西安交通大學
XI'AN JIAOTONG UNIVERSITY

PEREC 电力电子与新能源技术研究中心
Power Electronics & Renewable Energy Center

# Autonomous Control for Coordination of Distributed Source Converters and Microgrid

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Tutorial at PESA

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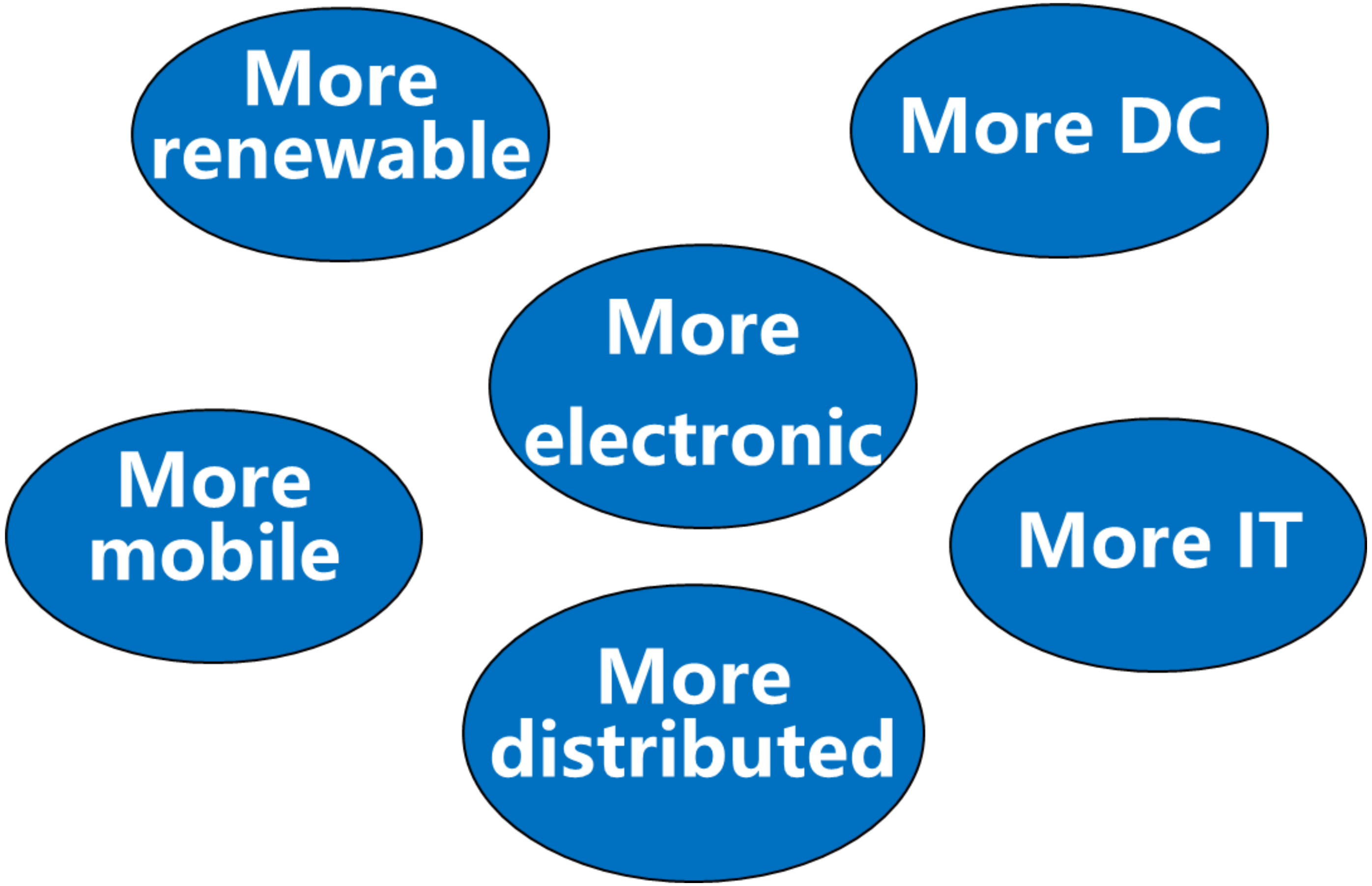
# Outline

电力电子与新能源技术研究中心
Power Electronics & Renewable Energy Center

# Background

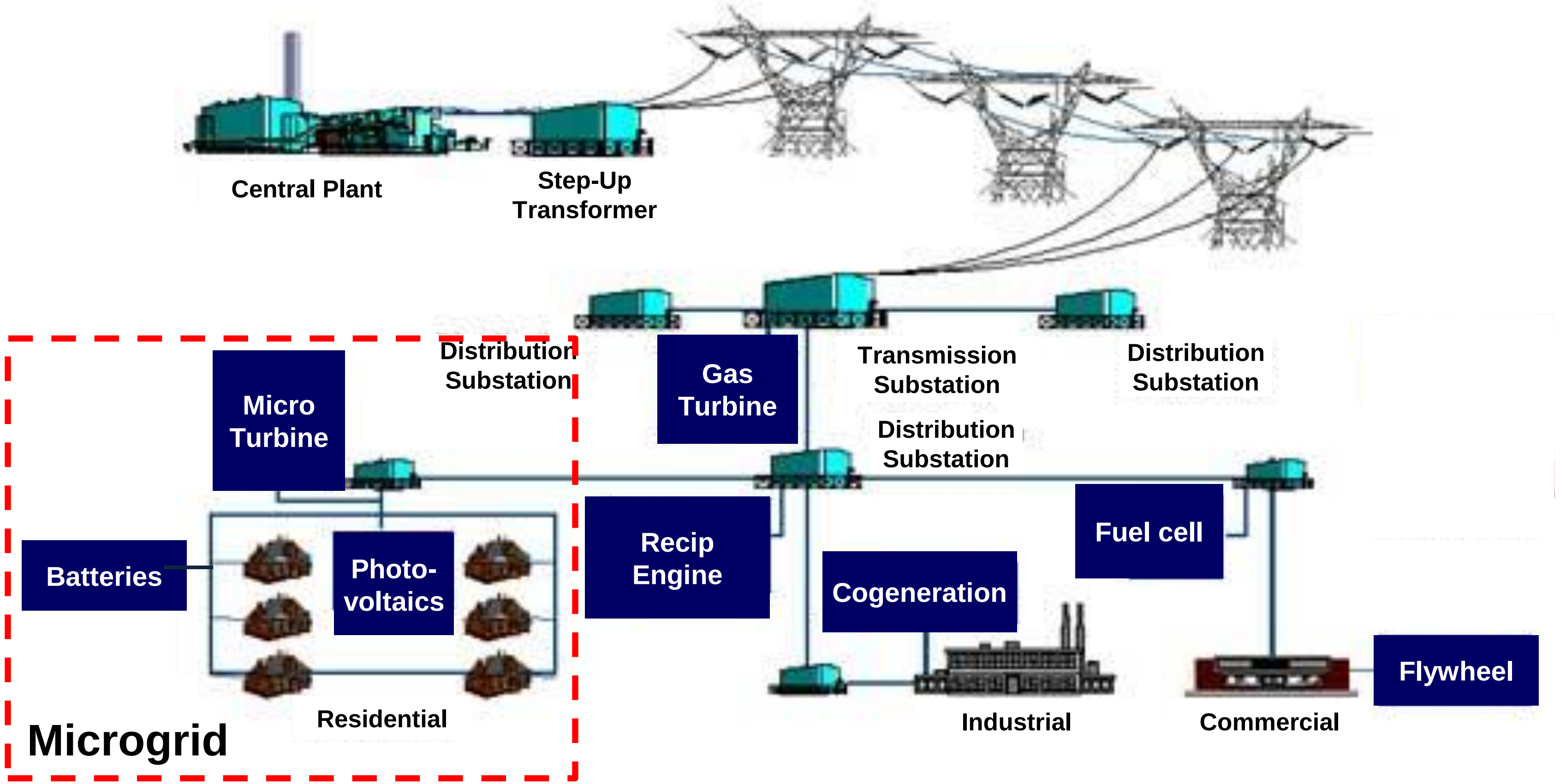
- **Developing Trends of Electric Power Systems**




- **There are 2 features that will bring revolutionary changes to how power system is configured, organized and operated.**

# Background

- More distributed generation



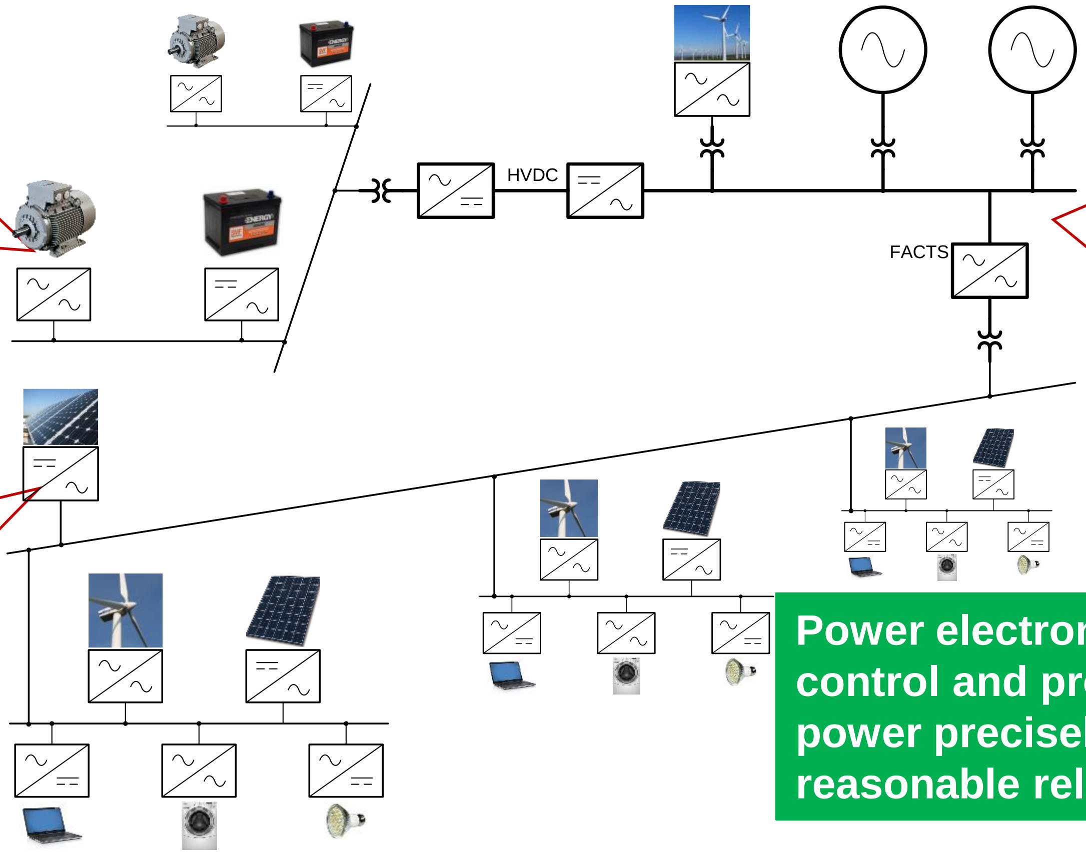

- More and more distributed generations will be employed to better incorporate renewable energies and to achieve higher reliability and lower transmission losses.

# Background

- More electronic

Improve user performance and efficiency

Incorporate renewable energies and batteries




Improve transmission and distribution performance

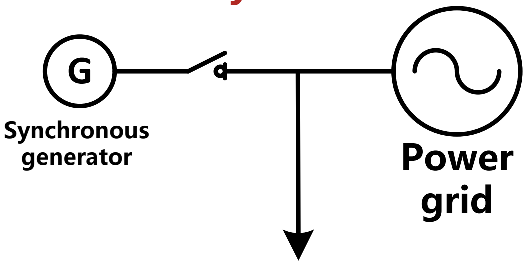
**Power electronic converters can control and process electric power precisely and fast with reasonable reliability and cost**

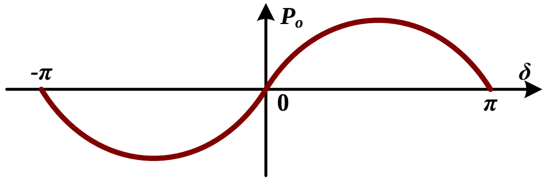
- **More and more power electronic converters will be used in power system: More electronic power system / Electronified power system.**

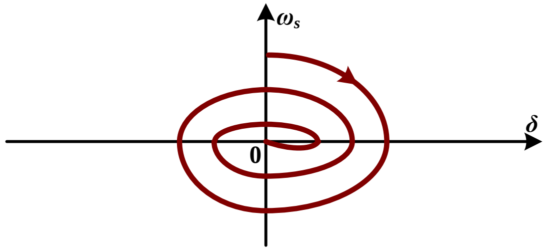
# Background

- Challenges to the coordination of energy source converters and microgrid

**Current Power System**

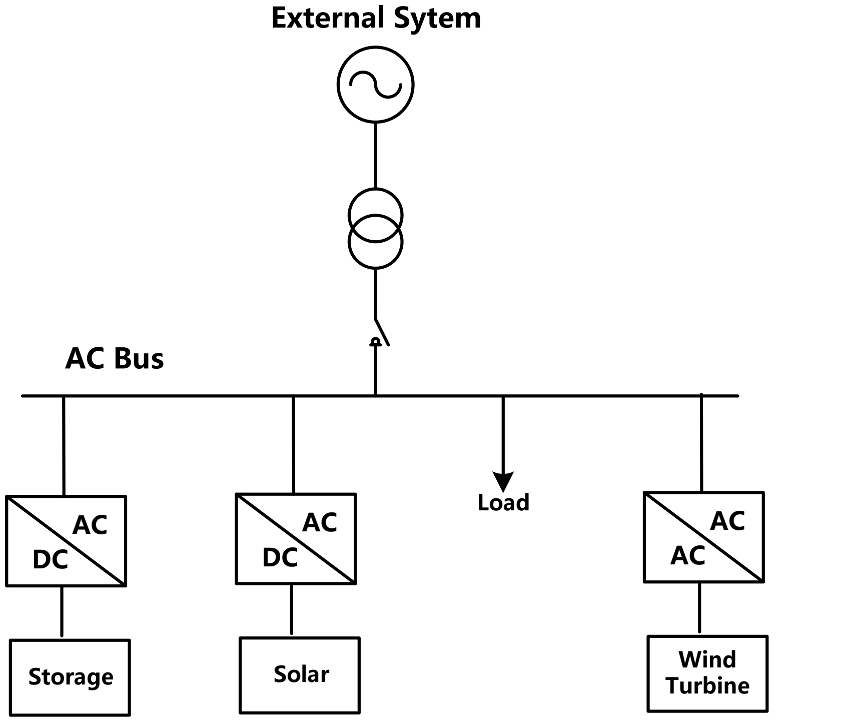



- Relatively small number of big generators to be coordinated
- Natural self-synchronization and power sharing of rotating-machine-based generators

**Energy Source Converters and Microgrid**

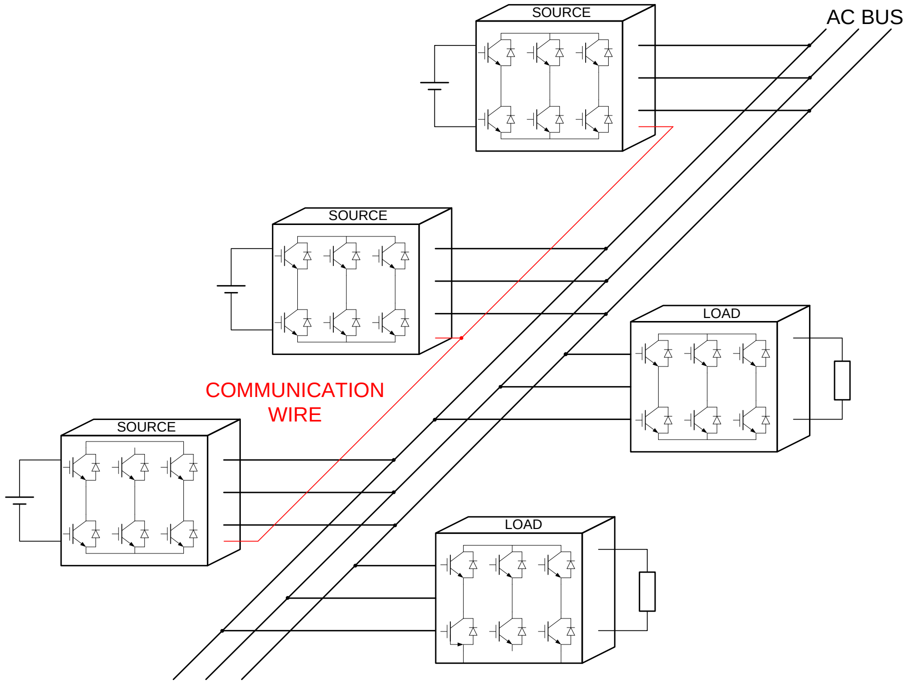



- Could be a large number of energy source converters to be coordinated
- Need to also coordinate frequent transfer between islanded mode and grid-connected mode

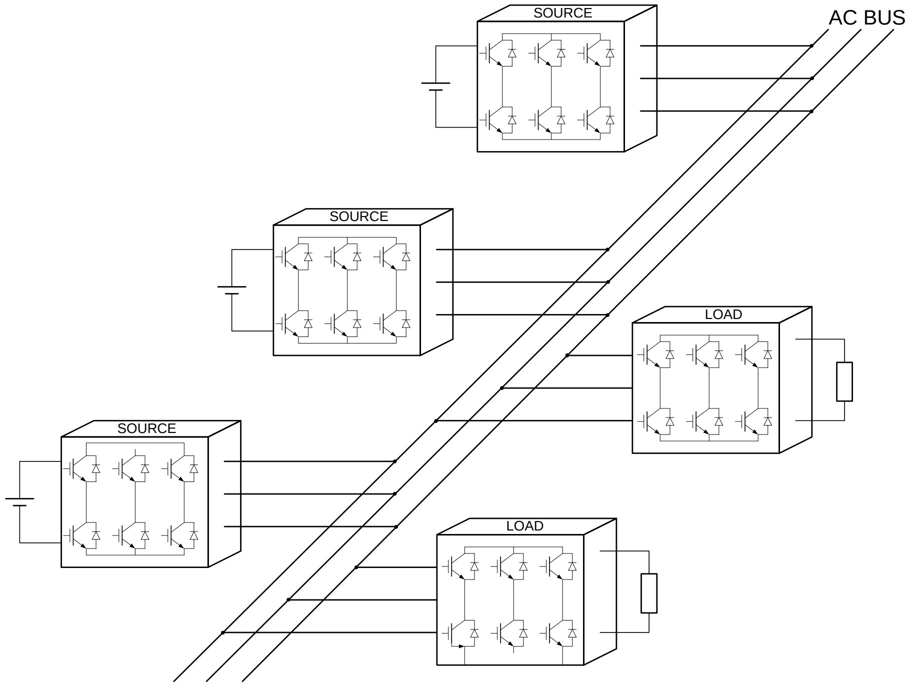
# Basics of Coordinative Control

- **Coordination of parallel energy source converters**
  - Adequate power sharing among parallel inverters
  - Bus voltage within a nominal magnitude/frequency range

**With communication**




**Without communication → Truly autonomous**



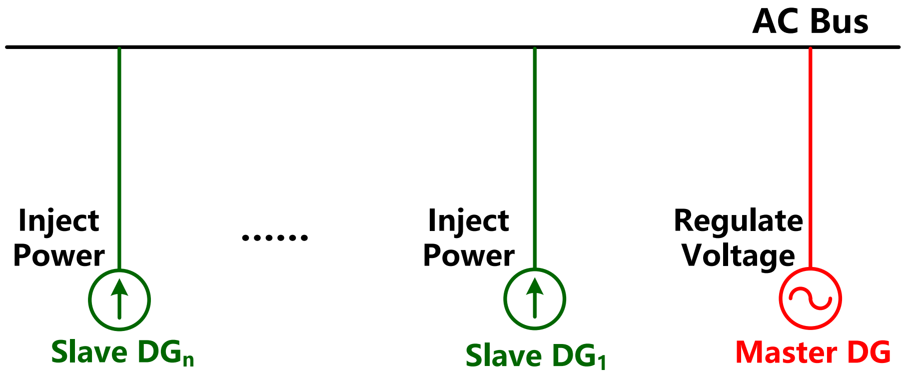

☺ **Plug and play**

☺ **Improved reliability**

# Basics of Coordinative Control

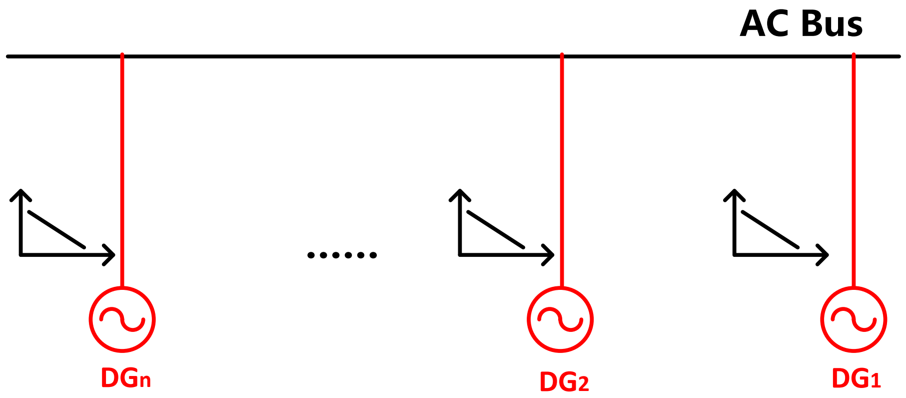
- Coordinative control without communication

## Master-slave control



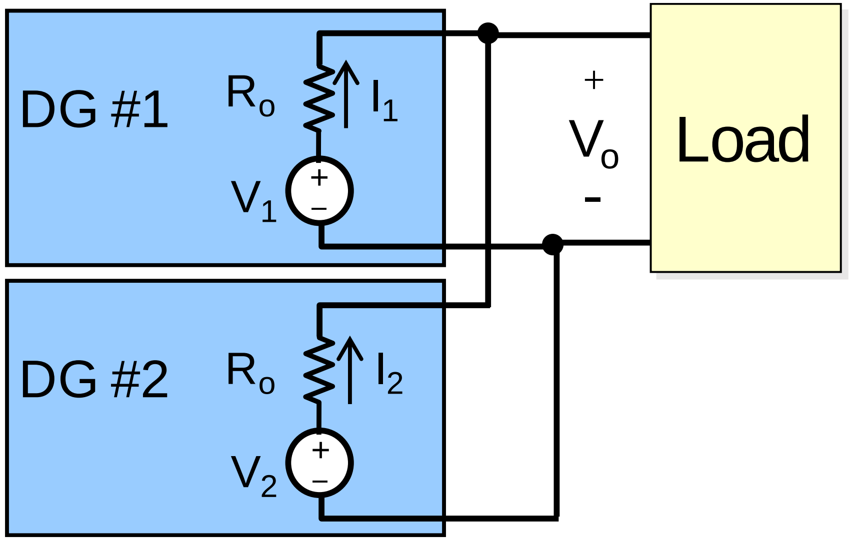

☹ Master-dependent reliability
☹ Large power rating of master
☹ Low voltage quality at the end of distribution line

## Droop control

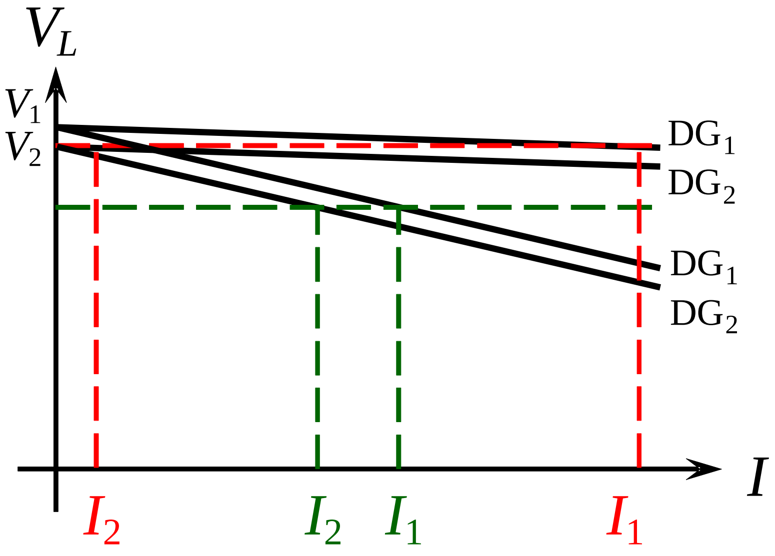


# Basics of Coordinative Control

- Droop control in DC power systems




**Droop Control** $V_0 = V_{nom} - n_i \cdot I_i$

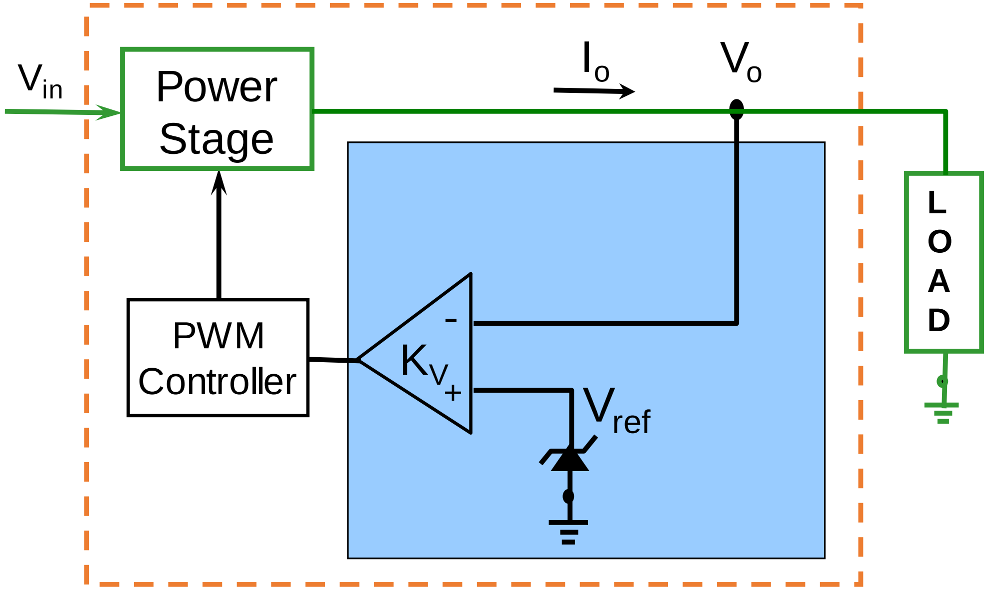


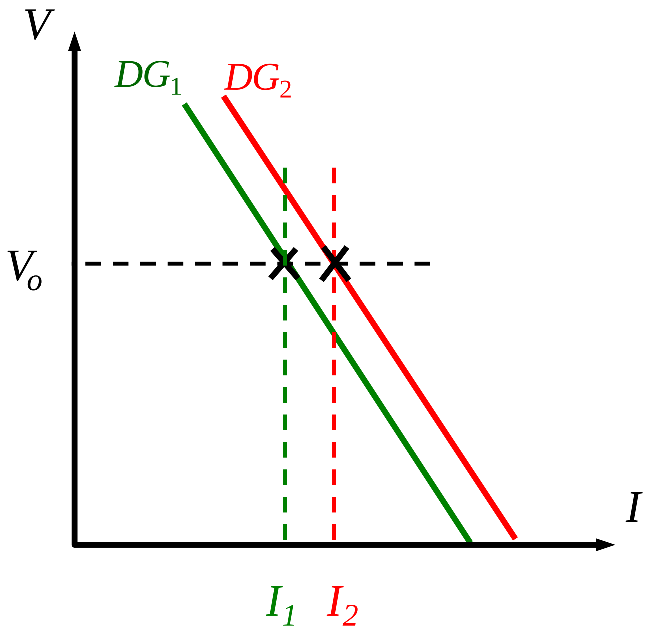

- **Power can be automatically shared between parallel DGs with proper droop gains.**

# Basics of Coordinative Control

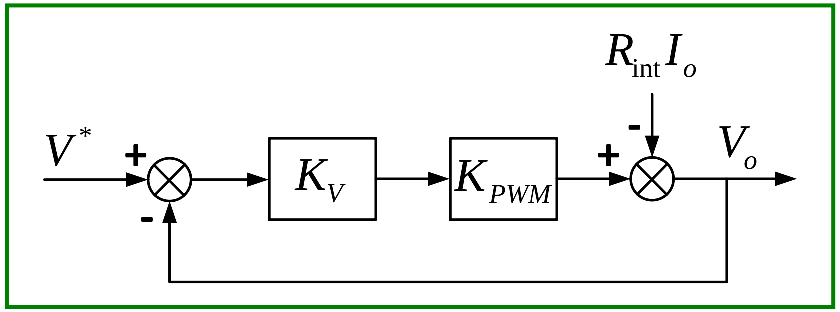
- **Droop control in DC power systems**

**Droop Scheme #1**
**Programmable voltage droop with finite DC loop gain**




$I_o$~ $V_o$ characteristics



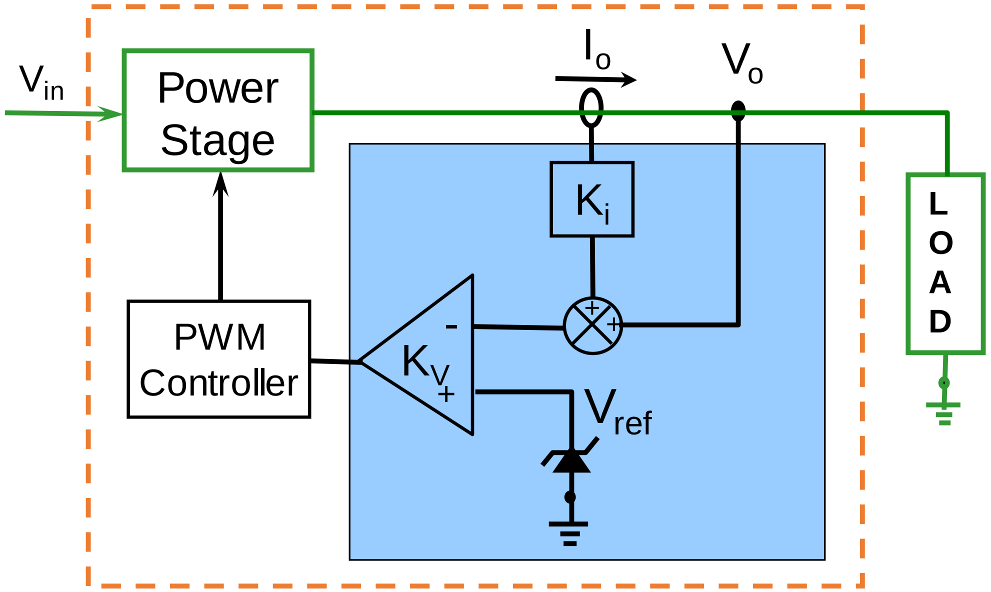

$$V_o = \frac{K_V K_{PWM}}{1 + K_V K_{PWM}} \cdot V_{ref} - \frac{R_{int}}{1 + K_V K_{PWM}} \cdot I_o$$

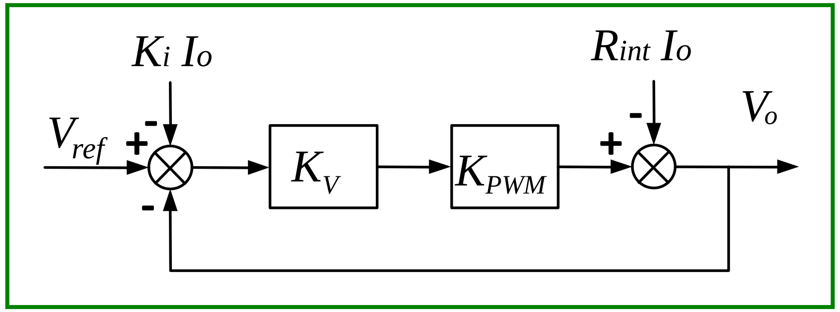
# Basics of Coordinative Control

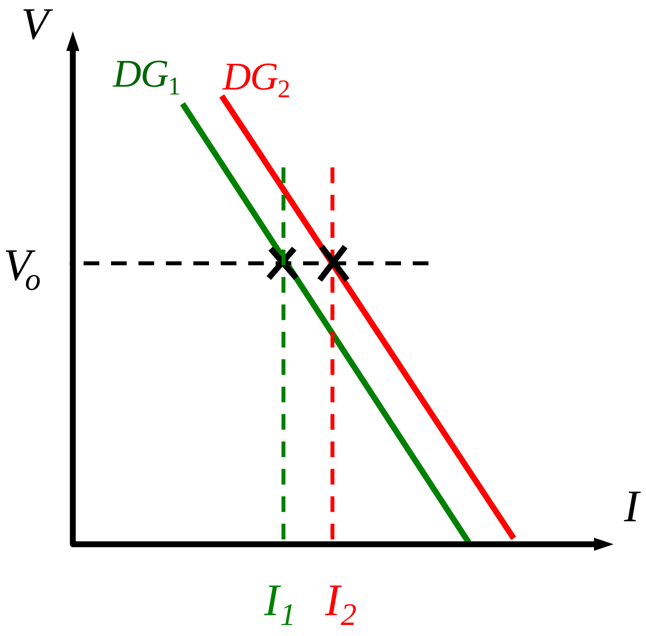
- **Droop control in DC power systems**

**Droop Scheme #2**

**Programmable voltage droop with infinite DC loop gain**



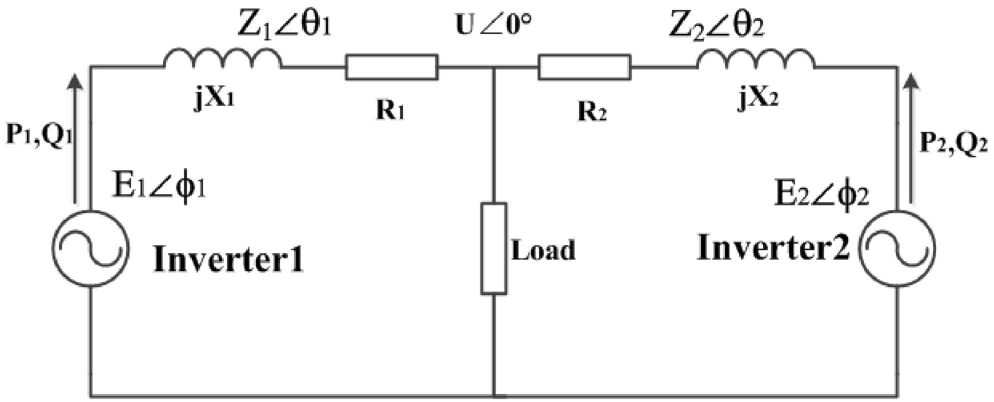




$I_o$~ $V_o$ characteristics

$$V_0 = V_{ref} - K_i I_0$$

# Basics of Coordinative Control

- **Droop control in AC power systems**




$$\begin{cases} P_n = \dfrac{E_n U_L \sin\phi_n}{Z_n}\sin\theta_n + \dfrac{U_L(E_n\cos\phi_n - U_L)}{Z_n}\cos\theta_n \\ Q_n = -\dfrac{E_n U_L \sin\phi_n}{Z_n}\cos\theta_n + \dfrac{U_L(E_n\cos\phi_n - U_L)}{Z_n}\sin\theta_n \end{cases}$$

When the impedance of distribution line is purely inductive, $\theta_n$=90°

$$\begin{cases} P_n = \dfrac{E_n U_L \sin\phi_n}{Z_n} \\ Q_n = \dfrac{U_L\left(E_n\cos\phi_n - U_L\right)}{Z_n} \end{cases}$$

As $\phi_n$ is very small, so further simplification can be done

$$\begin{cases} P_n = \dfrac{E_n U_L \phi_n}{Z_n} \\ Q_n = \dfrac{U_L\left(E_n - U_L\right)}{Z_n} \end{cases}$$

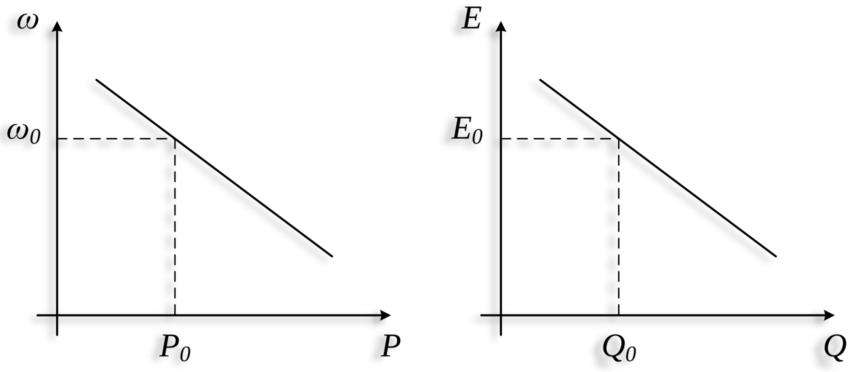
**Small-signal linearization** ⇒

$$\begin{cases} \Delta P_n \approx \dfrac{E_n U_L}{Z_n}\Delta\phi_n \\ \Delta Q_n \approx \dfrac{U_L}{Z_n}\Delta E_n \end{cases}$$

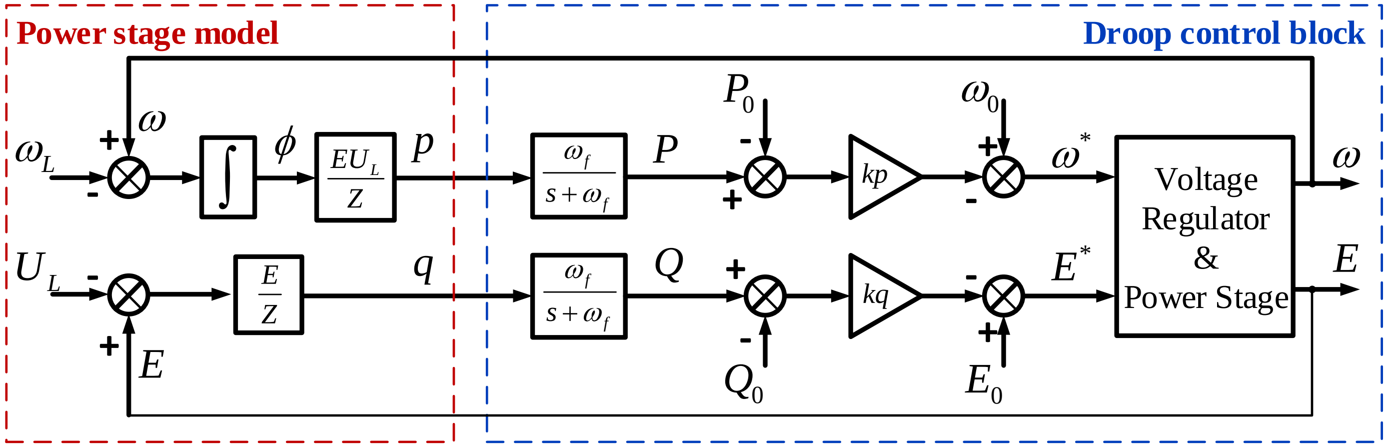
- **The real and reactive power could be controlled by controlling respectively the frequency and voltage amplitude.**

# Basics of Coordinative Control

- **Droop control in AC power systems**




Droop control diagram

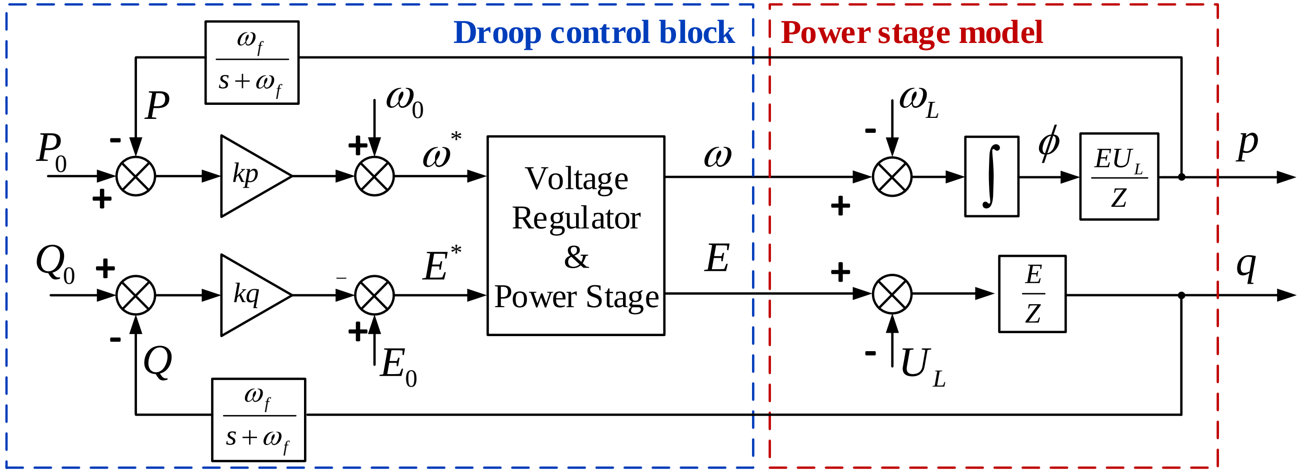



**Control characteristics**

$$\omega = \omega_0 - k_p(P - P_0)$$

$$E = E_0 - k_q(Q - Q_0)$$

**A droop-controlled inverter can be regarded as a current source with limited regulation gain and bandwidth.**

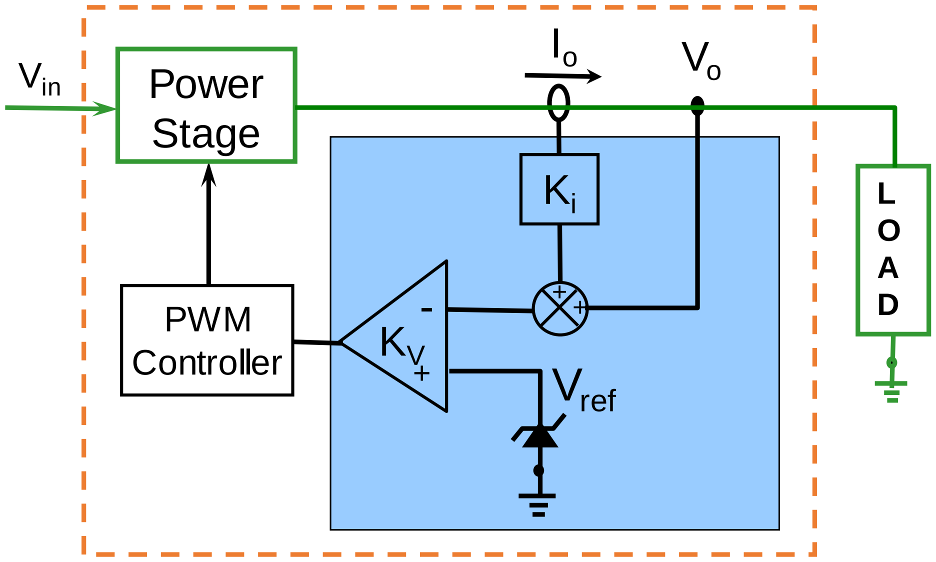


# Basics of Coordinative Control

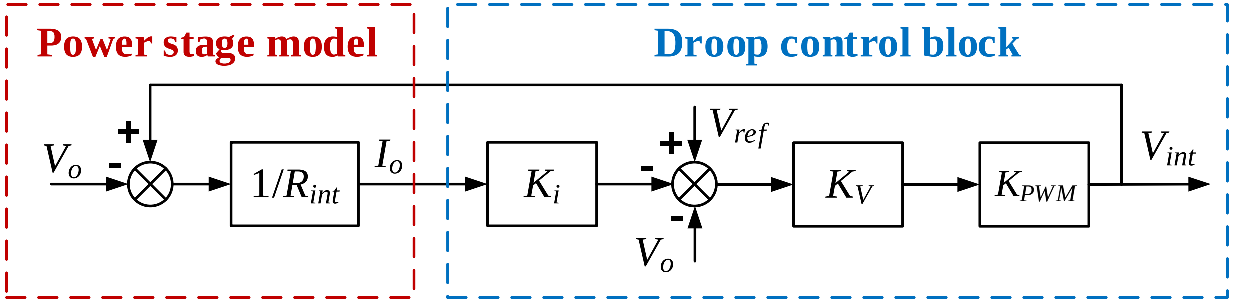
- Droop control in DC power systems

**Droop Scheme #2**

**Programmable voltage droop with infinite DC loop gain**

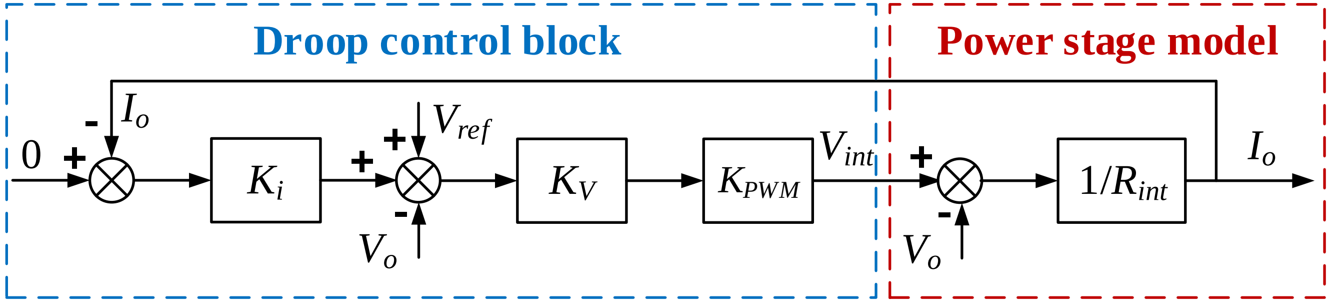



- **A droop-controlled converter can be regarded as a current source with limited regulation gain and bandwidth.**




**Control characteristics**

$$V_0 = V_{ref} - K_i I_0$$



# Basics of Coordinative Control

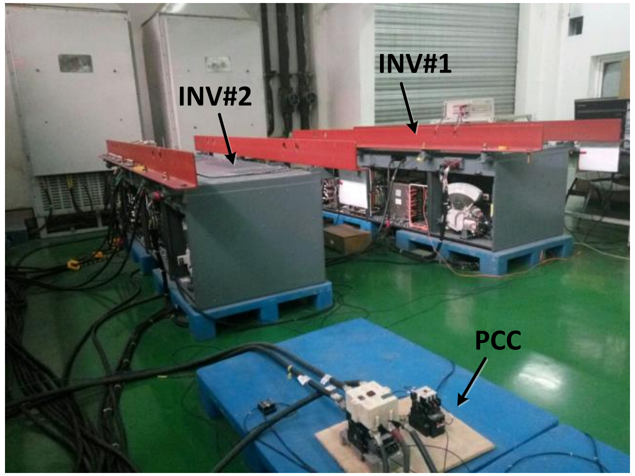
## ▪ Practical application of droop control： HYEE Project

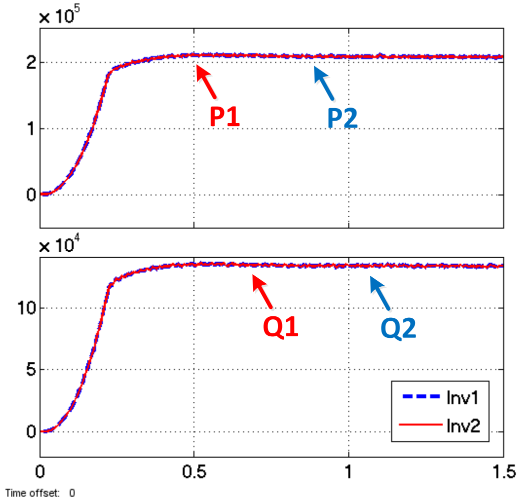
- **Trade-off between power sharing & voltage regulation → Careful design of droop gains**

| Technical parameters | |
|---|---|
| Power rating | 240 kVA |
| Power factor | 0.85 |
| Voltage deviation range | ±5% |
| Frequency deviation range | ±2% |

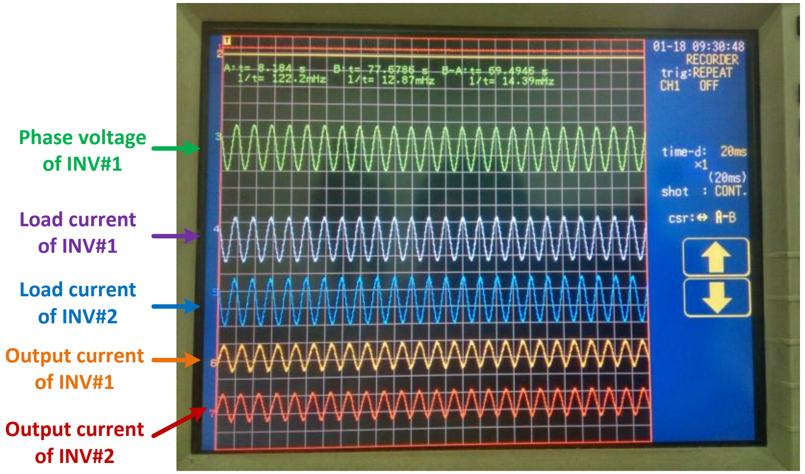
– Frequency and voltage deviation caused by the maximum power should be limited within the allowable range.

– The calculated droop gains might be decreased properly in order to stabilize the system.




Simulations




Experiments

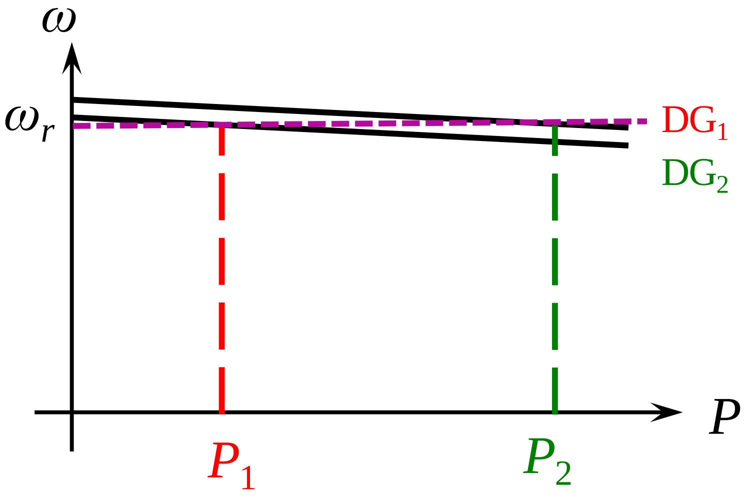
# Coordinative Control of Distributed Source Converters

- **Droop Control:** Synchronization & Active Power Sharing

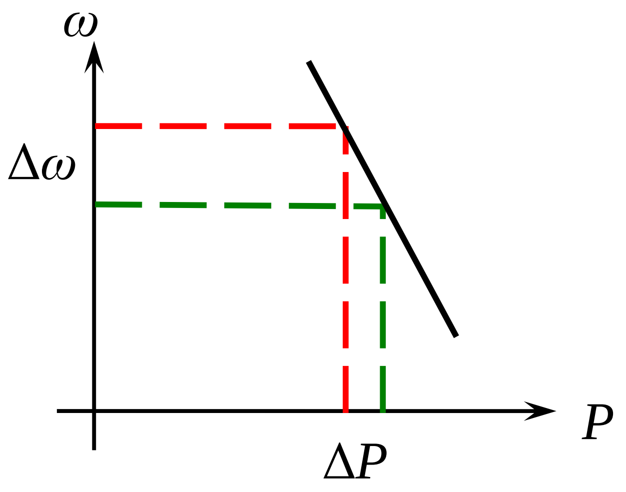
- **Improving coordination performance with advanced control:**
  - Secondary Control for Frequency Restoration
  - Reactive, Unbalanced and Harmonic Power Sharing
  - Selection of Small-AC-signal
  - Successive Approximation for Power Sharing

# Secondary Control for Frequency Restoration

- **Compromise between power sharing and voltage regulation**




Low droop gain

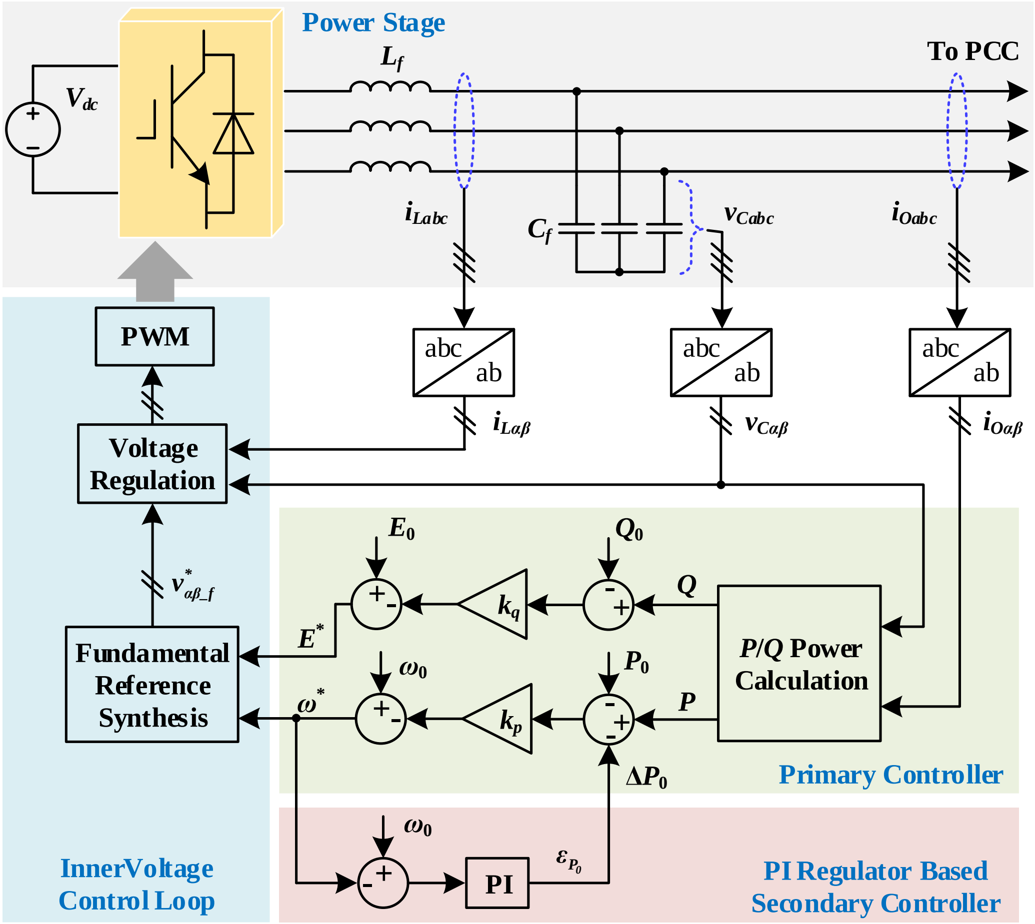



High droop gain

- When droop control is employed, compromise exists between the power sharing accuracy and the voltage regulation rate.
  - Low droop gain results in a bad accuracy of power sharing.
  - High droop gain results in a bad voltage regulation rate.

# Secondary Control for Frequency Restoration

- **PI regulator based decentralized secondary control**

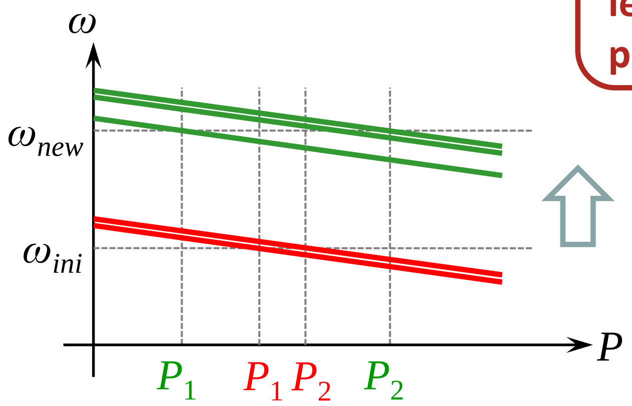



$$\omega^* = \omega_0 - k_p\left(P - P_0 - \Delta P_0\right)$$

$$\Delta P_0 = \varepsilon_{P_0}$$

$$\varepsilon_{P_0} = \left(k_{p\omega} + \frac{k_{i\omega}}{s}\right)\left(\omega_0 - \omega^*\right)$$

**Different value of compensation term leads to unequal power sharing**



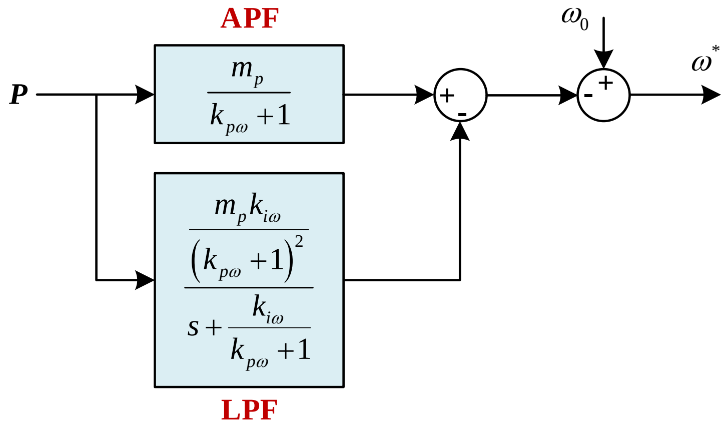
# Secondary Control for Frequency Restoration

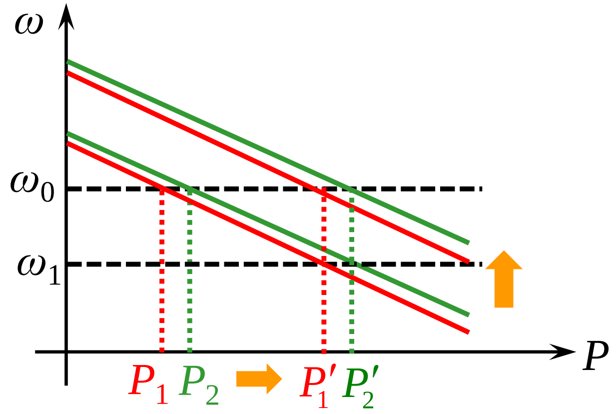
## ▪ Washout filter-based control

- **APF**: distribute power by droop control (**Fast**)
- **LPF**: restore the frequency (**Slow**)

$$\omega^* = \omega_0 - \frac{\frac{m_p}{k_{p\omega}+1}s}{s+\frac{k_{i\omega}}{k_{p\omega}+1}}P$$

HPF = 1-LPF




$$\omega^* = \omega_0 - \frac{m_p s}{s + k_{p\omega}s + k_{i\omega}}P$$

$$\begin{cases} \omega^* = \omega_0 - m_p P + \omega_c \\ \omega_c = \left(k_{p\omega} + k_{i\omega}/s\right)(\omega_0 - \omega^*) \end{cases}$$

**Droop Control**

**PI Regulator based Decentralized Secondary Control**

☹ Disturbances (e.g., new inverter plugging in) will result in **unequal active power sharing**.

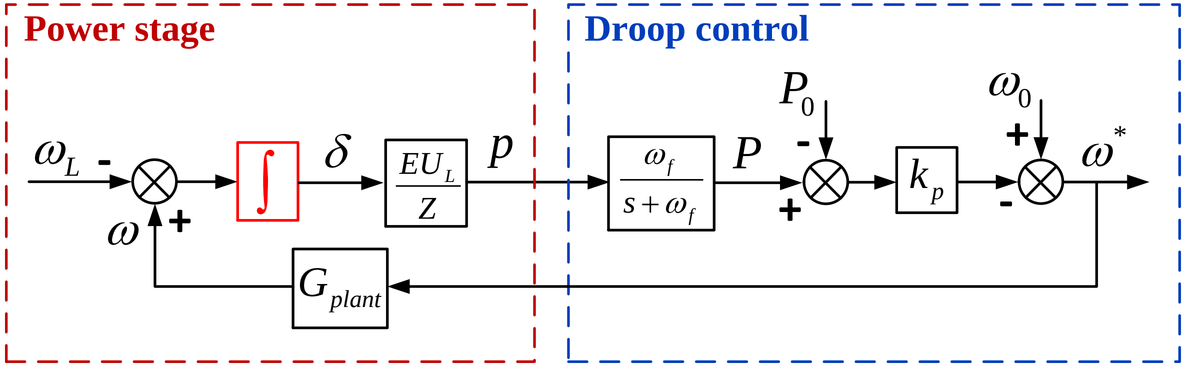

M. Yazdanian and A. Mehrizi-Sani, "Washout Filter-Based Power Sharing," *IEEE Trans. on Smart Grid*, vol. 7, no. 2, pp. 967-968, 2016.

Y. Han, H. Li, L. Xu, X. Zhao, and J. M. Guerrero, "Analysis of Washout Filter-Based Power Sharing Strategy—An Equivalent Secondary Controller for Islanded Microgrid Without LBC Lines," *IEEE Trans. on Smart Grid*, vol. 9, no. 5, pp. 4061-4076, 2018.

# Secondary Control for Frequency Restoration

## Rethinking of droop control

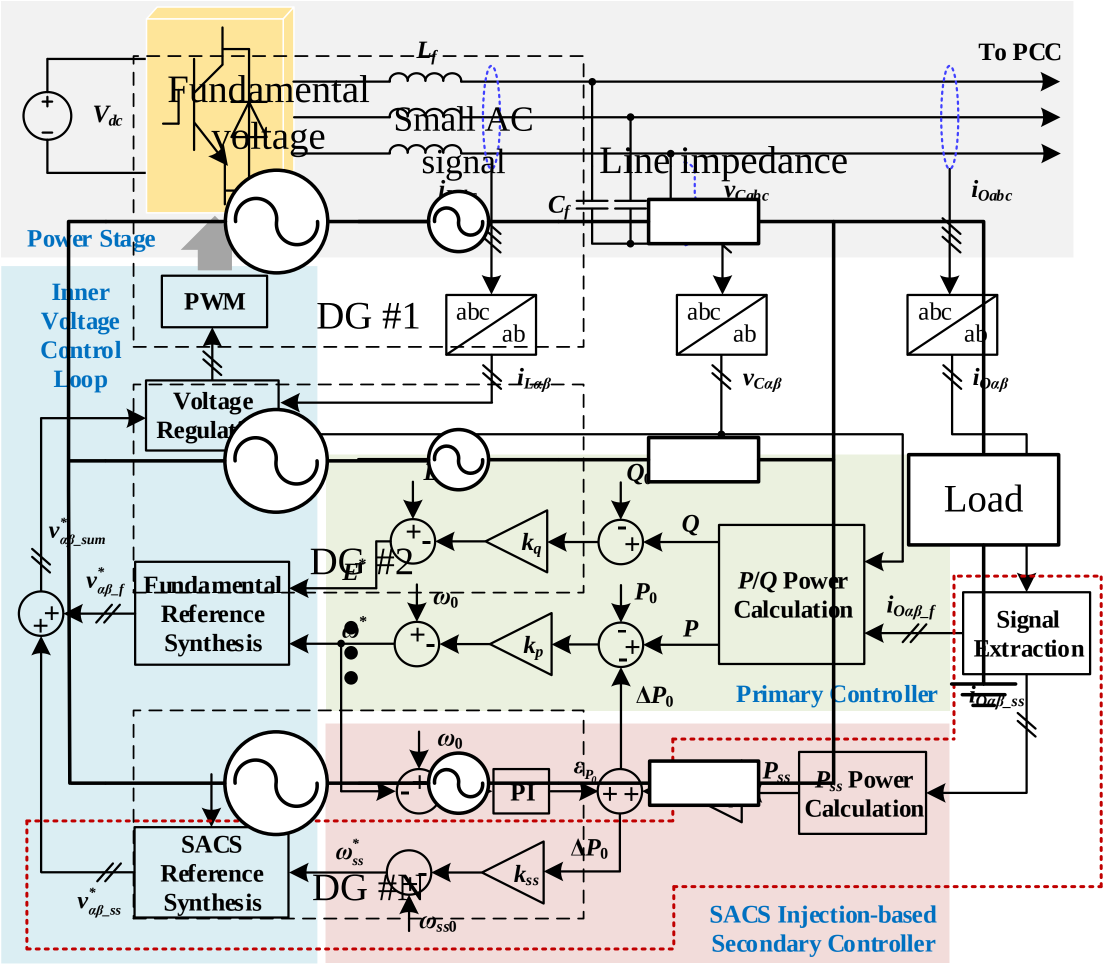
- Frequency is drooped with active power
- The **inherent integration of frequency** difference leads to a common steady-state frequency for all inverters
- A common frequency leads to good active power sharing




**Why not build a droop relation between a frequency variable and the variable to be shared?**

# Secondary Control for Frequency Restoration

- **Decentralized secondary control based on small-AC-signal injection**




**SACS frequency: global variable!**

- **Fundamental voltage** is droop controlled:

$$\omega^* = \omega_0 - k_p\left(P - P_0 - \Delta P_0\right)$$

$$E^* = E_0 - k_q(Q - Q_0)$$

- The **Small-AC-signal (SACS) frequency** is drooped with the **compensation value of nominal active power**:

$$\omega_{ss}^* = \omega_{ss0} - k_{ss}\Delta P_0$$

- The **compensation value of nominal active power** is the summation of **SACS active power** and **PI output** :

$$\varepsilon_{P_0} = \left(k_{p\omega} + \frac{k_{i\omega}}{s}\right)\left(\omega_0 - \omega^*\right)$$

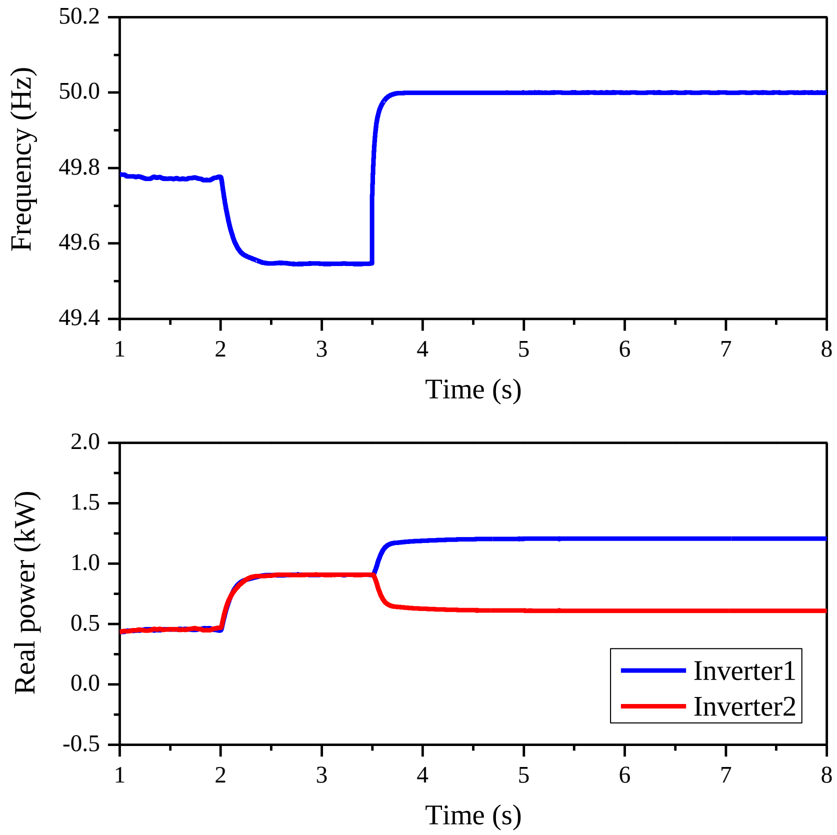
$$\Delta P_0 = \varepsilon_{P_0} + G_p P_{ss}$$

# Secondary Control for Frequency Restoration

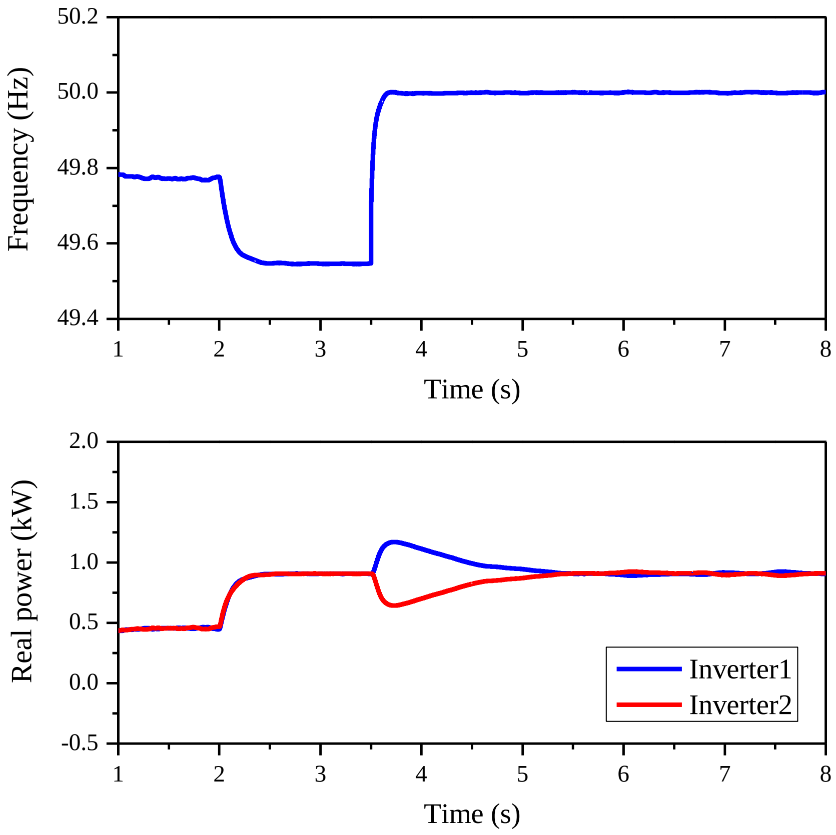
- **Decentralized secondary control based on small-AC-signal injection**

**Simulation results**

**PI regulator-based control**




**SACS injection-based control**

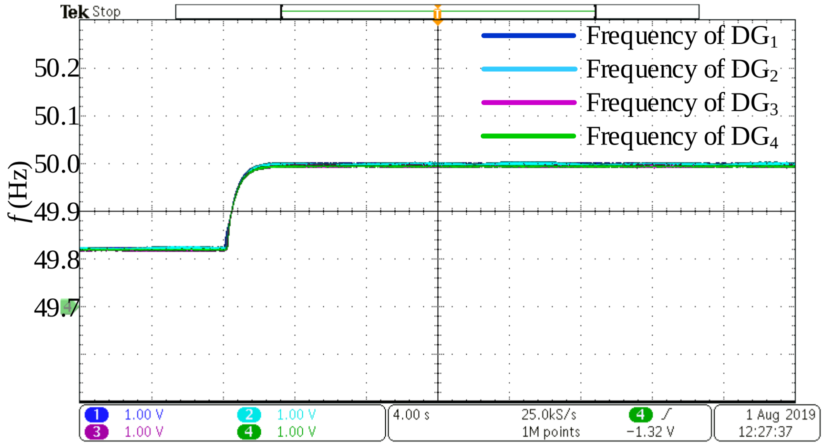


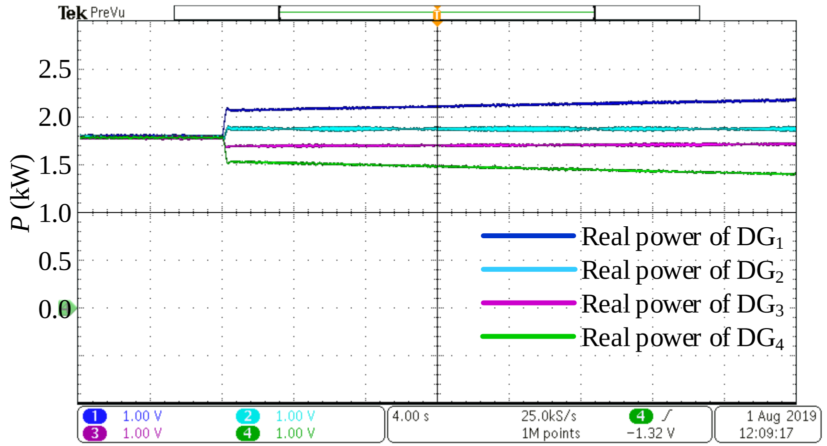
# Secondary Control for Frequency Restoration

- **Decentralized secondary control based on small-AC-signal injection**

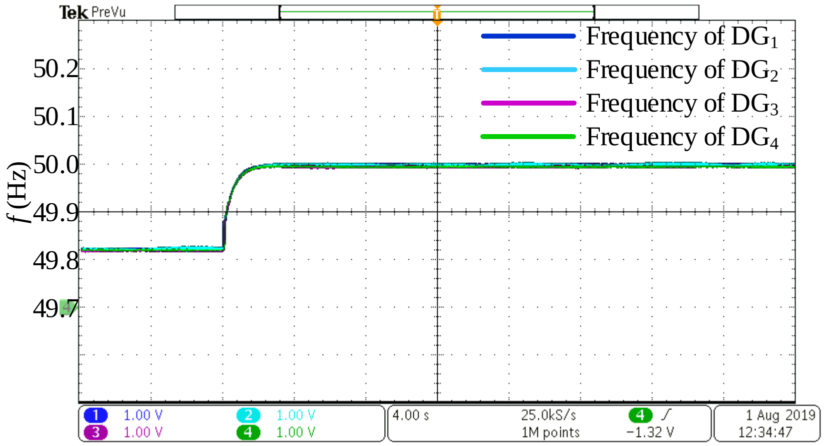
**Experimental results**

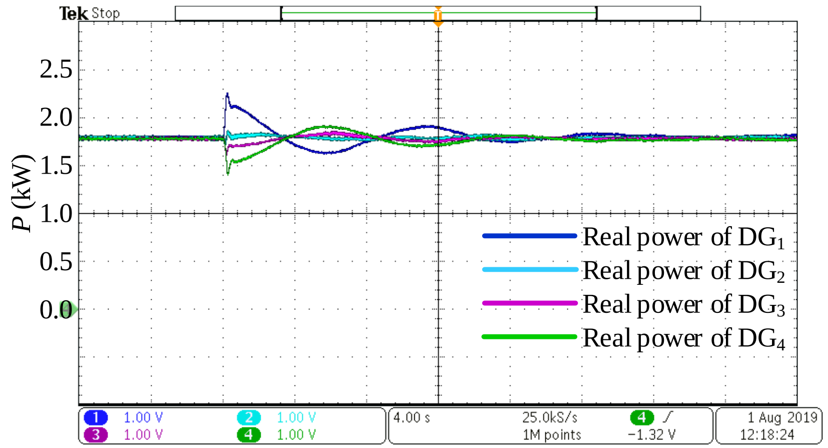
## PI regulator-based control




## SACS injection-based control



# Secondary Control for Frequency Restoration

- **Decentralized secondary control based on small-AC-signal injection**

**Summaries**

- Deviation of fundamental frequency can be effectively compensated
- Active power demand can still be equally shared
- Communication links are not required

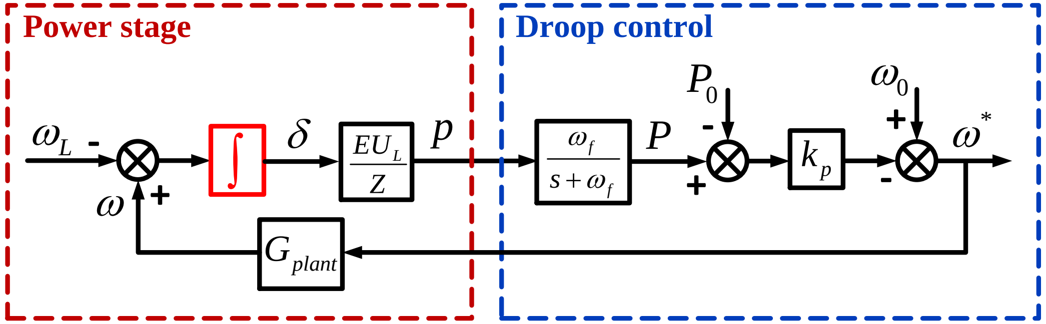
T. Wu, Z. Liu, J. Liu, B. Liu, S. Wang, "Small AC Signal Droop Based Secondary Control for Microgrids,“ *31st Annual IEEE Appl. Power Electron. Conf. Expo.*, 2016, pp. 3370-3375.

B. Liu, T. Wu, Z. Liu and J. Liu, "A Small-AC-Signal Injection-Based Decentralized Secondary Frequency Control for Droop-Controlled Islanded Microgrids," *IEEE Trans. Power Electron.*, vol. 35, no. 11, pp. 11634-11651, Nov. 2020.

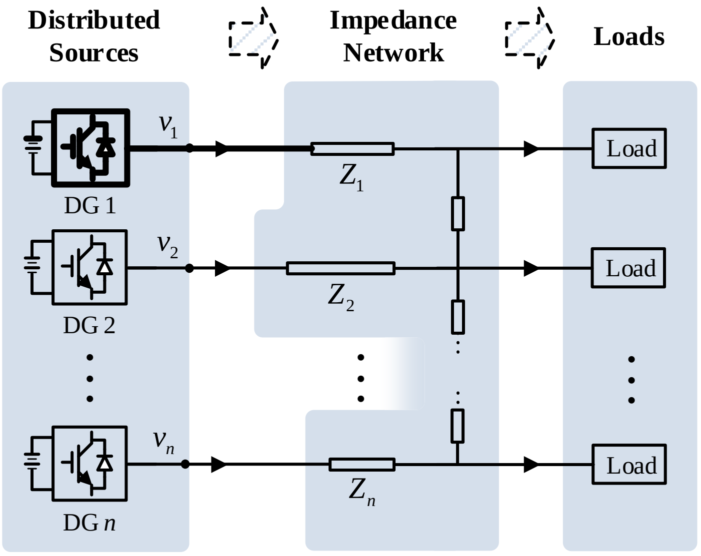
# Reactive, Unbalanced and Harmonic Power Sharing

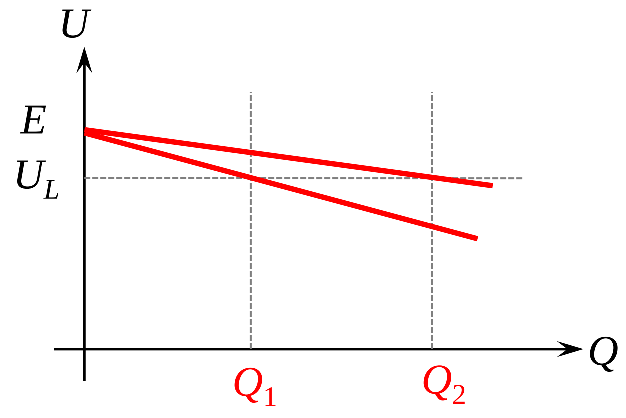
## Power Sharing Issues

- ***P* sharing** is always guaranteed by the **global fundamental frequency**




- ***Q* sharing** is determined by the **mismatched line impedances**

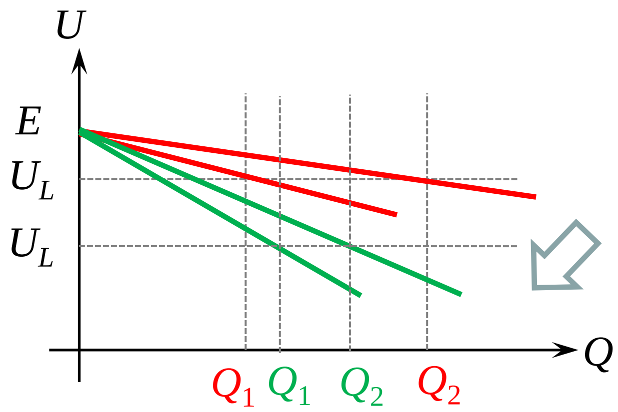


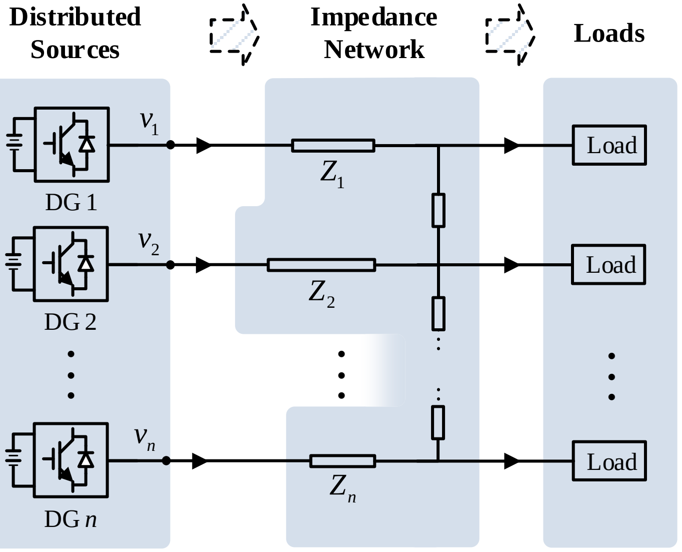



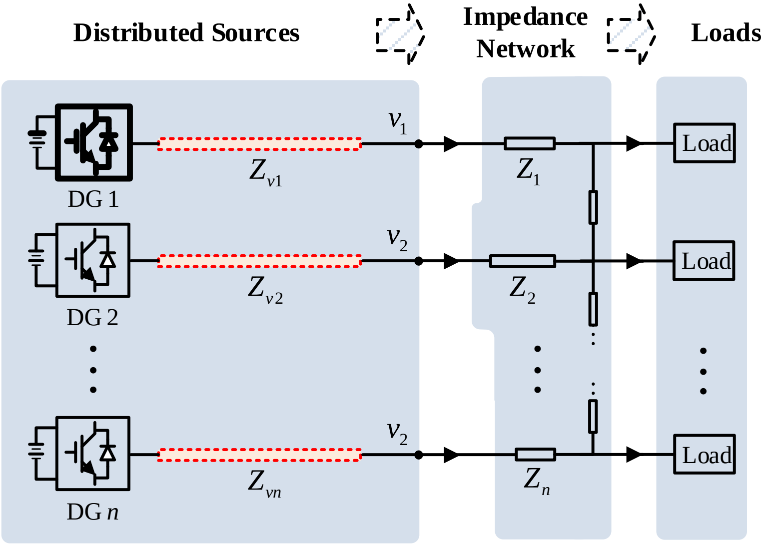
# Reactive, Unbalanced and Harmonic Power Sharing

## Conventional droop control and virtual impedance

- Conventional droop control
  - Improve $Q$ sharing
- Equivalent to 'virtual impedance'
  - Introduce large voltage drop
  - Can't realize accurate $Q$ sharing

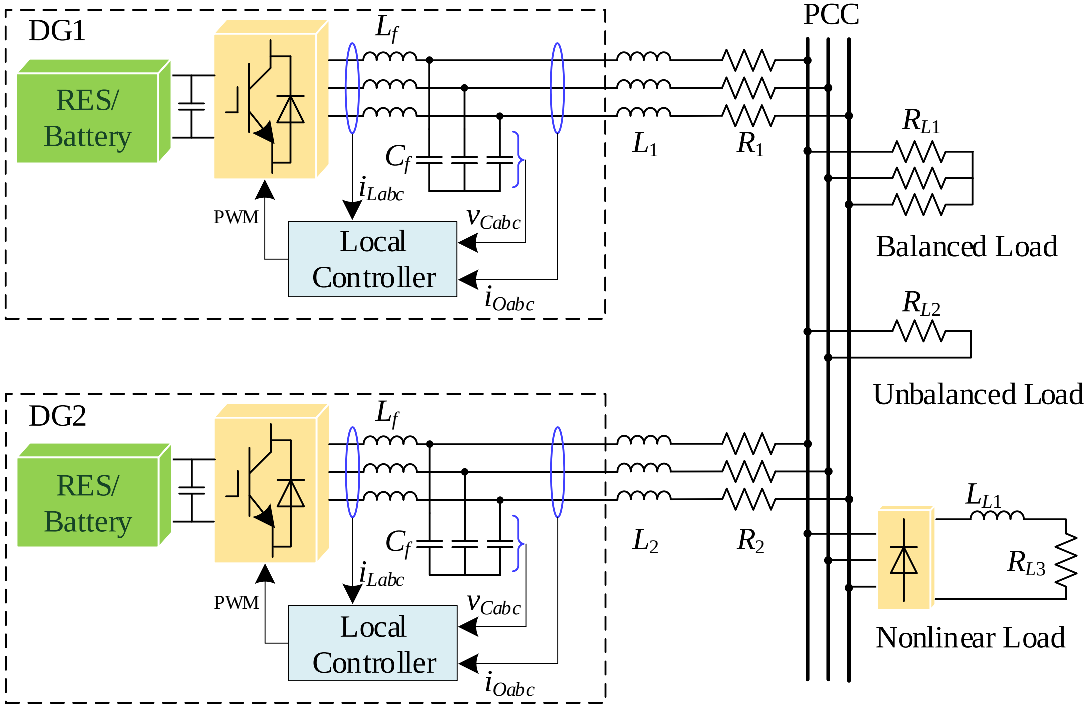


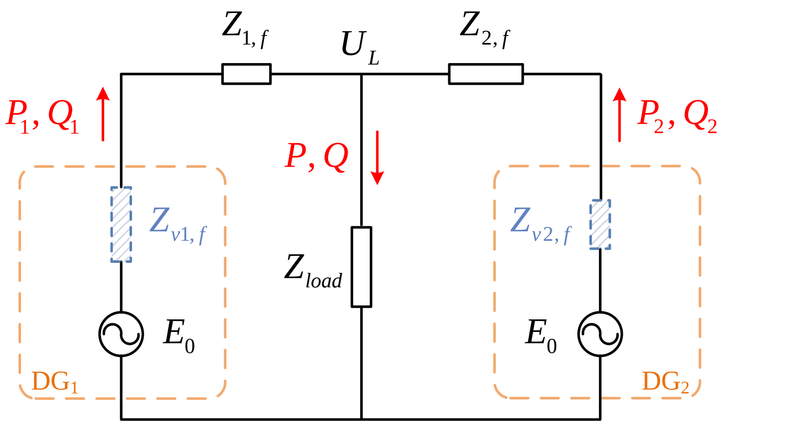



# Reactive, Unbalanced and Harmonic Power Sharing

- **Power Distribution & Virtual Impedance Control**

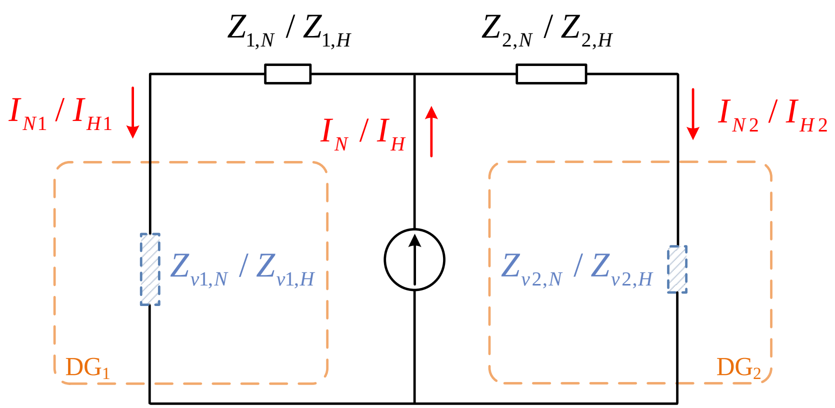



Equivalent circuit at
**fundamental positive sequence**

- $Q$ and $Q_{UH}$ distribution are both determined by the '**total impedance**' on each branch

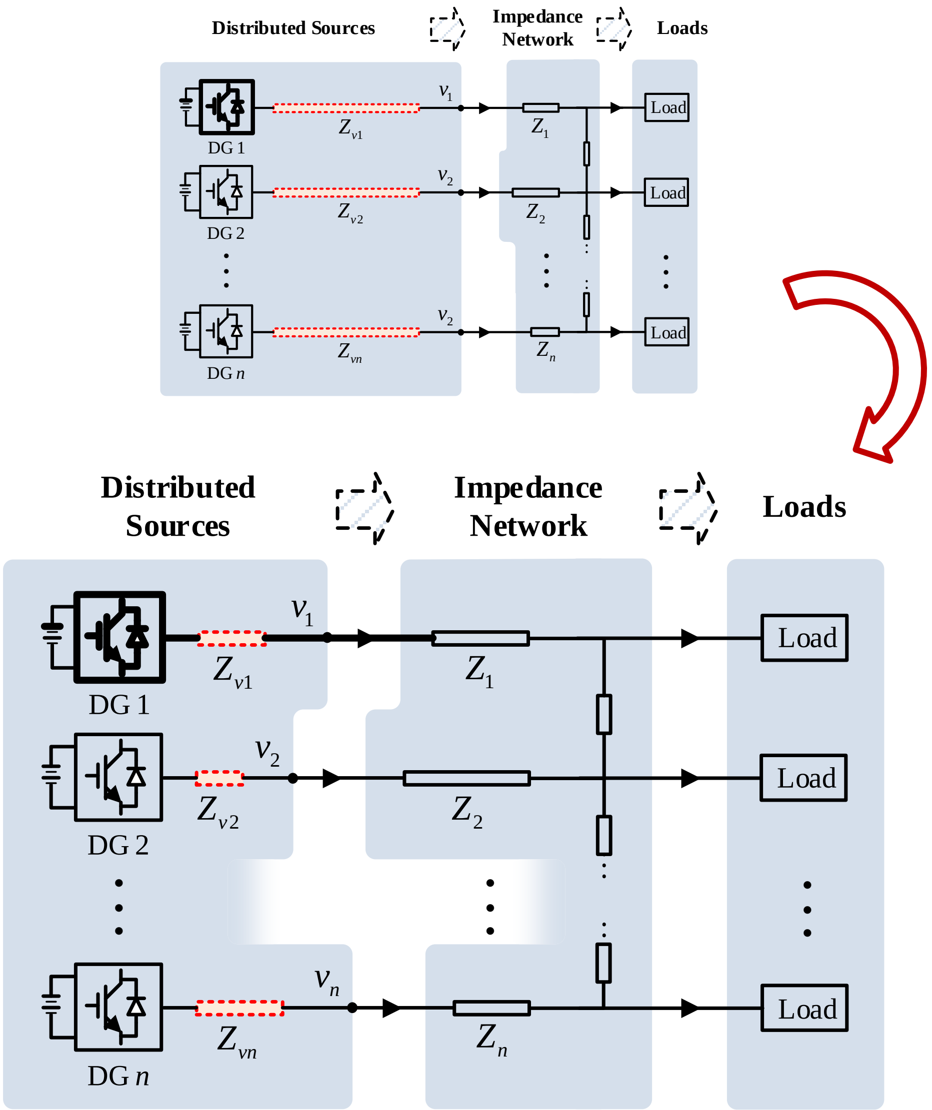
**Add virtual impedances at fundamental and harmonic frequencies**




Equivalent circuit at
**fundamental negative sequence and harmonic frequencies**

# Reactive, Unbalanced and Harmonic Power Sharing

## Power Distribution & Virtual Impedance Control




- How about adding **small and unequal virtual impedances** to compensate for the mismatch?

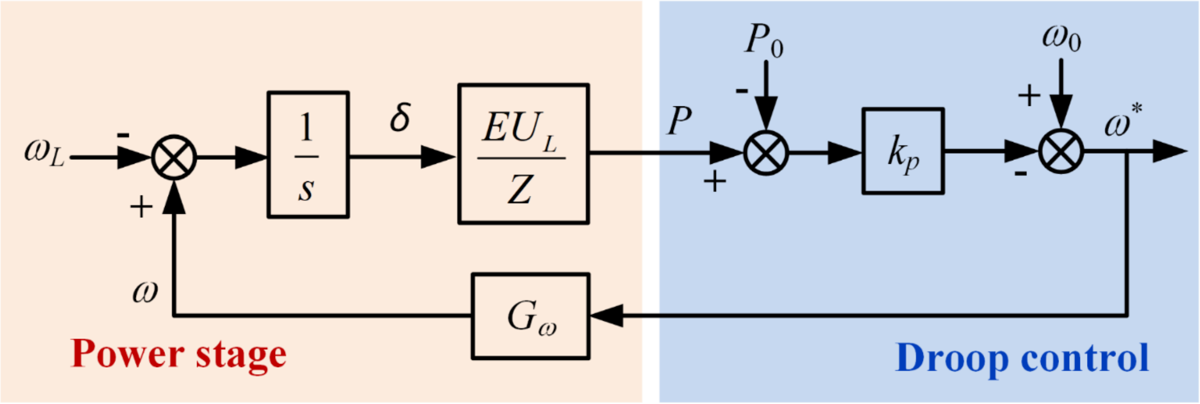
- **Power sharing** -> **differences** of virtual impedances
- **Voltage drop and THD** -> **average** virtual impedance

⇨ **These two control targets are Decoupled!**

- Power sharing & bus voltage control:
  - Not single-inverter behavior, but **coordination** of all distributed energy sources

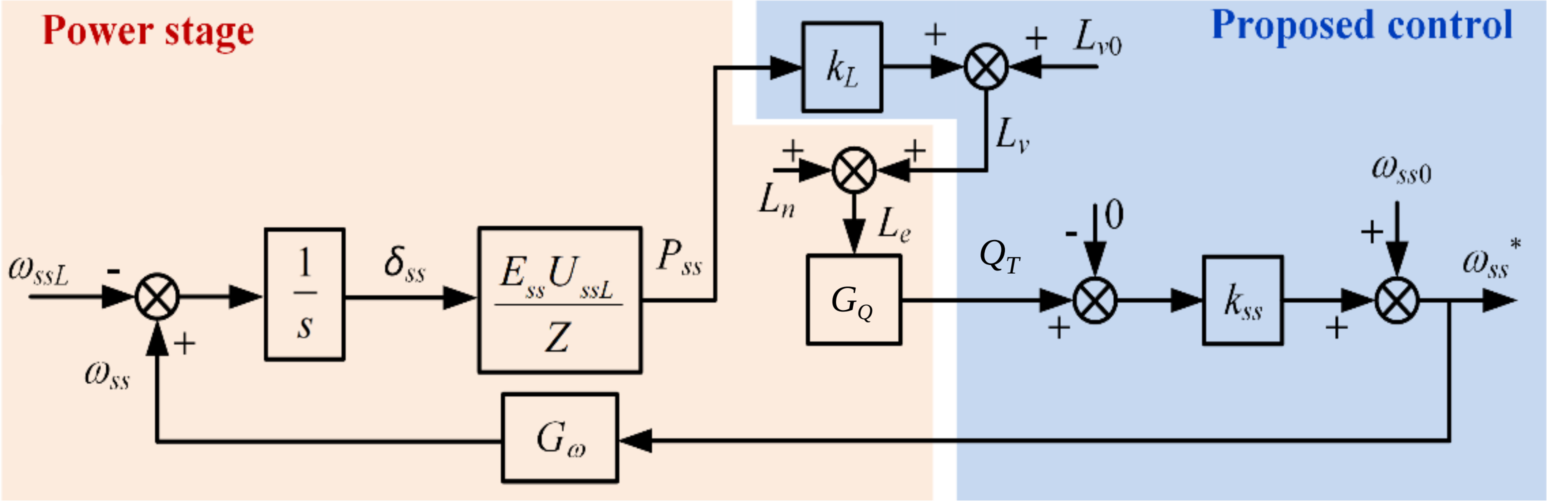
# Reactive, Unbalanced and Harmonic Power Sharing

- **Small-AC-signal injection-based control**
  - **How to obtain proper virtual impedances to compensate for the mismatch?**
  - ***P - ω* droop principle**



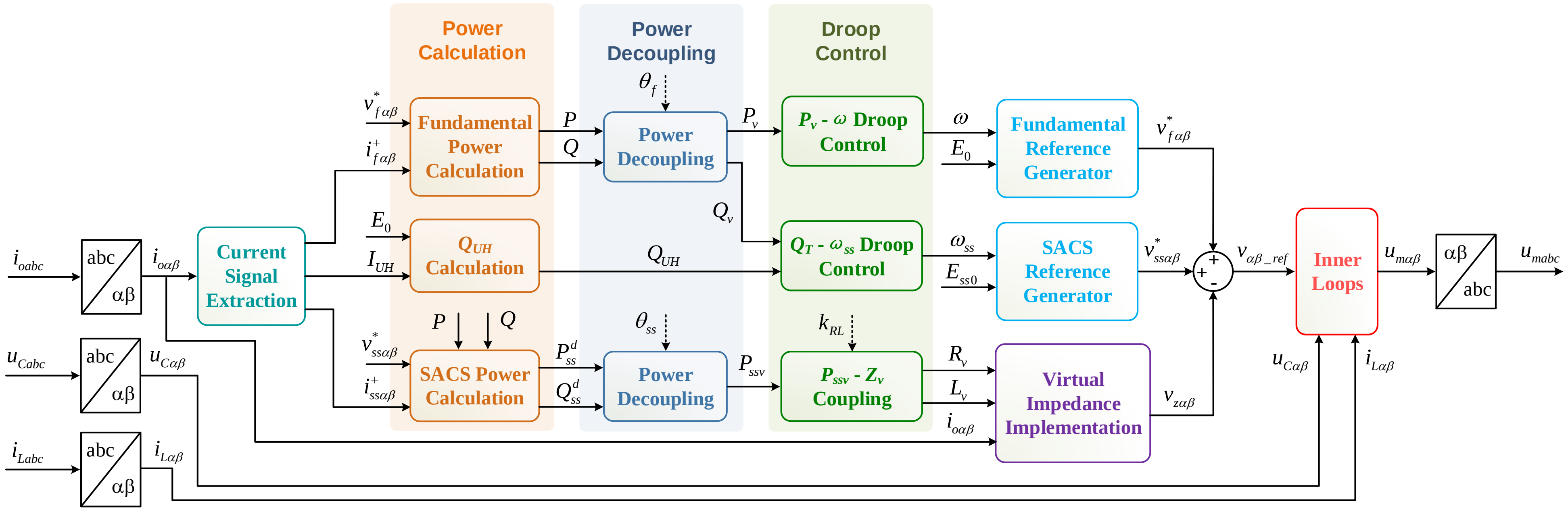

  - ***$Q_T$ - $\omega_{ss}$* droop introduced**

$$Q_T = \sqrt{Q^2 + Q_{UH}^2}$$



# Reactive, Unbalanced and Harmonic Power Sharing

- **Small-AC-signal injection-based control**




- **Droop relationship** between frequency of small-AC-signal and $Q$ and $Q_{UH}$

$$\omega_{ss}^{*} = \omega_{ss0} + k_{ss}\sqrt{Q^2 + Q_{UH}^2}$$

  - $\omega_{ss}^{*}$: small signal frequency reference value
  - $\omega_{ss0}$: small signal frequency rated value
  - $k_{ss}$: droop coefficient

- **Linking** active power of small signal with virtual impedance

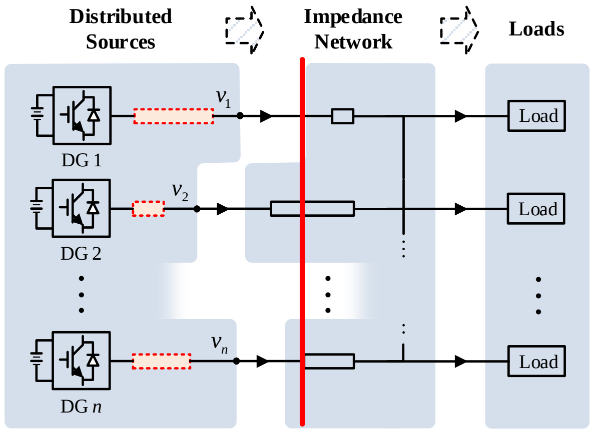
$$Z_v = Z_{v0} + k_Z P_{ss}$$

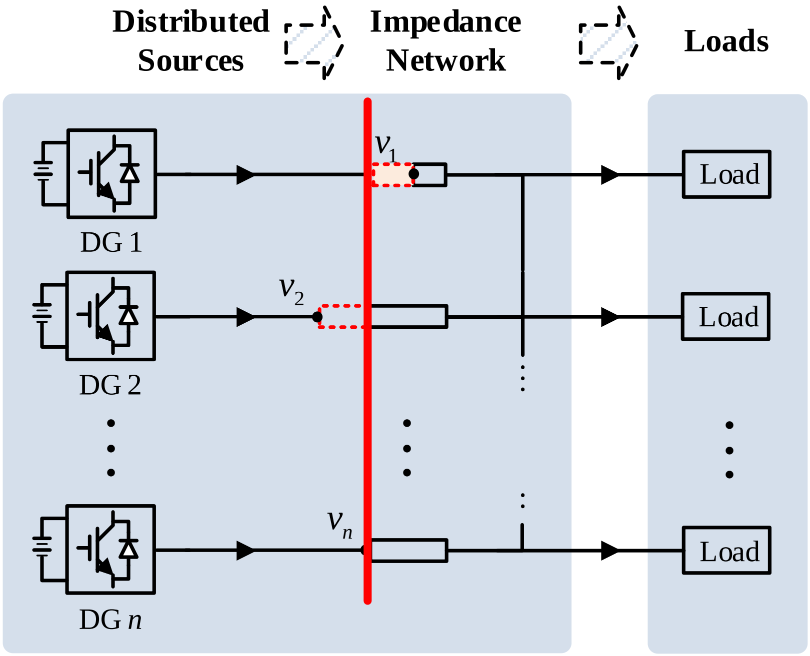
**Still impact the PCC voltage quality**

  - $Z_v$: virtual impedance.
  - $Z_{v0}$: preactivated virtual impedance value
  - $k_Z$: coupling coefficient

# Reactive, Unbalanced and Harmonic Power Sharing

- **Small-AC-signal injection-based control**




- **Average virtual impedance** would worsen the voltage deviation and distortion on the bus
- How about setting it around zero?

**How to estimate it?**

The **SACS power** of each DG are different in steady state

$$Z_{v1} \neq Z_{v2} \Rightarrow P_{ss1} \neq P_{ss2}$$

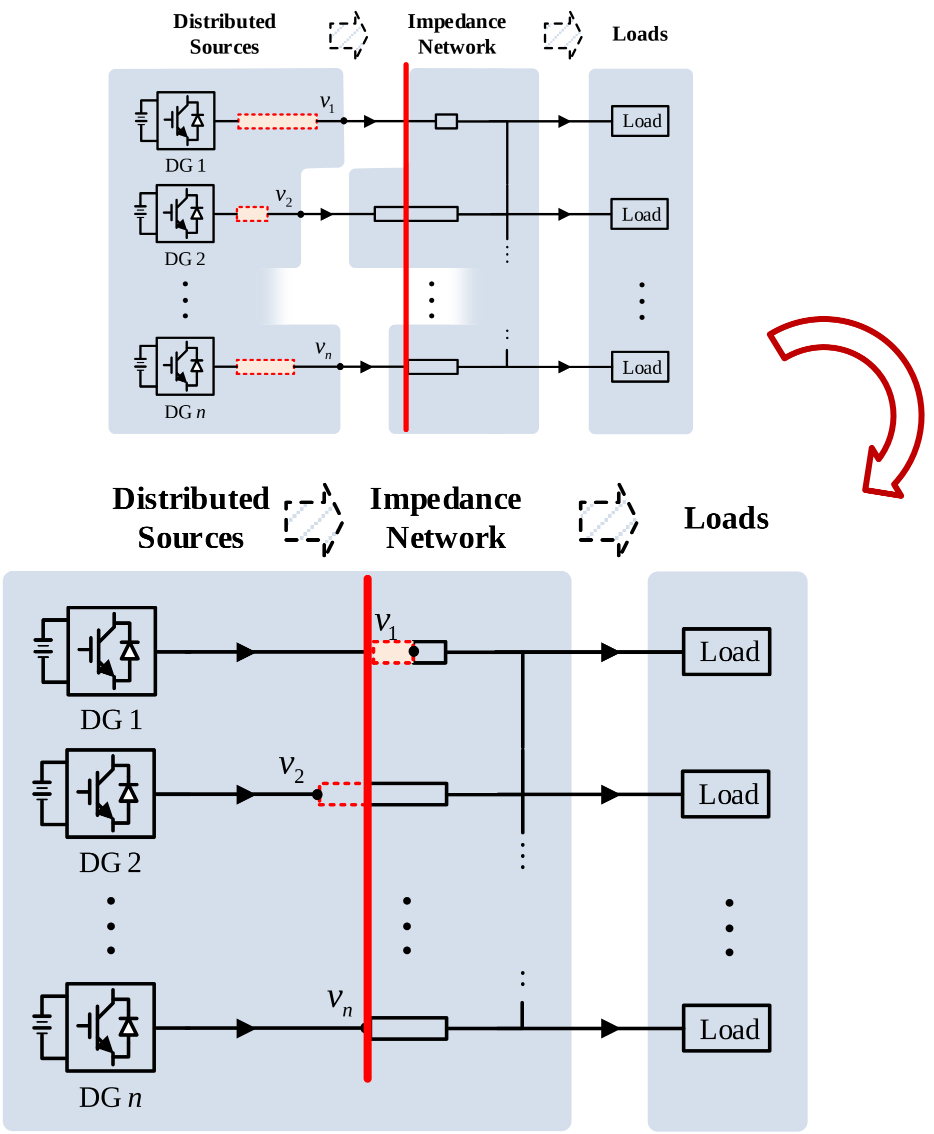
The **fundamental power** are equally shared

$$P_1 = P_2 = P_{ave}$$

- DGs have the information of average fundamental power but not the average SACS power

# Reactive, Unbalanced and Harmonic Power Sharing

- **Small-AC-signal injection-based control**




$$P_{ssave} = \left(\frac{E_{ss0}}{E_0}\right)^2 P_{ave} = \left(\frac{E_{ss0}}{E_0}\right)^2 P_1 = \left(\frac{E_{ss0}}{E_0}\right)^2 P_2 = \cdots$$

$$Z_v = Z_{v0} + k_Z P_{ss}$$

$$Z'_v = Z_{v0} + k_Z P'_{ss} \qquad P'_{ss} = P_{ss} - \left(\frac{E_{ss0}}{E_0}\right)^2 P$$

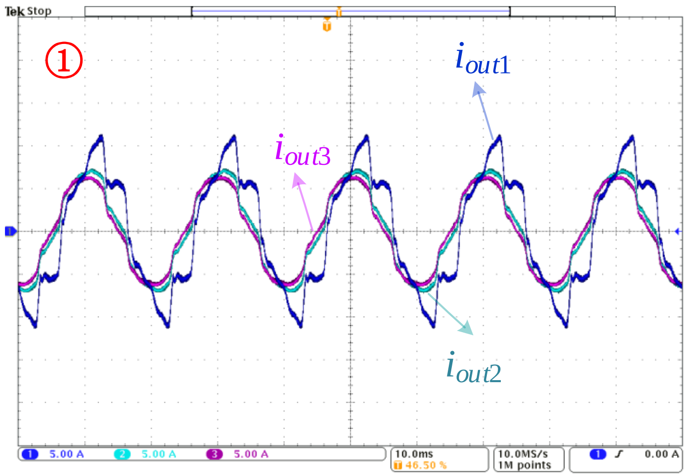
- The virtual impedances **balance original line impedances**
- The degradation of bus voltage quality caused by virtual impedance is eliminated

# Reactive, Unbalanced and Harmonic Power Sharing

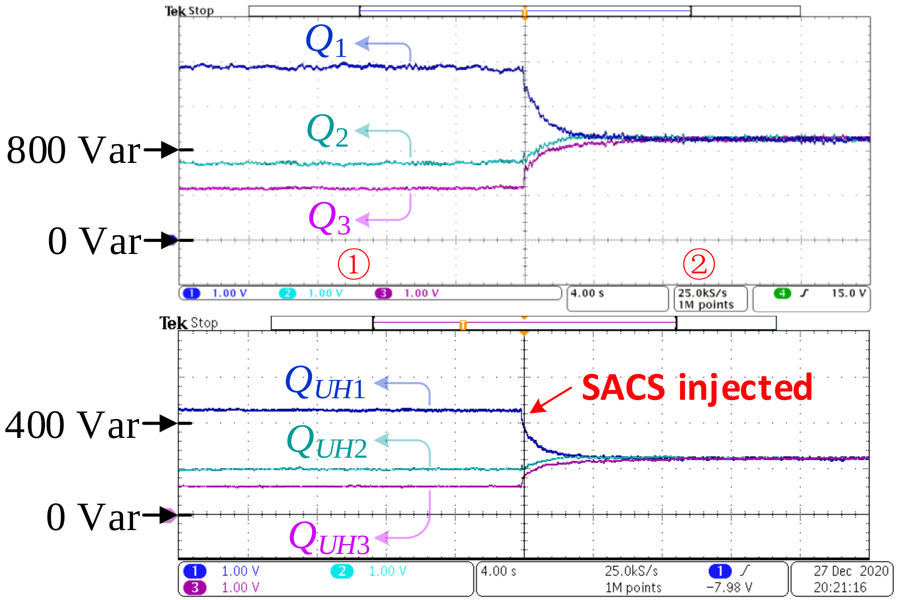
- **Small-AC-signal injection-based control**

**Experimental results**

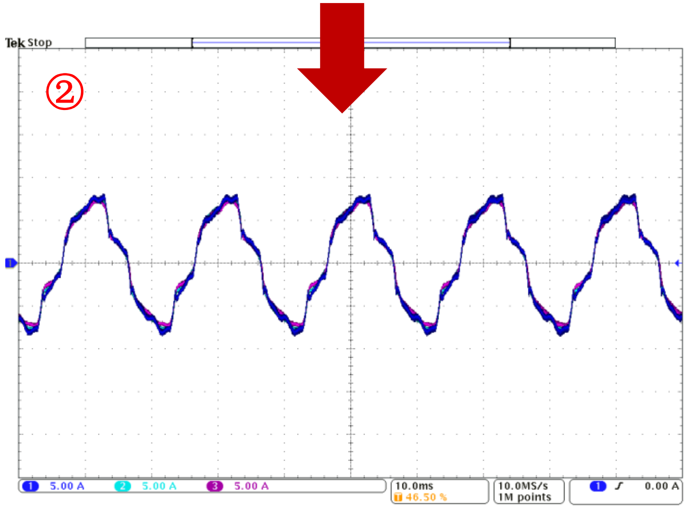
- **Equal power sharing**
  - Power Rating $S_1 : S_2 : S_3 = 1 : 1 : 1$
  - Feeder Impedance $L_1$ = 1.2 mH, $L_2$ = 3.5 mH, $L_3$ = 4.6 mH




Output currents before SACS injected




Output reactive, unbalanced and harmonic power of three inverters



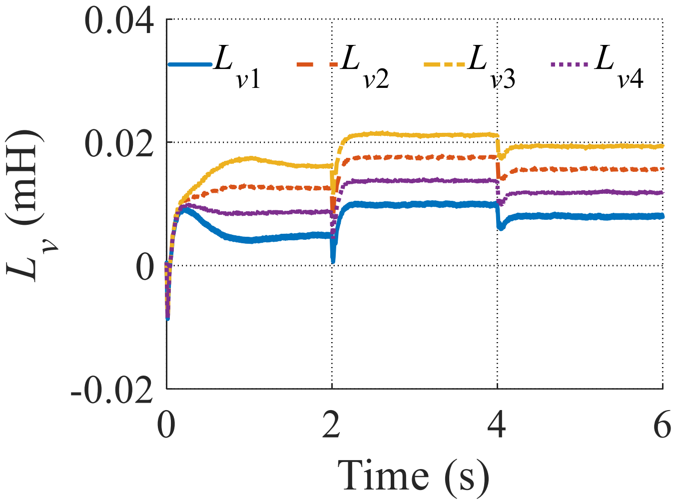

Output currents after SACS injected

# Reactive, Unbalanced and Harmonic Power Sharing

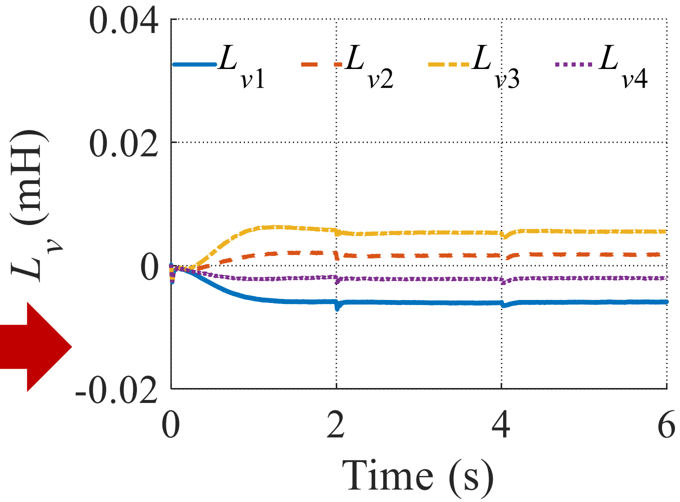
- **Small-AC-signal injection-based control**

**Simulation results**

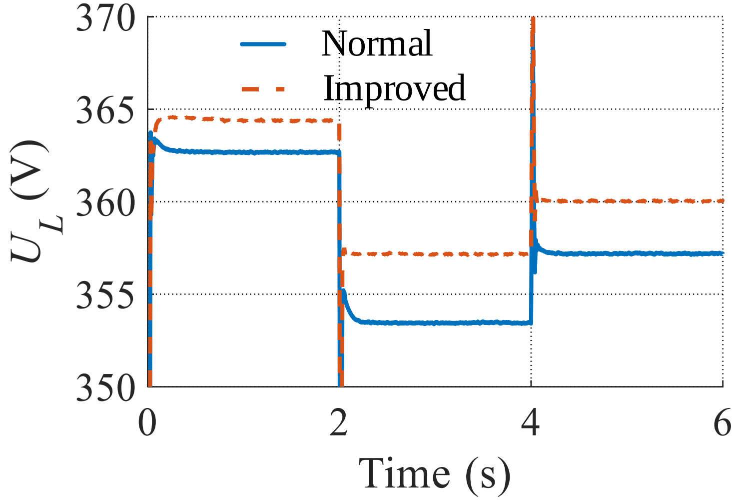
**Comparison of voltage drop**




Virtual impedances under normal *Pss* calculation




Virtual impedances under improved *Pss* calculation

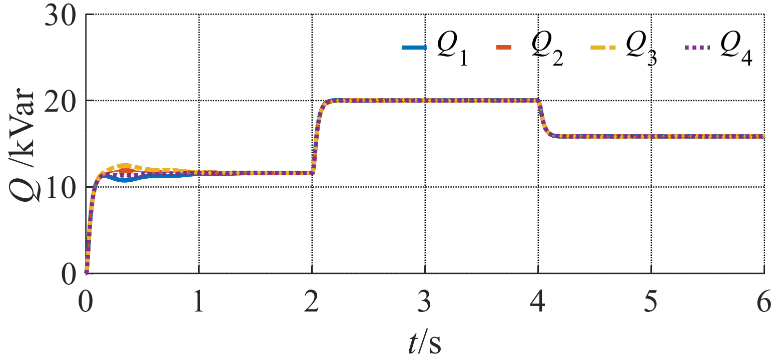



PCC voltage comparison

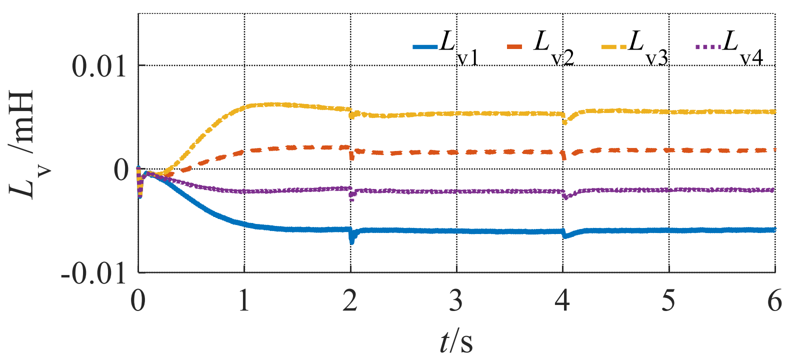
- **Small-AC-signal injection-based control**

**Simulation results**

**Single-PCC structure**

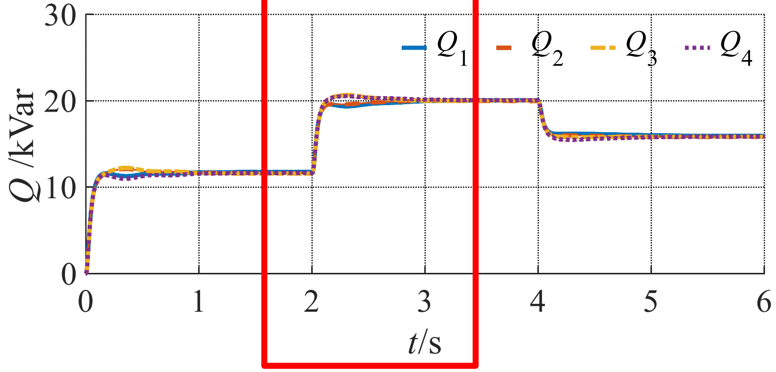



DG output reactive power

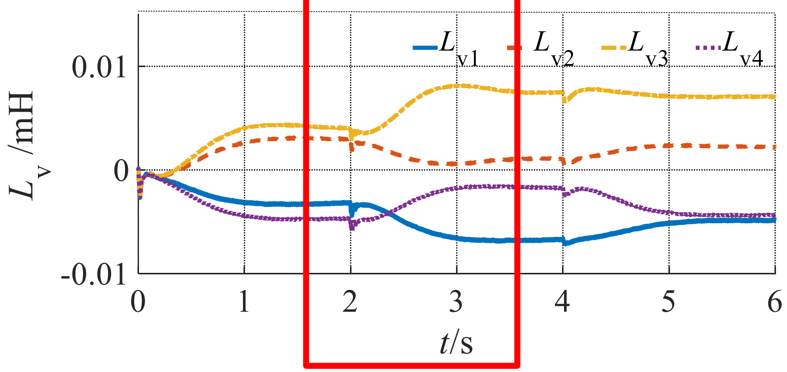



Virtual impedance

**Distributed structure**




DG output reactive power



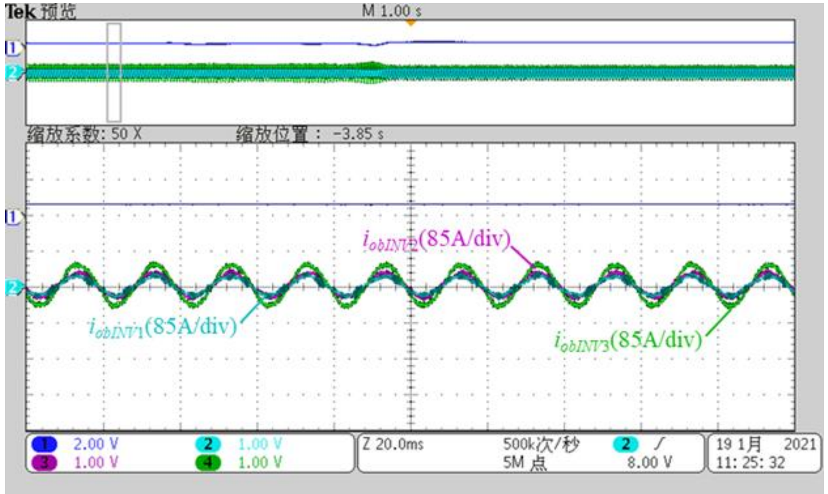

Virtual impedance

**Virtual impedances re-tuned when load changes**

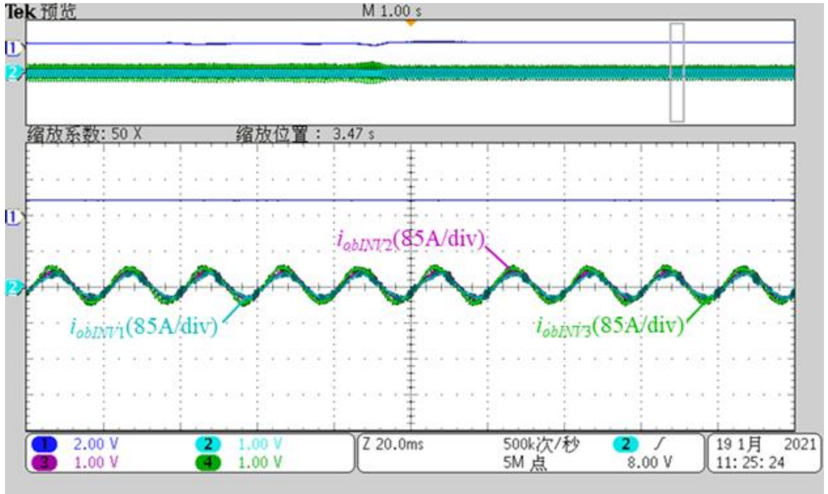
# Reactive, Unbalanced and Harmonic Power Sharing

- **Practical application：KEHUA Project**
  - Accurate power sharing achieved after the small-signal injection-based control applied.

| Technical parameters | |
|---|---|
| Power rating | 100kVA |
| INV #1 inductance in series | 15μH |
| INV #2 inductance in series | 15μH |
| INV #3 inductance in series | 18μH |


Phase-B current before SACS control applied




Phase-B current after SACS control applied

# Reactive, Unbalanced and Harmonic Power Sharing

## Small-AC-signal injection-based control

### Summaries

- Reactive, unbalanced and harmonic power can be equally or proportionally shared among inverters.
- Plug and play, no communication link or central controller is needed.
- No need to measure feeder impedance, and compatible with conventional droop control.
- Impacts of virtual impedances on PCC voltage quality can be eliminated by proper design.

B. Liu, Z. Liu, J. Liu, R. An, H. Zheng, and Y. Shi, "An Adaptive Virtual Impedance Control Scheme Based on Small-AC-Signal Injection for Unbalanced and Harmonic Power Sharing in Islanded Microgrids," in *IEEE Transactions on Power Electronics*, vol. 34, no. 12, pp. 12333-12355, 2019.

R. An, Z. Liu, J. Liu and B. Liu, "A Comprehensive Solution to Decentralized Coordinative Control of Distributed Generations in Islanded Microgrid Based on Dual-Frequency-Droop," in *IEEE Transactions on Power Electronics*, vol. 37, no. 3, pp. 3583-3598, March 2022.

# Selection of Small-AC-Signal

## Selection of the amplitude for small-AC-signal

- **Trade-off between power quality consideration and the difficulty to extract the SACS.**
- IEEE Std 519-2014 establishes harmonic limits on voltage as **8%** for THD and **5%** of the fundamental voltage for any single harmonic voltage
- The amplitude of rated fundamental voltage in experiments is **200V.**
- Given some margins, the amplitude of the small AC signal is set as **2V**, which could guarantee both the THD and the distortion of any single harmonic below **2%.**

*IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems*, IEEE Std 519-2014 (revision of IEEE Std 519-1992), 2014

# Selection of Small-AC-Signal

- **Selection of the frequency for small-AC-signal**

- Avoid frequency of pre-existing harmonics

  ☹ **($6k \pm 1$)th-order harmonics** usually exist due to nonlinear loads

  ☹ **Other harmonics** due to modulation effects

- Avoid frequency of inter-harmonics

  ☹ Standard for inter-harmonics is more **rigorous**

- Avoid high frequency

  ☹ High frequency will be **filtered out** by the output L-C filter ($f_c$ = 700 Hz)

- Avoid low frequency

  ☹ Low frequency is **difficult to be extracted** from the fundamental signal

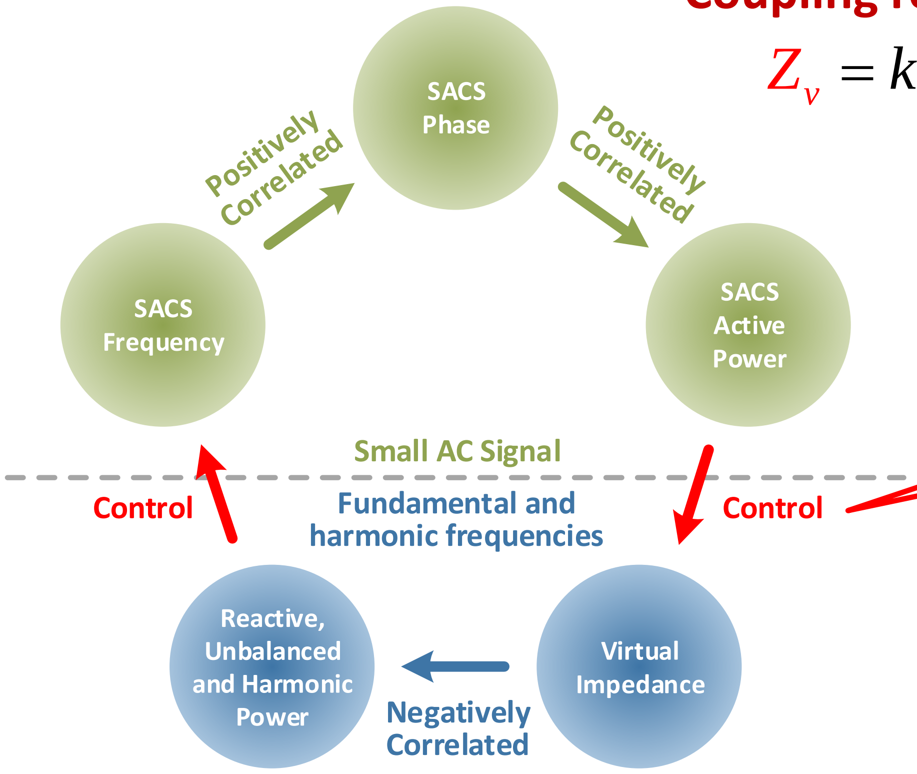
**ARE THESE ENOUGH?**

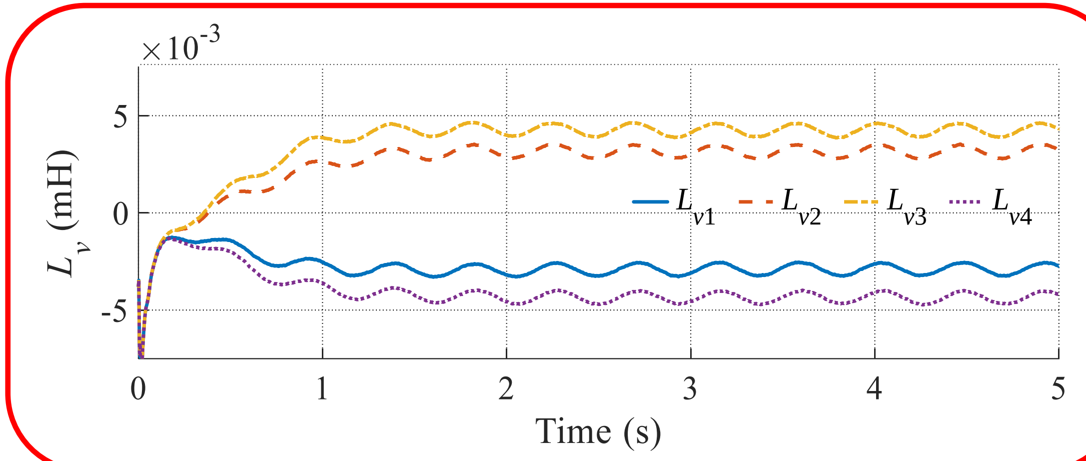
# Selection of Small-AC-Signal

- **Phenomenon description**

**Coupling relation**

$$Z_v = k_Z P_{ss}$$



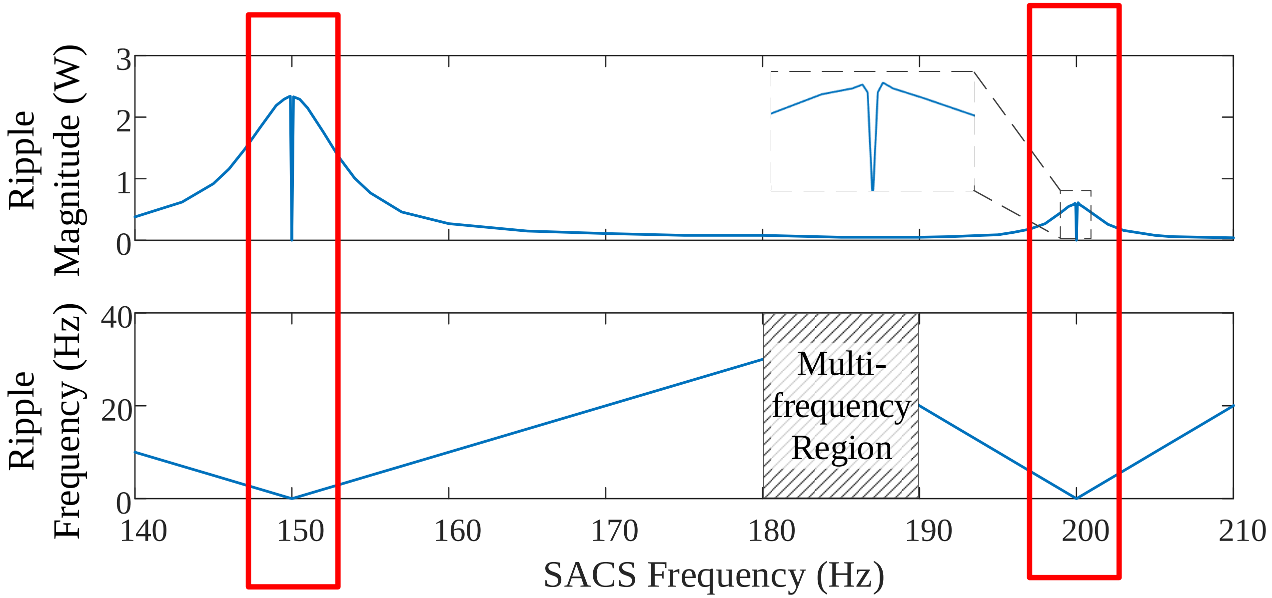

- Ideally, $Z_v$ and $P_{SS}$ should contain only DC component
- **Abnormal low-frequency steady-state ripples** observed on their waveforms when the reference SACS frequency was selected as **150 Hz, 200 Hz…**

- Reference SACS voltage is used to calculate the power:
  - Output **currents contain another component** near the SACS frequency
  - **Its frequency is so close to the SACS** that can hardly be removed by the MSOGI-QSG

# Selection of Small-AC-Signal

## Phenomenon description

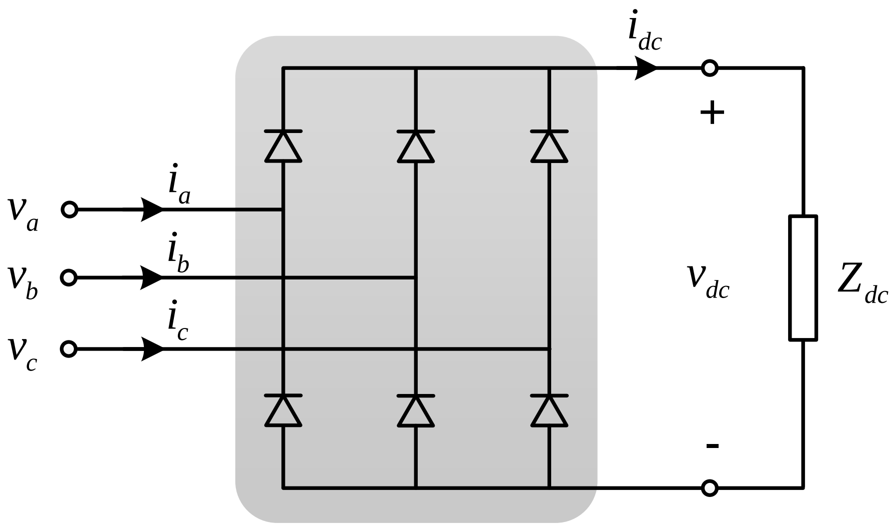
- Ripples disappear when **nonlinear loads** are disconnected
- Ripple frequency **changes with the SACS frequency $f_{ss}$ and fundamental frequency $f$**
- Ripples of DGs are **in phase**, not circulating

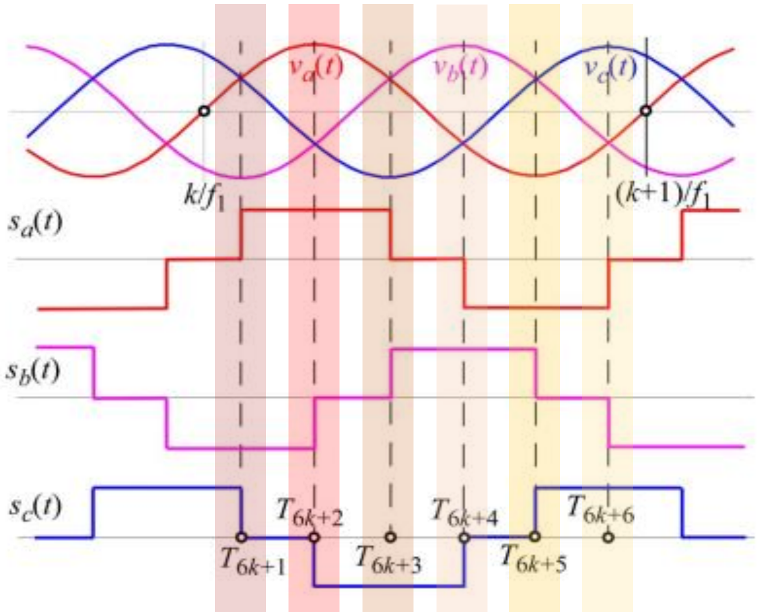



- **Fix $f$ at 50 Hz and tune $f_{ss}$ from 100 Hz to 350 Hz:**
  - **$f_{ss}$ around 150 Hz**: ripple frequency is exactly the difference between **150 Hz** and **$f_{ss}$**
    e.g., when $f_{ss}$ = 149 or 151 Hz, ripple frequency is 1 Hz;
  - **$f_{ss}$ around 200 Hz**: ripple frequency is twice the difference between **200 Hz** and **$f_{ss}$**
    e.g., when $f_{ss}$ = 199 or 201 Hz, ripple frequency is 2 Hz;
  - $f_{ss}$ around 100 or 300 Hz: no obvious low-frequency ripple

# Selection of Small-AC-Signal

- **Analysis of the cause of ripples**




- It is true that different AC components in output voltage are independent in **linear systems**
- With **nonlinear loads, i.e., three-phase diode rectifiers**, will they be coupled together and generate **new frequency components**?

⇨

- Give the expressions of AC voltages & check components in AC currents
- **KEY: How to express its commutation characteristics?**

**Obtain the mapping function $s_x(t)$ through calculating the commutation points**

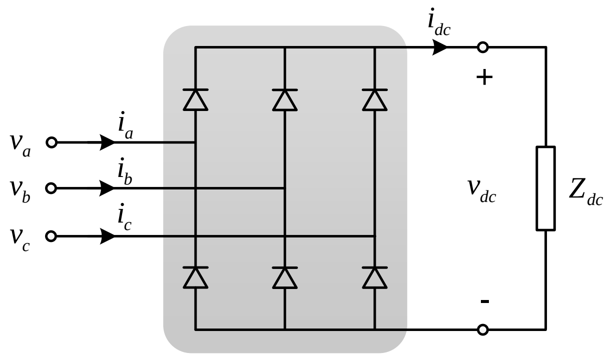
# Selection of Small-AC-Signal

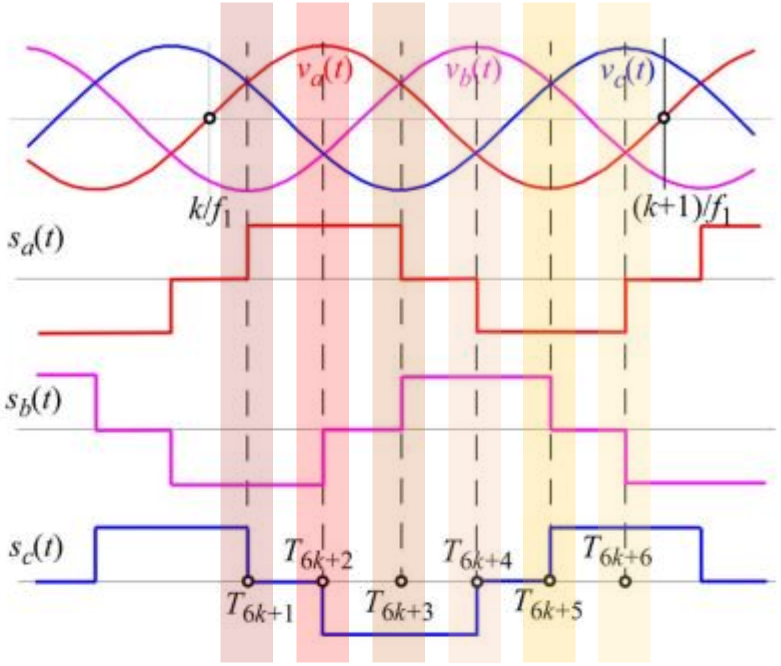
## Analysis of the cause of ripples

**AC voltages** → Mapping $s_x(t)$ → **DC voltages**

**DC voltages** → Loads → **DC currents**

**DC currents** → Mapping $s_x(t)$ → **AC currents**




$$v_{dc}(t) = s_a(t)v_a(t) + s_b(t)v_b(t) + s_c(t)v_c(t)$$

$$i_x(t) = s_x(t)i_{dc}(t) \quad (x = a, b, c)$$

Fourier ⇔

$$\mathbf{V}_{\mathbf{dc}}(j2\pi f) = \sum_{x=a,b,c} \mathbf{S}_{\mathbf{x}}(j2\pi f) * \mathbf{V}_{\mathbf{x}}(j2\pi f)$$

$$\mathbf{I}_{\mathbf{dc}}(j2\pi f) = \frac{\mathbf{V}_{\mathbf{dc}}(j2\pi f)}{\mathbf{Z}_{\mathbf{dc}}(j2\pi f)}$$

$$\mathbf{I}_{\mathbf{x}}(j2\pi f) = \mathbf{S}_{\mathbf{x}}(j2\pi f) * \mathbf{I}_{\mathbf{dc}}(j2\pi f) \quad (x = a, b, c)$$


Z. Bing, K. J. Karimi and J. Sun, "Input Impedance Modeling and Analysis of Line-Commutated Rectifiers," *IEEE Trans. Power Electron.*, vol. 24, no. 10, pp. 2338-2346, Oct. 2009.

# Selection of Small-AC-Signal

- **Example 1: $f_{ss}$ around 200 Hz**

$$v_{dc}(t) = s_a(t)v_a(t) + s_b(t)v_b(t) + s_c(t)v_c(t)$$

$$i_x(t) = s_x(t)i_{dc}(t) \quad (x = a, b, c)$$

Fourier

$$\mathbf{V}_{dc}(j2\pi f) = \sum_{x=a,b,c} \mathbf{S}_x(j2\pi f) * \mathbf{V}_x(j2\pi f)$$

$$\mathbf{I}_{dc}(j2\pi f) = \frac{\mathbf{V}_{dc}(j2\pi f)}{\mathbf{Z}_{dc}(j2\pi f)}$$

$$\mathbf{I}_x(j2\pi f) = \mathbf{S}_x(j2\pi f) * \mathbf{I}_{dc}(j2\pi f) \quad (x = a, b, c)$$

- In this case, ripples are mainly caused by **interaction between fundamental wave and SACS**

$$\mathbf{V}_a[i] = \begin{cases} \dfrac{V}{2} e^{\mp j\frac{\pi}{2}}, & i = \pm f \\ \dfrac{V_{ss}}{2} e^{\mp j(\frac{\pi}{2} - \varphi_{ss})}, & i = \pm f_{ss} \end{cases}$$

$$\mathbf{V}_b[i] = \begin{cases} \dfrac{V}{2} e^{\pm j\frac{5\pi}{6}}, & i = \pm f \\ \dfrac{V_{ss}}{2} e^{\pm j(\frac{5\pi}{6} + \varphi_{ss})}, & i = \pm f_{ss} \end{cases}$$

$$\mathbf{V}_c[i] = \begin{cases} \dfrac{V}{2} e^{\pm j\frac{\pi}{6}}, & i = \pm f \\ \dfrac{V_{ss}}{2} e^{\pm j(\frac{\pi}{6} + \varphi_{ss})}, & i = \pm f_{ss} \end{cases}$$

$$\mathbf{S}_a[i] = \begin{cases} -\dfrac{(-1)^k j\sqrt{3}}{\pi(6k \pm 1)}, & i = (6k \pm 1) f \\ \dfrac{V_{ss} e^{\pm j\varphi_{ss}}}{\pi V} \cos(\dfrac{2k\pi}{3} \mp \dfrac{\pi}{6}) e^{\mp j\frac{\pi}{2}} e^{jk\pi}, & i = 2kf \pm f_{ss} \end{cases}$$

$$\mathbf{S}_b[i] = \begin{cases} -\dfrac{(-1)^k j\sqrt{3} e^{\mp j\frac{2\pi}{3}}}{\pi(6k \pm 1)}, & i = (6k \pm 1) f \\ \dfrac{V_{ss} e^{\pm j\varphi_{ss}}}{\pi V} \cos(\dfrac{2k\pi}{3} \mp \dfrac{\pi}{6}) e^{\pm j\frac{5\pi}{6}} e^{-j\frac{k\pi}{3}}, & i = 2kf \pm f_{ss} \end{cases}$$

$$\mathbf{S}_c[i] = \begin{cases} -\dfrac{(-1)^k j\sqrt{3} e^{\pm j\frac{2\pi}{3}}}{\pi(6k \pm 1)}, & i = (6k \pm 1) f \\ \dfrac{V_{ss} e^{\pm j\varphi_{ss}}}{\pi V} \cos(\dfrac{2k\pi}{3} \mp \dfrac{\pi}{6}) e^{\pm j\frac{\pi}{6}} e^{j\frac{k\pi}{3}}, & i = 2kf \pm f_{ss} \end{cases}$$

$$\mathbf{V}_{dc}[i] = \sum_{k=-\infty}^{\infty} \sum_{x=a,b,c} \mathbf{S}_x[k]\mathbf{V}_x[i-k]$$

$$= \begin{cases} \dfrac{(-1)^m 3\sqrt{3}V}{\pi(1-36m^2)}, & i = 6mf \\ \dfrac{(-1)^m 3\sqrt{3}V_{ss} e^{-j\varphi_{ss}}}{2\pi(6m+1)}, & i = (6m+1)f - f_{ss} \\ \dfrac{(-1)^m 3\sqrt{3}V_{ss} e^{j\varphi_{ss}}}{2\pi(6m-1)}, & i = (6m-1)f + f_{ss} \end{cases}$$

# Selection of Small-AC-Signal

- **Example: $f_{ss}$ around 200 Hz**

$$v_{dc}(t) = s_a(t)v_a(t) + s_b(t)v_b(t) + s_c(t)v_c(t)$$

$$i_x(t) = s_x(t)i_{dc}(t) \quad (x = a, b, c)$$

**Fourier** ⇔

$$\mathbf{V}_{dc}(j2\pi f) = \sum_{x=a,b,c} \mathbf{S}_x(j2\pi f) * \mathbf{V}_x(j2\pi f)$$

$$\mathbf{I}_{dc}(j2\pi f) = \frac{\mathbf{V}_{dc}(j2\pi f)}{\mathbf{Z}_{dc}(j2\pi f)}$$

$$\mathbf{I}_x(j2\pi f) = \mathbf{S}_x(j2\pi f) * \mathbf{I}_{dc}(j2\pi f) \quad (x = a, b, c)$$

- Ripple frequency is **twice** the difference between $f_{ss}$ and **200 Hz ($f_{ss0}$)**

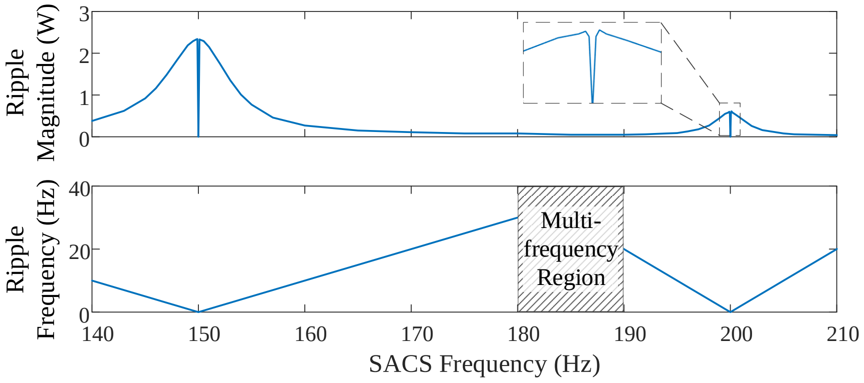
⇒ - Assume $f$ = 50 Hz and $f_{ss} = f_{ss0} + \Delta f$, then figure out if $f_{ss0} - \Delta f$ can be generated

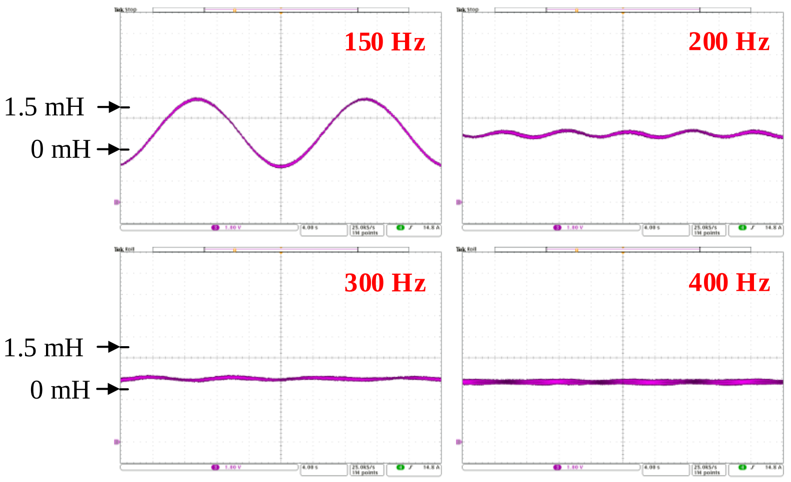
| $f_{ss0}$ | Combinations | Conditions | $\mathbf{I}_x[i]$ at $i = f_{ss0} - \Delta f$ |
|---|---|---|---|
| 100 Hz | $\mathbf{S}_x[2kf - f_{ss}]$ & $\mathbf{I}_{dc}[6mf]$ | $k = 2 - 3m$ | $I_a = I_b = I_c = 0$ |
| 150 Hz | $\mathbf{S}_x[(6k$ [illegible] | [illegible] $m$ | $I_a = e^{-2\pi/3} I_b = e^{2\pi/3} I_c$ (Negative sequence) |
| 200 Hz | $\mathbf{S}_x[($ [illegible] | [illegible] | $I_a = e^{2\pi/3} I_b = e^{-2\pi/3} I_c$ (Positive sequence) |
| 300 Hz | $\mathbf{S}_x[($ [illegible] ; $\mathbf{S}_x[2kf - f_{ss}]$ & $\mathbf{I}_{dc}[6mf]$ | $k = 6 - 3m$ | $I_a = e^{-2\pi/3} I_b = e^{2\pi/3} I_c$ (Negative sequence) |

- $f_{ss}$ **around 150 or 300 Hz: negative-sequence currents**, which will be filtered out by the MSOGI-QSG;
- $f_{ss}$ **around 200 Hz: positive-sequence currents at $f_{ss}$ - 2Δ$f$** will remain.

# Selection of Small-AC-Signal

## Design guidelines of SACS frequency




($f$ = 50.016 Hz & $f_{ss}$ = 150, 200, 300, 400 Hz)

- **In practice, $f_{ss}$ and $f$ are drooped respectively, so $f_{ss}$ is not exactly multiple of $f$**

1) Avoid $(6k + 4)f_0$ ($k$ is non-negative integer), or there will be ripples due to the **nonlinear loads and the injected SACS**.
2) Avoid $(6k + 3)f_0$, or there will be ripples due to the **nonlinear and unbalanced loads**.
3) The $f_{ss0}$ is recommended to be selected as **300, 400 or 100 Hz.**

4) Avoid pre-existing harmonics.
5) Avoid inter-harmonics or subharmonics, unless the mentioned harmonics already exist, because the limitations for them are more rigorous.
6) Avoid high or low frequencies.

# Selection of Small-AC-Signal

## Selection of SACS frequency

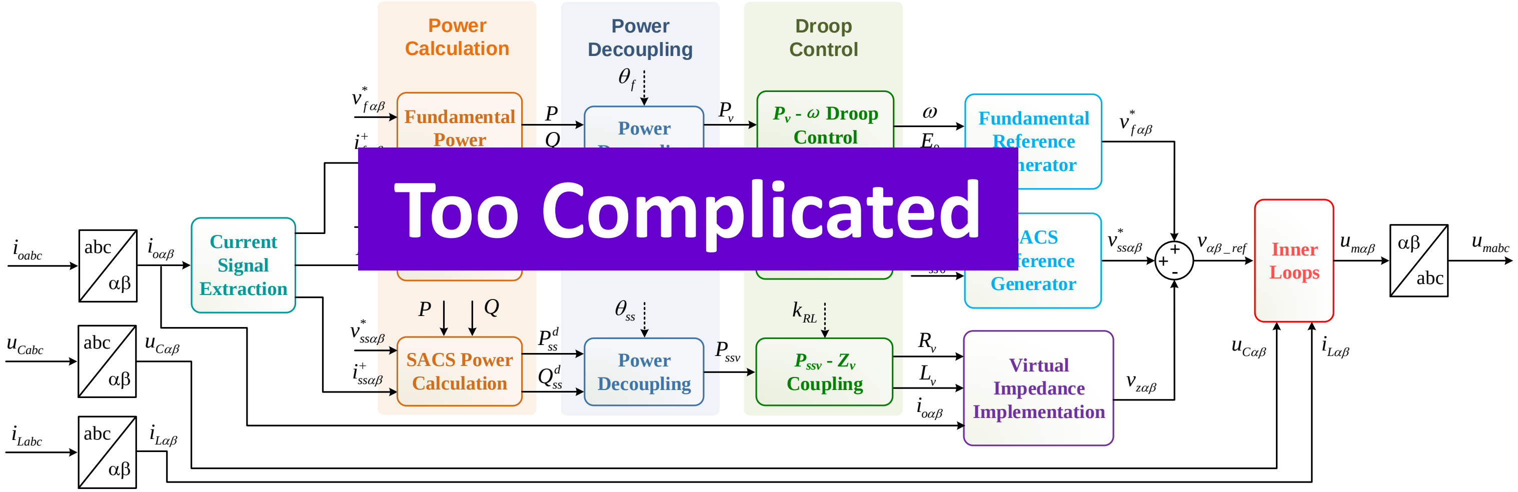
### Summaries

- Causes of steady-state ripples on virtual impedance waveforms are analyzed in theory and verified by simulation and experiment results.
- Guideline to eliminate these ripples is provided accordingly.
- These conclusions obtained are also applicable to other SACS-based methods.

R. An, Z. Liu, J. Liu and B. Liu, "A Comprehensive Solution to Decentralized Coordinative Control of Distributed Generations in Islanded Microgrid Based on Dual-Frequency-Droop," in *IEEE Transactions on Power Electronics*, vol. 37, no. 3, pp. 3583-3598, March 2022.

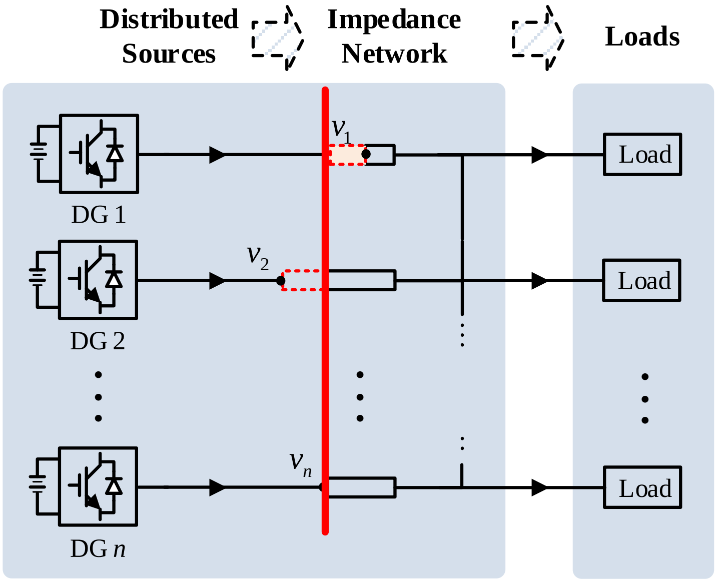
# Successive Approximation for Power Sharing

- Other way to obtain proper virtual impedance




**Too Complicated**

- SACS injection & extraction
- More control objectives? More SACSs needed
- Several parameters to be designed
- ....
- **Other way to obtain proper virtual impedance?**



# Successive Approximation for Power Sharing

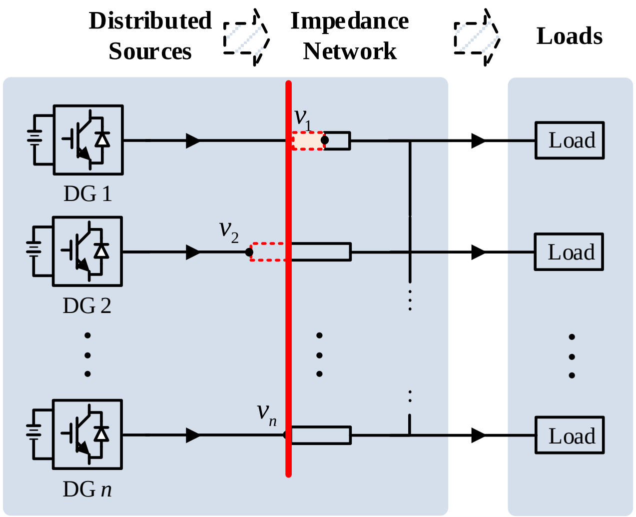
## Virtual impedance tuning

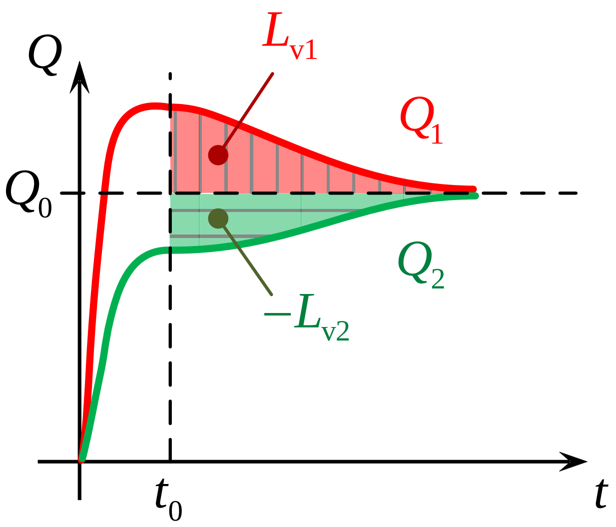
- How to let a DG know **its own direction for virtual impedance tuning?**
- Introduce integral into reactive power control loop ➡ **adaptive virtual impedance (AVI)**

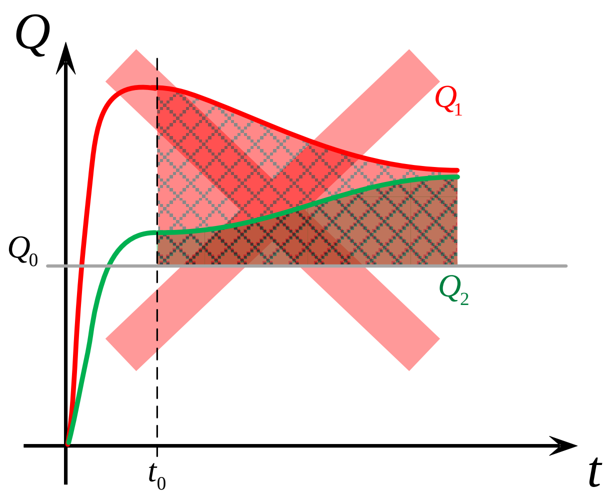
$$L_{\mathrm{v}} = k_{\mathrm{avi}} \int_{t_0}^{t} (Q - Q_0) d\tau$$

- Ideally, $Q_0$ for each DG should be equal to the **average reactive power demand**

**Hard to realize without high-bandwidth communication in existing solutions**



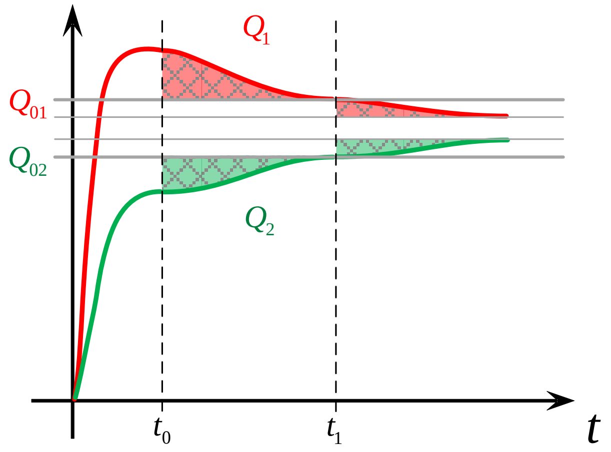



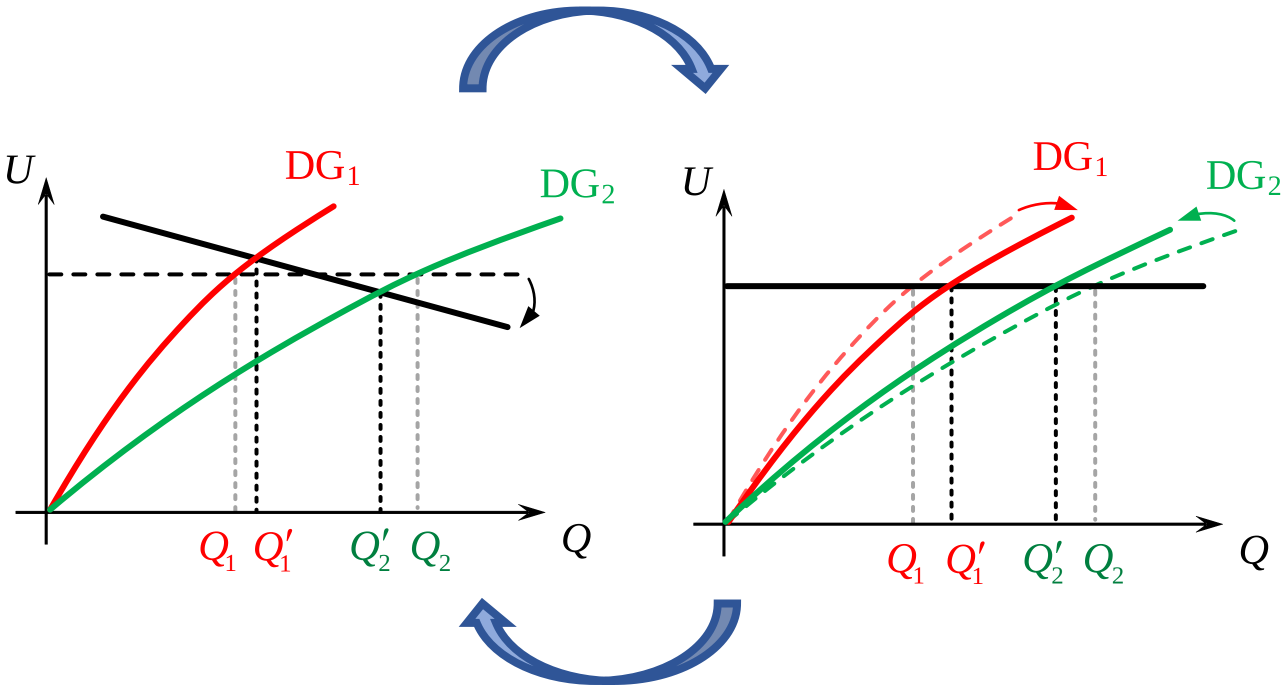



# Successive Approximation for Power Sharing

- **System perspective**

  - Possible solution: tuning the virtual impedance from a **system perspective** and through a **progressive process**?

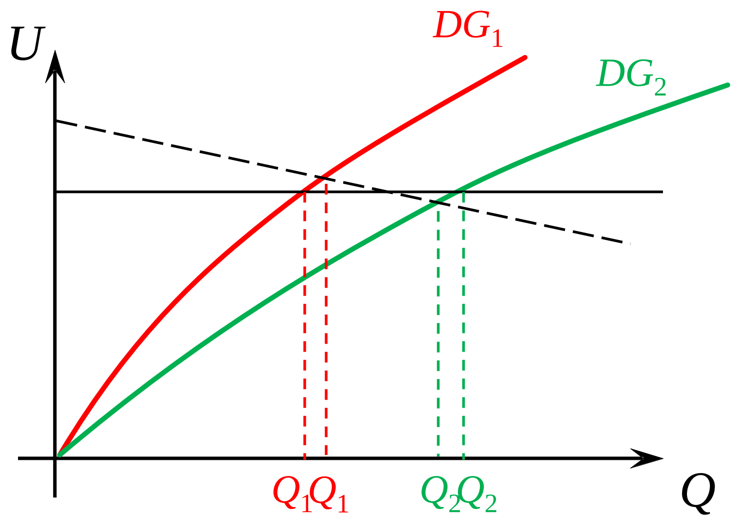


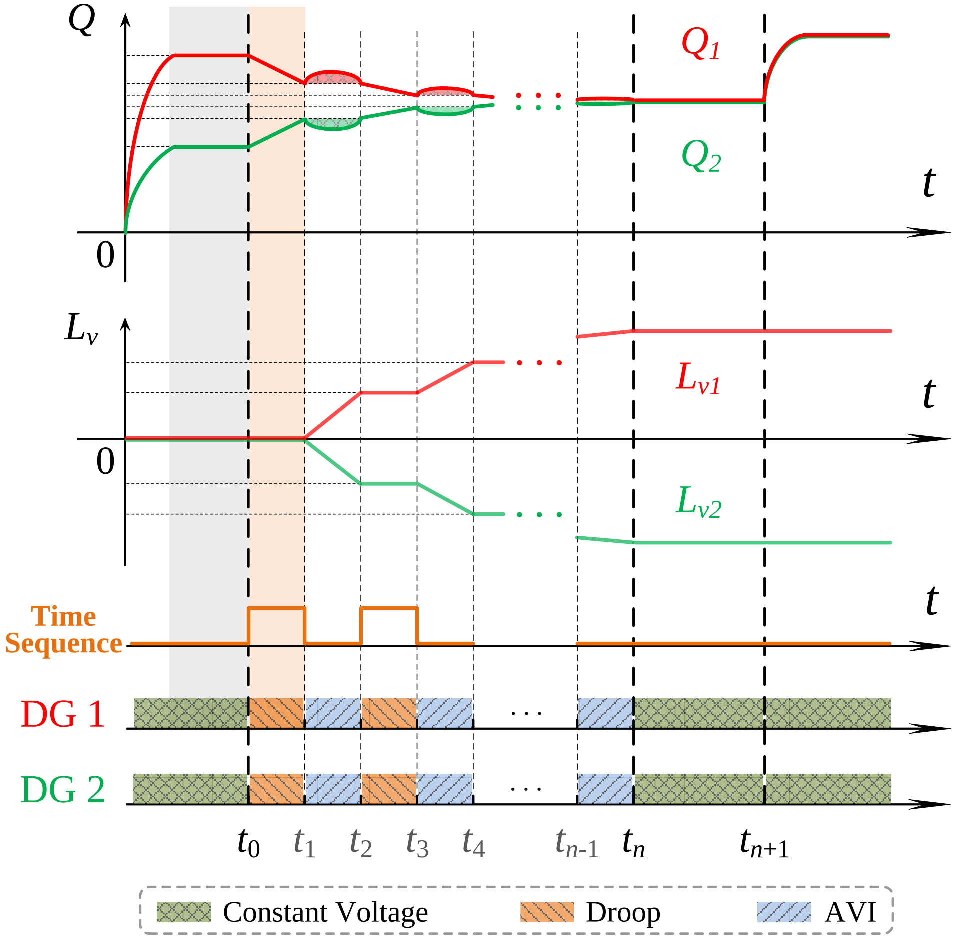




- Estimate a more desirable operation point with **droop control**
- Move toward it by **tuning virtual impedances**
- Repeat this procedure
- The virtual impedances will finally **successively approximate** appropriate values

# Successive Approximation for Power Sharing

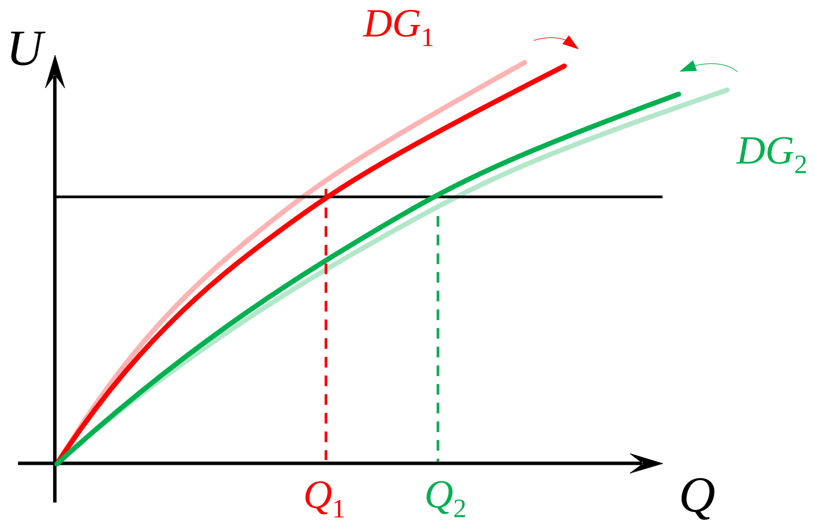
- **Example of tuning process**

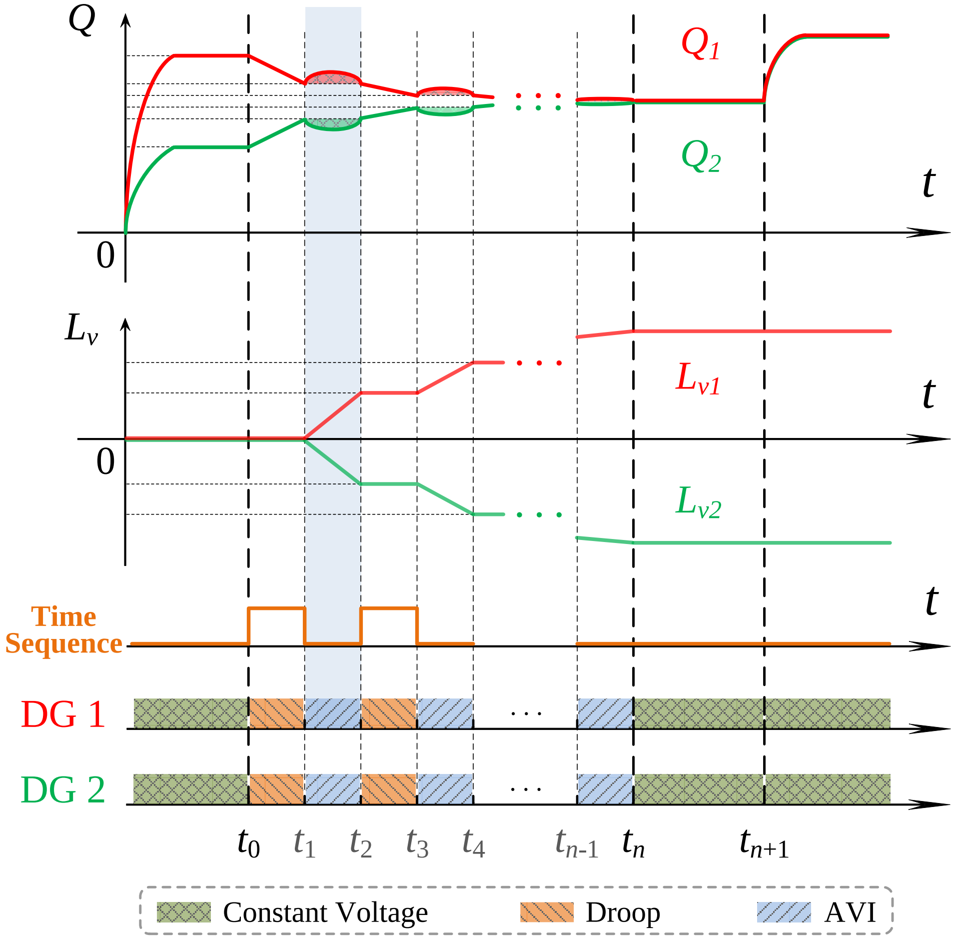


# Successive Approximation for Power Sharing

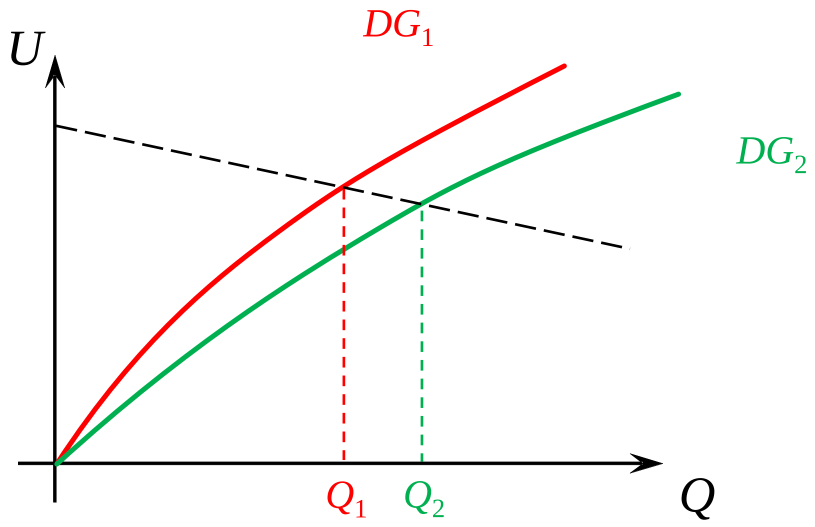
- **Example of tuning process**

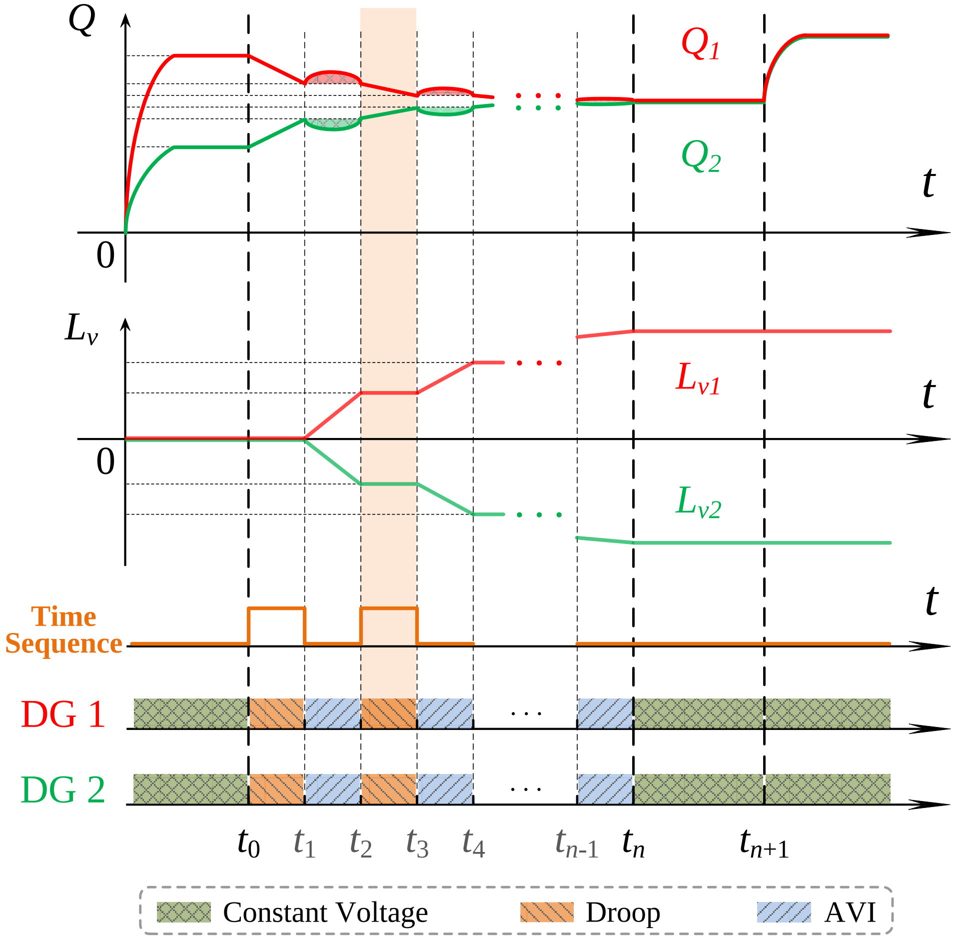


# Successive Approximation for Power Sharing

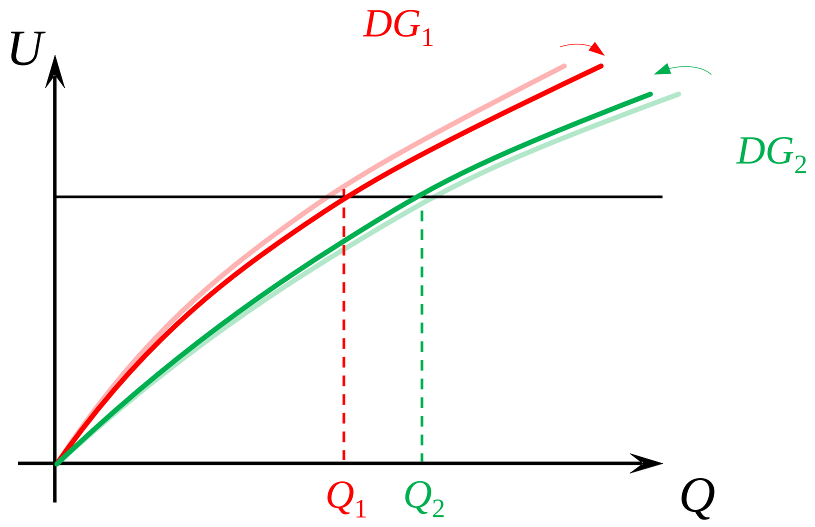
- **Example of tuning process**

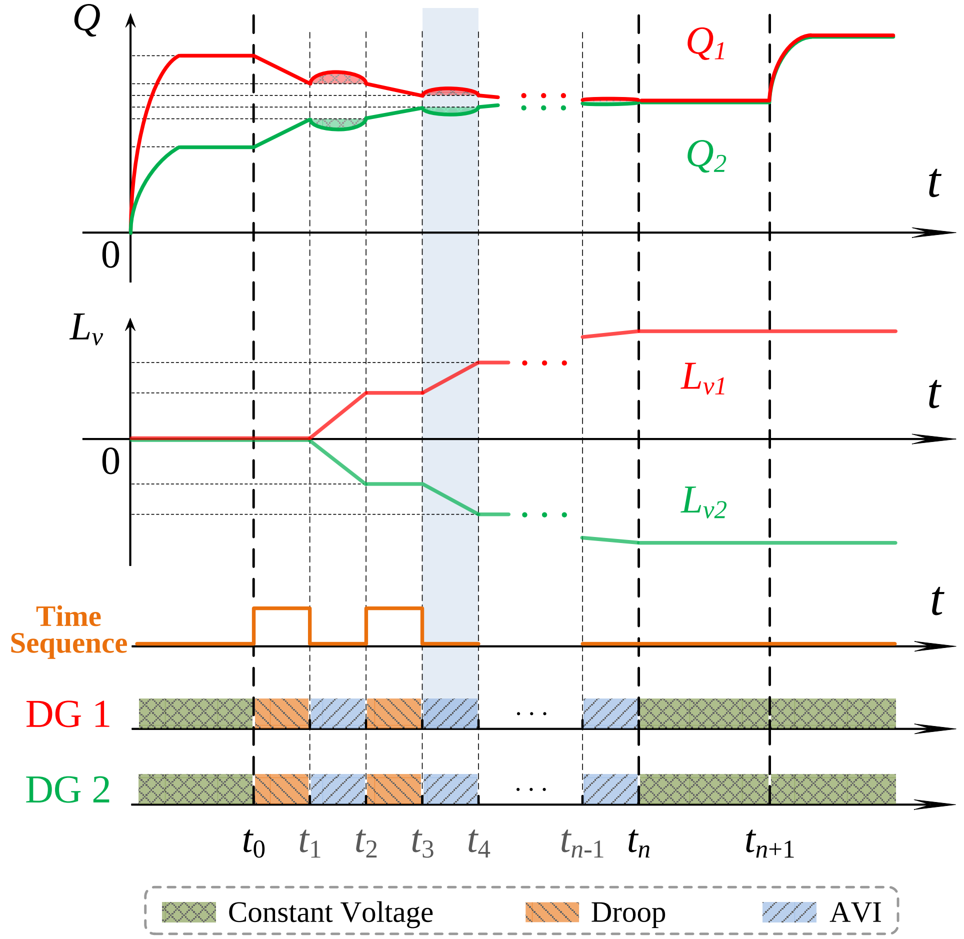


# Successive Approximation for Power Sharing

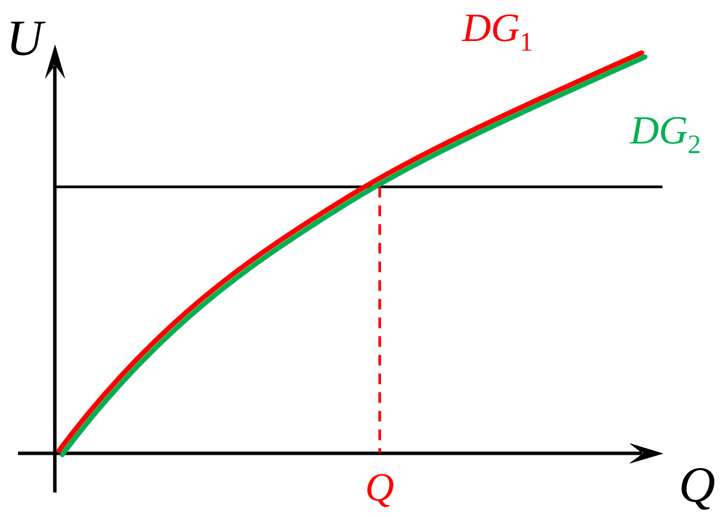
- **Example of tuning process**

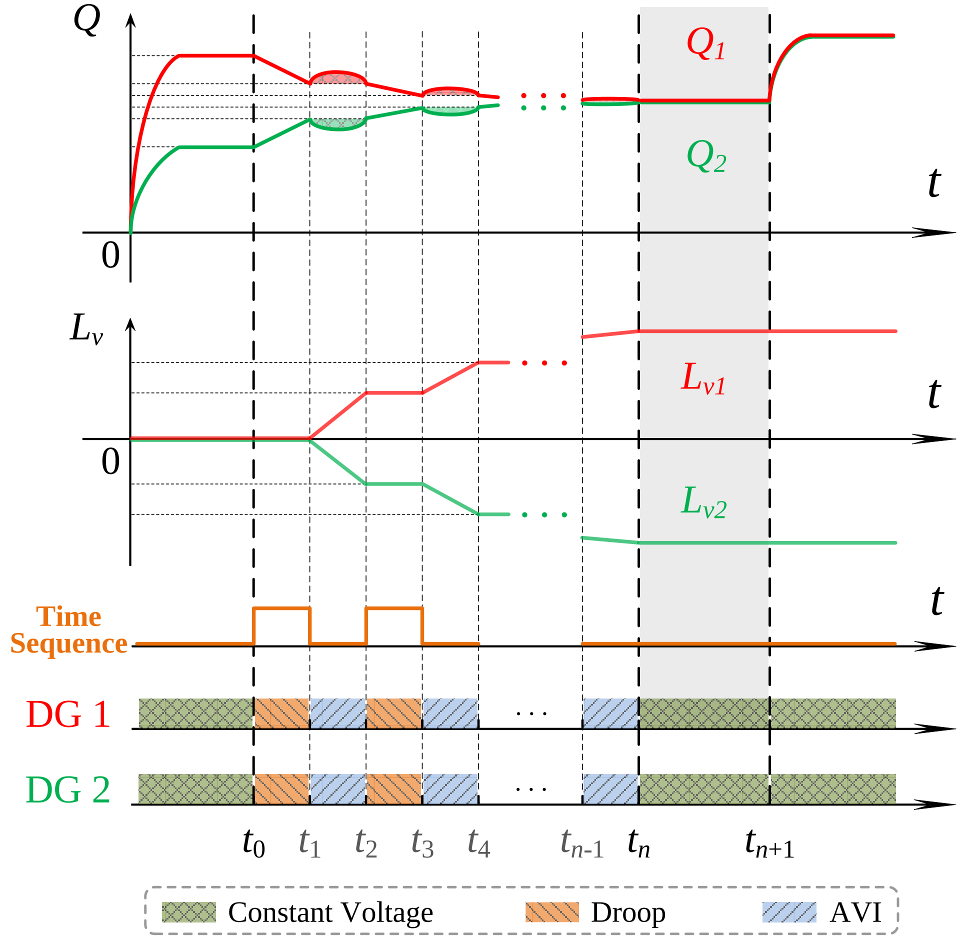


# Successive Approximation for Power Sharing

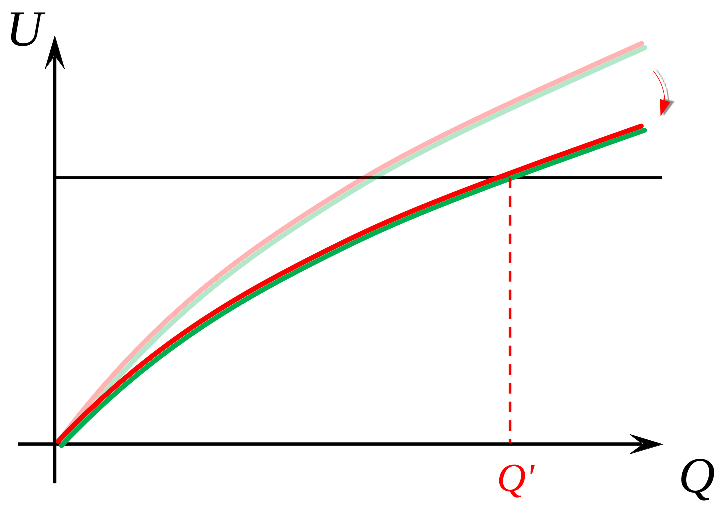
- **Example of tuning process**

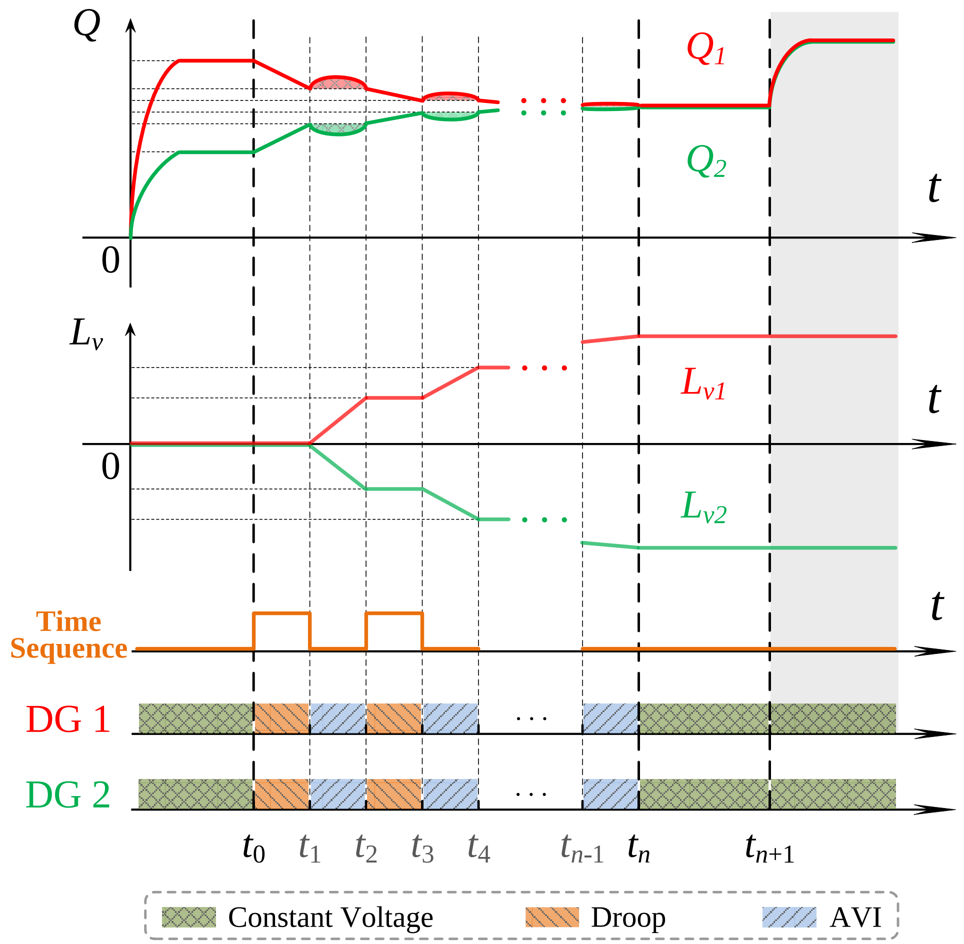


# Successive Approximation for Power Sharing

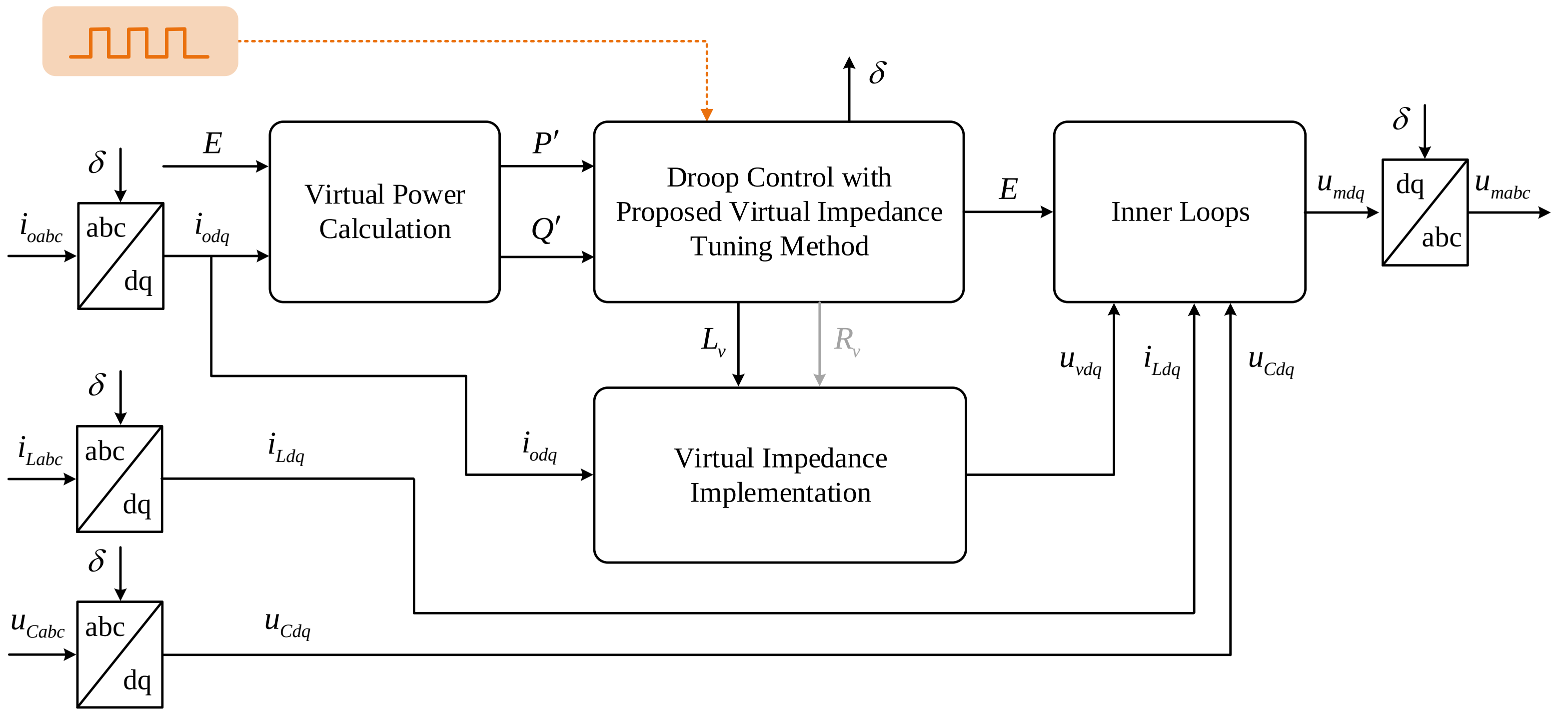
- **Example of tuning process**



# Successive Approximation for Power Sharing

- **Successive-approximation-based virtual impedance tuning**

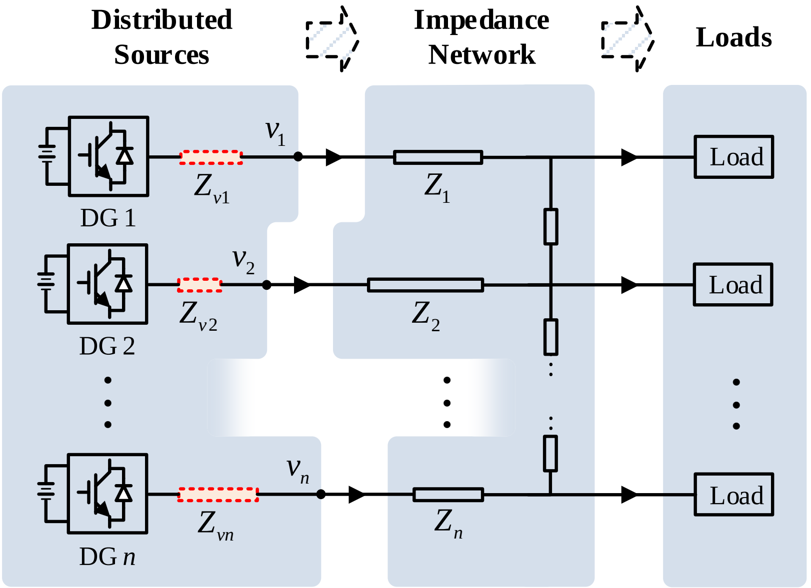


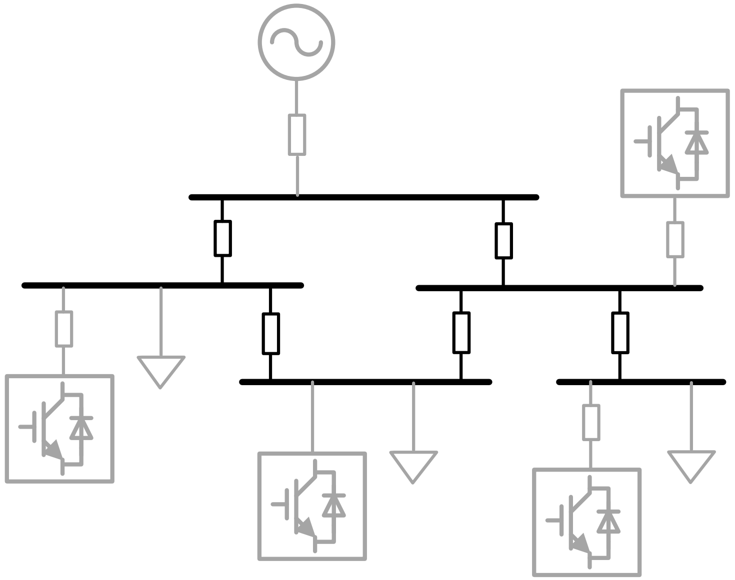

- Each DG successively tunes its virtual impedances in a **common sequence**
- **The average of virtual impedances is kept near 0**, minimizing the voltage deviations
- **Simple to implement, compatible with conventional droop control**

**What should be noticed in practical applications?**

# Successive Approximation for Power Sharing

- **Successive-approximation-based virtual impedance tuning**



- **Extension to distributed microgrid**
  - **Continuous virtual impedance tuning** to adapt to load changes
  - **Amplitude limiting** of virtual impedance to constrain the average virtual impedance when system parameter drift
- **Virtual impedances for unbalanced and harmonic power sharing**

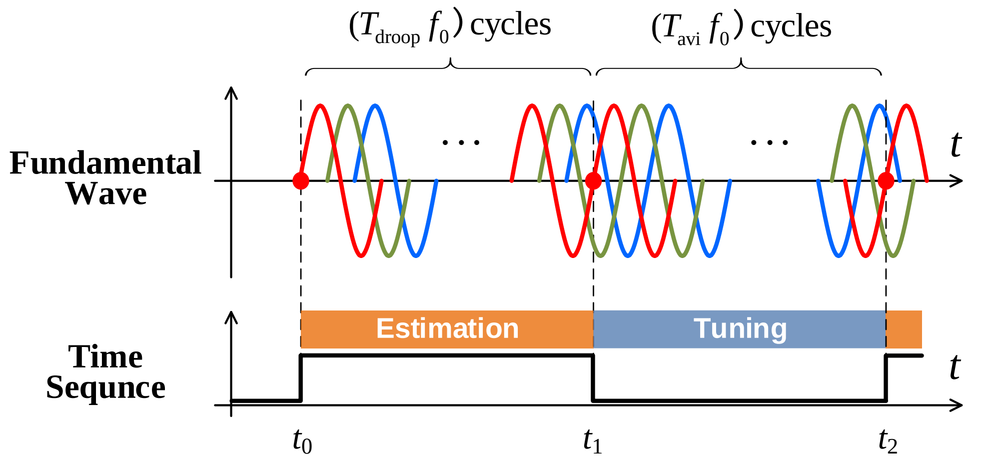
# Successive Approximation for Power Sharing

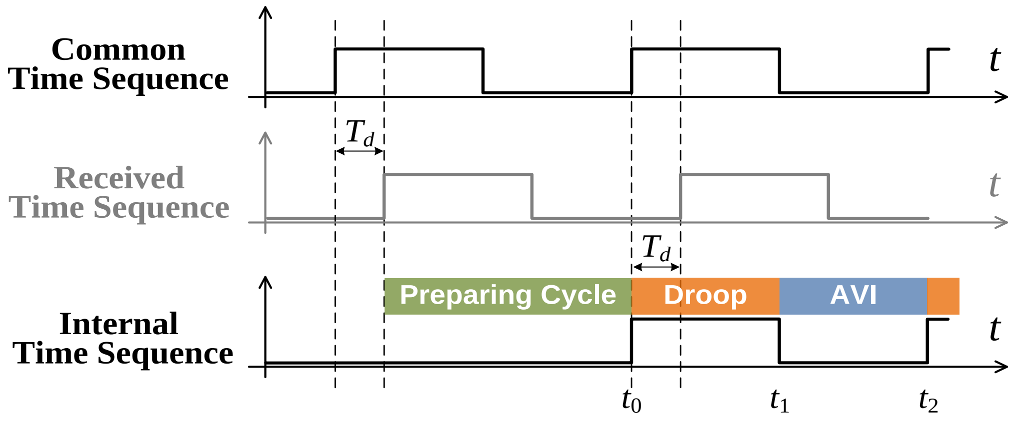
## Successive-approximation-based virtual impedance tuning

- **Autonomous triggering and synchronization of DG internal time sequence**
  - Monitoring bus voltage to learn the common sequence before plugging in
  - Differences in DSP crystal frequencies may cause drifting of DGs' sequences

  ➔ Using **multiples of fundamental cycle** as a reference for mode switching

- **Compensation for sequence delays**
- **Dead time between two modes**

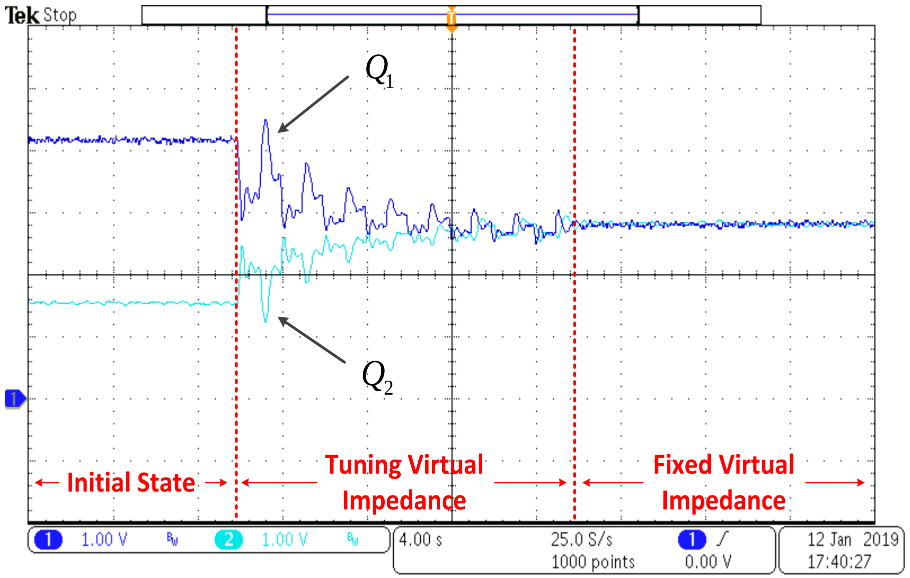


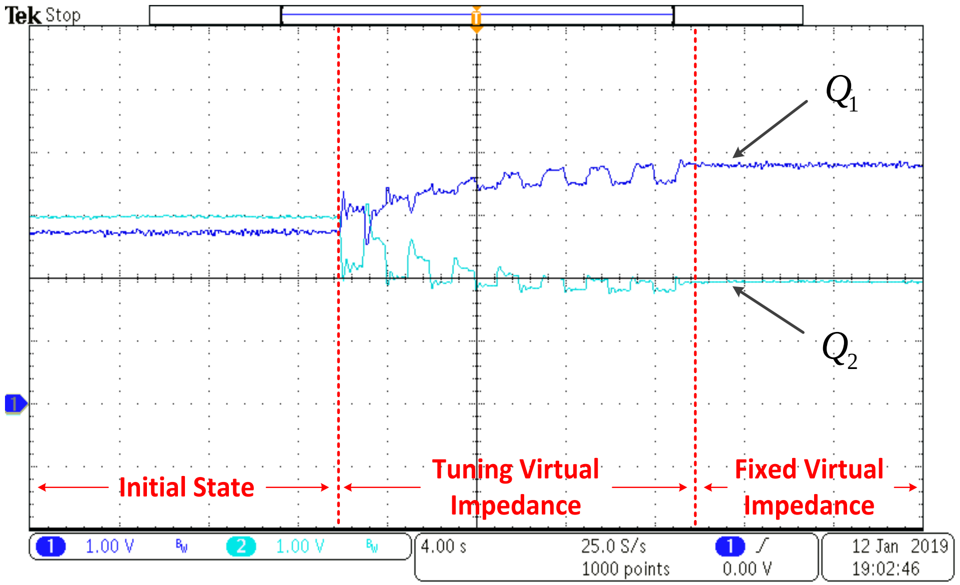
# Successive Approximation for Power Sharing

- **Successive-approximation-based virtual impedance tuning**

**Experimental results**




Reactive power equal sharing

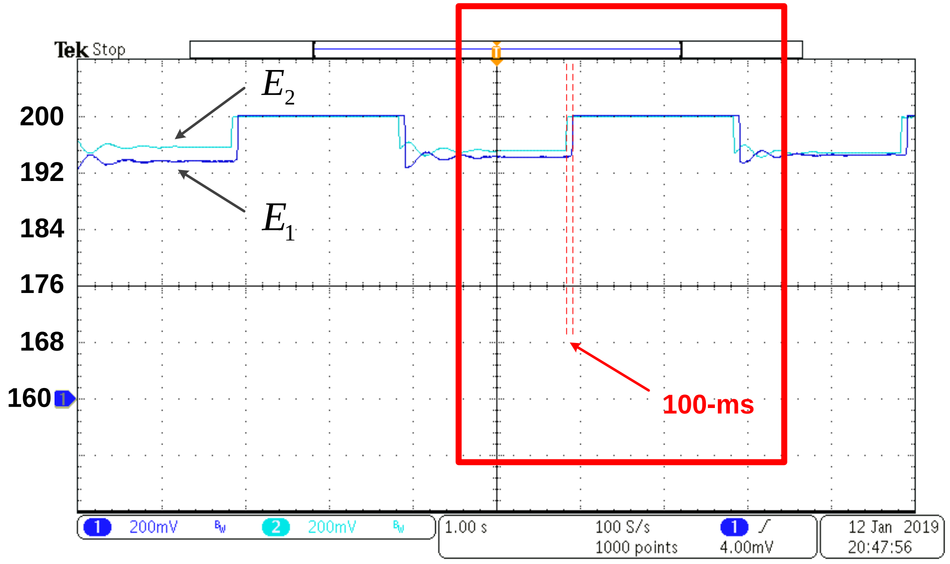



Reactive power proportional sharing

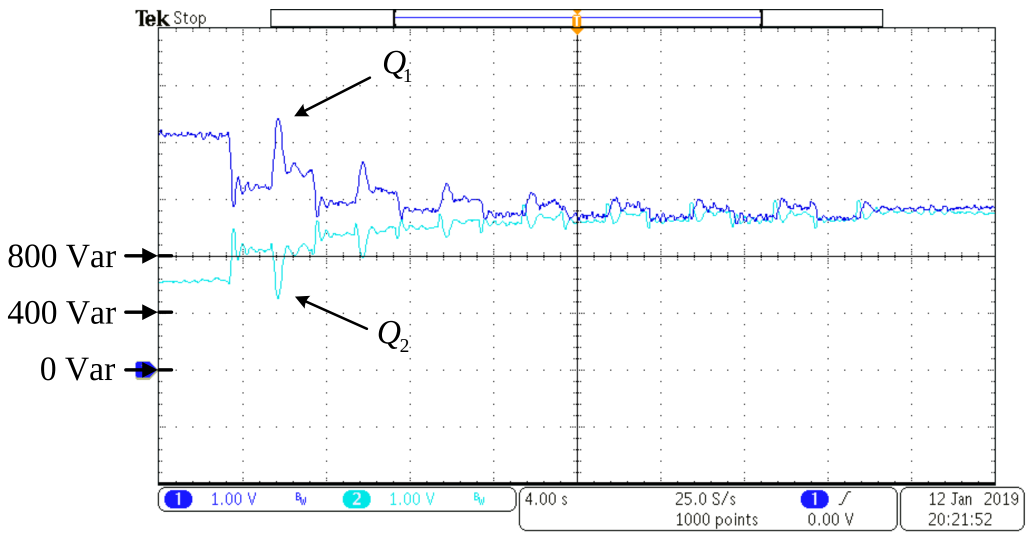
# Successive Approximation for Power Sharing

- **Successive-approximation-based virtual impedance tuning**

**Experimental results**




Voltage reference




Reactive power sharing

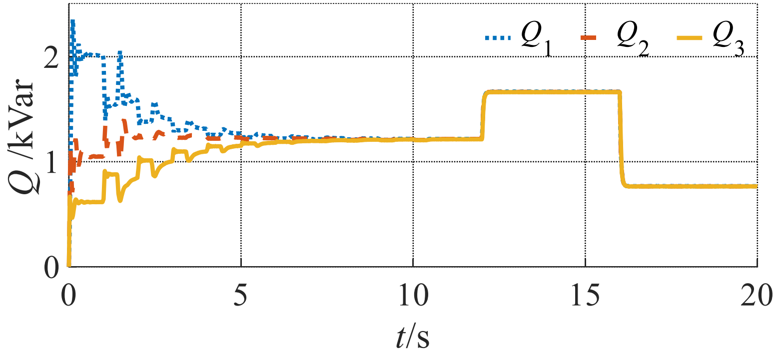
**Robust to time sequence difference**

# Successive Approximation for Power Sharing

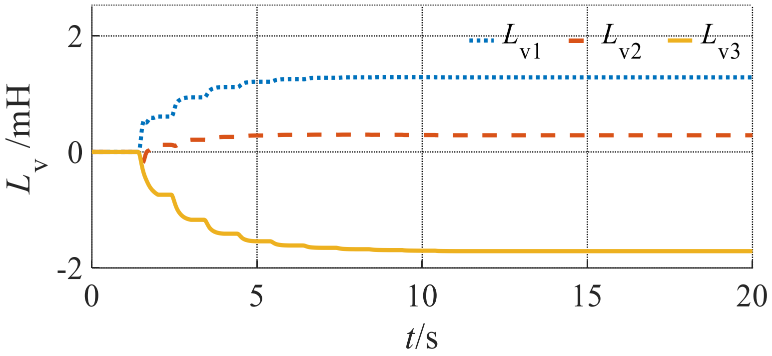
- **Successive-approximation-based virtual impedance tuning**

**Simulation results**

**Single-PCC structure**

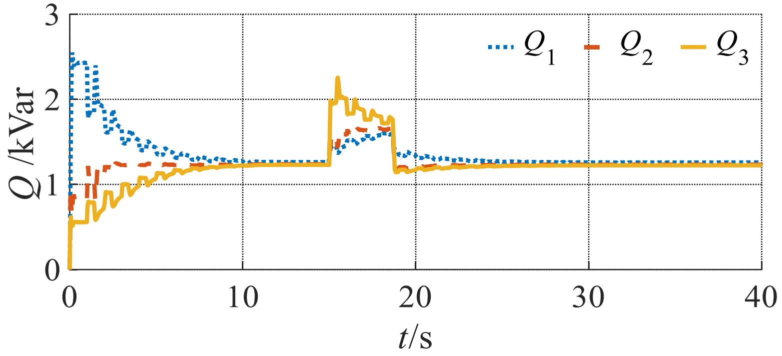



DG output reactive power

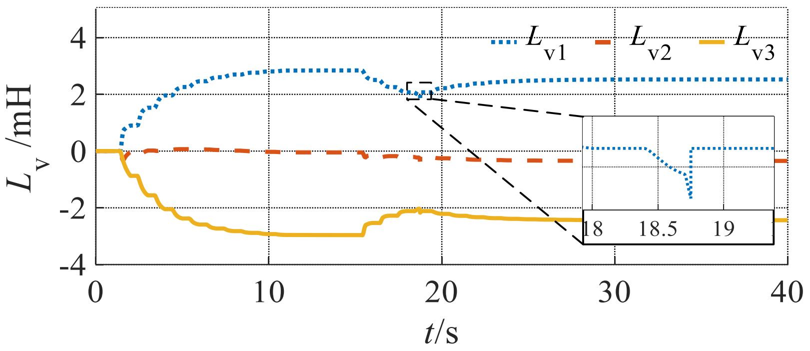



Virtual impedance

**Distributed structure**




DG output reactive power




Virtual impedance

# Successive Approximation for Power Sharing

- **Successive-approximation-based virtual impedance tuning**

**Summaries**

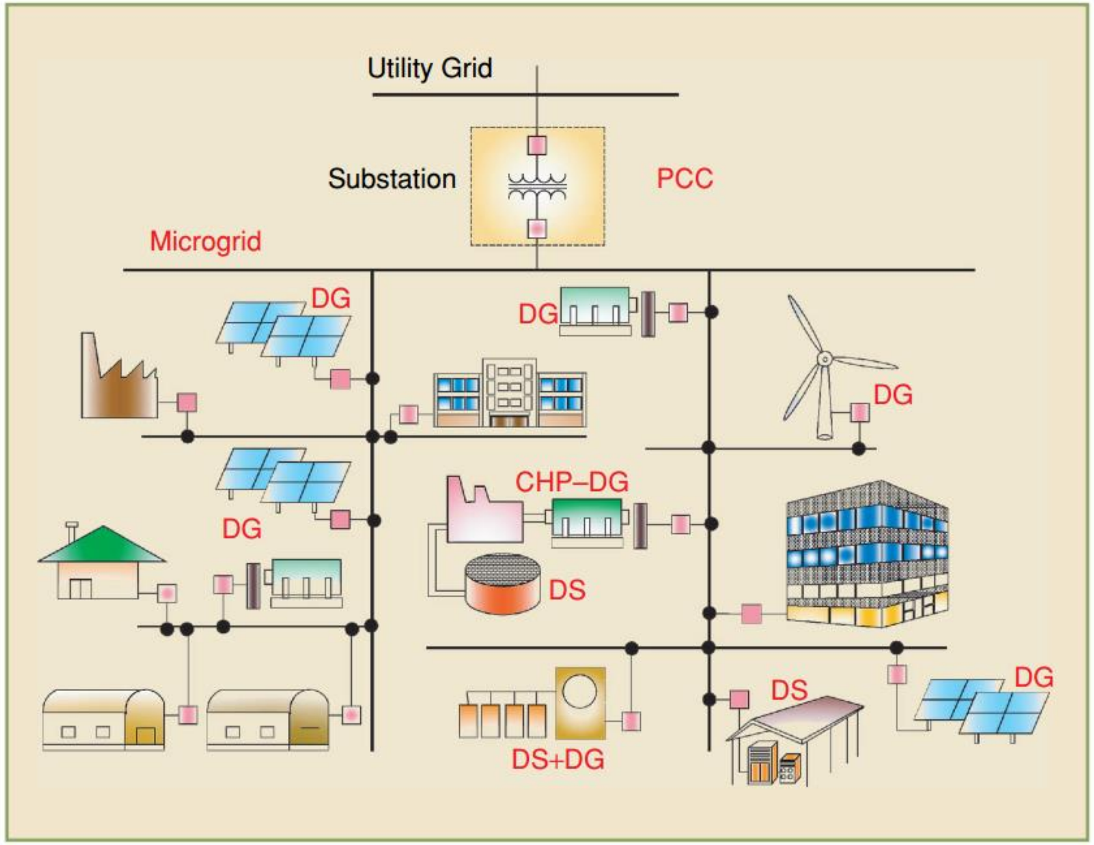
- Effectively compensating the mismatched line impedances to achieve accurate power sharing
- Balancing the original line impedances, no extra voltage amplitude deviations at the PCC
- **Easy implementation, plug and play, especially suitable for application scenarios with a large number of sources**
- Minimizing the dependency on communications

R. An, Z. Liu and J. Liu, "Successive-Approximation-Based Virtual Impedance Tuning Method for Accurate Reactive Power Sharing in Islanded Microgrids," in IEEE Transactions on Power Electronics, vol. 36, no. 1, pp. 87-102, Jan. 2021.

# Coordinative Control at Microgrid Level

## Microgrid

- a localized group of sources and loads with the capability to operate either as a **grid-connected** or as an **islanded system**



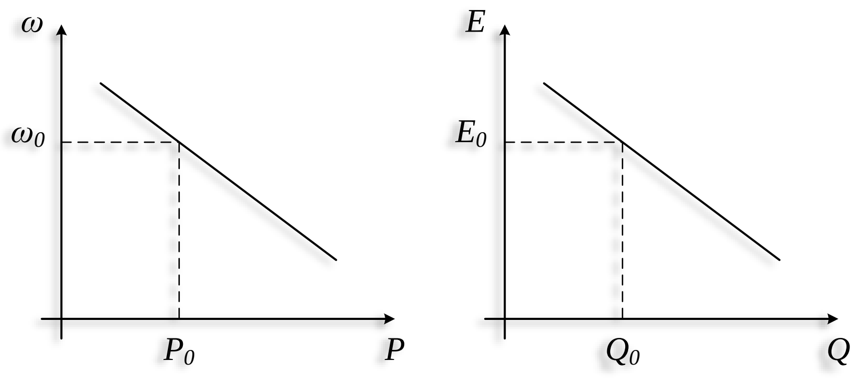

- **Grid-connected(GC) Mode**
  - DGs work together to achieve voltage regulation and supply local loads
- **Stand-alone(SA) Mode (Islanded Mode)**
  - DGs output power according to the demands from upper level control
- **Transition Process**
  - Seamless transfer between GC and SA operation modes

**DG control methods**

**Power stage (Physical Connection )**

# Coordinative Control at Microgrid Level

## Droop control in GC mode




**Control characteristics**

$$\omega = \omega_0 - k_p (P - P_0)$$

$$E = E_0 - k_q (Q - Q_0)$$

⇒

$$P - P_0 = \frac{\omega_g - \omega_0}{-k_p}$$

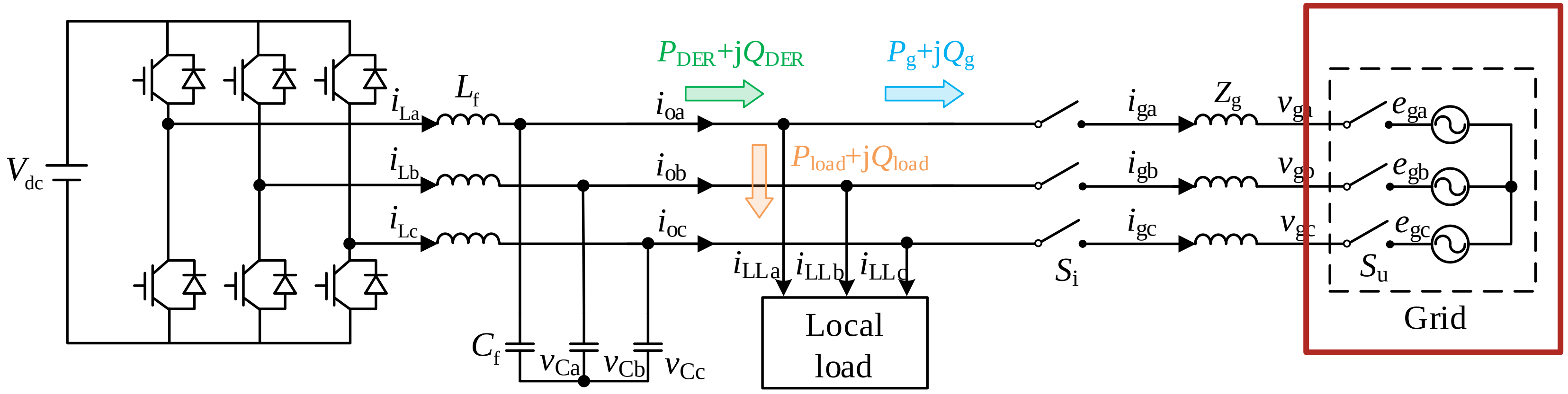
$$Q - Q_0 = \frac{E_g - E_0}{-k_q}$$

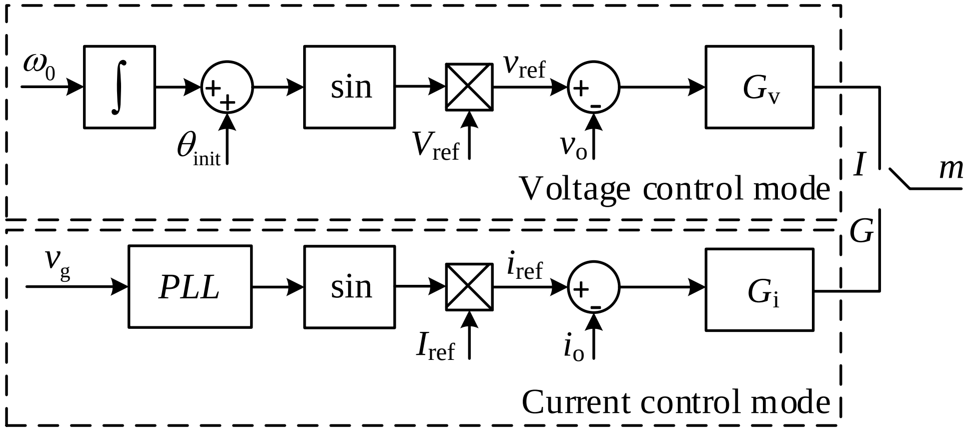
- **Bus voltage** is clamped by the **grid voltage** in GC Mode
- **DG output power** is also determined by the grid
  - When the grid is normal, i.e., $\omega_g = \omega_0$, there is $P = P_0$。
  - When the **grid frequency deviates and fluctuates**, i.e., $\omega_g \neq \omega_0$; since $k_p$ is small, the difference between $P$ and $P_0$ is large, and continuously changing.
  - when the **grid voltage is distorted**, the DG output current would contain harmonics
- **Poor dynamic performance** for power tracking

# Transfer of Control Strategies

## Hybrid current and voltage mode control

- Transfer **DG control structures** according to **system operating states**



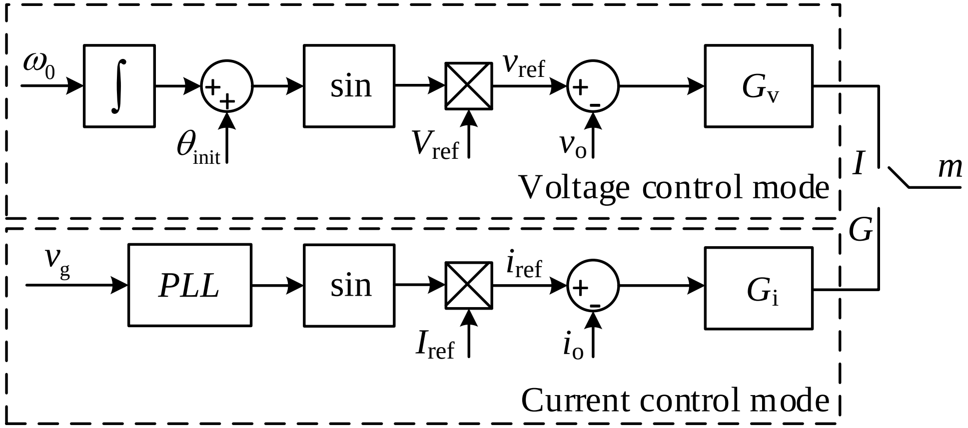




- **SA Mode**
  - DGs provide local voltage supports
  - ➔ Voltage control mode
- **GC Mode**
  - Strong external voltage source
  - ➔ Current control mode

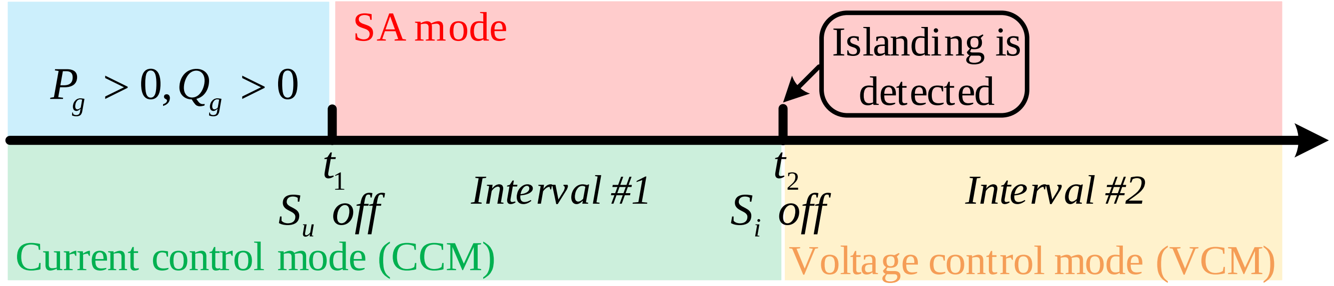
# Transfer of Control Strategies

## Hybrid current and voltage mode control

- Transfer **DG control structures** according to **system operating states**



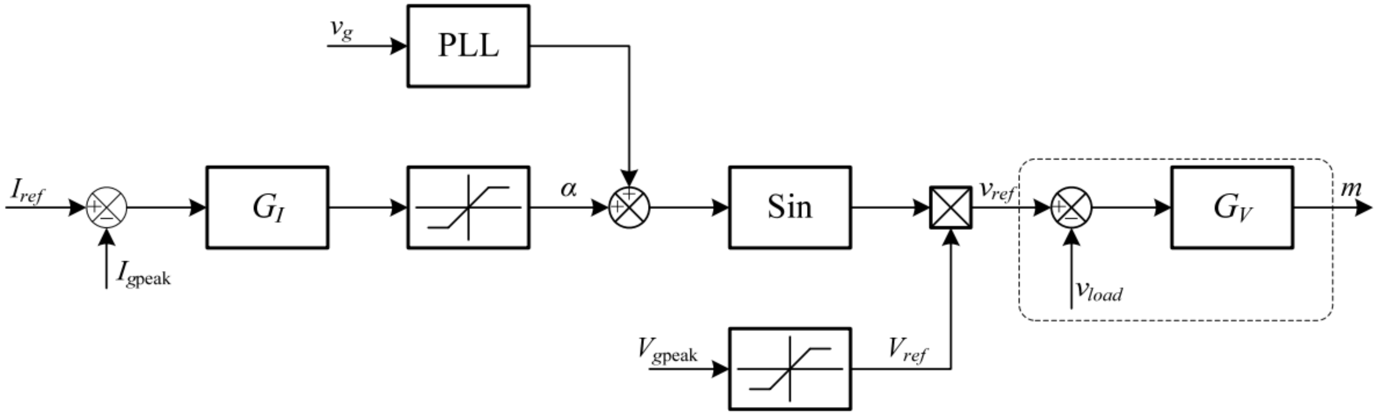

- ☹ **Undesired transients** when control mode transfers or reference changes
- ☹ Rely on **islanding detection** methods or **communication** with the grid interface to obtain the real-time operating state
- ☹ **Delays & possible mis-actions** may cause deterioration of voltage quality




Detailed process from GC to SA state

# Transfer of Control Strategies

- **Indirect current control**
  - **limiters in the control blocks become saturated or desaturated**
    - When islanding occurs, the change of operating states cause **the saturation of limiter**; the inverter changes from linear control region to nonlinear control region to realize **autonomous transfer of control strategies**
    - When the fault is cleared, the inverter returns to the linear control region.
  - **Seamless transfer & not rely on islanding detection**



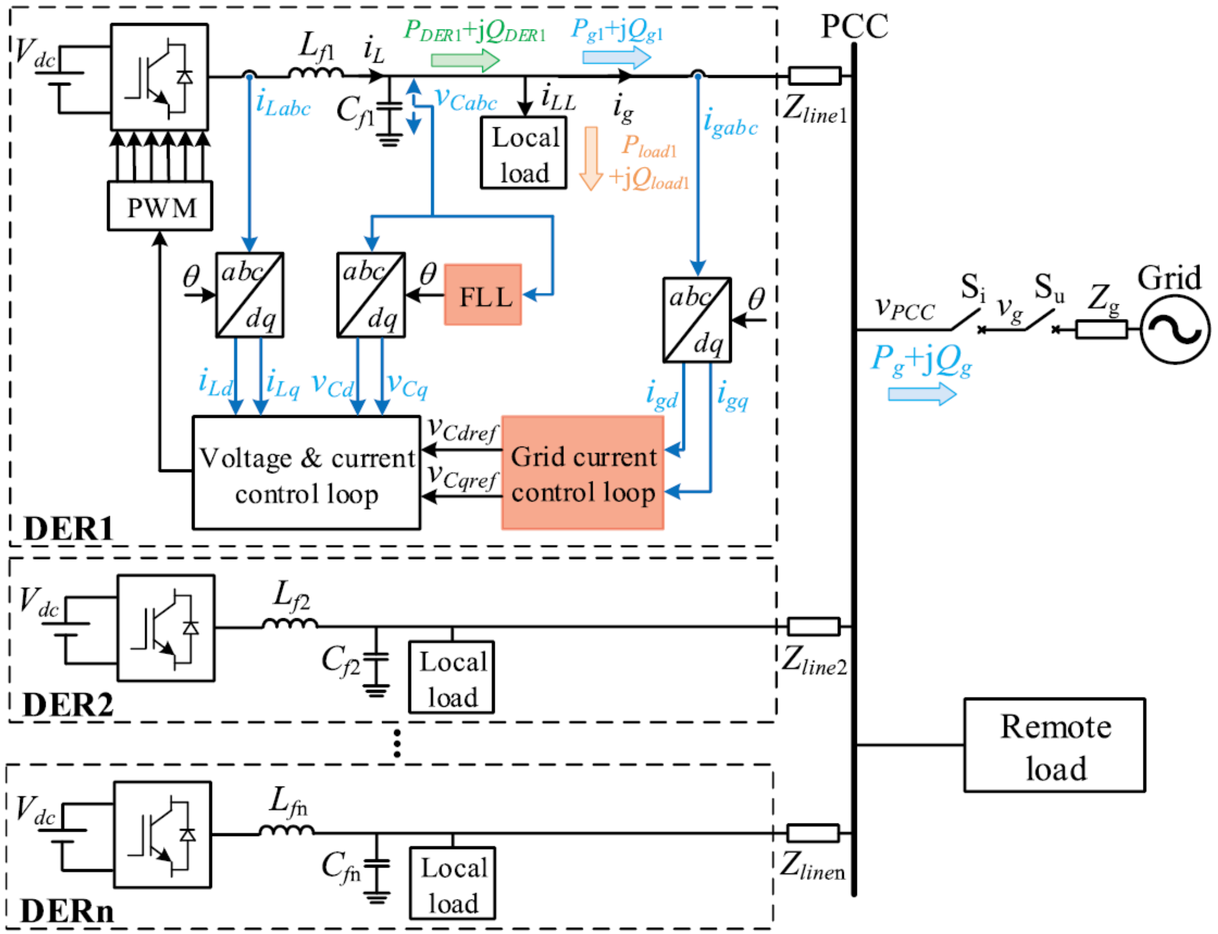

Control block of single-phase indirect current control method

- ☹ Nonlinearity in the control system make it **hard to design**
- ☹ **Load voltage deteriorates in case of nonlinear loads** because of the absence of inner voltage control
- ☹ **Physical meaning is not clear**

J. Kwon, S. Yoon and S. Choi, "Indirect Current Control for Seamless Transfer of Three-Phase Utility Interactive Inverters," in IEEE Transactions on Power Electronics, vol. 27, no. 2, pp. 773-781, Feb. 2012

# Transfer of Control Strategies

- A universal controller with seamless transfer capability
  - How to avoid these drawbacks?



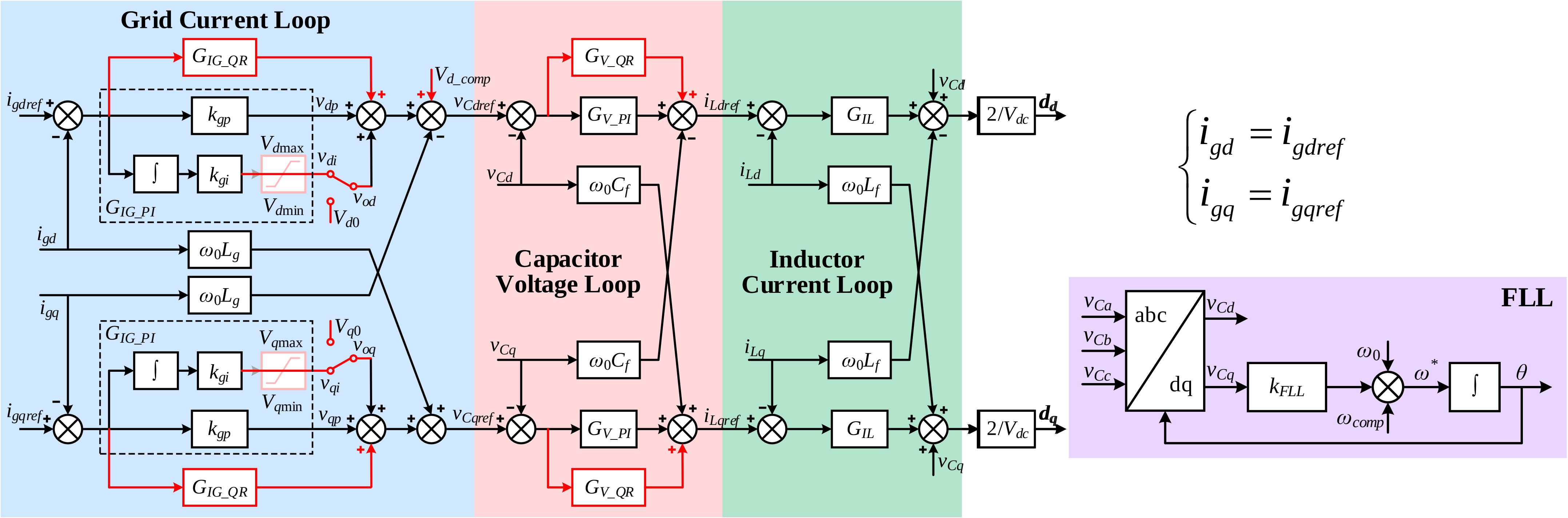

- **Improved indirect current control:**
  - $S_u$ is controlled by the grid.
  - $S_i$ is controlled by the microgrid.
  - Autonomously transfer DG control structures according to the model of **three-phase DG system in the SRF**
  - Physical meaning is more clear
  - **Synchronization of multiple inverters** are considered.
  - Regulate the grid current accurately when the grid voltage is **distorted** in GC mode

# Transfer of Control Strategies

- A universal controller with seamless transfer capability

**GC mode**

- Grid current loop + capacitor voltage loop + inductor current loop
- Grid current is not limited.
- QR controllers are used to suppress 5th and 7th harmonics.



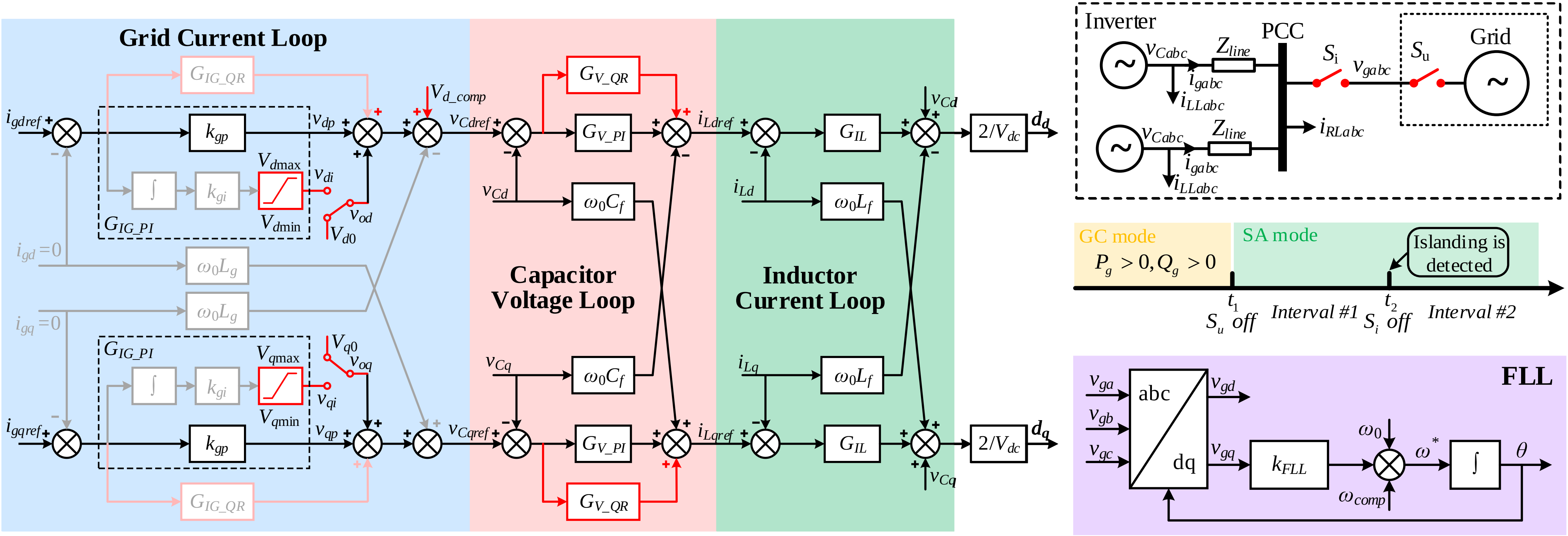

$$\begin{cases} i_{gd} = i_{gdref} \\ i_{gq} = i_{gqref} \end{cases}$$

# Transfer of Control Strategies

- A universal controller with seamless transfer capability

GC mode to SA mode

- $t_1$: $S_u$ turns-off, $i_{gd}$=0, $i_{gq}$=0.
- $t_1$~$t_2$: $v_{di}$ increases and $v_{qi}$ decreases until $v_{di}$=$V_{dmax}$ and $v_{qi}$=$V_{qmin}$, $G_{IG\_QR}$ changes from PI controller to P controller.
- t2: islanding is detected, $G_{IG\_QR}$ stops working to improve power quality, $v_{od}$ and $v_{oq}$ switch to $V_{d0}$ and $V_{q0}$ respectively.



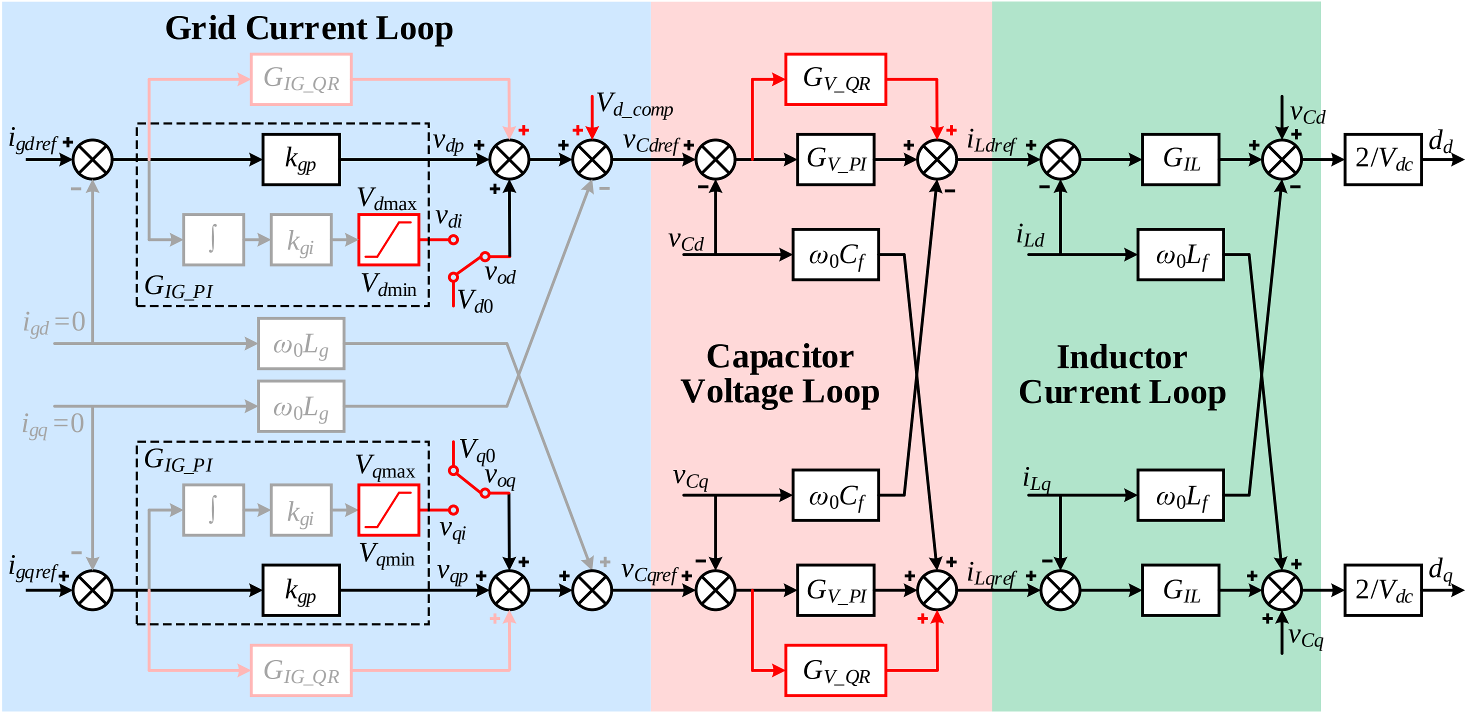
# Transfer of Control Strategies

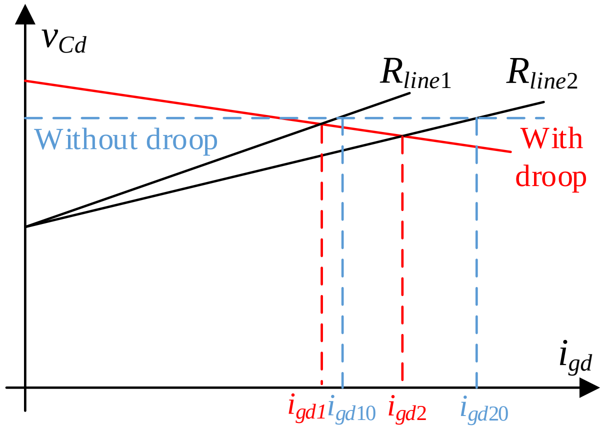
- **A universal controller with seamless transfer capability**

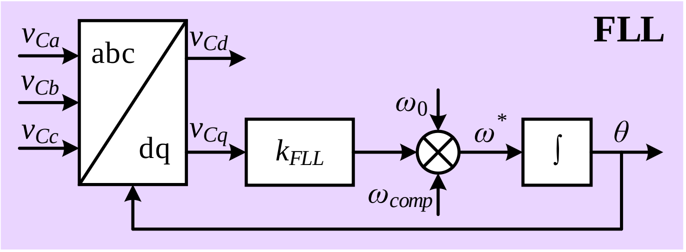
SA mode

– A droop relationship between $i_{gq}$ and $\omega^*$

$$\begin{cases} v_{Cdref} = V_{d0} + k_{gp} \cdot (i_{gdref} - i_{gd}) \\ v_{Cqref} = V_{q0} + k_{gp} \cdot (i_{gqref} - i_{gq}) \end{cases} + \quad \omega^* = \omega_0 + k_{FLL} \cdot v_{Cq} \Rightarrow \omega^* - \omega_0 = k_{FLL} \cdot k_{gp} \cdot (i_{gqref} - i_{gq})$$



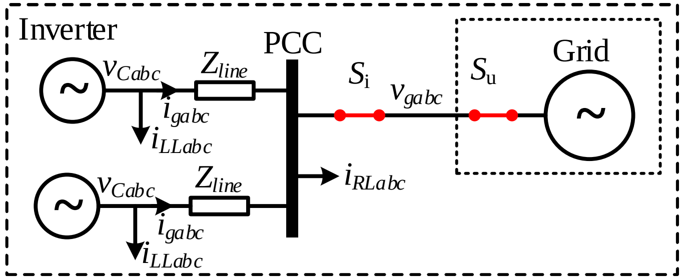



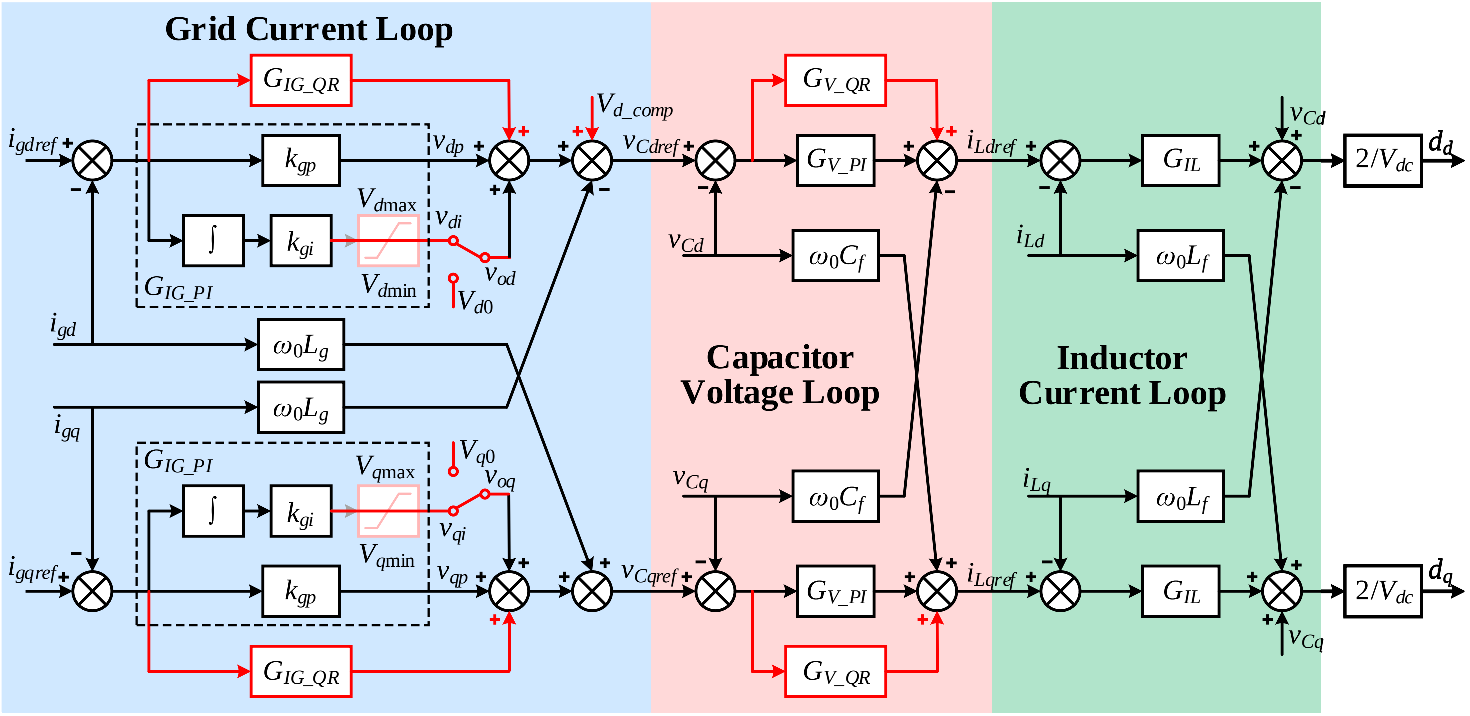
# Transfer of Control Strategies

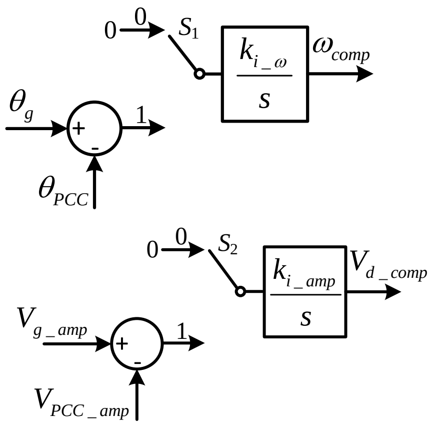
- **A universal controller with seamless transfer capability**

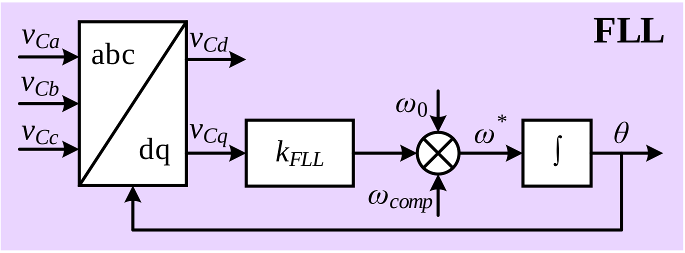
SA mode to GC mode

- Grid voltage is restored, $S_u$ turns-on.
- $v_{od}$ and $v_{oq}$ switch to $v_{di}$ and $v_{qi}$.
- $S_1$ and $S_2$ switch to channel 1 for pre-synchronization.
- $S_i$ turns-on.



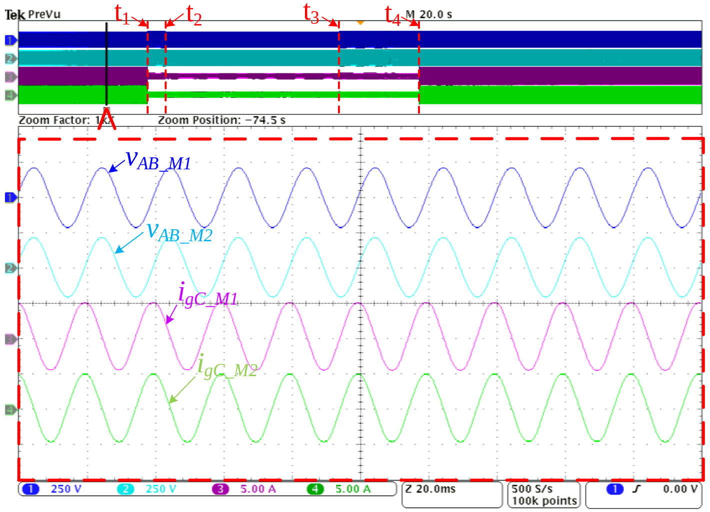



# Transfer of Control Strategies

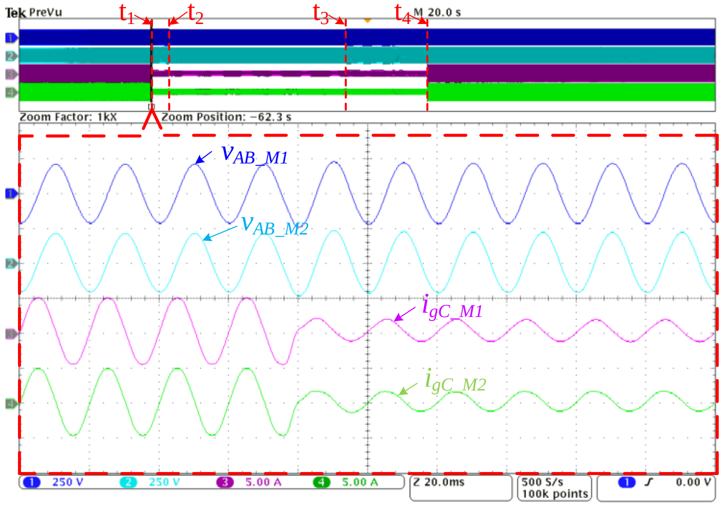
- A universal controller with seamless transfer capability

**Experimental results**

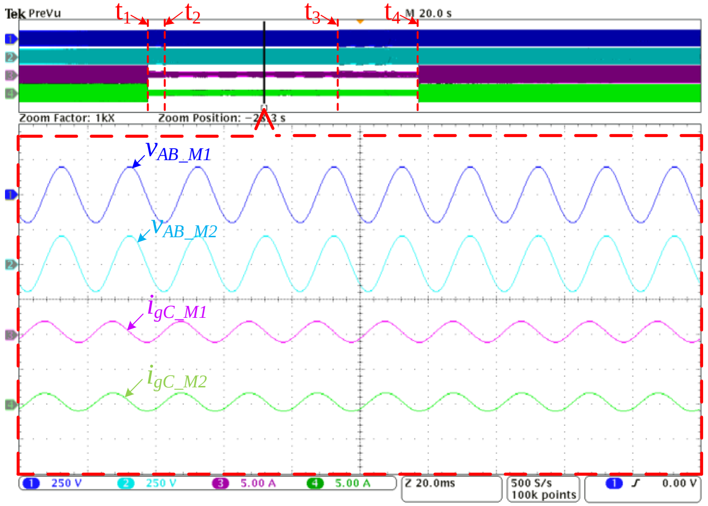
**GC mode**



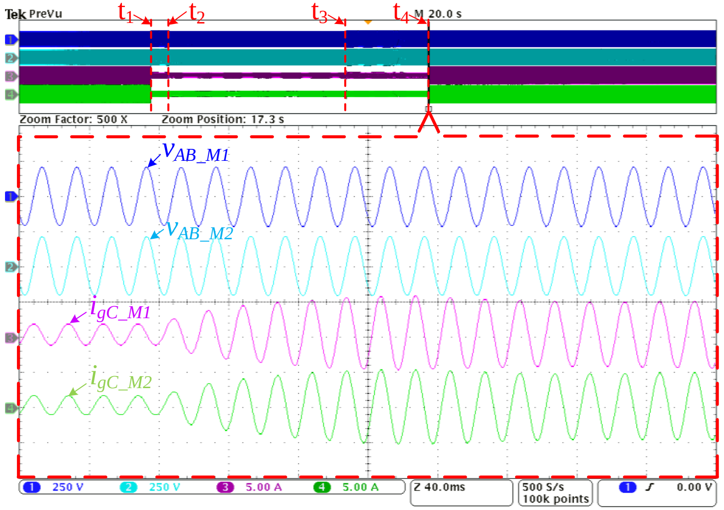

**From GC to SA**




**SA mode**




**From SA to GC**



# Transfer of Control Strategies

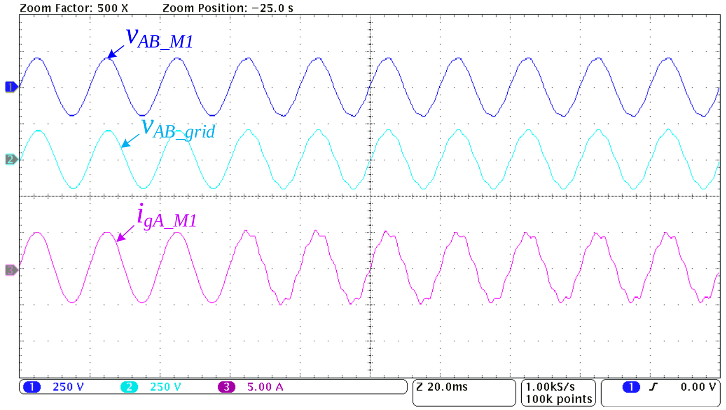
- **A universal controller with seamless transfer capability**

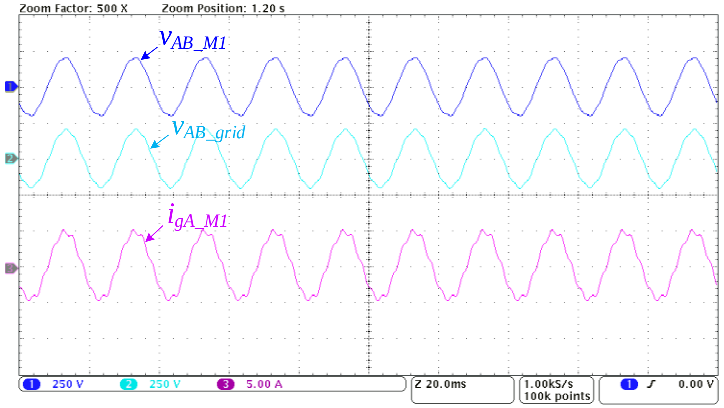
**Experimental results**

Harmonic is inserted

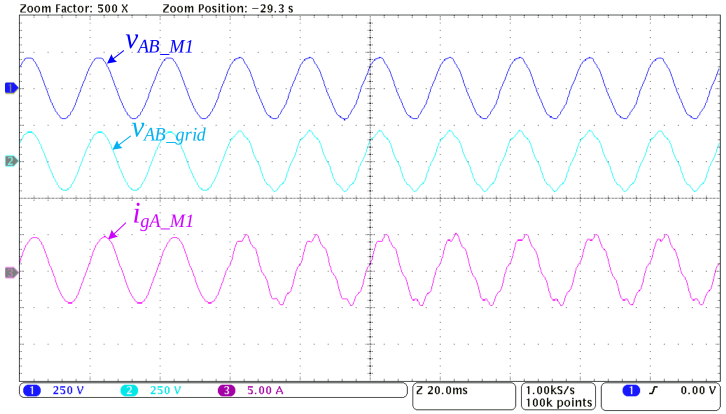
After some time

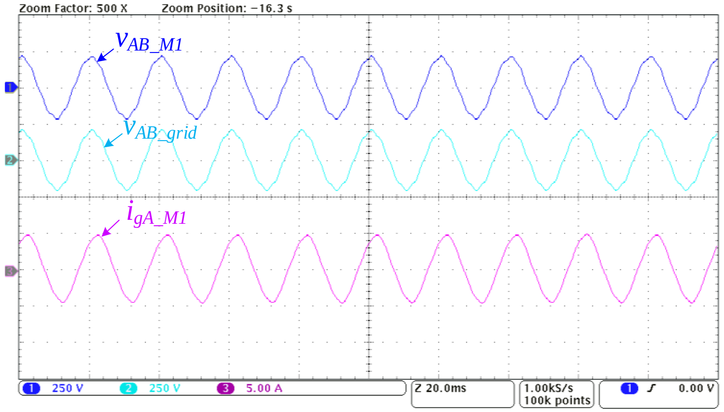
**Droop control**




**Proposed control**

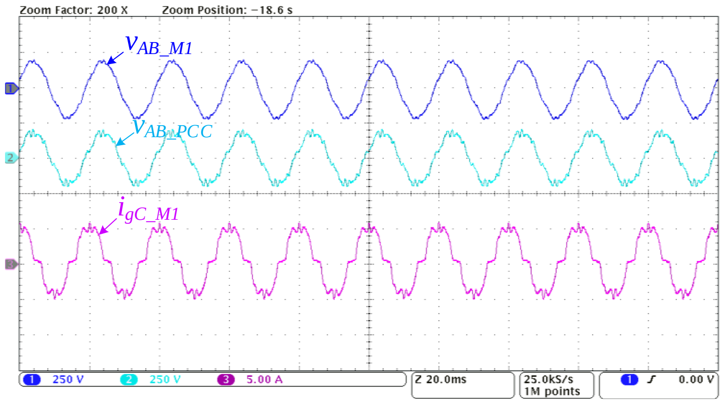


# Transfer of Control Strategies

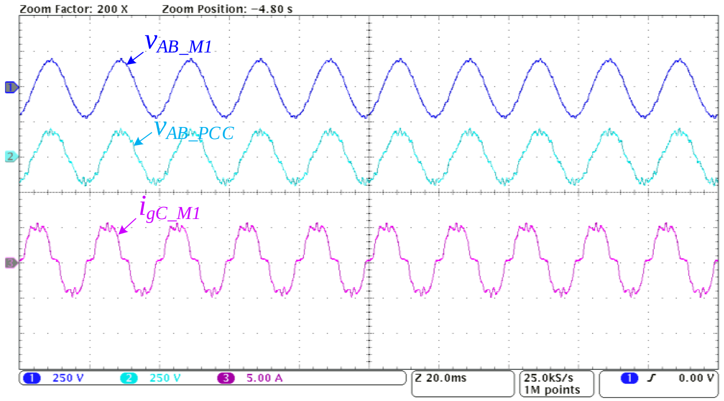
- **A universal controller with seamless transfer capability**

## Experimental results




### Droop control

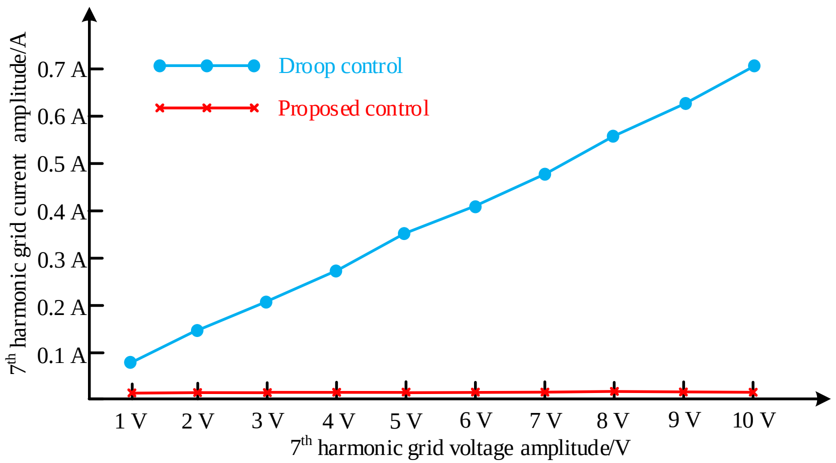
| Order | U1 [V] | hdf[%] | Order | U1 [V] | hdf[%] |
|---|---|---|---|---|---|
| Total | 142.9 | | dc | --------- | ------- |
| 1 | 142.8 | 99.88 | 2 | 0.2 | 0.14 |
| 3 | 1.5 | 1.03 | 4 | 0.0 | 0.03 |
| 5 | 5.1 | 3.55 | 6 | 0.1 | 0.04 |
| 7 | 3.3 | 2.32 | 8 | 0.1 | 0.09 |
| 9 | 0.1 | 0.07 | 10 | 0.1 | 0.09 |
| 11 | 1.5 | 1.02 | 12 | 0.1 | 0.05 |
| 13 | 2.1 | 1.45 | 14 | 0.1 | 0.05 |
| 15 | 0.5 | 0.38 | 16 | 0.2 | 0.15 |




### Proposed control

| Order | U1 [V] | hdf[%] | Order | U1 [V] | hdf[%] |
|---|---|---|---|---|---|
| Total | 142.9 | | dc | --------- | ------- |
| 1 | 142.9 | 99.98 | 2 | 0.2 | 0.16 |
| 3 | 1.5 | 1.03 | 4 | 0.1 | 0.04 |
| 5 | 0.3 | 0.22 | 6 | 0.0 | 0.03 |
| 7 | 0.2 | 0.13 | 8 | 0.1 | 0.05 |
| 9 | 0.2 | 0.15 | 10 | 0.1 | 0.05 |
| 11 | 1.5 | 1.07 | 12 | 0.0 | 0.03 |
| 13 | 1.6 | 1.13 | 14 | 0.1 | 0.07 |
| 15 | 0.6 | 0.43 | 16 | 0.2 | 0.13 |

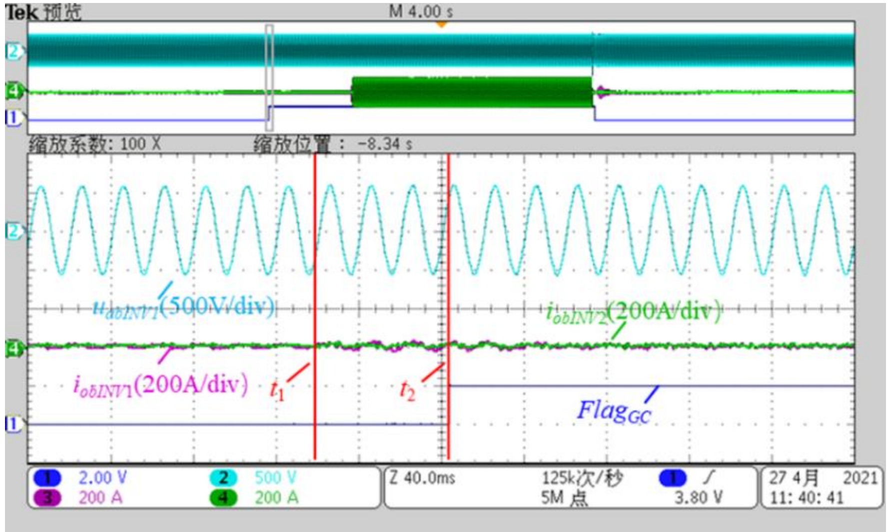
### Comparison



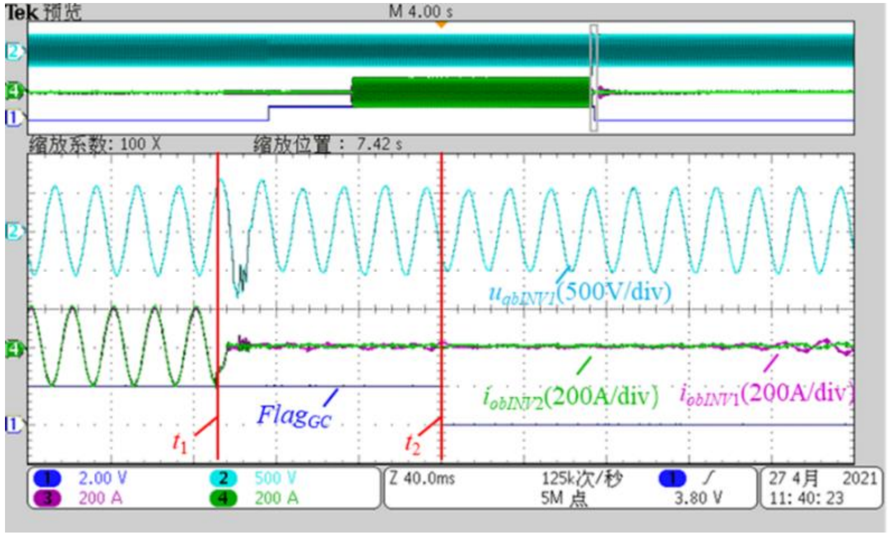
# Transfer of Control Strategies

- **Practical application： KEHUA Project**
  - Good performance in all operating states achieved after the universal controller with seamless transfer capability applied.

| Technical parameters | |
|---|---|
| Power rating | 100kVA |
| Line-to-line voltage | 400V |
| Load condition (SA to GC) | No load |
| Power setpoint in GC (GC to SA) | 100kW |


Transition from SA state to GC state




Transition from GC state to SA state

# Transfer of Control Strategies

- **A universal controller with seamless transfer capability**

**Summaries**

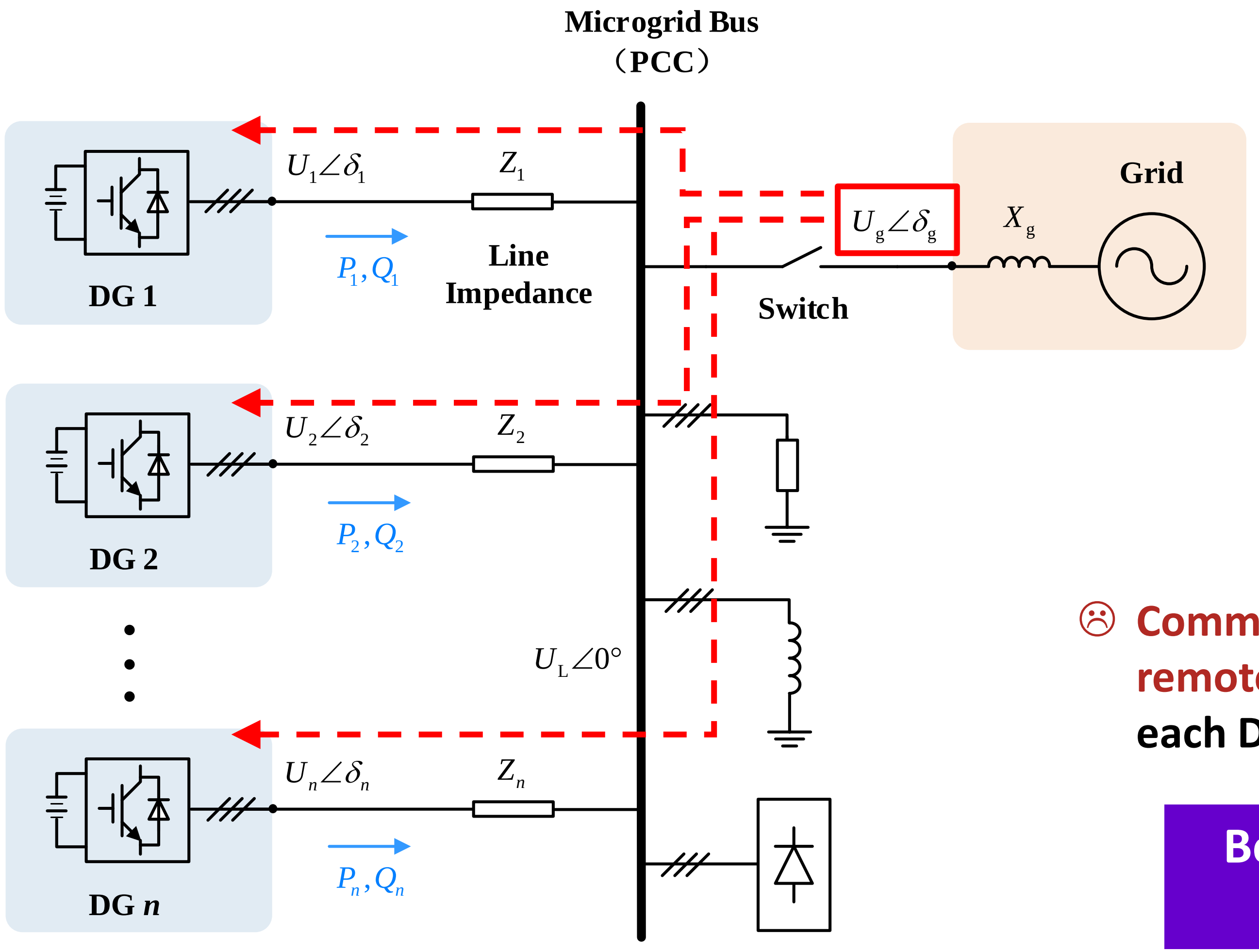
- The transfer of control targets between SA and GC mode is seamless
- Does not rely on islanding detection methods or communication with the grid interface to obtain the system operating states.
- The physical meaning of the Indirect Current Control is more clear for three-phase DG system in the SRF.
- In microgrid system consisting of multiple DGs, the power quality is guaranteed in case of nonlinear loads and grid distortion.

Z. Liu and J. Liu, "Indirect Current Control Based Seamless Transfer of Three-phase Inverter in Distributed Generation," *IEEE Transactions on Power Electronics*, vol. 29, no. 7, pp. 3368–3383, Jul. 2014.

X. Meng, Z. Liu, H. Zheng, and J. Liu, "A Universal Controller Under Different Operating States for Parallel Inverters With Seamless Transfer Capability," *IEEE Transactions on Power Electronics*, vol. 35, no. 9, pp. 9796–9814, Sep. 2020.

# Coordinative Control at Microgrid Level

## Barrier for fully-autonomous microgrid




- When transferring from SA state to GC state, the microgrid voltage should be **synchronized** with the grid voltage
- Numerous dispersed sources are far from the grid interface

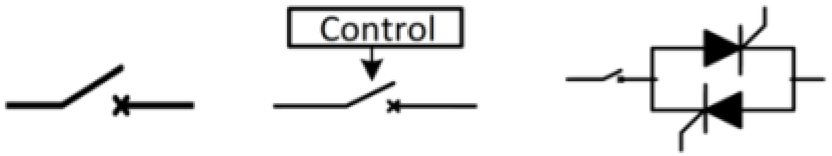
⇩

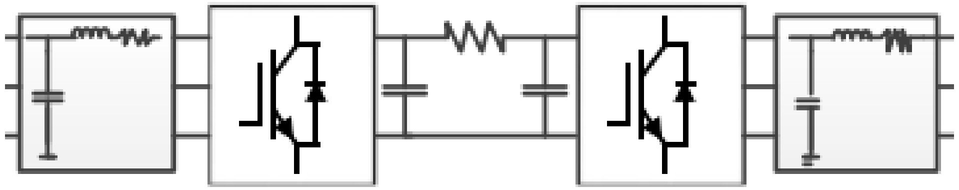
☹ **Communication is required to send the remote information at the grid interface to each DG for pre-synchronization!**

**Becomes the barrier for fully-autonomous microgrid**

# Flexible Transfer Converter

- **Conventional grid interface**



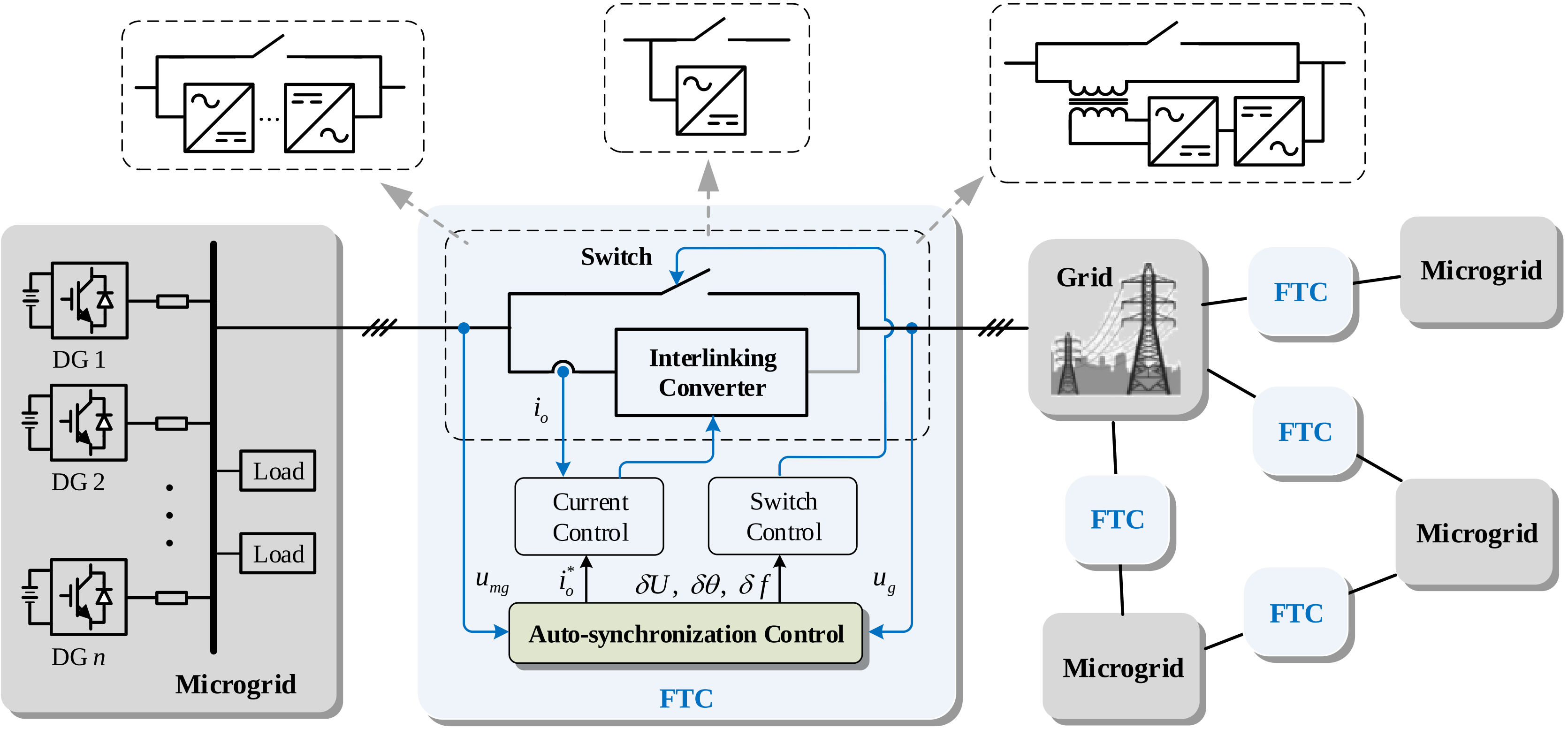



- **Switch:**
  - ✓ e.g., static transfer switch, mechanic switch, etc.
  - ☺ High efficiency
  - ☺ Low cost
  - ☺ High reliability
  - ☺ High Current Carrying Capability
  - ☹ Fail to control the power flow
  - ☹ Hard to re-connect after faults

- **Interlinking Converter (IC):**
  - ✓ e.g., back-to-back converter, matrix converter, UPQC, SST, etc.
  - ☺ Controllable power flow
  - ☺ Auxiliary services
  - ☹ Low efficiency
  - ☹ High cost
  - ☹ Low reliability
  - ☹ Power dispatch restricted by capacity

# Flexible Transfer Converter

## Concept of Flexible Transfer Converter (FTC)

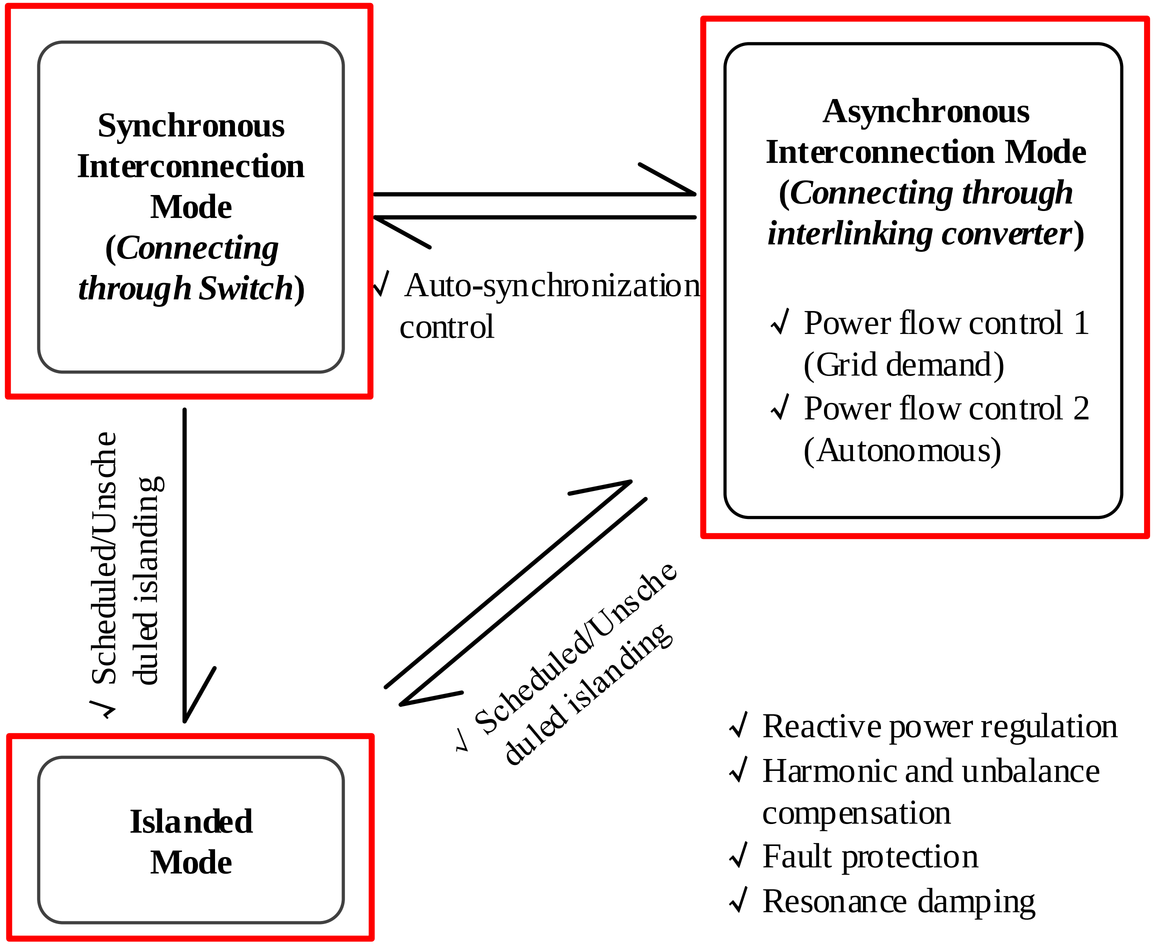



- Enabling **autonomous control** of microgrids, even for re-connection
- **Fast and soft disconnection/re-connection**
- **Possible auto-synchronization** while connected and dispatching of power
- Different topologies and control strategies for **normally-islanded** and **normally-connected microgrids**

# Flexible Transfer Converter

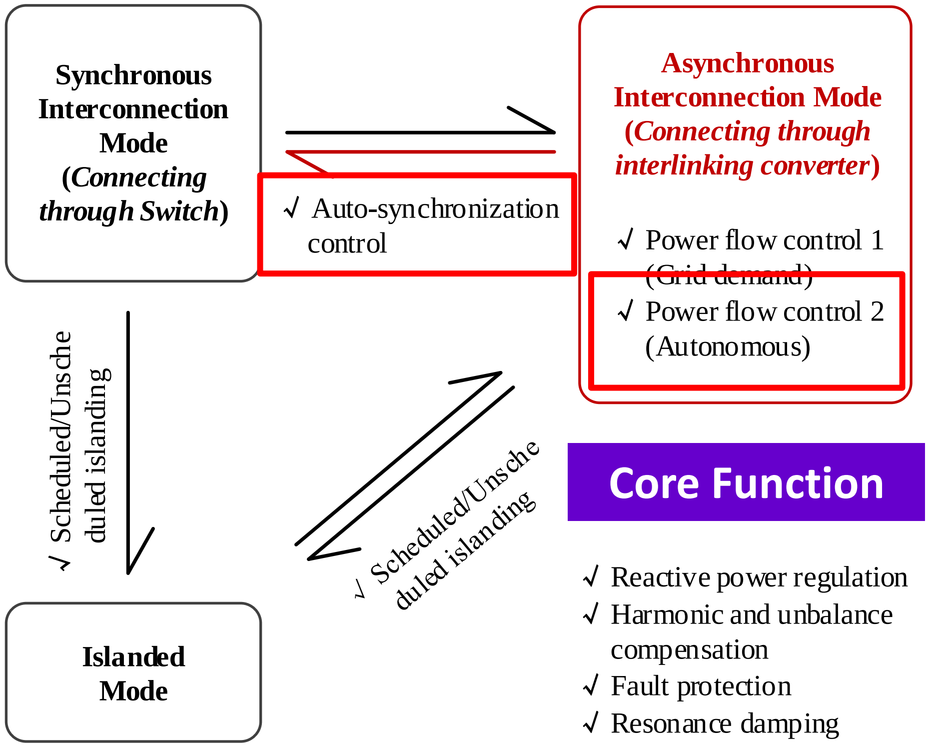
## Concept of Flexible Transfer Converter (FTC)

- **Three basic operating modes:**
  - Achieve fast and soft re-connection, dispatch power in response to grid demands or based on local measurements in the **Asynchronous Connection Mode**.
  - Auto-synchronize both sides and smoothly transfer to the **Synchronous Connection Mode** to reduce transmission losses or handle IC capacity shortage.
  - When islanding occurs, the FTC stops power dispatching and transfers to the **Islanded Mode**.



# Flexible Transfer Converter

## Asynchronous Connection Mode




- **DGs need to provide voltage regulation in SA mode**

➔ working under droop control or VSG control:

$$\omega = \omega_0 - k_p (P - P_0)$$

- By controlling $P$, the frequency and phase can be indirectly controlled to **achieve pre-synchronization**
- Bus frequency reflects mismatch between $P$ and $P_0$
- Based on this, the **power flow** at the grid interface can be optimized

$$V = V_0 - k_q (Q - Q_0)$$

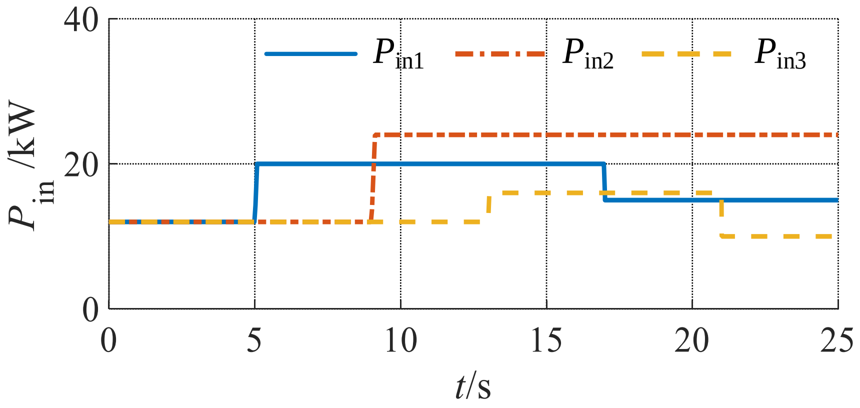
- Similar for $Q$ and $V$

# Flexible Transfer Converter

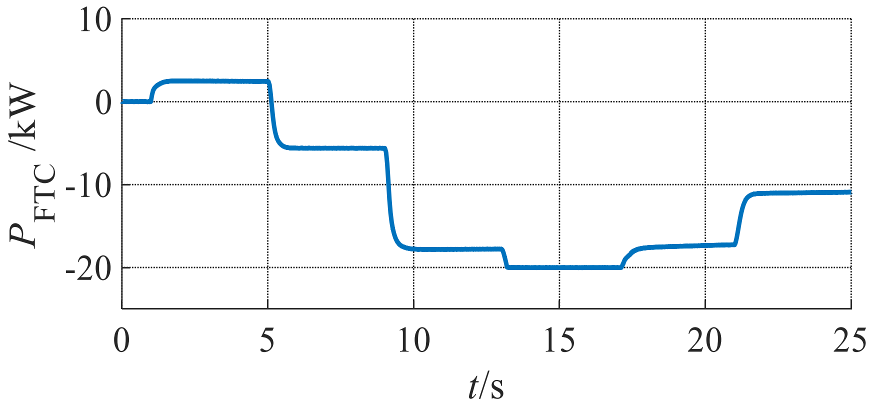
- **Control of a general-purpose FTC**

**Simulation results**

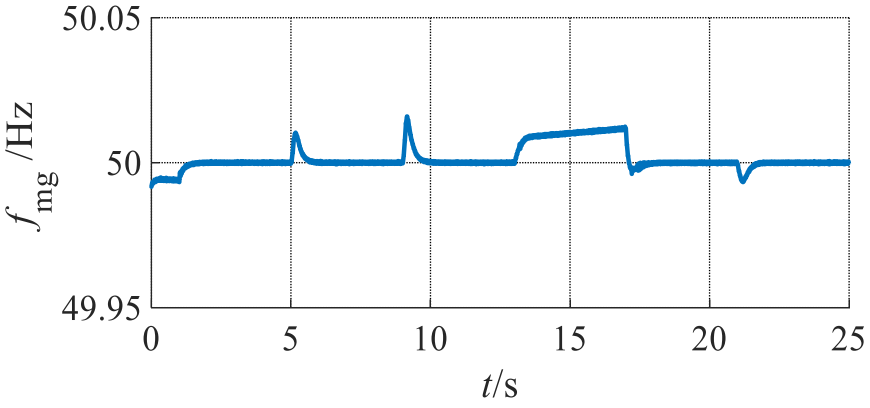
**Autonomous power control**



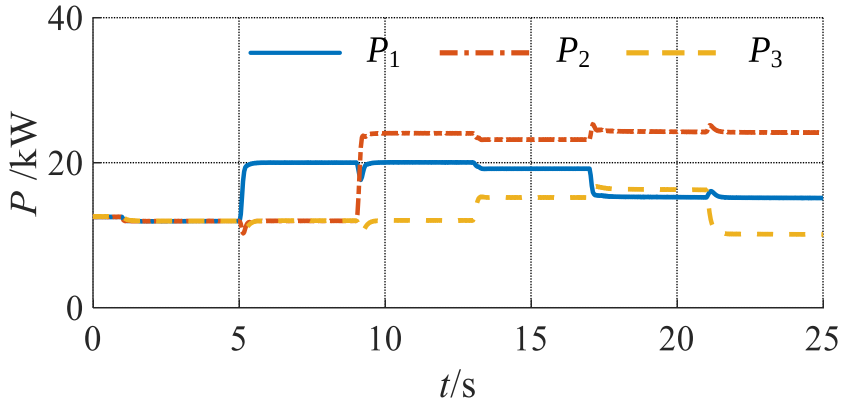

RES generation power




FTC output active power




Bus frequency



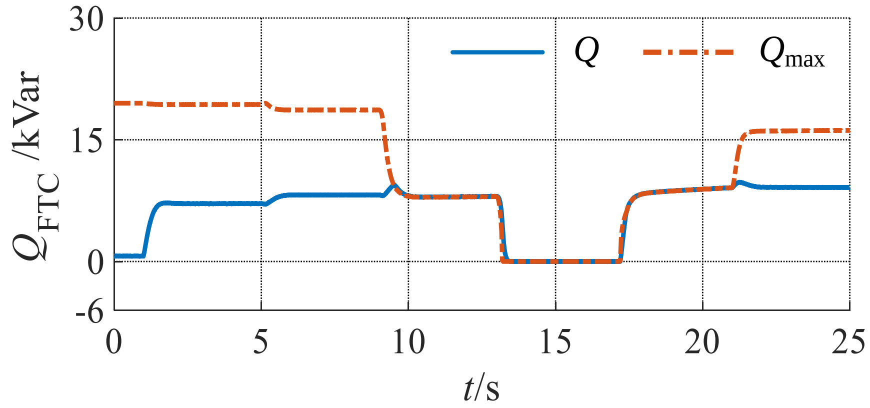

DG output active power

# Flexible Transfer Converter

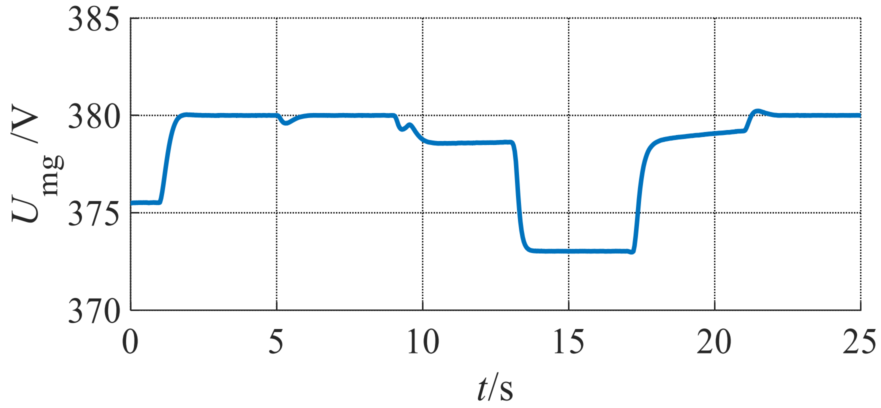
- **Control of a general-purpose FTC**

**Simulation results**

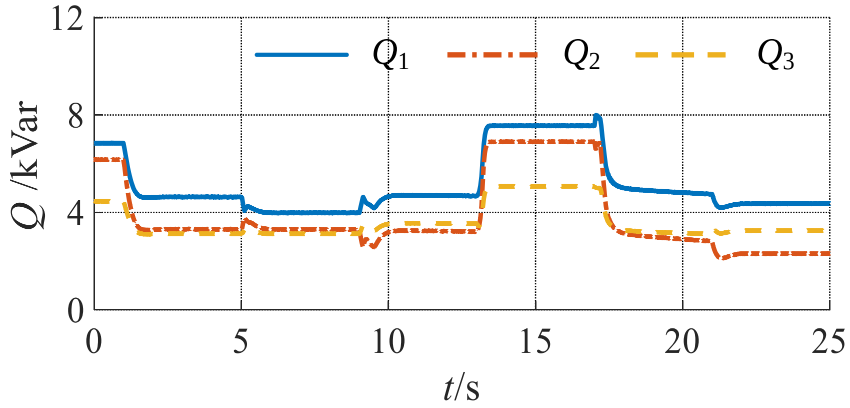
**Autonomous power control**



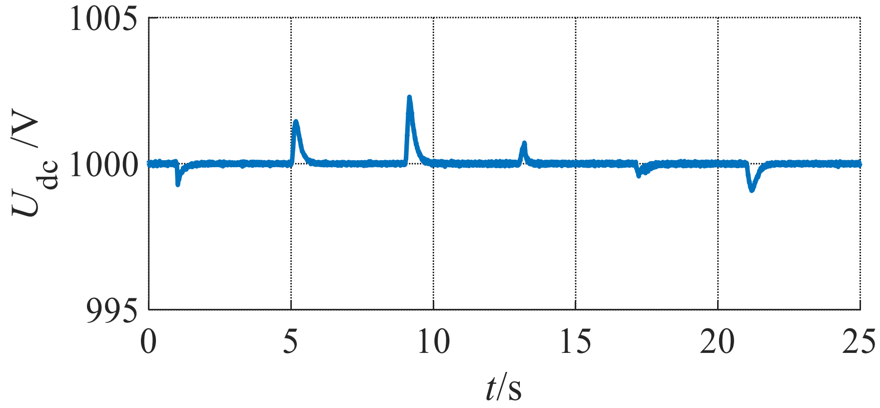

FTC output reactive power




Bus voltage amplitude




DG output reactive power



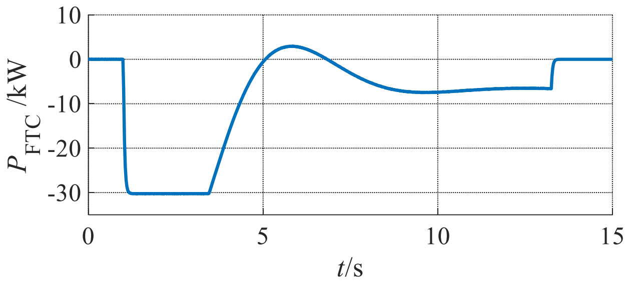

FTC DC-side voltage

# Flexible Transfer Converter

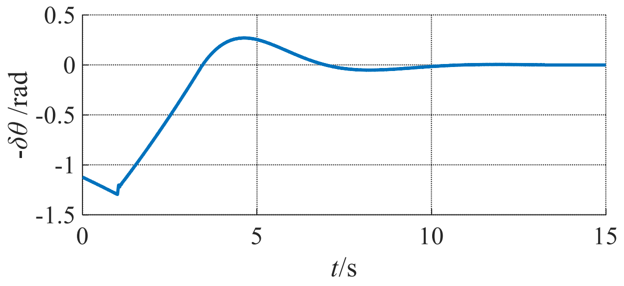
## ▪ Control of a general-purpose FTC

**Simulation results**

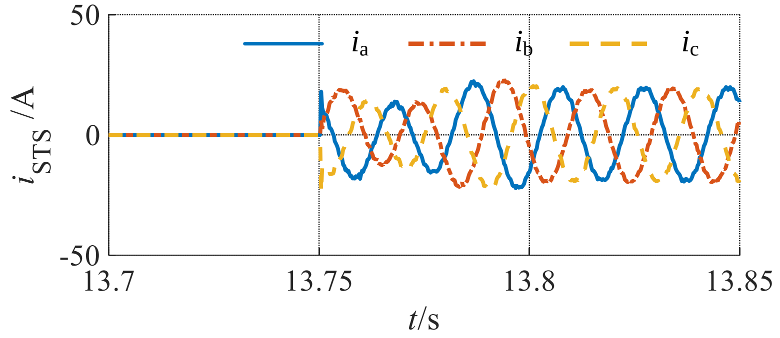
**Auto-synchronization control**



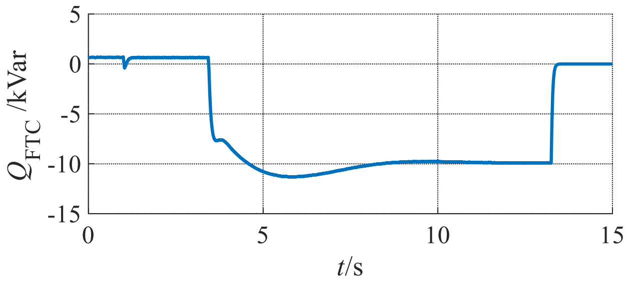

FTC output active power



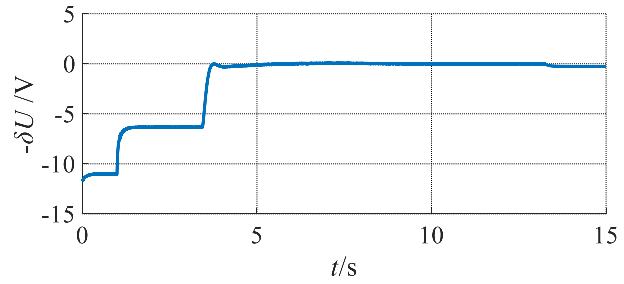

Phase difference




Inrush currents on the switch




FTC output reactive power

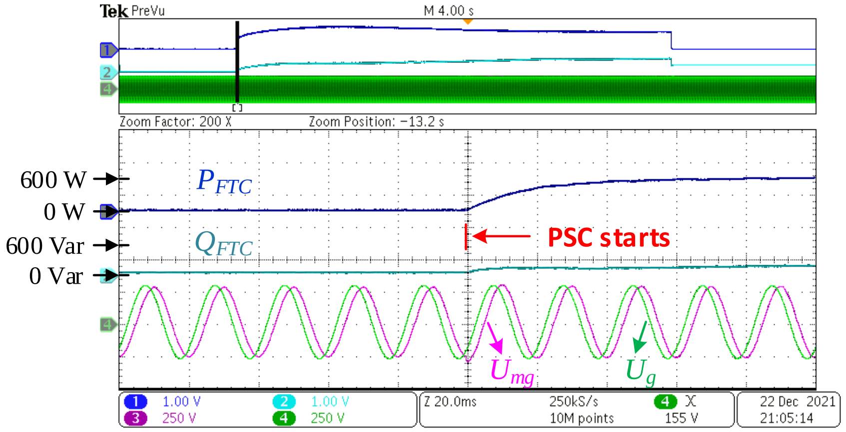


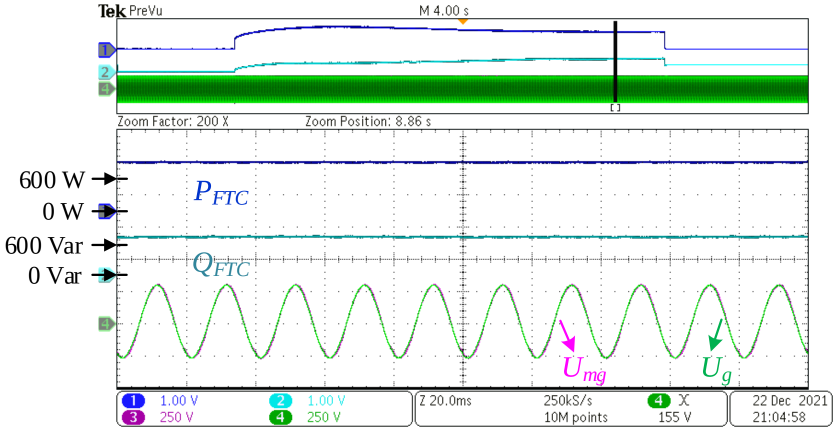

Amplitude difference

# Flexible Transfer Converter

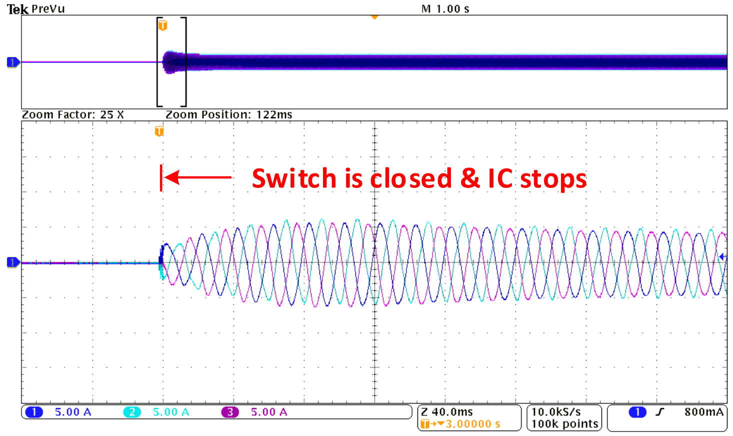
- **Control of a general-purpose FTC**

## Experimental results

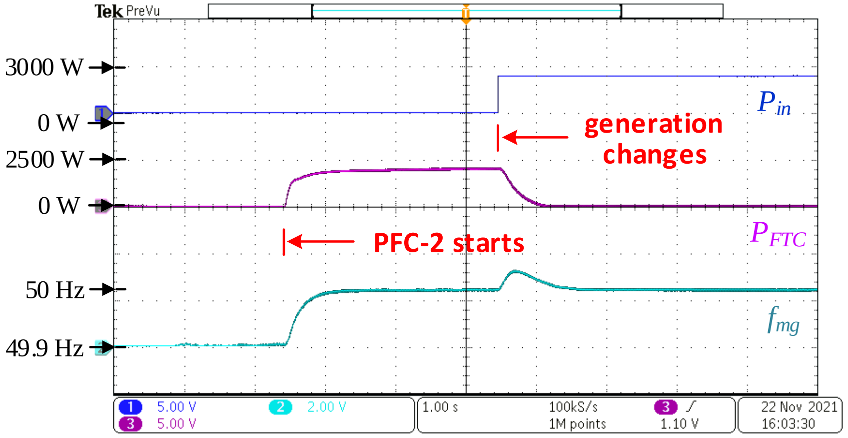



Auto-synchronization process




Inrush currents on the switch




Autonomous power control

# Flexible Transfer Converter

## Flexible Transfer Converter

### Summaries

- Compared to conventional interfaces,  the FTC enhances the flexibility, reliability and efficiency, while also extending the IC's service life to its maximum extent.
- A universal FTC properly controls the power dispatch and flexibly switch the microgrid between different modes without communications with DGs.
- Universal DG control is necessary to coordinate with the FTC in a decentralized manner.

- **Simplified topologies and control strategies for normally-islanded and normally-connected FTCs is under study.**

R. An, J. Liu, Z. Liu and Z. Song, "Flexible Transfer Converters Enabling Autonomous Control and Power Dispatch of Microgrids," in IEEE Transactions on Power Electronics, vol. 37, no. 11, pp. 13767-13781
R. An, J. Liu, Z. Song, Z. Liu and Y. P. Y. Deng, " A Control Method for Flexible Transfer Converter to Enable Autonomous Control of AC Microgrids," 2022 IEEE Applied Power Electronics Conference and Exposition (APEC), Houston, TX, USA, 2022.

# Other Issues for Advanced Coordinative Control

- Decoupling of the two power channels
- Precise voltage amplitude control for complex network
- Dynamic power sharing
- Small-signal stability

# Plug-and-Play Grid-Organizing Framework

- The merits of today's power grid

  A few big non-electronic producers dominate a grid

  - Plug and play
  - Does not usually need real-time communications

  - Steady-state operating point determined by
    - Coordination among the big producers
    - Loaded/regenerated power of each load and small producer
  - Stability determined by the big producers

# Plug-and-Play Grid-Organizing Framework

- The really critical challenge for future power grids
  - High ratio of big electronic producers at large grid level
  - Numerous small electronic or non-electronic producers, consumers, and prosumers at micro-grid level
  - Frequent disconnection and re-connection between micro-grid and large grid

To develop a framework of standards specifying structure and working state of micro-grids, and terminal characteristics of each electronic producer/consumer/router to preserve the merits of traditional grids

# Plug-and-Play Grid-Organizing Framework

- To ensure
  - ➡ Coordinated steady-state operating points of all the producers
    - Coordinative control for producers to ensure adequate power sharing and, if in islanded mode, voltage and frequency regulation
  - ➡ Stability
  - ➡ Smooth and fast transfer of micro-grids between islanded mode and grid-connected mode
  - ➡ Plug and play
  - ➡ NOT rely on communications → autonomous
  - ➡ Compatible with non-electronic part

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# Thank you!

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