla_x h(x)^T \dot{x} + \alpha_h(h(x)) \geq 0$$

If this condition is satisfied for all time, the system cannot leave the safe set. Both CBFs are relative-degree-one

07 Super-linear Barrier and γ Bound

SUPER-LINEAR α_H

$$\alpha_h(z) = \gamma(z+1)\log(z+1) \leq z.f_s$$

γ BOUND (Theorem II)

$$\gamma \leq \frac{f_s}{(h^{max}+1).\log(h^{max}+1)}$$

Smooth control far from the limit; aggressive enforcement near the boundary

08 Unified CLF-CBF-QP

QUADRATIC PROGRAM - SOLVED EVERY SWITCHING CYCLE

$$u^* = argmin\ 2(x - x^{ref})^T PBu + \lambda\|u\|^2$$
$$s.t\ \nabla h_d(x)^T \dot{x} + \gamma_d(h_d+1)\log(h_d+1) \geq 0$$
$$\nabla h_q(x)^T \dot{x} + \gamma_d\left(h_q+1\right)\log(h_q+1) \geq 0$$

The CLF cost drives tracking; the CBF constraints are hard limits. When far from the limits, the QP behaves like a pure tracker.

09 Safety: Peak Current

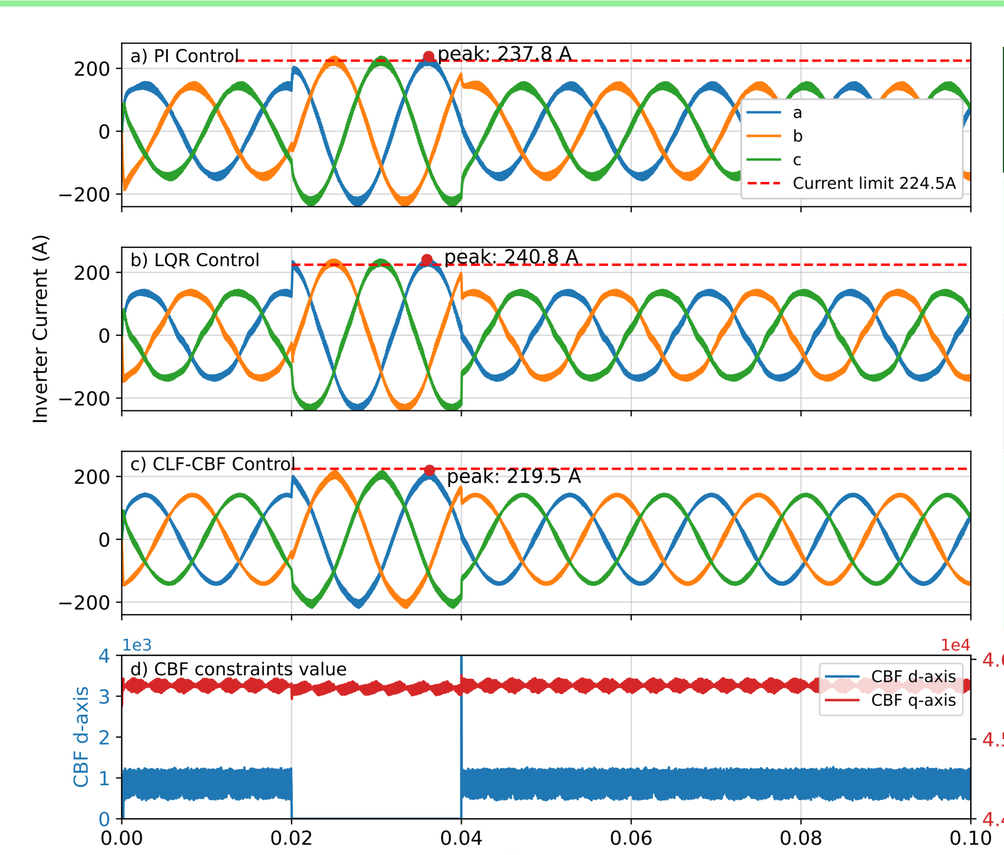

Fig. 2 – Three-phase inverter current under 0.6 pu voltage sag (0.02-0.04s). Red dashed line = 224.5 A safe limit. Bottom Panel: CBF constraint values :- strictly positive

Controller	Peak (A)	Limit (A)	Safe?
PI	237.8	224.5	✗
LQR	240.8	224.5	✗
CLF-CBF-QP	**219.5**	**224.5**	✓

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10 Dynamics: Current Tracking

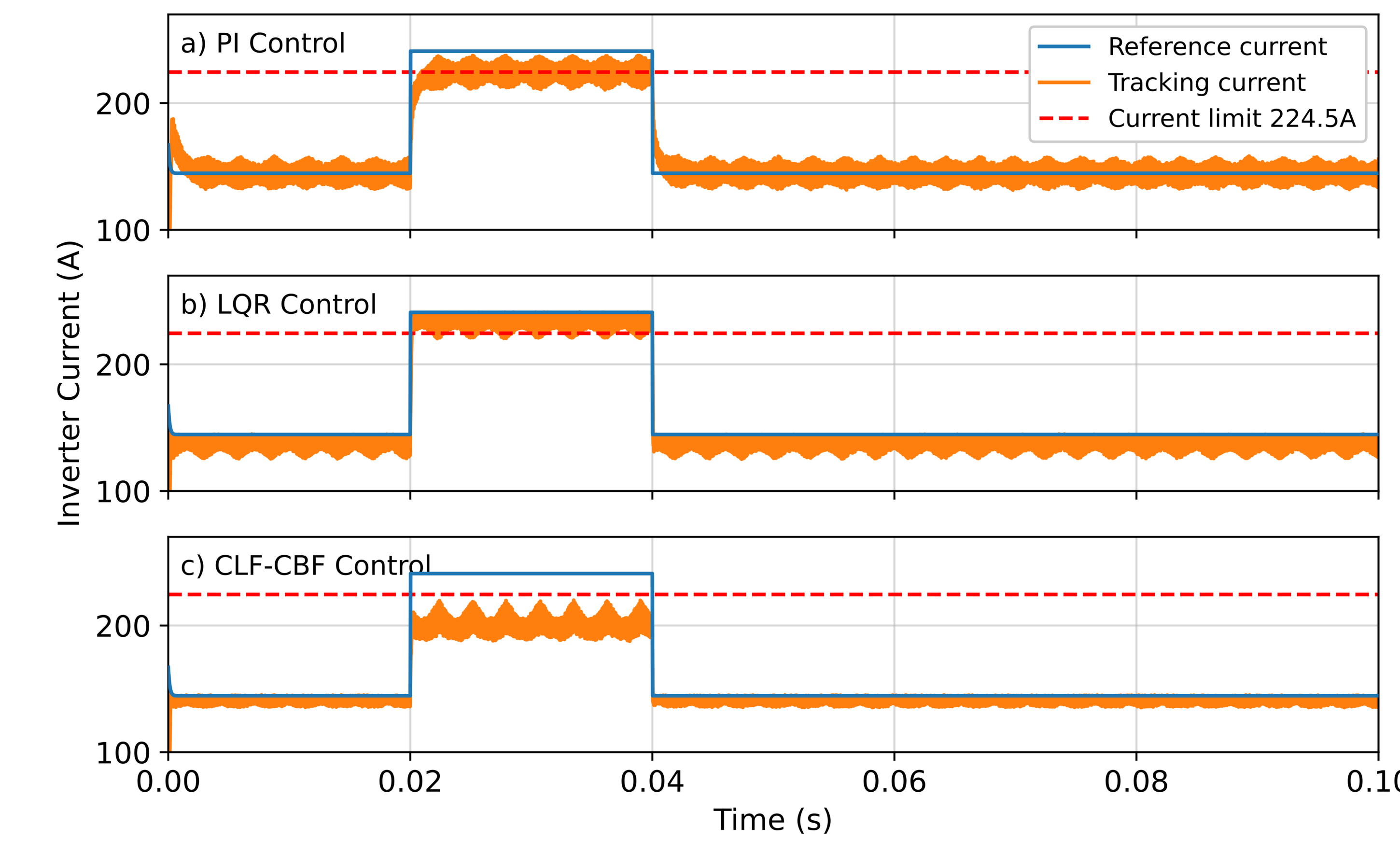

Fig. 3 – d-axis current tracking. PI overshoots and recovers slowly. LQR recovers fast but breaches the limit. CLF-CBF-QP: fast recovery, limit never crossed

- **PI** – overshoots and recovers slowly
- **LQR** – fast recovery, but breaches the limit
- **CLF-CBF-QP** – fast recovery, limit never crossed

11 Power Quality: THD

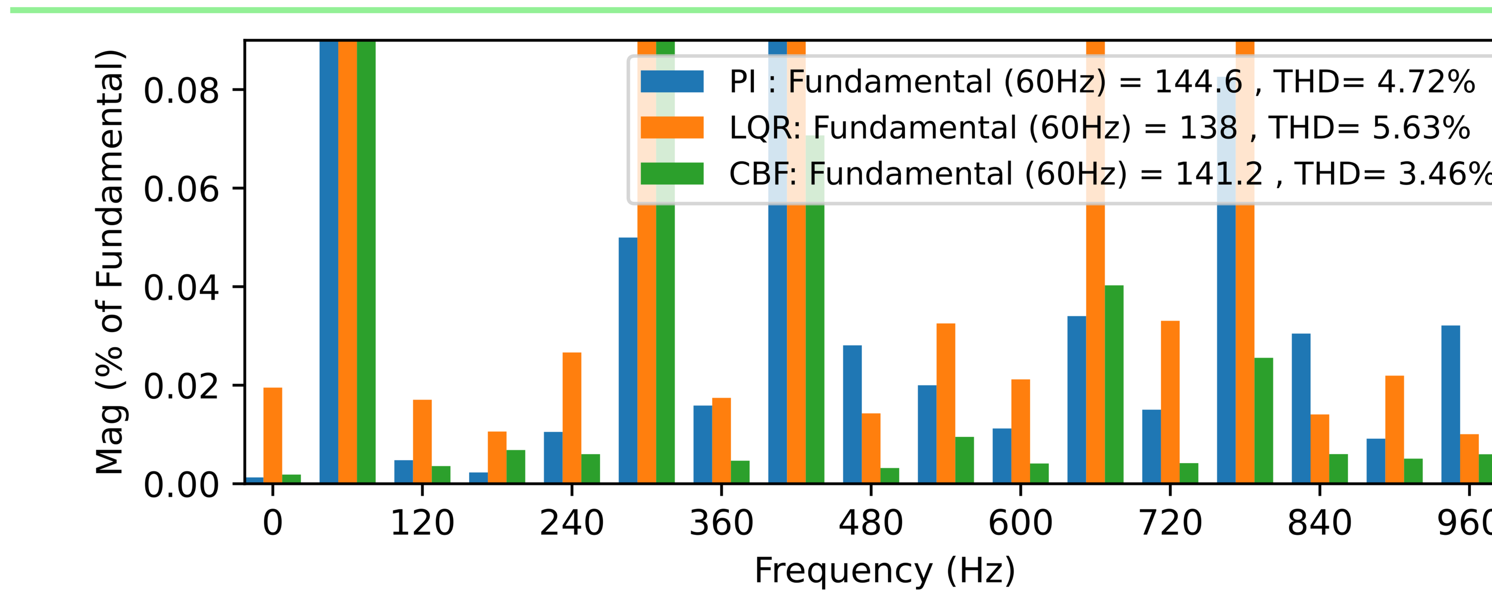

Fig. 4 – FFT of inverter output current. CLF-CBF are the smallest across the harmonic spectrum

The super-linear barrier allows smooth, minimal corrections away from the limit

12 Conclusion

- CLF-CBF embeds the current limit in the control law with formal guarantees
- CBF constraint values strictly positive throughout the voltage sag
- Lower peak current, lower THD

13 References

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