Harmonic Stability in Power Electronic Based Power Systems

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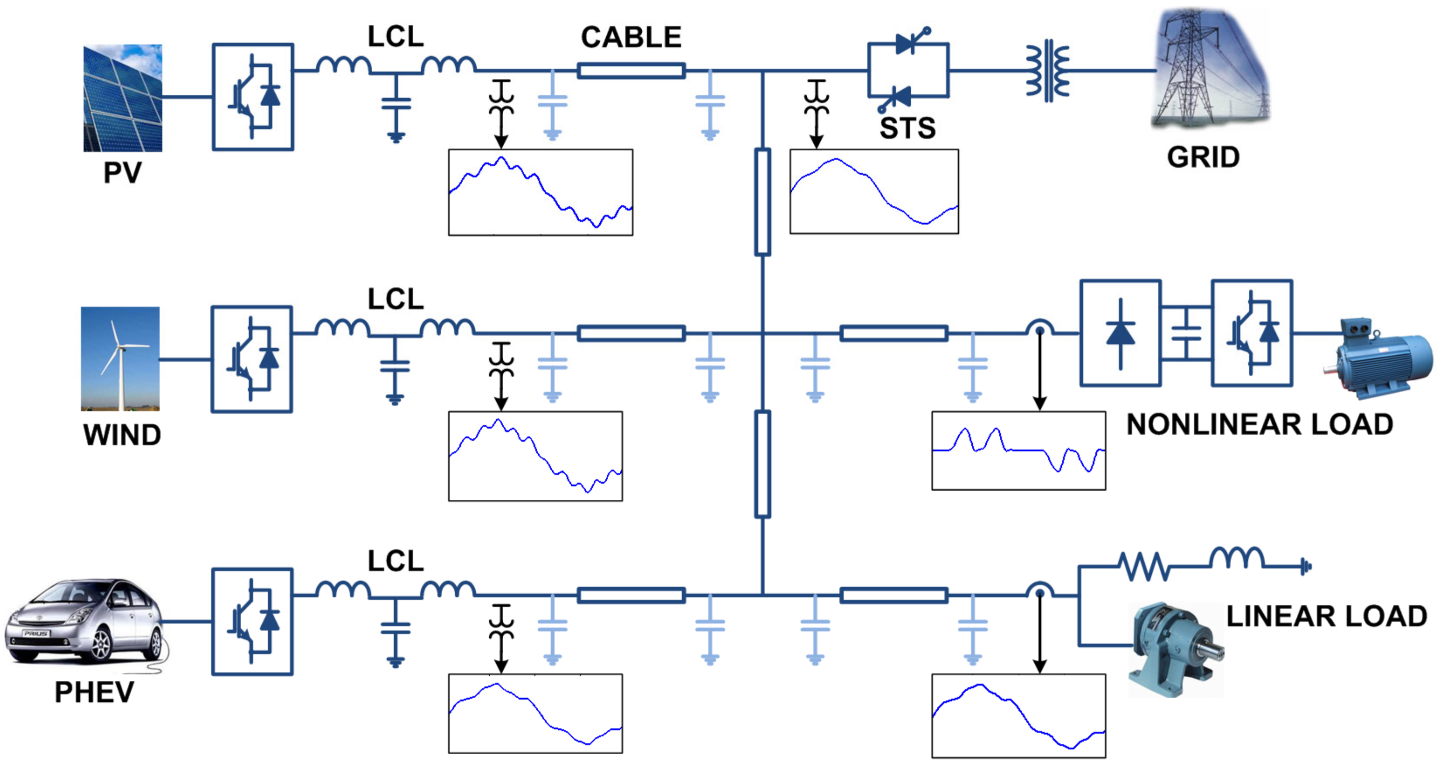
Outline

- **Challenge in power electronic based power system**
- **Harmonic instability**
  Basic concept, historical review, phenomena
- **Basic analysis**
  Current control, grid synchronization
- **Conclusions**

Challenge

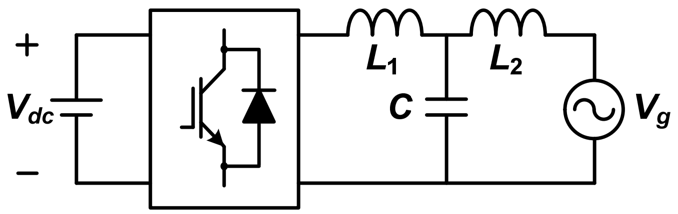
Harmonic Coupling and Controller Interaction



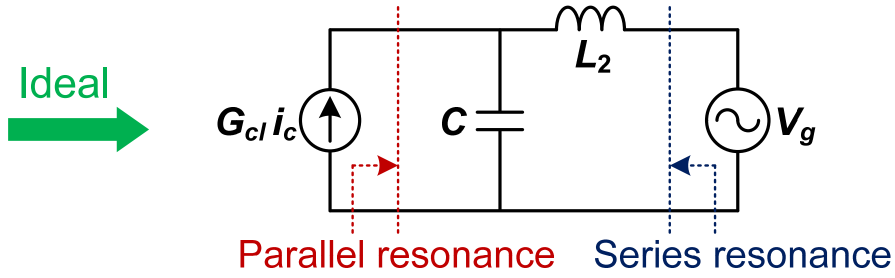
- Nonlinear characteristic of passive components under square wave condition
- More resonances in converter-filters and cables
- Interactions of harmonic and inter-harmonic components

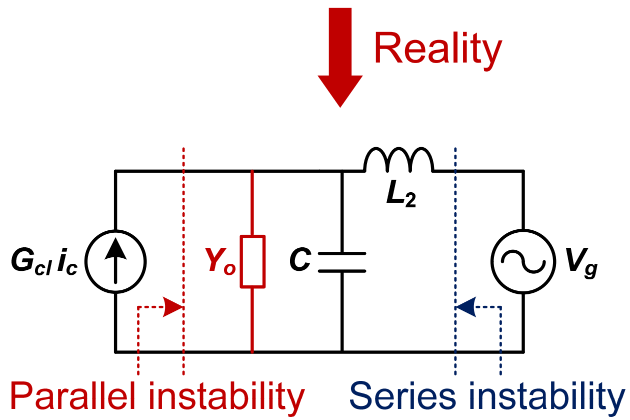
Basic Concept

Harmonic Instability in Voltage Source Converters (VSCs)



Grid-Connected Converter





Harmonic Instability differs from Harmonic Resonance in its dependence on Control Dynamics!

- **Re{Y_o}>0, stable but may be resonant**
- **Re{Y_o}=0, resonant, zero damping**
- **Re{Y_o}<0, unstable, negative damping**

Historical Review

Harmonic Instability is a Waveform-Distortion Instability

Harmonic instability between controlled static convertors and a.c. networks

(first paper 1967)

J. D. Ainsworth, B.Sc.(Eng.), C.Eng., M.I.E.E.

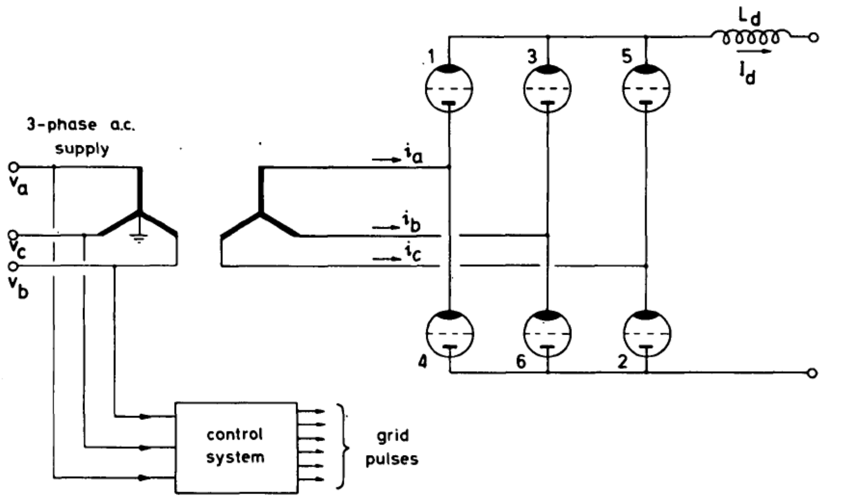


Fig. 1
Basic 6-pulse convertor circuit

Paper 5321 P, first received 2nd March and in revised form 12th April 1967
Mr. Ainsworth is with the Nelson Research Laboratories, The English Electric Co. Ltd., Stafford, England
PROC. IEE, Vol. 114, No. 7, JULY 1967

the control system causes firing-pulse irregularity, which may exaggerate the original distortion. Transformer-saturation effects have also been suggested.[2,7] The phenomenon dis-

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Irregular valve firing pulses due to a positive feedback of distorted ac voltage

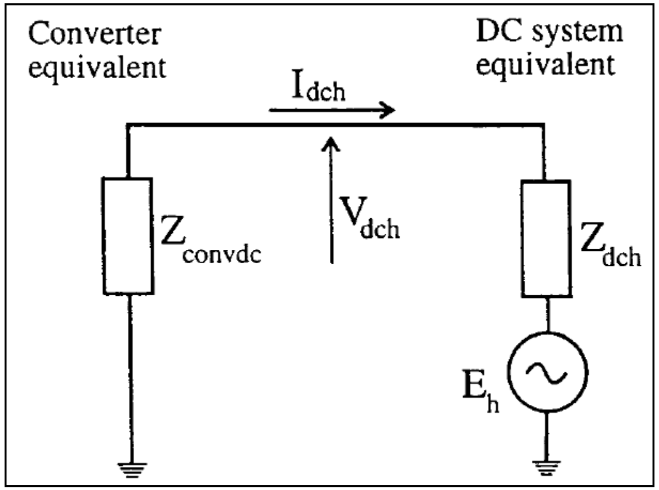
Historical Review

Harmonic Instability Phenomena in LCC-HVDC Systems

- **Harmonic instability occurs with low Short-Circuit Ratio (SCR)**

$$SCR = \frac{\text{short-circuit power of ac system (VA)}}{\text{dc power rating of converter (W)}}$$

- **Composite resonance**
  - Coupling of ac- and dc-side impedance
  - Converter- and system-related resonance



Equivalent converter and dc system

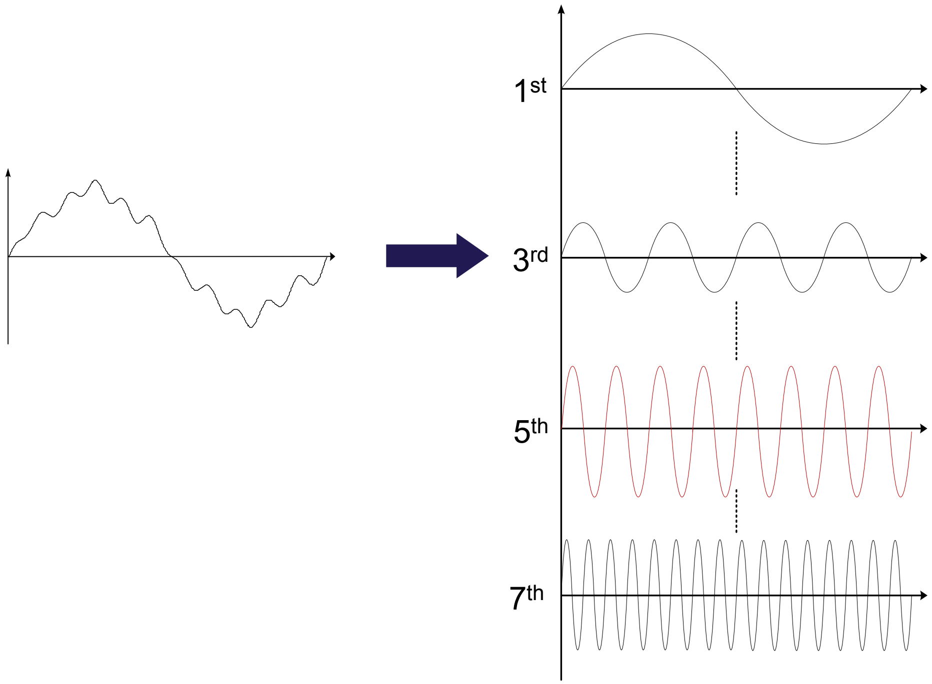
A. Wood and J. Arrillaga, “Composite resonance: a circuit approach to the waveform distortion dynamics of an HVDC converter,” IEEE Trans. Power Del., vol. 10, no. 4, pp. 173-192, Oct. 1995.

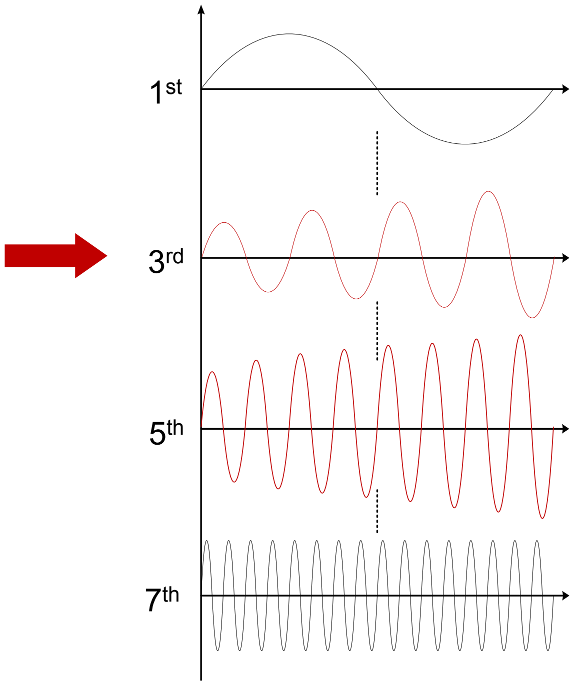
Instability Phenomena

Harmonic Instability is Magnified Resonance (Frequency Coupling)

Harmonic Resonance

Harmonic Instability



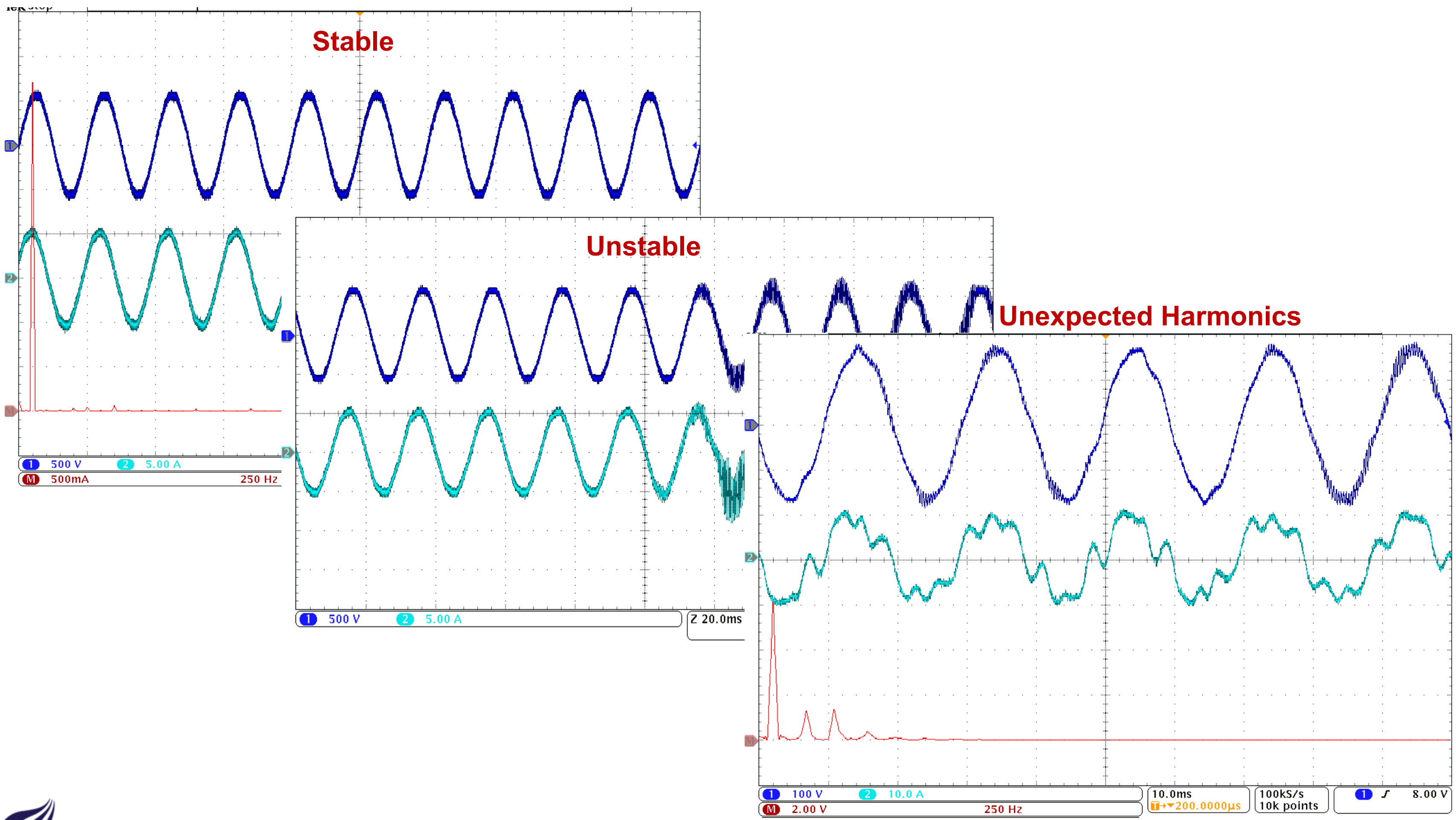


Harmonic stability also named as resonance stability in electrical railway systems

I. Pendharkar, "Resonance stability in electrical railway systems – a dissipativity approach," European Control Conference (ECC), 2013, pp. 4574-4579.

Instability Phenomena

An Example of Harmonic Instability with Single VSC



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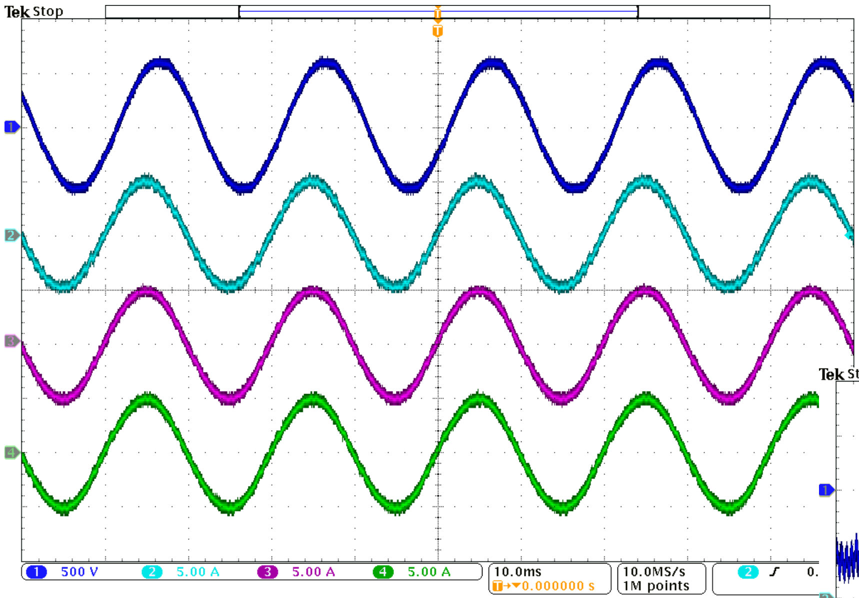
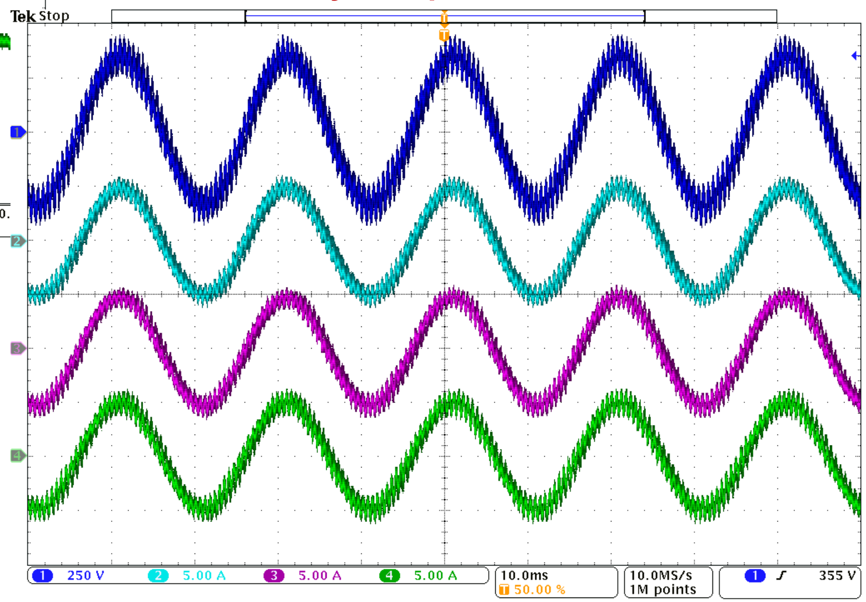
Instability Phenomena

An Example of Harmonic Instability with Three Paralleled VSCs

Stable



Critically-Damped Resonance



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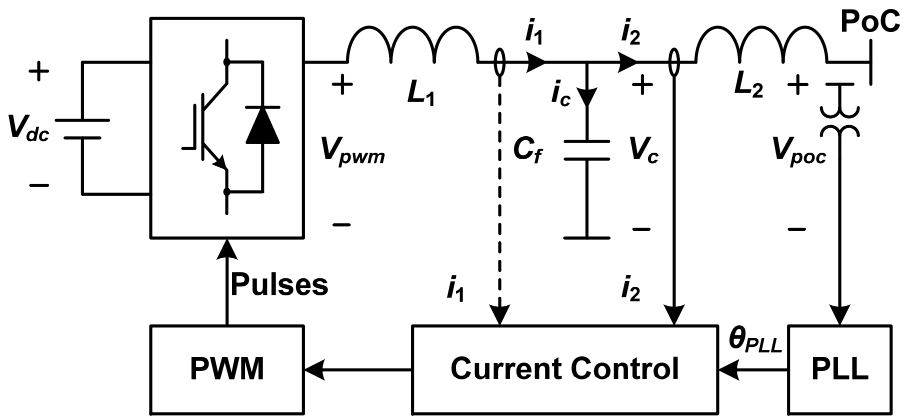
Basic Analysis

How do control loops affect output admittance of converter?

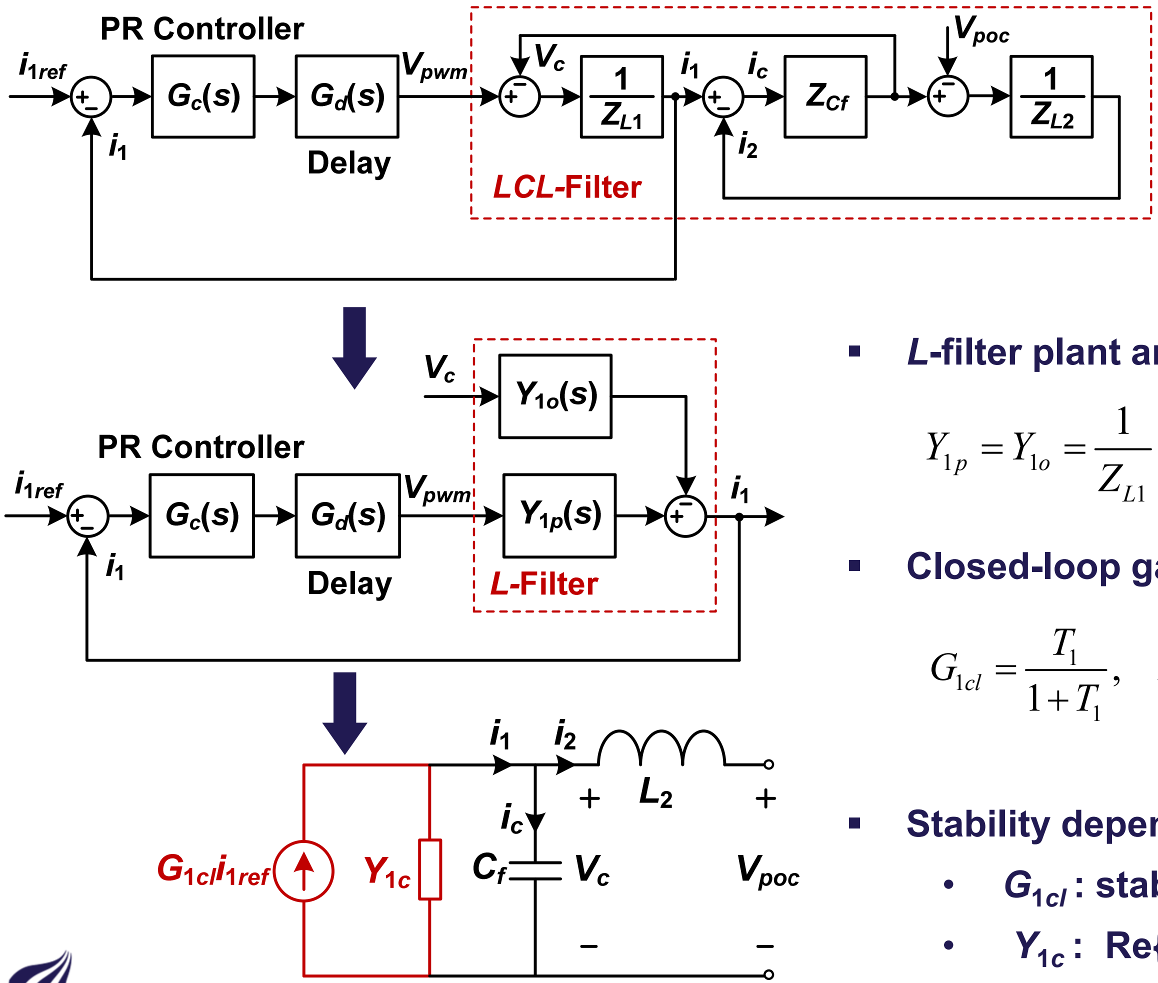


Single-loop current control

- **Assumption**
  - Constant dc-link voltage
- **Focus**
  - Converter current control
  - Phase-Locked Loop (PLL)

Current Control

Converter Current Control



- ***L*-filter plant and open-loop gain**

$$Y_{1p} = Y_{1o} = \frac{1}{Z_{L1}}, \quad T_1 = G_c G_d Y_{1p}$$

- **Closed-loop gain and output admittance**

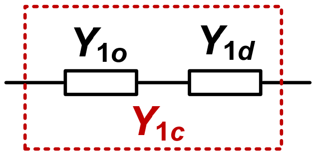
$$G_{1cl} = \frac{T_1}{1+T_1}, \quad Y_{1c} = \frac{Y_{1o}}{1+T_1} = \frac{1}{\frac{1}{Y_{1o}} + \frac{1}{Y_{1d}}}, \quad Y_{1d} = \frac{1}{G_c G_d}$$

- **Stability depends on**
  - G_{1cl} : stable open-circuit behavior
  - Y_{1c} : Re{ Y_{1c} }≥0

Current Control

Output Admittance Evaluation

- **Including proportional gain k_p only for PR current controller**



Converter current

$$Y_{1d} = \frac{1}{G_c G_d} = \frac{1}{k_p} e^{j1.5\omega T_s} = \frac{1}{k_p}\left[\cos(1.5T_s\omega) + j\sin(1.5T_s\omega)\right]$$

$$\mathrm{Re}\{Y_{1d}(j\omega)\} < 0 \Rightarrow \omega \in (\omega_s/6, \omega_s/2]$$

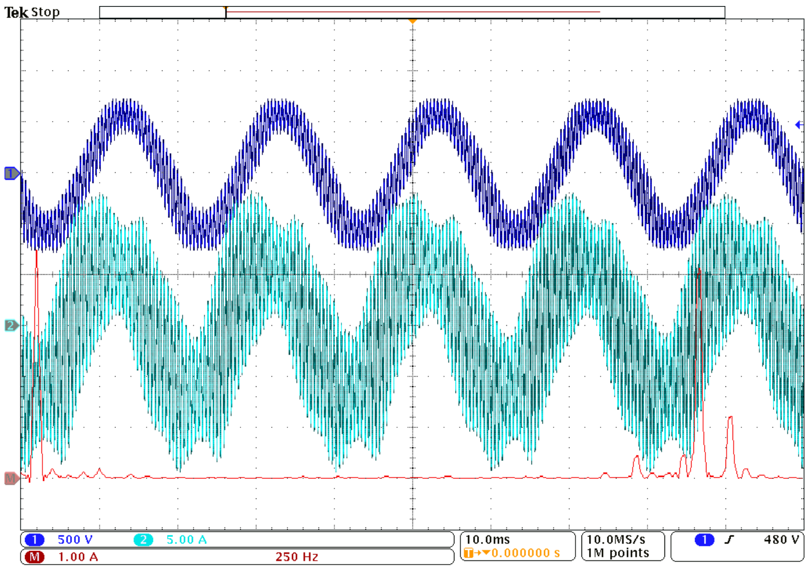
T_s: computation delay; $0.5T_s$: PWM delay

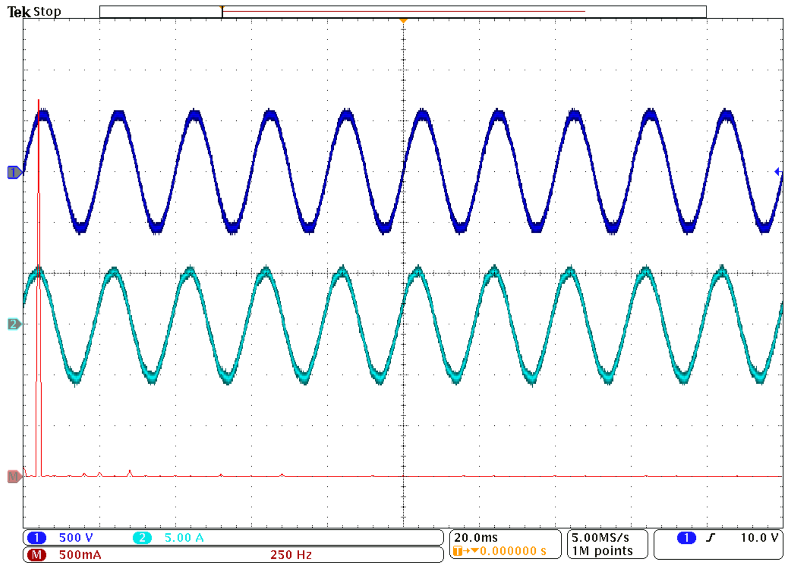
Time delay (1.5Ts) plays a key role in destabilizing current control

Current Control

Stability of Converter Current Control at PoC

- **Reducing time delay for stability improvement**





$$G_d(s) = e^{-1.5T_s s} \Rightarrow \omega \in (\omega_s/6, \omega_s/2]$$

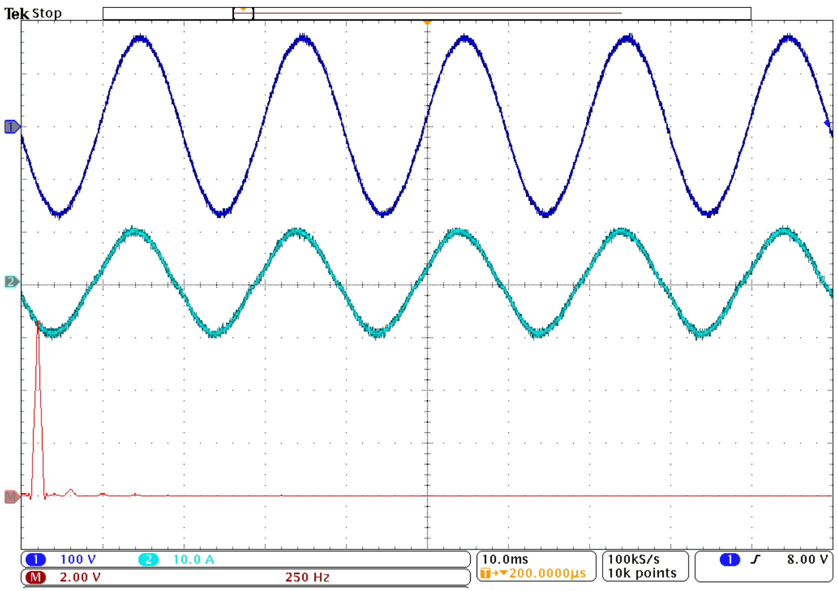
T_s: computation delay; $0.5T_s$: PWM delay

$$G_d(s) = e^{-T_s s} \Rightarrow \omega \in (\omega_s/4, \omega_s/2]$$

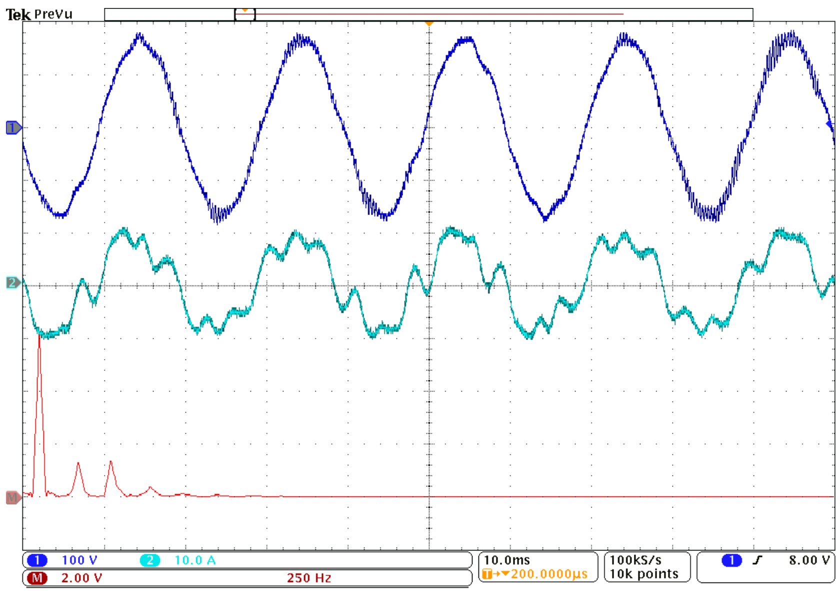
$0.5T_s$: reduced computation delay with interrupt shift

Grid Synchronization

Experimental Verification



PLL Bandwidth 100 Hz



PLL Bandwidth 200 Hz

C. Zhang, X. Wang, and F. Blaabjerg, “Analysis of phase-locked loop influence on the stability of single-phase grid-connected inverter,” in Proc. IEEE PEDG 2015.

Conclusions

In Summary

- **Harmonic stability describes dynamic interactions in the form of waveform distortion**
  - Either harmonic or inter-harmonic interactions
  - Both above and below the fundamental frequency
- **Harmonic stability extends small-signal stability to frequency-coupled stability**
- **Harmonic stability differs from harmonic resonance in its dependence on control system**
- **Harmonic stability includes switching frequency oscillation**

Thank You! Questions?

“ THE HIDDEN HARMONY IS BETTER THAN THE OBVIOUS ”

- P. PICASSO

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