Frequency Shift Acceleration Control for Anti-islanding of a Distributed Generator

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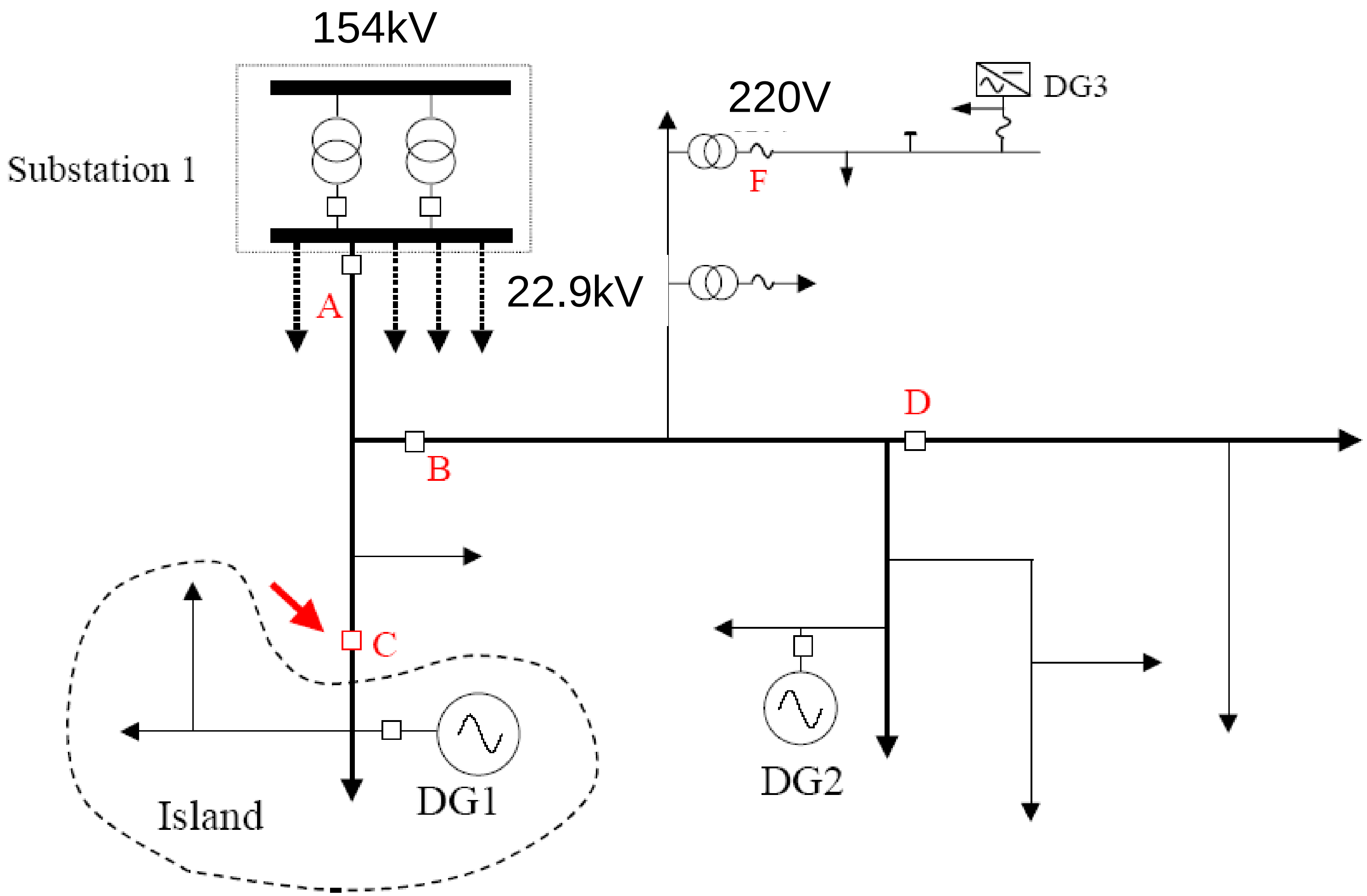
Overview

1. Introduction
2. Frequency Shift Acceleration Control
3. Design of Acceleration Gain
4. Simulation Results
5. Experimental Results
6. Conclusion

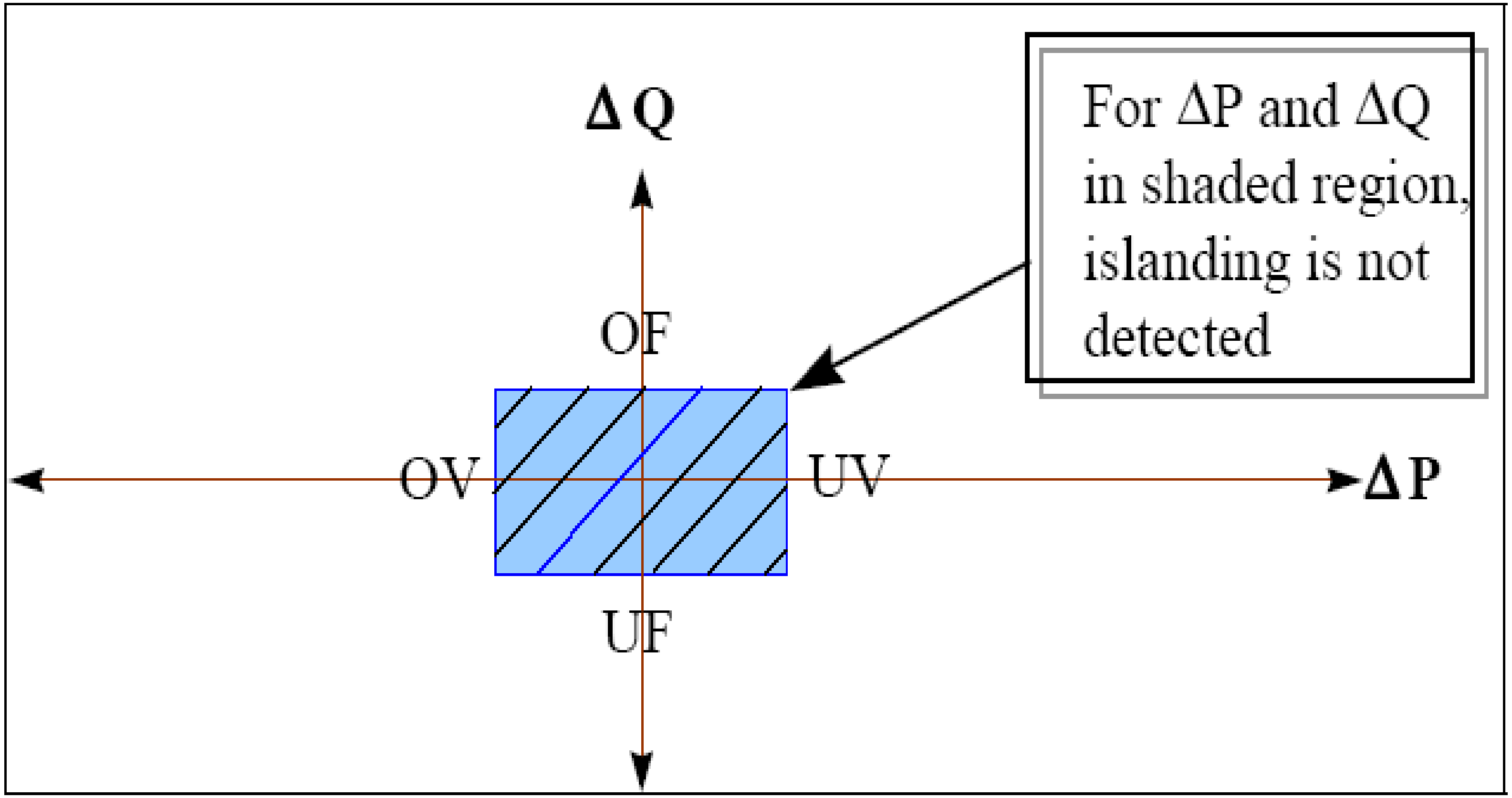
Introduction

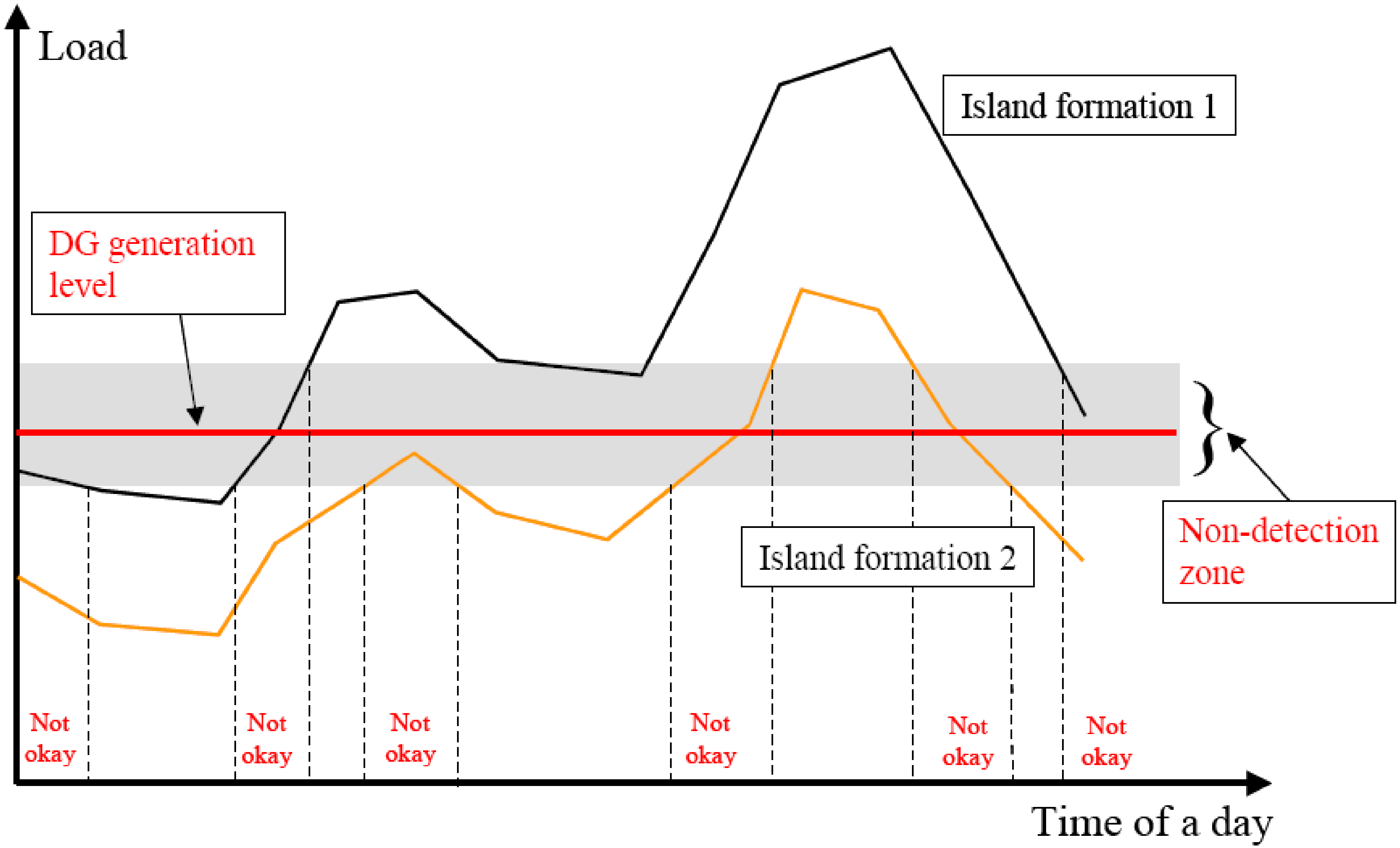
- Islanding
- Anti-islanding Methods
  - Passive
  - Active
- Proposed Algorithm
  - DQ control
  - Small signal analysis
  - Simulation & Experiment

Islanding



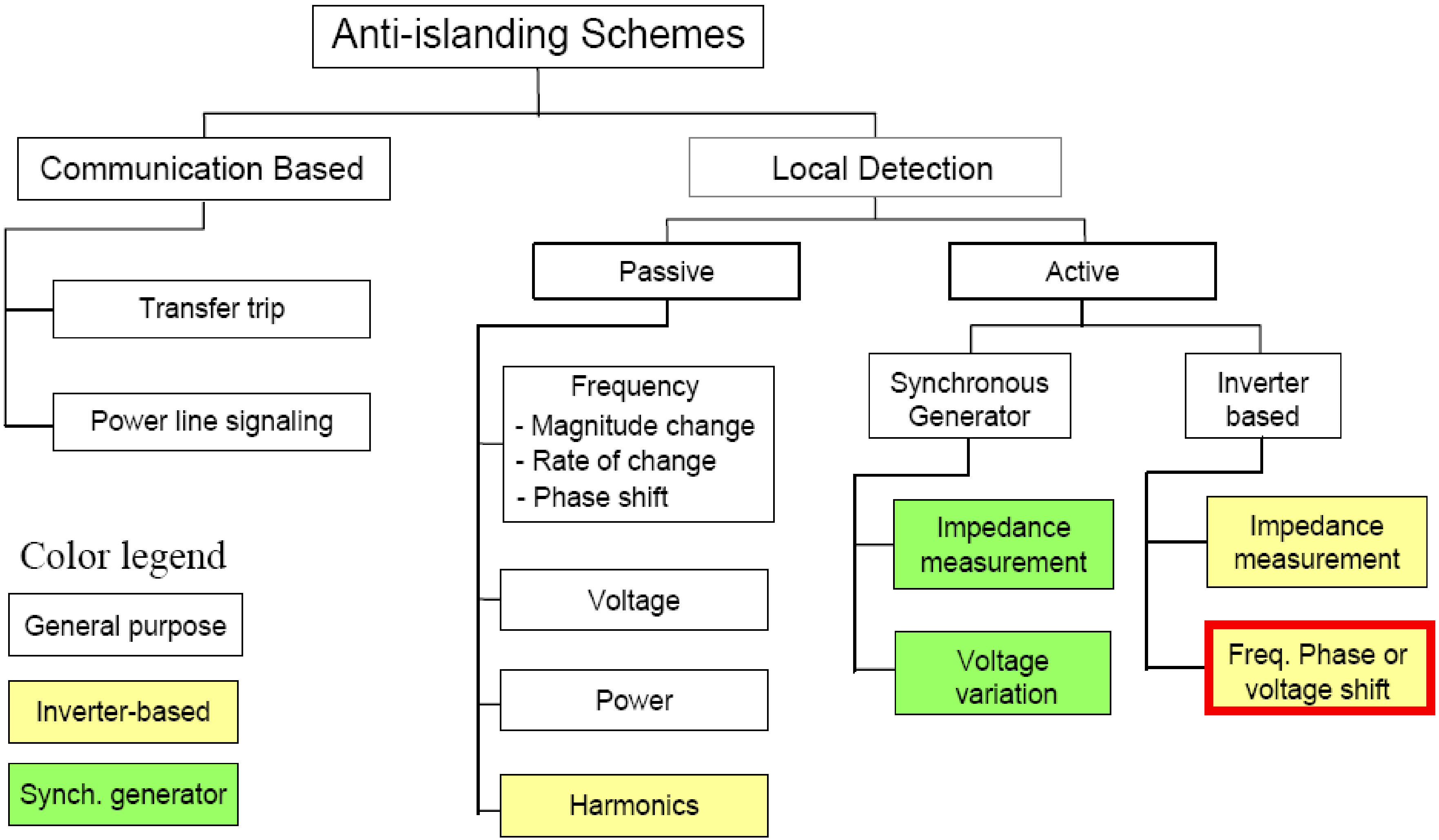
Non-Detection Zone (NDZ)





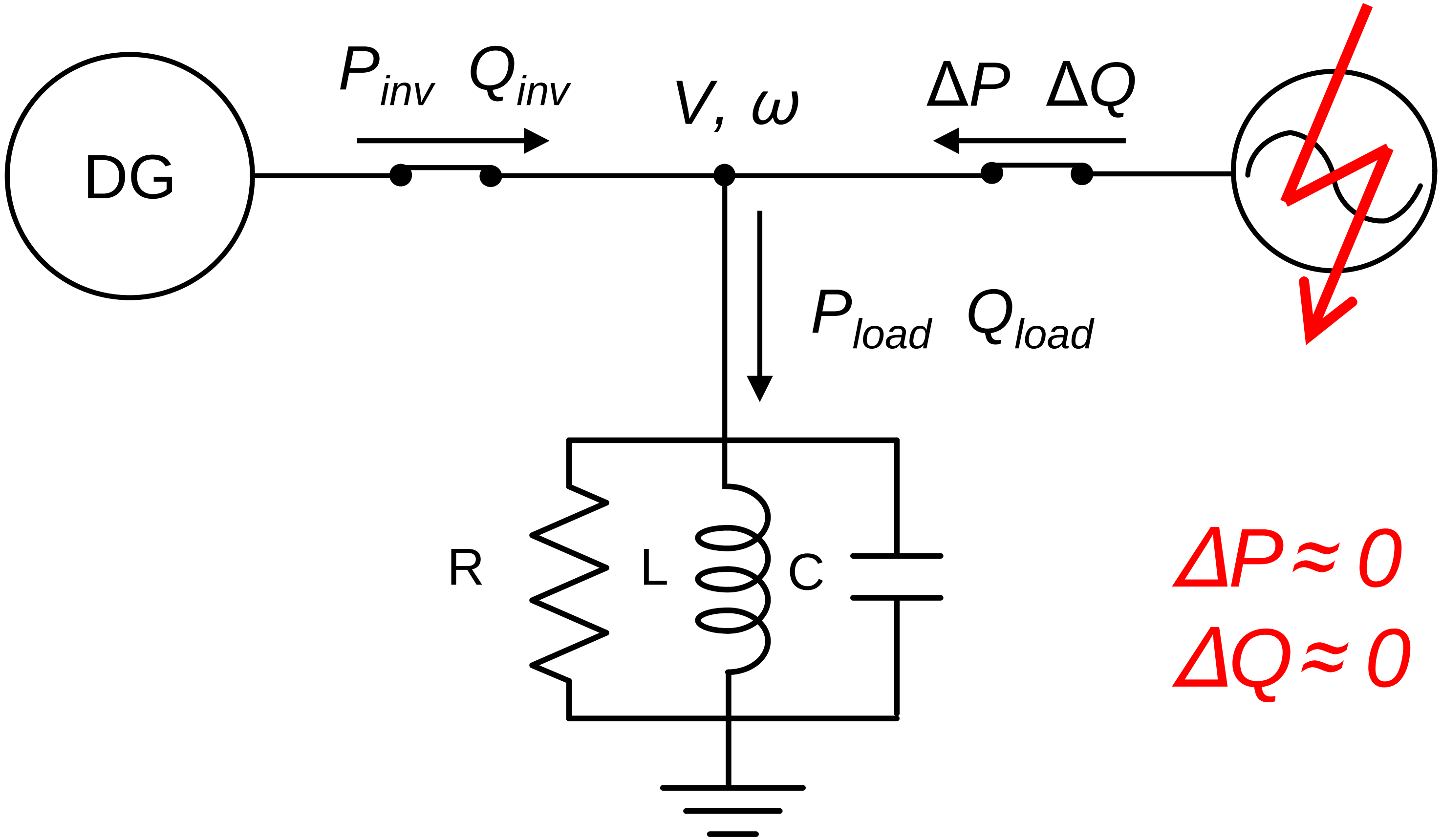
NDZ Impacts Islanding Detection

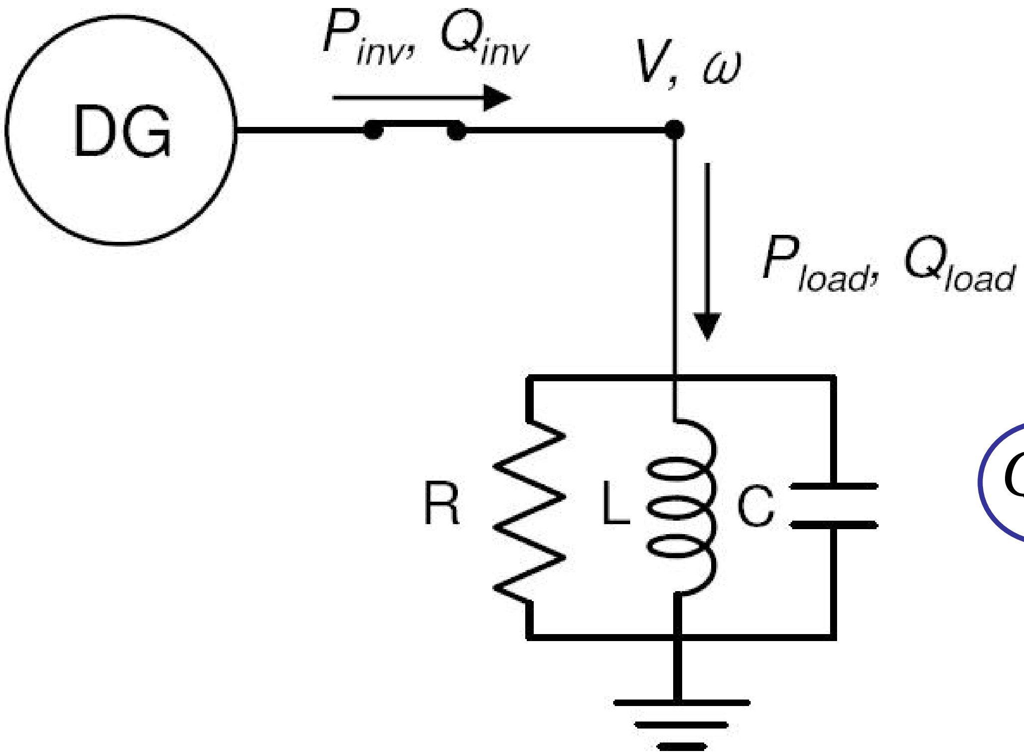
Anti-islanding Methods



FSAC

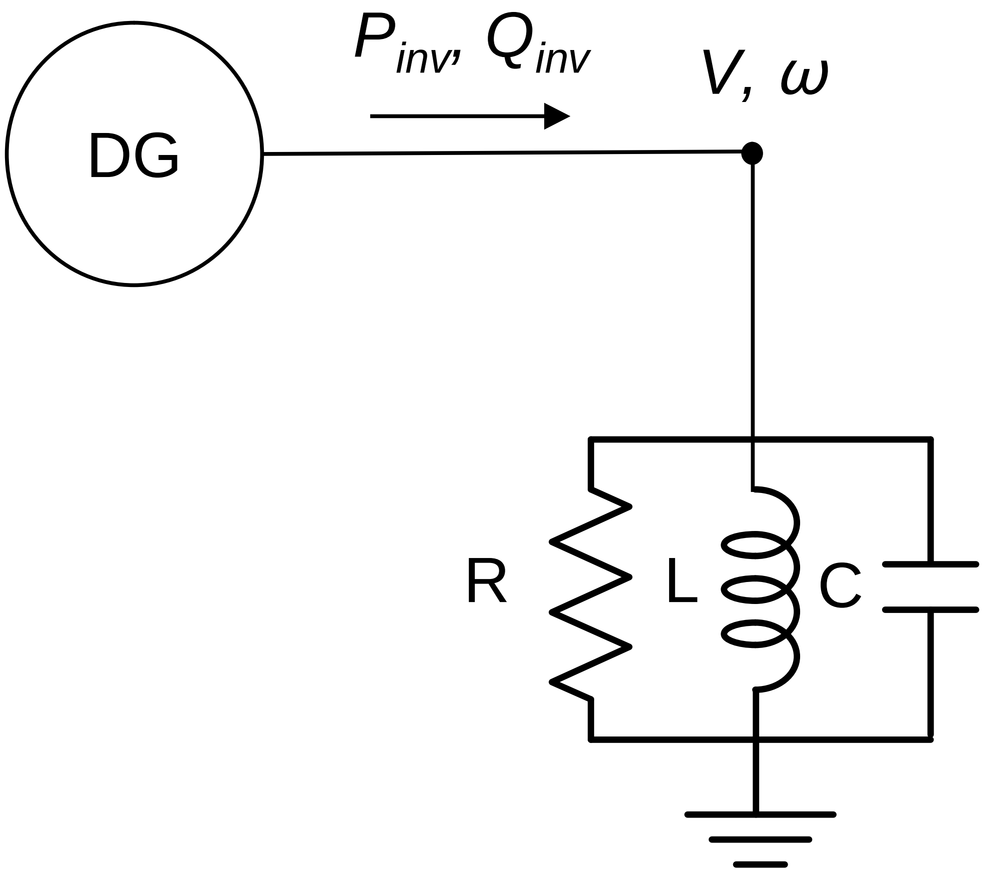
- Islanding Condition





$$P_{inv} = P_{load} = \frac{V^2}{R}$$

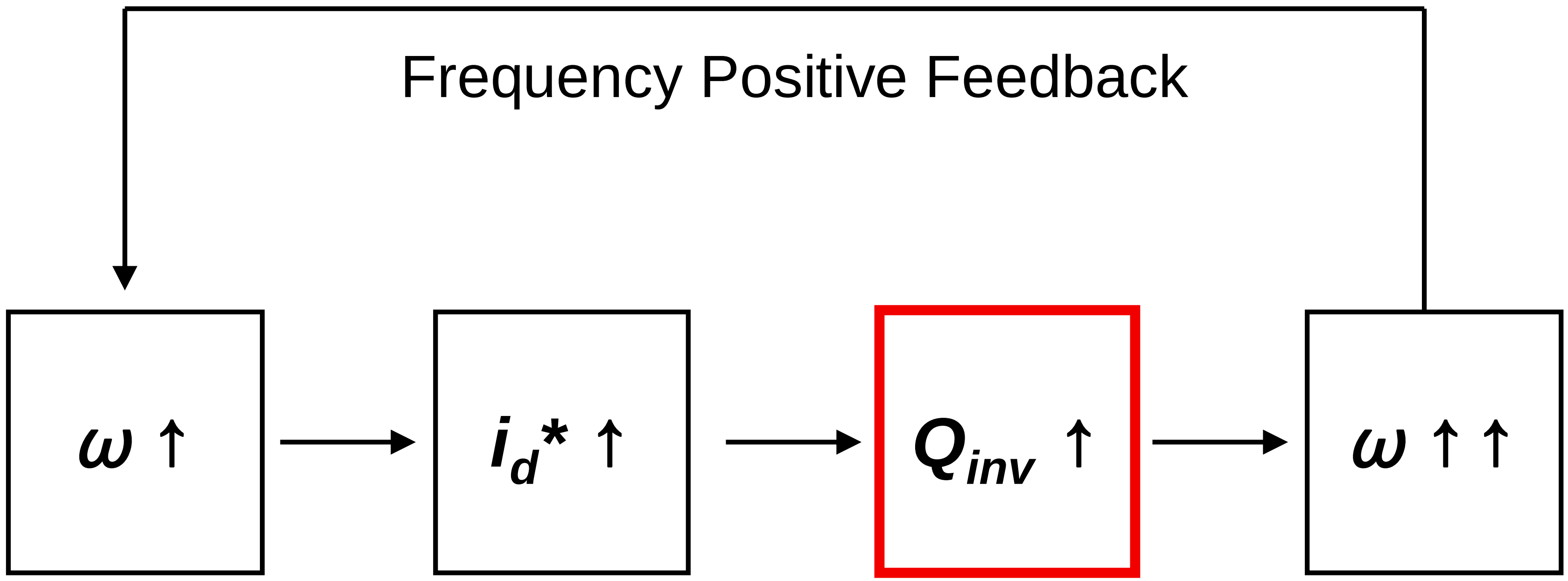
$$Q_{inv} = Q_{load} = V^2\left(\frac{1}{\omega L} - \omega C\right)$$



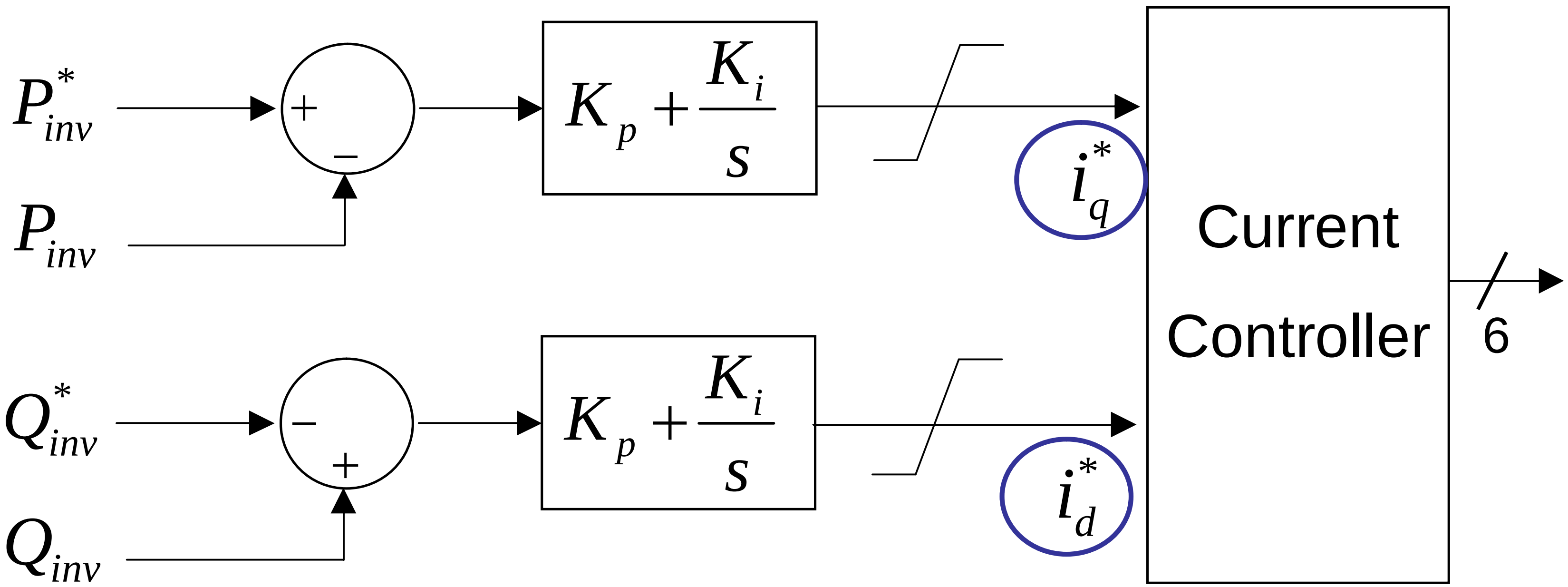
$\boldsymbol{P_{inv}} \uparrow \rightarrow \boldsymbol{V} \uparrow$

$\boldsymbol{Q_{inv}} \uparrow \rightarrow \boldsymbol{\omega} \downarrow$

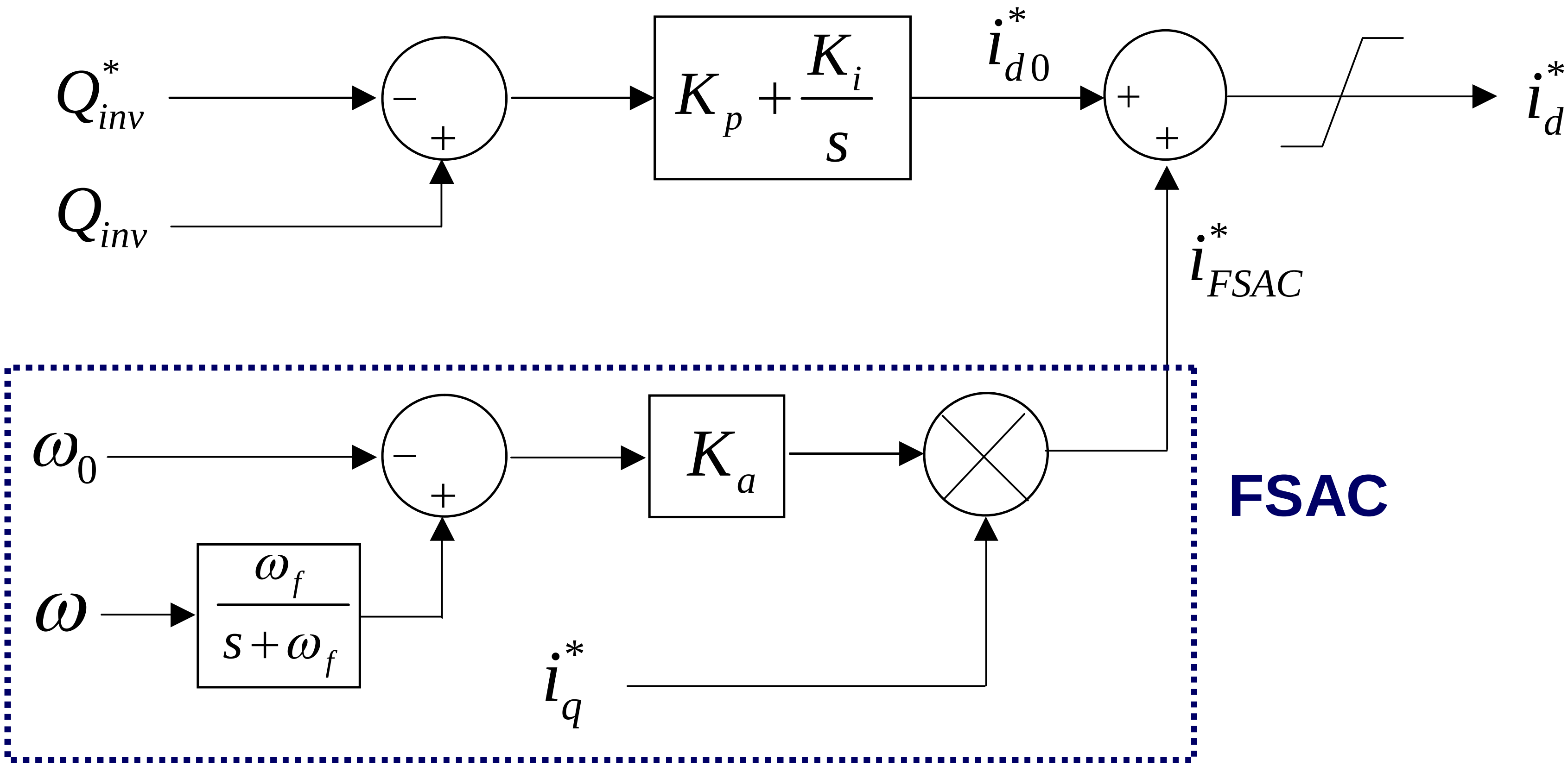
- Key Idea



- Power controller of DG inverters



▪ Q controller with FSAC



$$K_{pf} = i_q^* \cdot K_a$$

K_{pf} : Positive feedback gain

K_a : Frequency shift acceleration gain

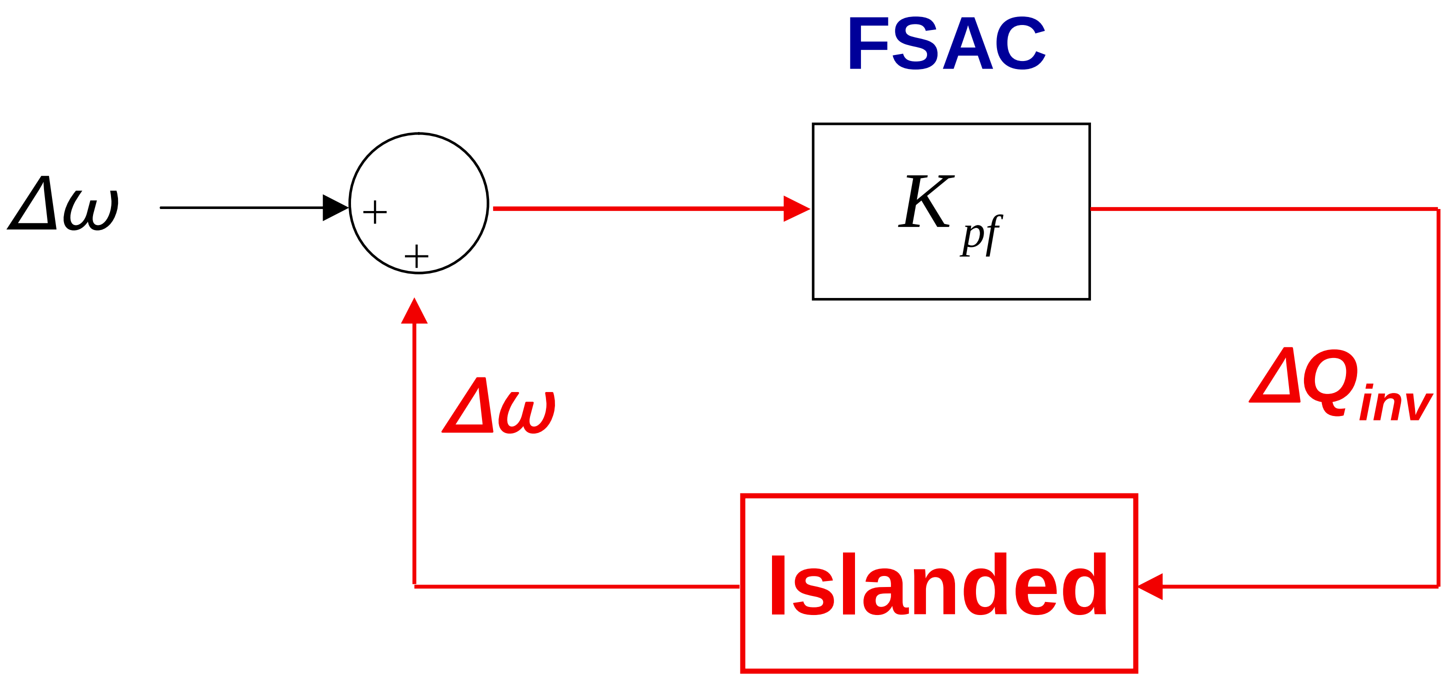
Design of Acceleration Gain

- When *islanded*, **large** enough to destabilize system ***Small Signal Analysis***

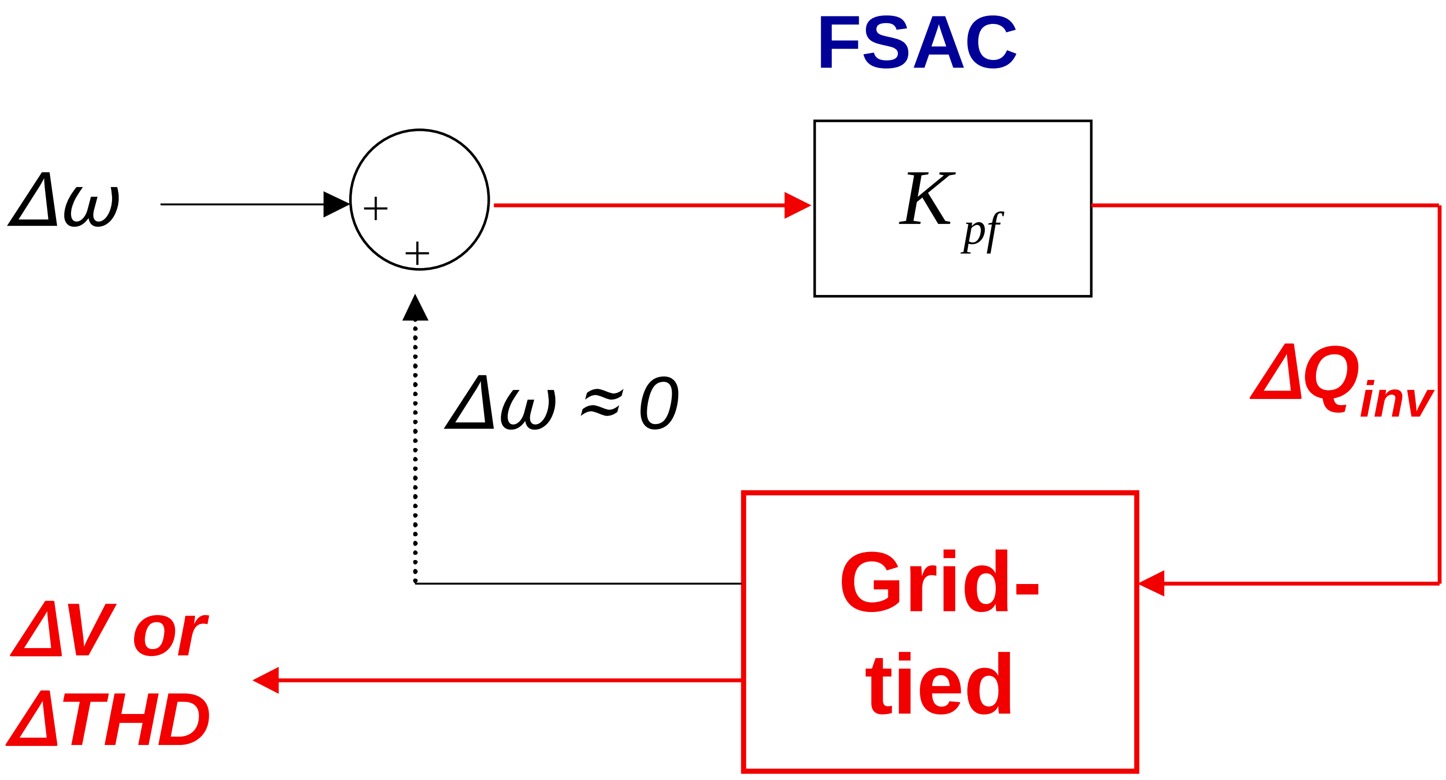
- When *grid-tied*, **small** enough to keep ΔQ beyond the limit

Frequency Step Response

- K_{pf} > Lower Limit



- K_{pf} < Upper Limit



- Lower Limit by Small Signal Analysis

$$\left(Q_{inv} - Q^*\right)\left(K_P + \frac{K_i}{s}\right) + \left(\omega \frac{\omega_f}{s+\omega_f} - \omega_0\right) K_{pf} = i_d^*$$

$$\left(K_P + \frac{K_i}{s}\right) \Delta Q_{inv} + K_{pf} \frac{\omega_f}{s+\omega_f} \Delta\omega = \Delta i_d$$

$$s^2 + \left[\frac{e_q\left\{2 + 3e_q\left(K_p + \frac{K_i}{\omega_f}\right)\right\}\left(\frac{Q_f}{\omega_0 R}\right) - K_{pf}}{2e_q\left(\frac{Q_f}{\omega_0 R}\right)\left(1 + \frac{3}{2} e_q K_p\right)}\right]\omega_f s + \frac{3}{2} e_q \left(\frac{K_i \omega_f}{1 + \frac{3}{2} e_q K_p}\right) = 0$$

For the islanded system to be unstable

$$K_{pf} > \left\{ 2 + 3e_q \left(K_p + \frac{K_i}{\omega_f} \right) \right\} \cdot \left(\frac{Q_f}{\omega_0} \right) \cdot \left(\frac{e_q}{R} \right)$$

i_q

$$K_a > \left\{ 2 + 3\sqrt{2} V_n \left(K_p + \frac{K_i}{\omega_f} \right) \right\} \cdot \left(\frac{Q_f}{\omega_0} \right)$$

V_n : Inverter terminal voltage, ω_f : Measuring frequency

Q_f : Quality factor, ω_0 : Nominal frequency

FSAC eliminates

real power dependency of control gain !!

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- Upper Limit by Freq. Step Response

$$\Delta i_d(s) = (K_P + \frac{K_i}{s})\Delta Q_{inv}(s) + K_{pf}\,\Delta\omega(s)$$

$$\left|\Delta Q_{inv}(s)\right| = \frac{K_{pf}}{K_p + 2/\left(3e_q\right) + K_i/s}\left|\frac{\Delta\omega}{s}\right|$$

$$\Delta Q_{inv}(t) = \frac{K_{pf}}{K_p + 2/\left(3e_q\right)}\left|\Delta\omega\right|\exp\left[st\right]$$

Maximum Q disturbance due to frequency step change

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$$\Delta Q_{\max} > \frac{K_{pf}}{K_p + 2/(3e_q)} \left|\Delta\omega_{\max}\right|$$

$$\eta_{preset} = \Delta Q_{\max} / P_{inv}$$

$$K_{pf} < \left(1 + \frac{3}{2} e_q K_p\right) \frac{\eta_{preset}}{\left|\Delta\omega_{\max}\right|} \cdot i_q^*$$

$$K_a < \left(1 + \frac{3\sqrt{2}}{2} V_n K_p\right) \frac{1}{\left|\Delta\omega_{\max}\right|} \cdot \eta_{preset}$$

Simulation Results

- Simulation conditions

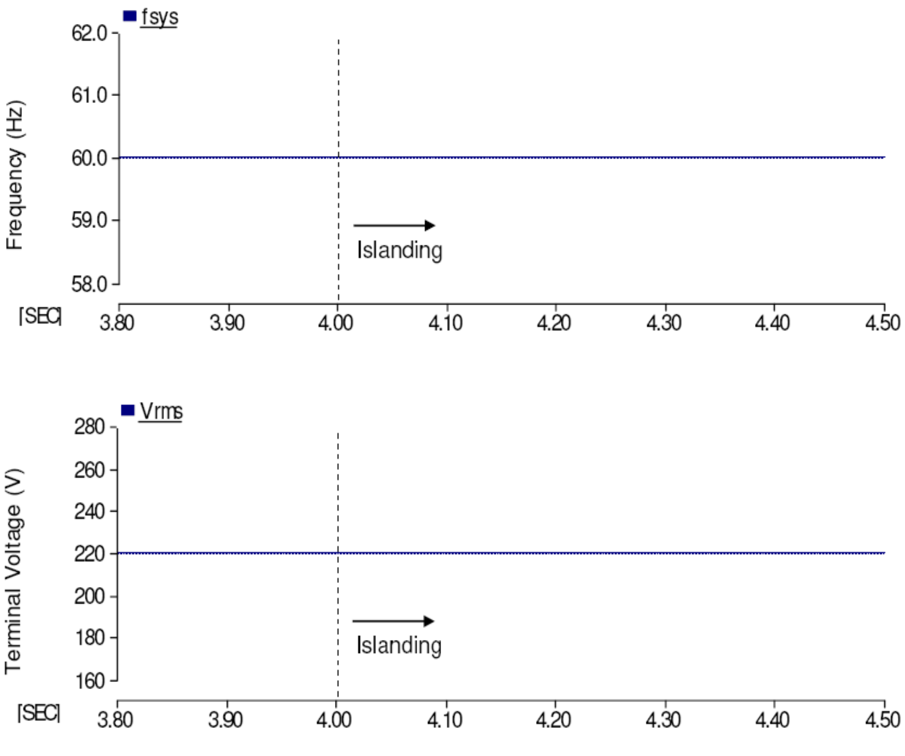
  - $P_{inv} = P_{load} = 20kW$, $Q_{inv} = Q_{load} = 0kVar$
  - Detection condition (IEEE P1547)

    - Voltage : 110% > or < 88%

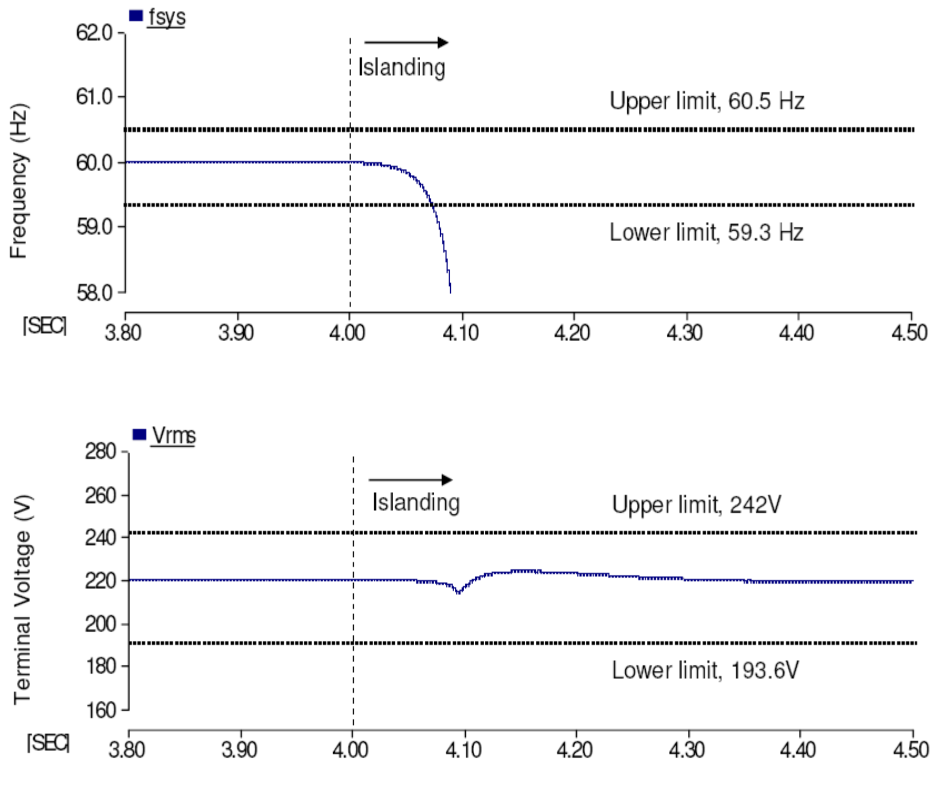
    - Frequency : 60.5 Hz > or < 59.3 Hz
  - R-L-C Load (IEEE 929 & UL 1741)

    Quality factor $Q_f = 2.5 \rightarrow Q_L$ & $Q_C = 2.5 \times P_{inv}$
  - Calculated Range of K_a : ***$0.076 < K_a < 0.3$***
  - **$\eta_{preset} = 0.1$**

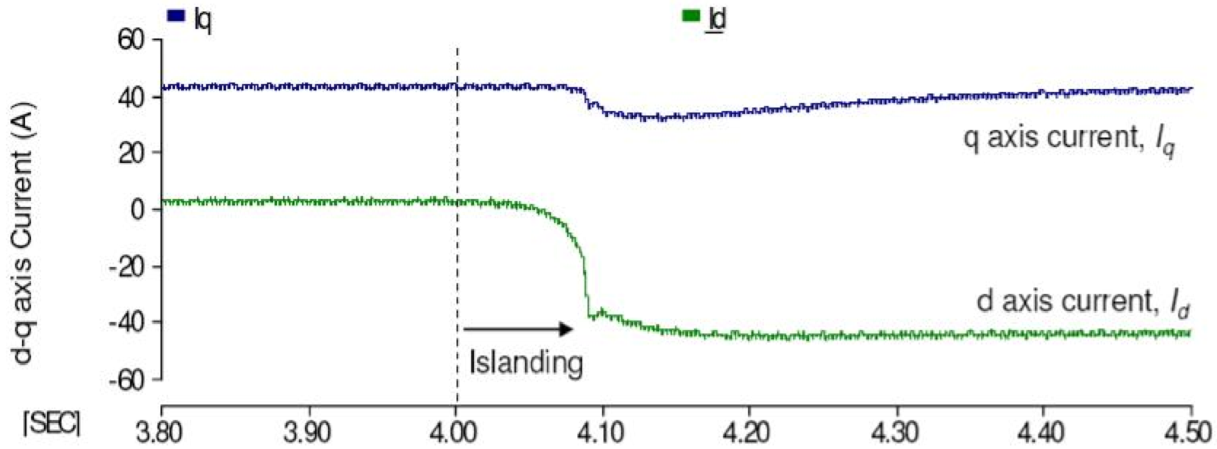
Without FSAC



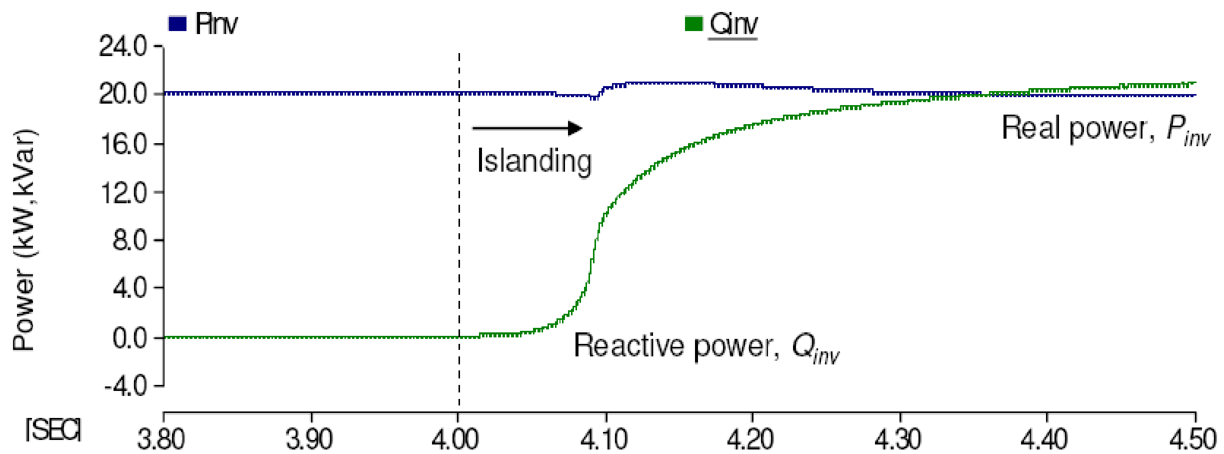
With FSAC (K_a = 0.15)



q-and d-axis current



Real and Reactive Power



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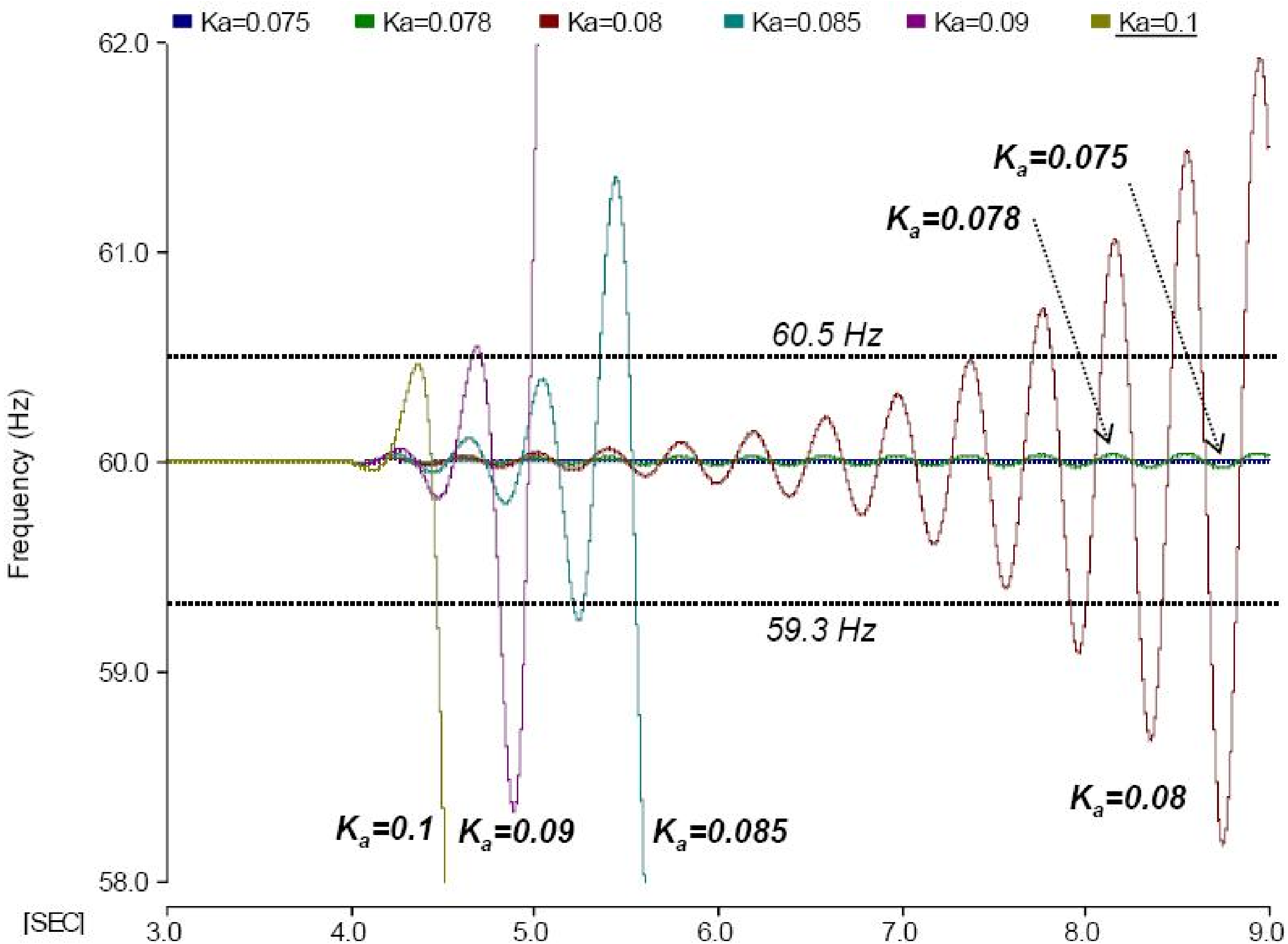
Frequency Variations with Different gains of K_a



Calculated & Simulated results for Lower Limit of K_a

K_p	K_i	Calculated x100	Simulatedx100
2	5	2.6	**2.8**
	20	2.6	**3.0**
	50	2.6	**3.3**
5	5	4.5	**4.6**
	20	4.5	**4.7**
	50	4.5	**5.0**
10	5	7.6	**7.6**
	20	7.6	**7.7**
	50	7.6	**7.8**
15	5	10.6	**10.6**
	20	10.7	**10.7**
	50	10.7	**10.7**
20	5	13.7	**13.6**
	20	13.8	**13.7**
	50	13.8	**13.7**

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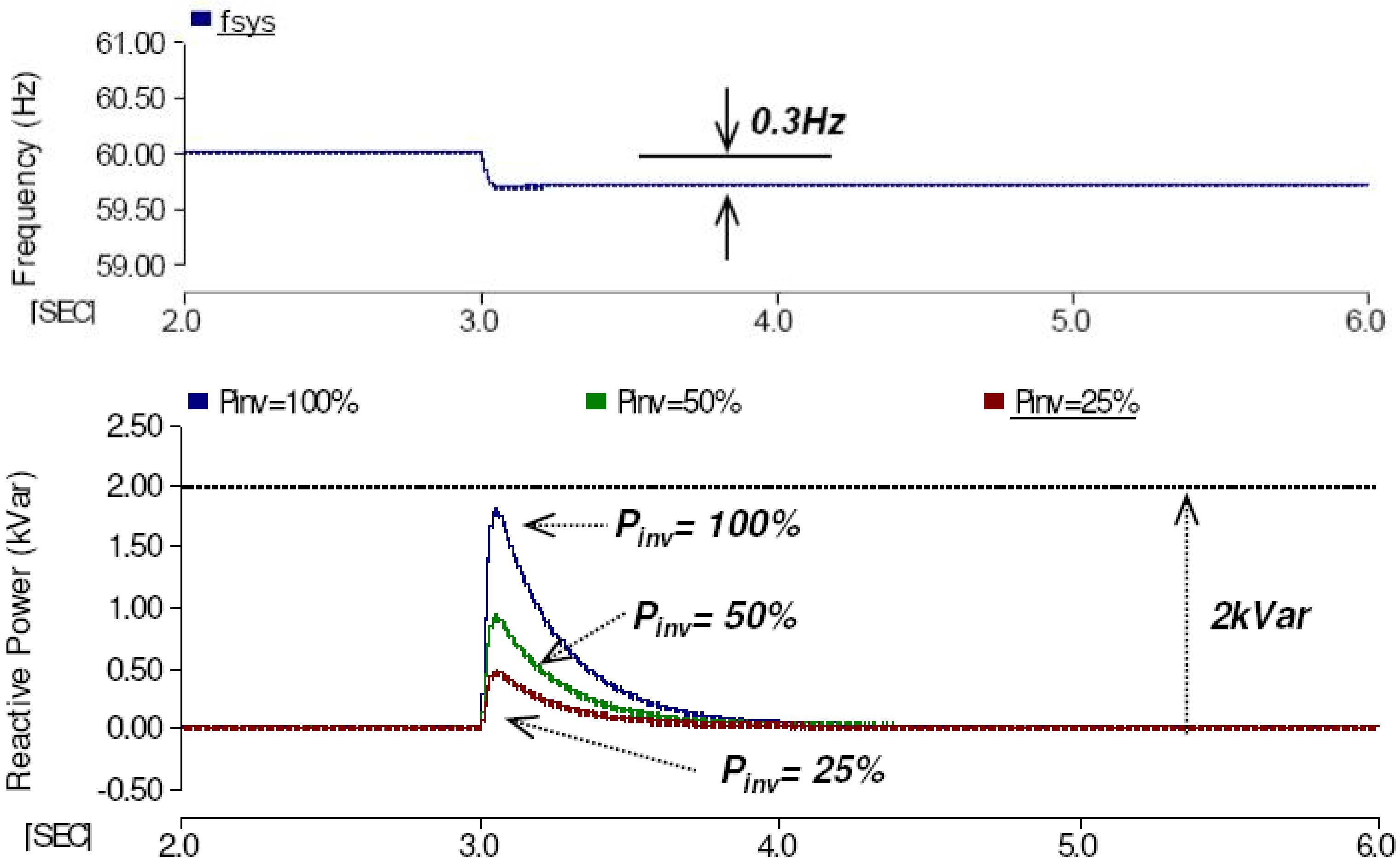
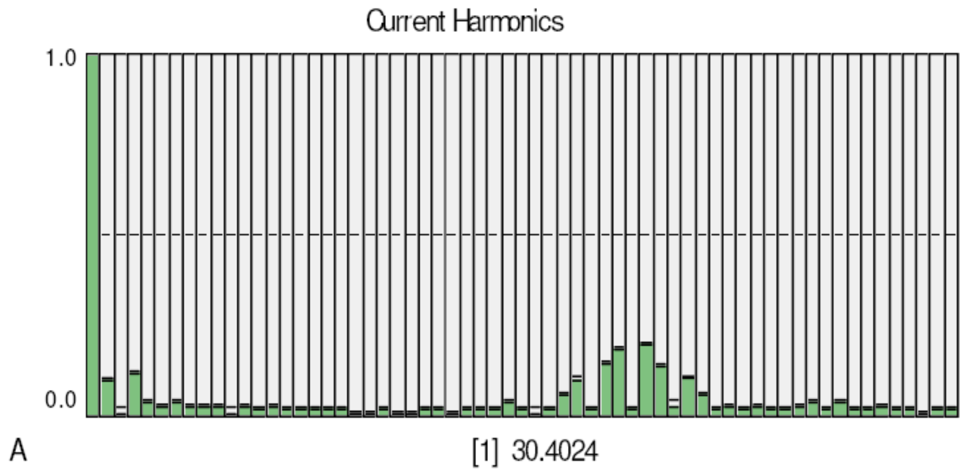
Q_{inv} disturbance due to Δω in grid-tied operation



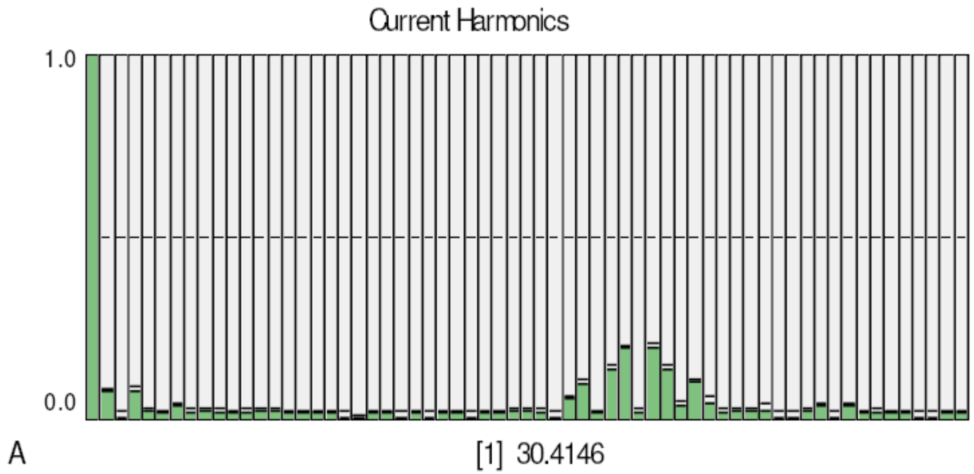
Q_{inv} at K_a = 0.3

Harmonic Spectrum

Without FSAC

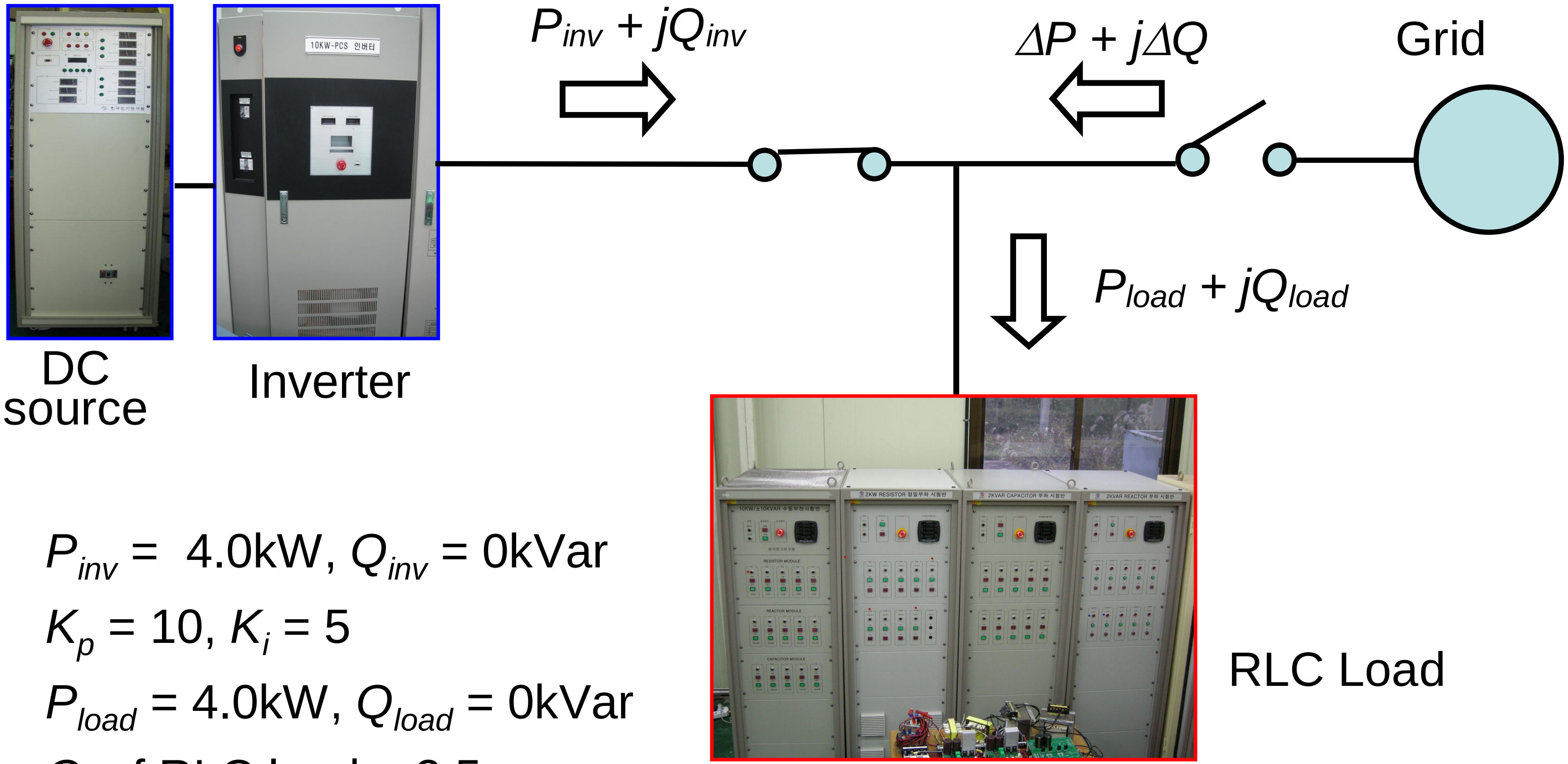


With FSAC



1st freq. → 63rd

Experimental Results



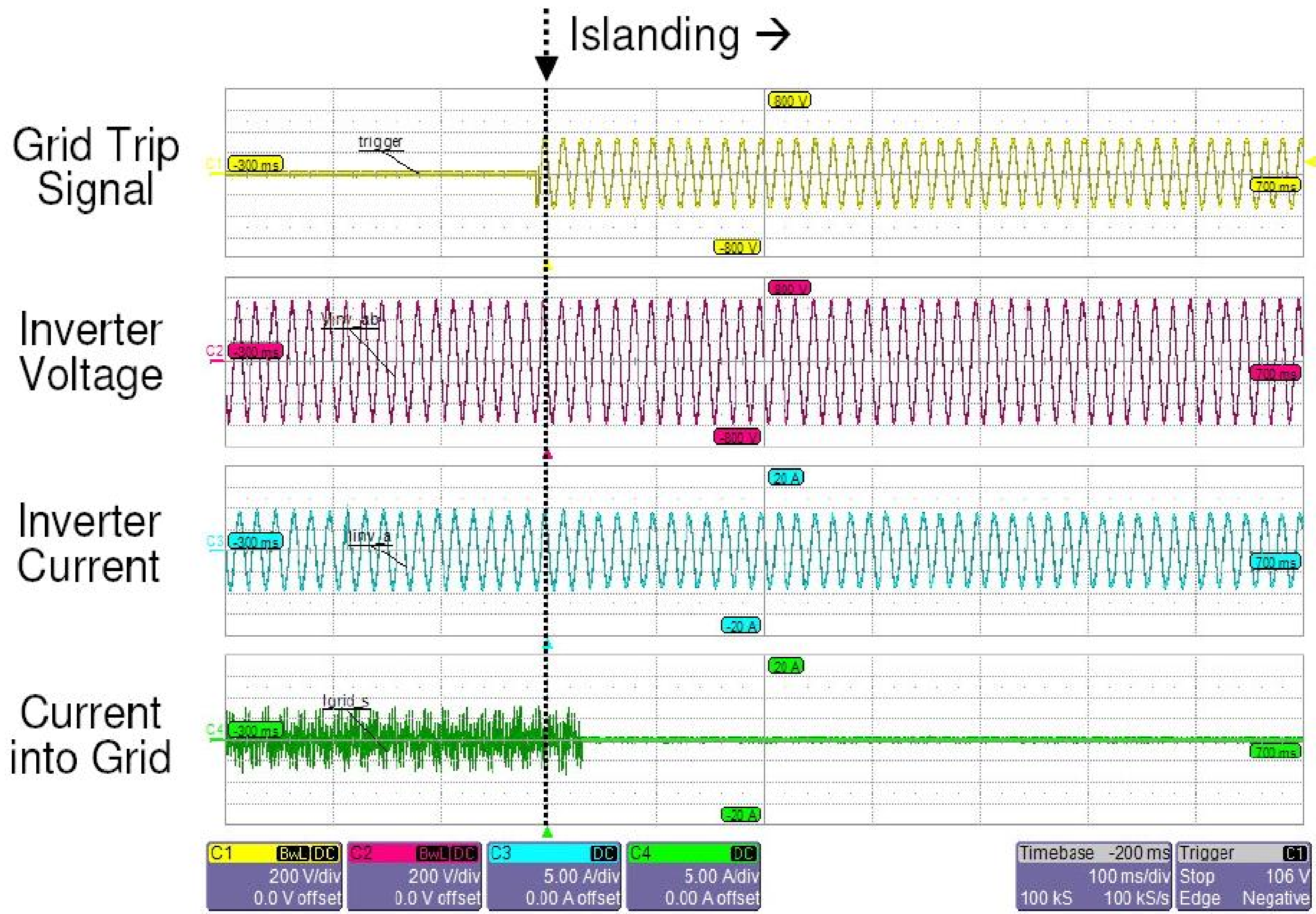
P_{inv} = 4.0kW, Q_{inv} = 0kVar

K_p = 10, K_i = 5

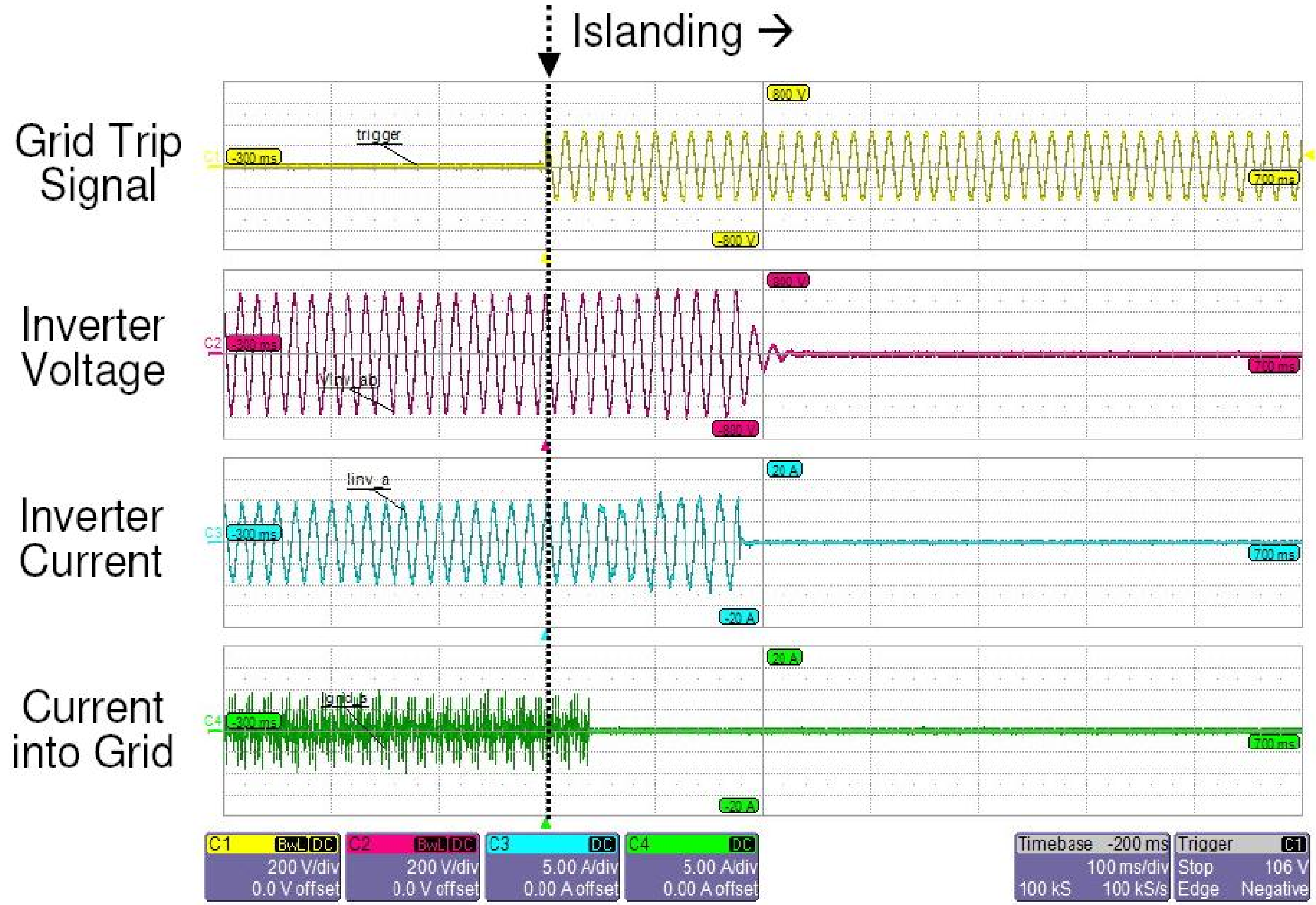
P_{load} = 4.0kW, Q_{load} = 0kVar

Q_f of RLC load = 2.5

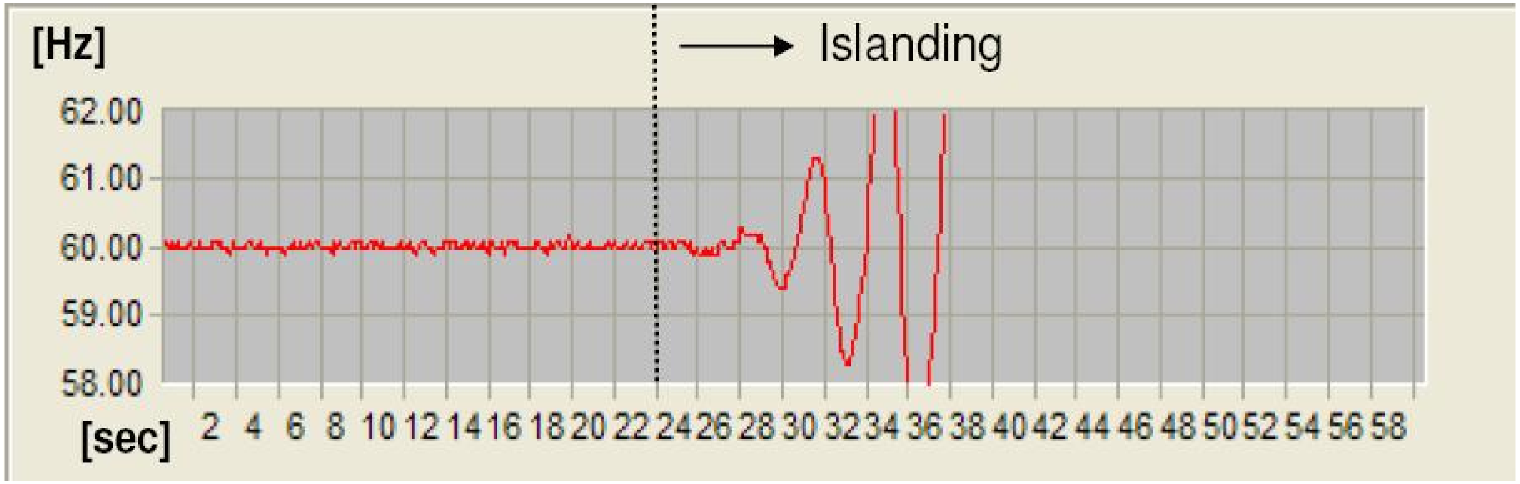
Before FSAC Implementation



After FSAC Implementation (K_a = 0.1)



Frequency with FSAC ($K_a = 0.057$)



Lower limit of K_a :

Calculation/simulation/experiment = 0.076/0.078/0.057

→ Acceptable

Conclusion

- Based on dq control and positive feedback
- P_{inv} dependency of control gain removed
- Design method and criteria suggested
- FSAC enables
  - Zero NDZ possible
  - Minimizing impact on power quality
  - Easy implementation