

Adaptive Control of Grid-Connected Inverters Based on Online Grid Impedance Measurements

Mauricio Cespedes and Jian Sun
Rensselaer Polytechnic Institute



2013 CFES Ann. Conf.
Troy, New York



imagination at work

Outline of the Presentation

- Effect of Grid Impedance on Stability of Grid-Connected Inverters
- Inverter Impedance Models
- Derivation of Adaptive Rules
- Online Grid Impedance Identification
- Experimental Demonstration
- Conclusions

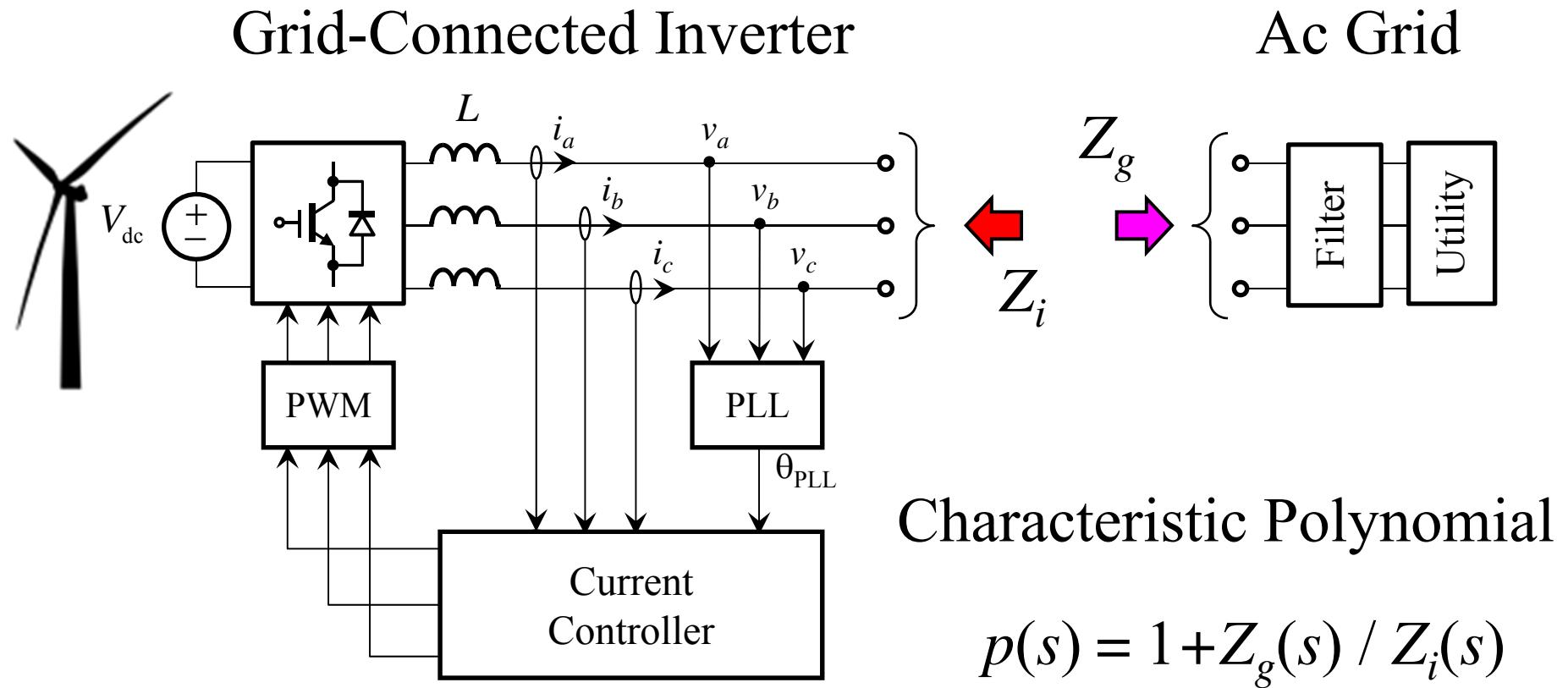


Rensselaer



imagination at work

Impedance of the Inverter and Grid



Applies to Both Positive-Sequence and Negative-Sequence

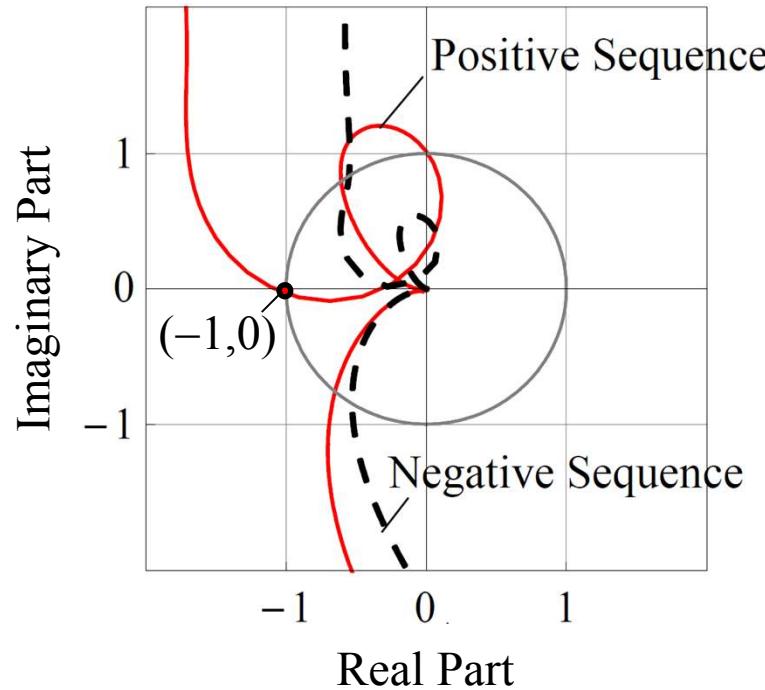


Rensselaer

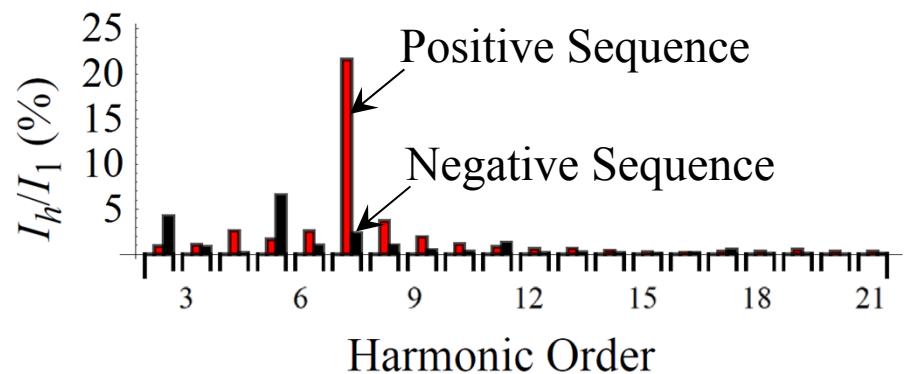
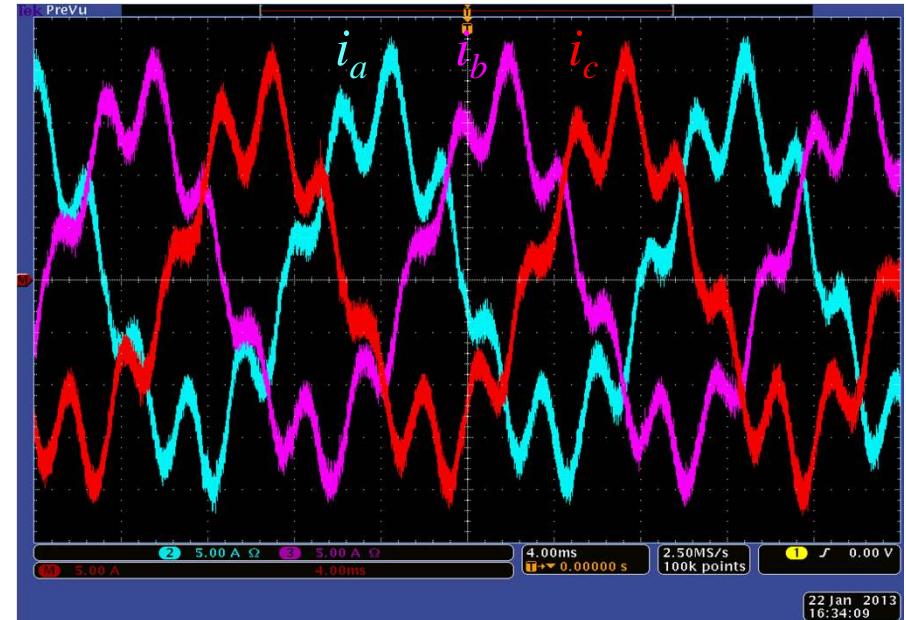


imagination at work

Incompatible System Impedances



Sequence	GM	PM
Positive	$\sim 0 @ 420 \text{ Hz}$	$\sim 0 @ 420 \text{ Hz}$
Negative	$> 10 \text{ dB}$	$> 45^\circ$

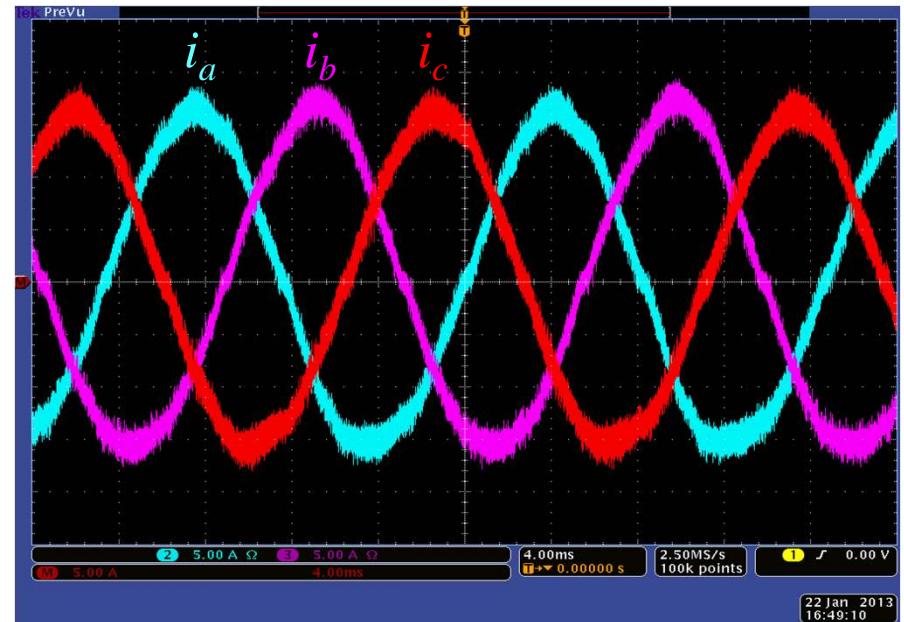
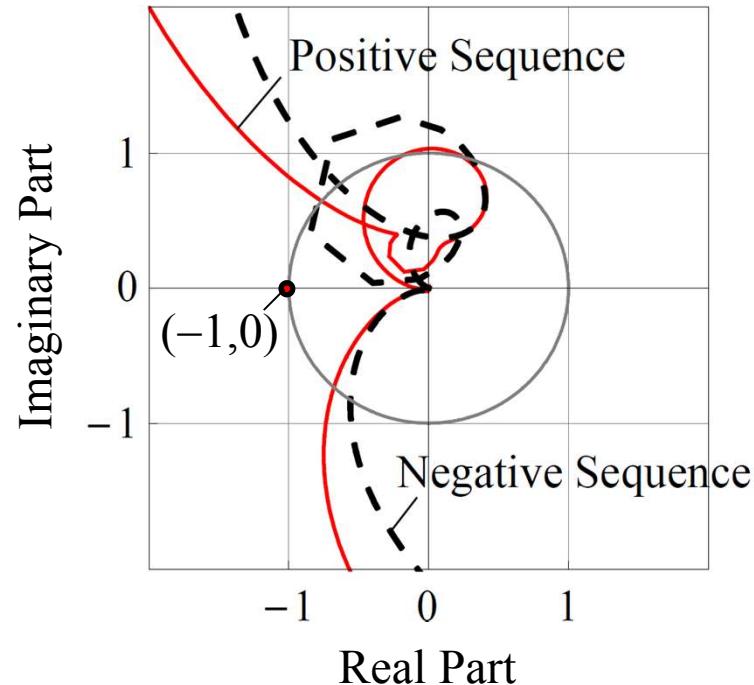


Rensselaer

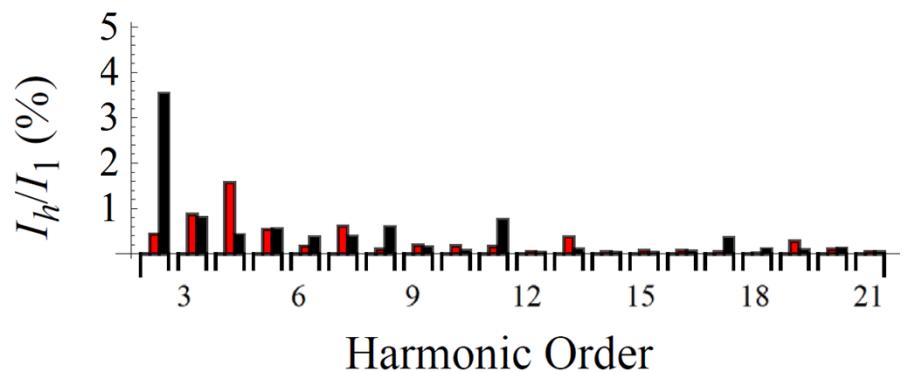


imagination at work

Compatible System Impedances



Sequence	GM	PM
Positive	>10 dB	> 30°
Negative	> 10 dB	> 30°

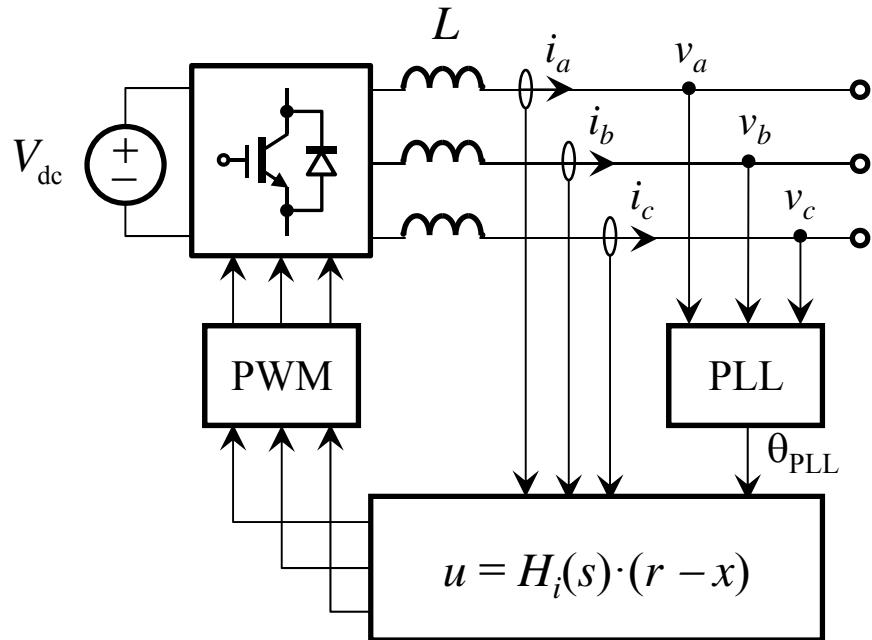


Rensselaer



imagination at work

Inverter Impedance Models



Parameter	Value
V_{dc}	550 V
V_1	$120\sqrt{2}$ V
L	1.2 mH (0.06 pu)
I_1	40 A

Applying the Harmonic Linearization Method:

$$Z_p(s) = \frac{H_i(s)(V_{\text{dc}}/2) + sL}{1 - T_{\text{PLL}}(s - j\omega_1) \left[H_i(s) \frac{V_{\text{dc}}/2}{V_1} \mathbf{I}_1 \right]}$$

$$Z_n(s) = \frac{H_i(s)(V_{\text{dc}}/2) + sL}{1 - T_{\text{PLL}}(s + j\omega_1) \left[H_i(s) \frac{V_{\text{dc}}/2}{V_1} \mathbf{I}_1^* \right]}$$

where $T_{\text{PLL}}(s) \triangleq V_1 H_{\text{PLL}}(s) / [1 + V_1 H_{\text{PLL}}(s)]$



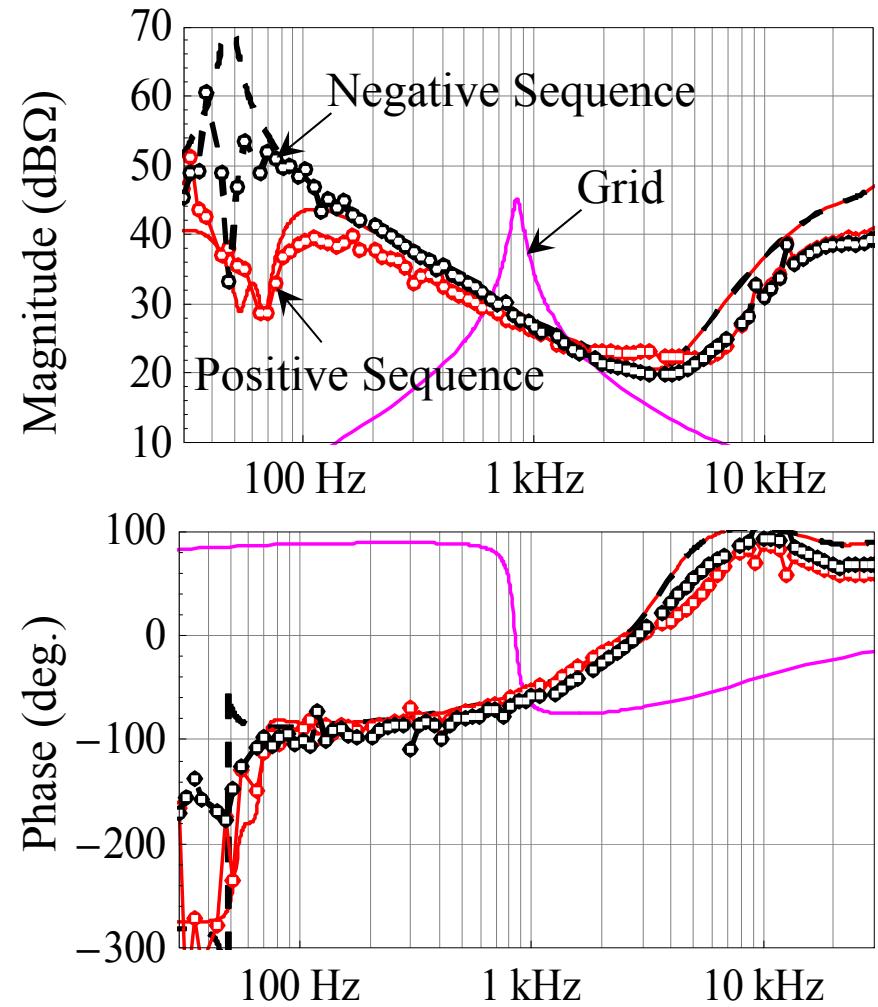
Rensselaer



imagination at work

Experimental Verification

- Impedance Sweep
 - Model is Verified
 - $Z_p \sim Z_n$ at $f >> f_1$
- Modeling Outcomes
 - Current Controller Integrator Resembles a Capacitor
 - $$H_i(s) = K_p + K_i/s$$
 - PLL Acts As a Delay that Decreases Damping



Rensselaer



imagination at work

Adaptive Control Rule Derivation

- Apply the Routh-Hurwitz Stability Criterion to the Characteristic Polynomial
 - Positive Sequence
 - Negative Sequence
- Simplify the Grid Impedance Model
 - Assume Inductive Grid
 - Valid at Low Frequencies
- Simplify the Inverter Impedance Model
 - See Next Slide

$$1 + Z_g(s)/Z_i(s)$$

$$Z_g(s) = sL_g$$



Rensselaer



imagination at work

Inverter Impedance Simplification

- Simplification of Inverter Impedance Models

$$1. \quad H_i(s)(V_{\text{dc}}/2) + sL \approx (K_p + K_i/s)(V_{\text{dc}}/2)$$

$$2. \quad (I_1/2)e^{j\phi_{i1}} \approx (I_1/2)$$

$$3. \quad T_{\text{PLL}}(s \pm j\omega_1) \approx (1 + s/\omega_{\text{PLL}})^{-1}$$

- Simplified Characteristic Polynomial

$$p(s) = 1 + (sL_g)/\left\{H_i(s)\frac{V_{\text{dc}}}{2}\left[1 - \frac{1}{1 + s/\omega_{\text{PLL}}} \frac{I_1/2}{V_1} H_i(s) \frac{V_{\text{dc}}}{2}\right]^{-1}\right\}$$



Rensselaer



imagination at work

Adaptation Rule of PLL Bandwidth

- Stability Conditions

1. $\frac{\omega_1}{\omega_{\text{PLL}}}(\omega_i L) > \omega_1 L_g \left[\frac{1}{2} \frac{L/L_B}{\omega_1/\omega_i} - 1 \right]$, term in brackets always negative

2. $\omega_{\text{PLL}} < \frac{2\omega_1}{L_g/L_B}$, the larger L_g , the smaller ω_{PLL} should be

3. $\omega_{\text{PLL}} < \frac{2\omega_1}{L_g/L_B} \frac{1}{\sqrt{a+1}}$, more stringent than 2. above if $a > 0$

- System is Stable if and Only if

$$\omega_{\text{PLL}} < \frac{2\omega_1}{L_g/L_B} \frac{1}{\sqrt{a+1}}, \quad a = 2 \frac{\omega_1/\omega_i}{L/L_B} \quad \text{when } a > 1$$

ω_i : Current Loop Bandwidth; L_B is base inductance



Rensselaer

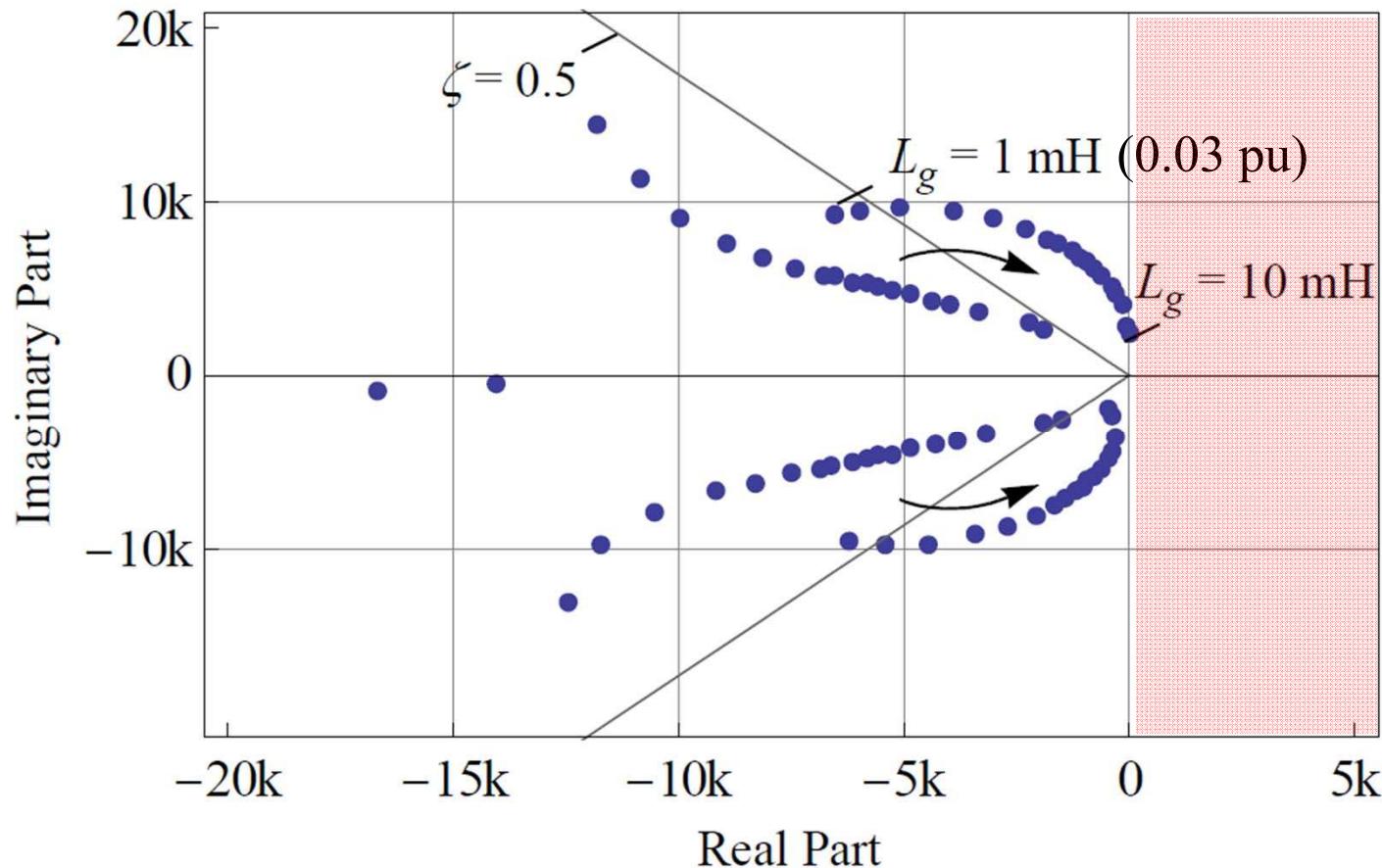


imagination at work

10

Roots of Characteristic Polynomial

Introduce Adaptive Rule in the Full-Order System Model, No Simplifications:



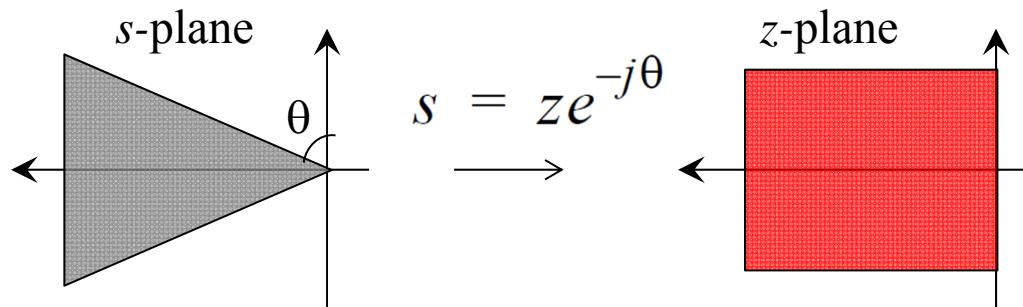
Rensselaer



imagination at work

Summary of PLL Adaptation

- Adaptation Rule Derived Assuming $f \gg f_1$
 - Hence Stability Cannot Be Guaranteed if $L_g > 0.33$ pu
- Adaptive Rule Does Not Guarantee Minimum Damping Ratio
 - Rotation Mapping Introduces Complex-Valued Coefficients to the Characteristic Polynomial



$$P(z) = z^2 + z\alpha_1 + \alpha_2$$
$$\alpha_k = p_k + jp_k$$

Routh-Hurwitz Fails



Rensselaer

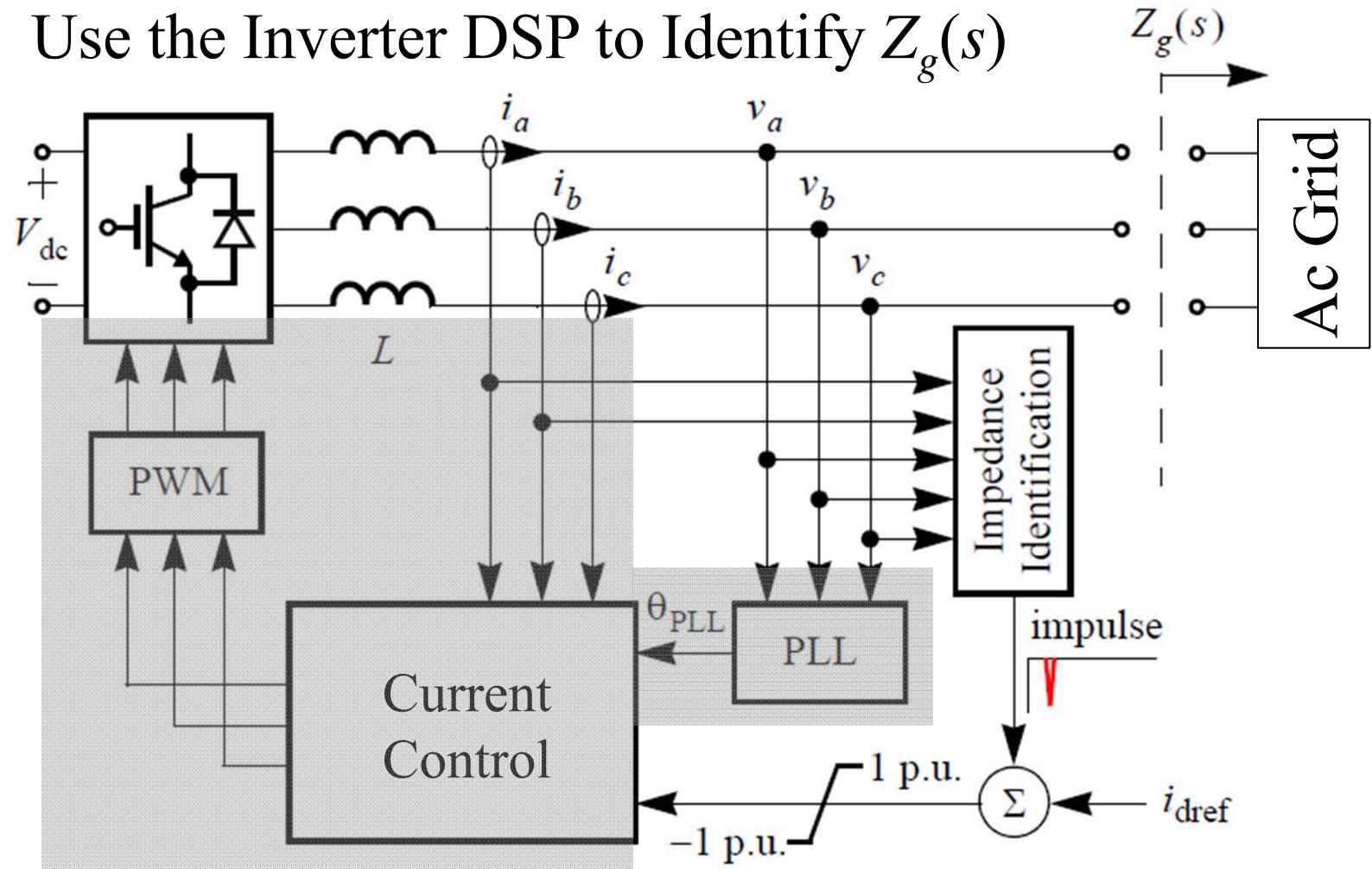


imagination at work

12

Online $Z_g(s)$ Identification

Use the Inverter DSP to Identify $Z_g(s)$



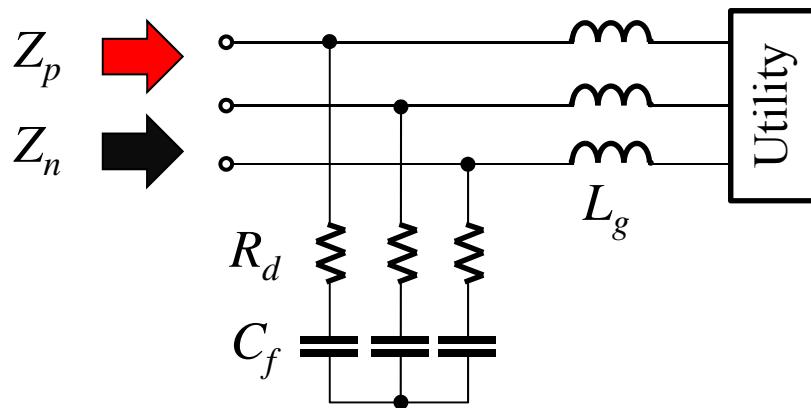
Rensselaer



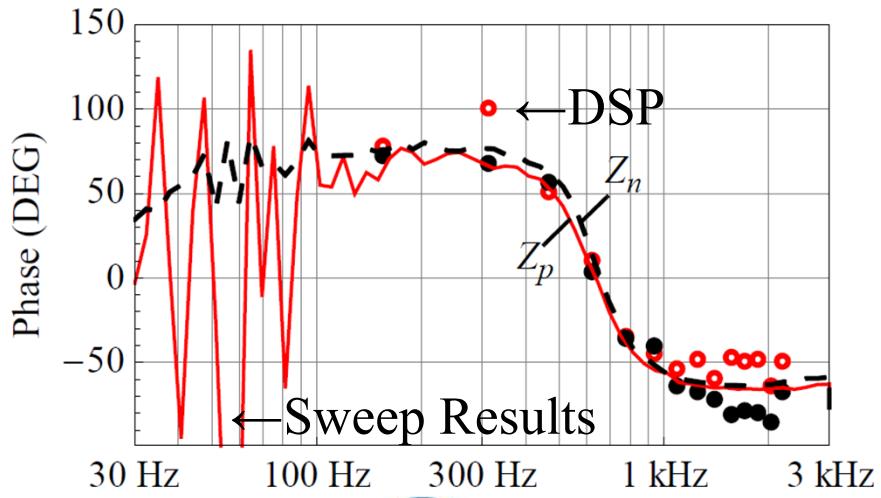
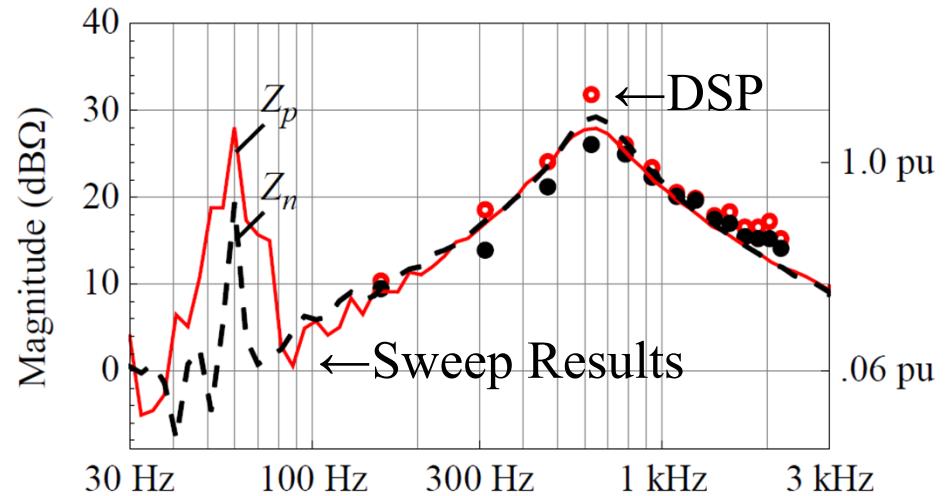
imagination at work

13

Grid Impedance Identification



Element	Value	Perspective
L_g	3.3 mH	0.06 pu
R_d	1.87 Ω	3 watts / phase
C_f	20 μF	0.12 pu
Utility Grid	164 μH	0.03 pu



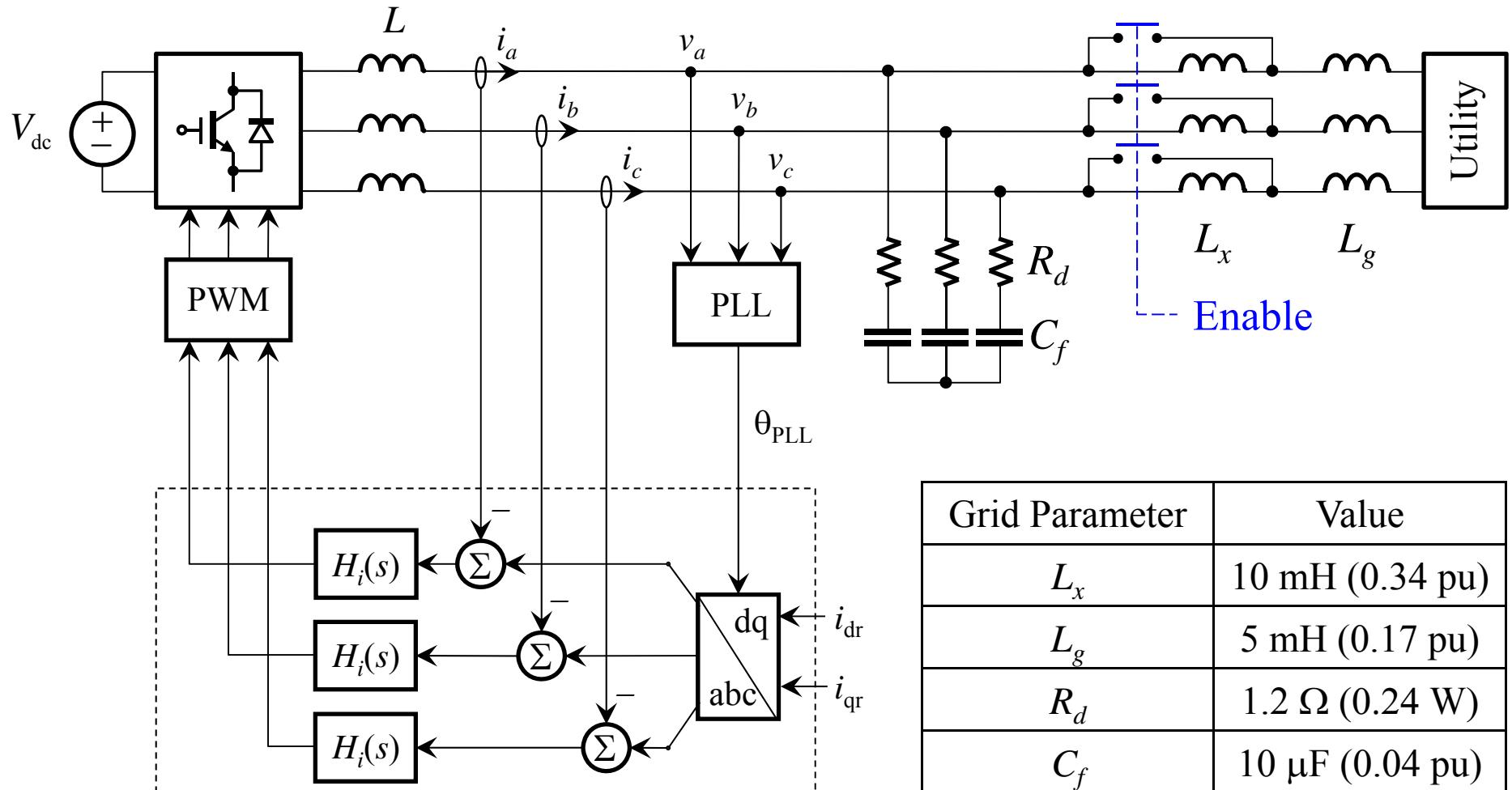
Rensselaer



imagination at work

14

Experimental Demonstration



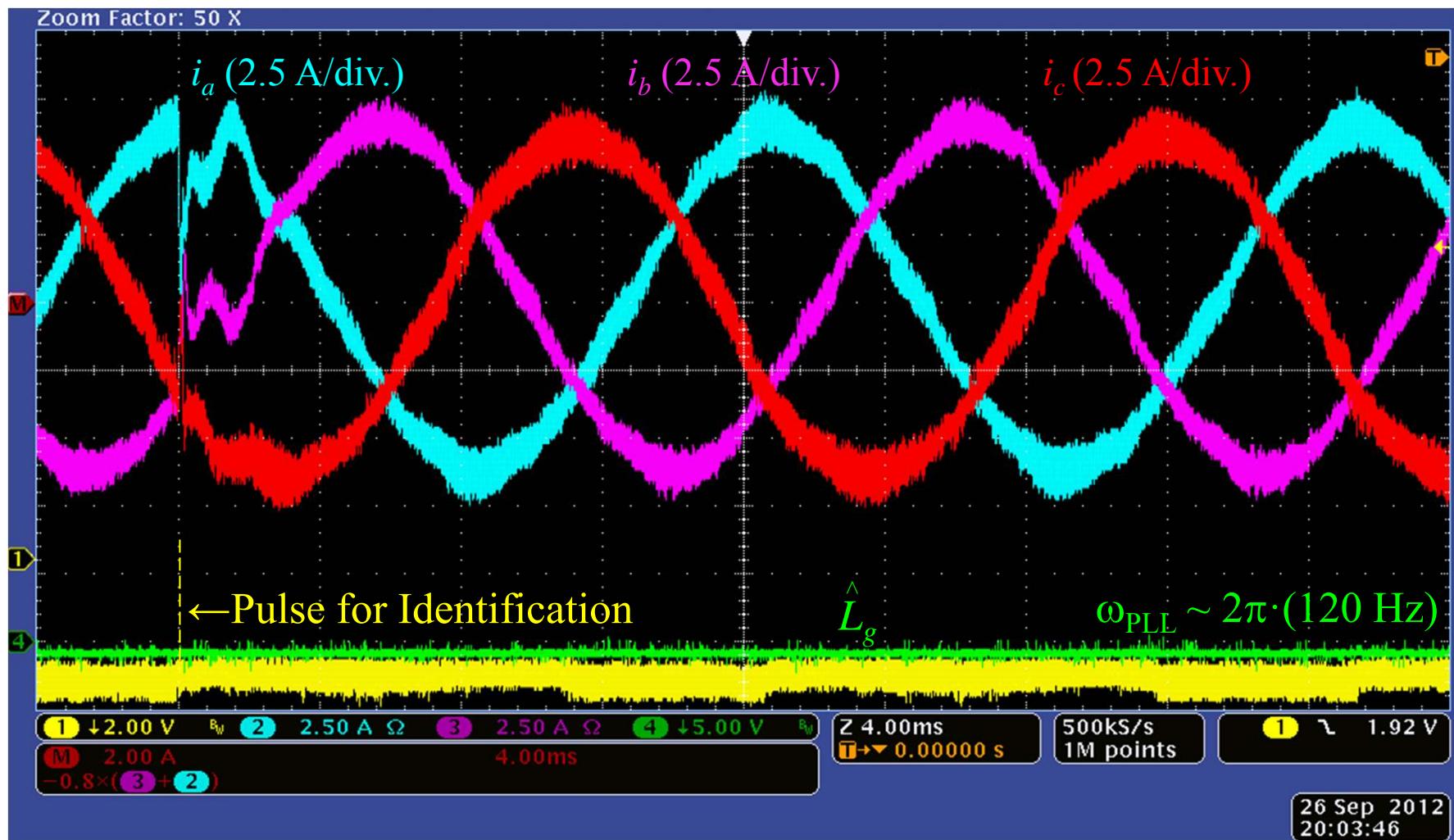
Rensselaer



imagination at work

15

Identification of Strong Grid



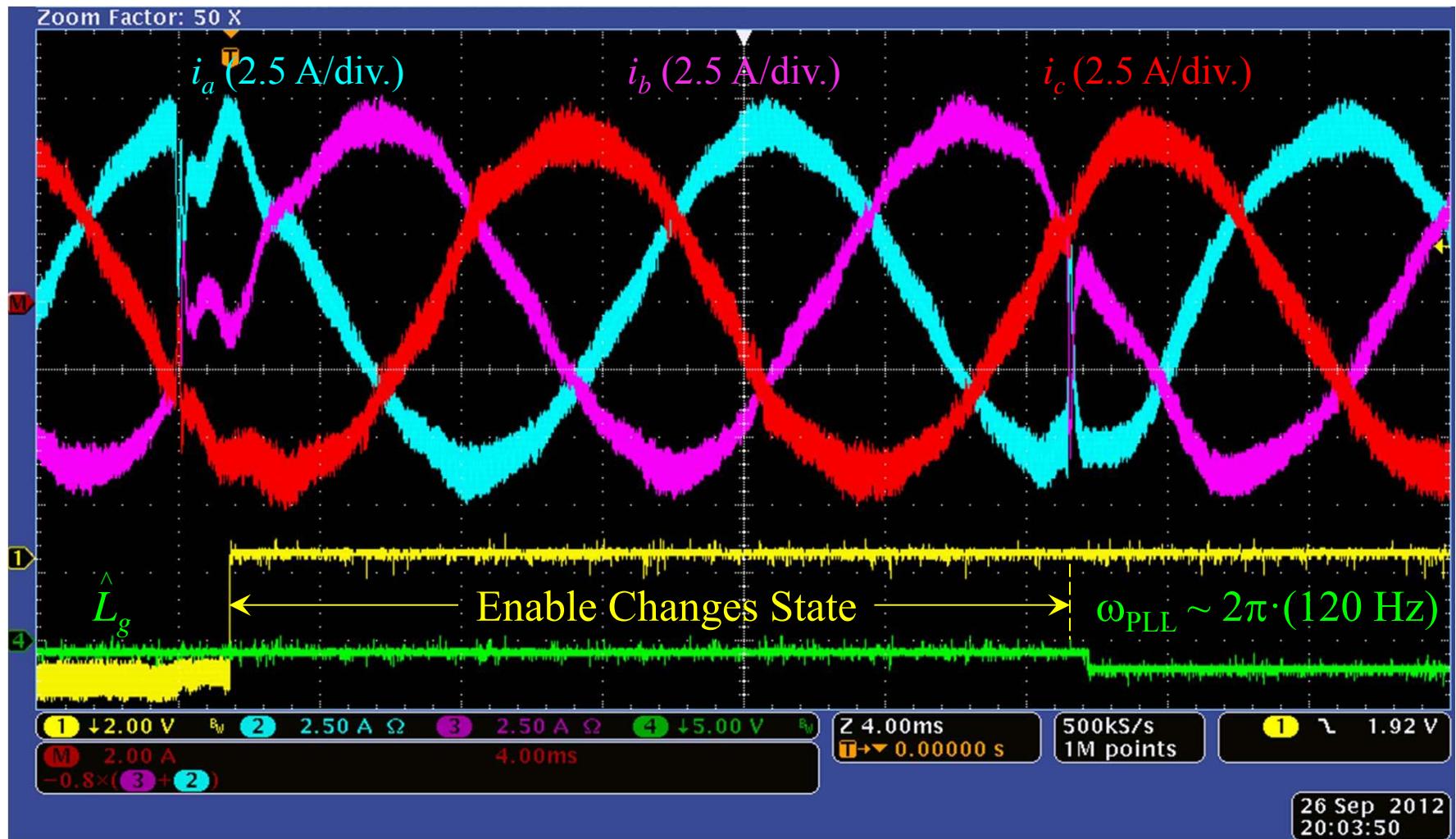
Rensselaer



imagination at work

16

Weak Grid Transition



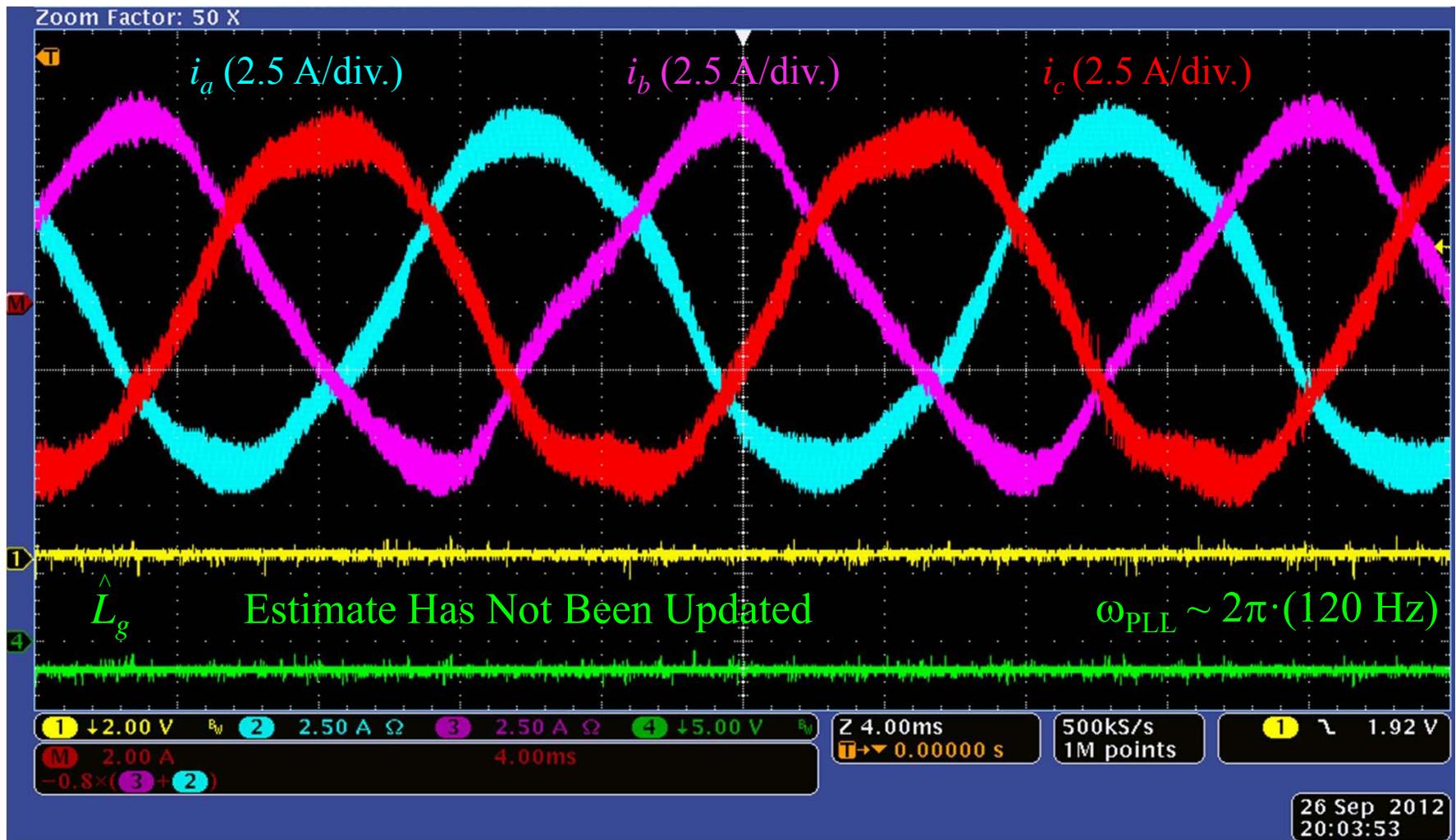
Rensselaer



imagination at work

17

Resonance During Weak Grid



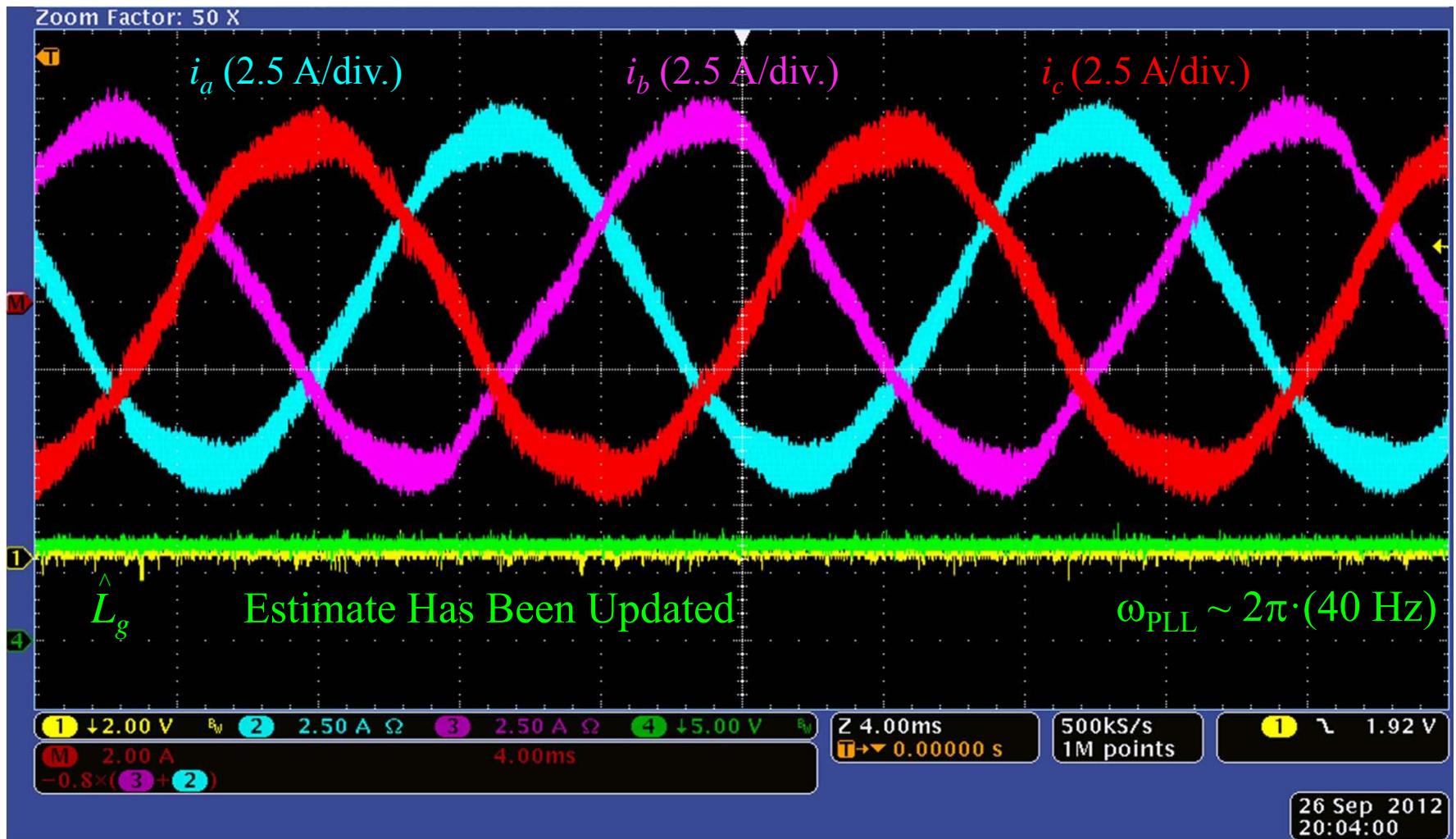
Rensselaer



imagination at work

18

Adaptation to Weak Grid



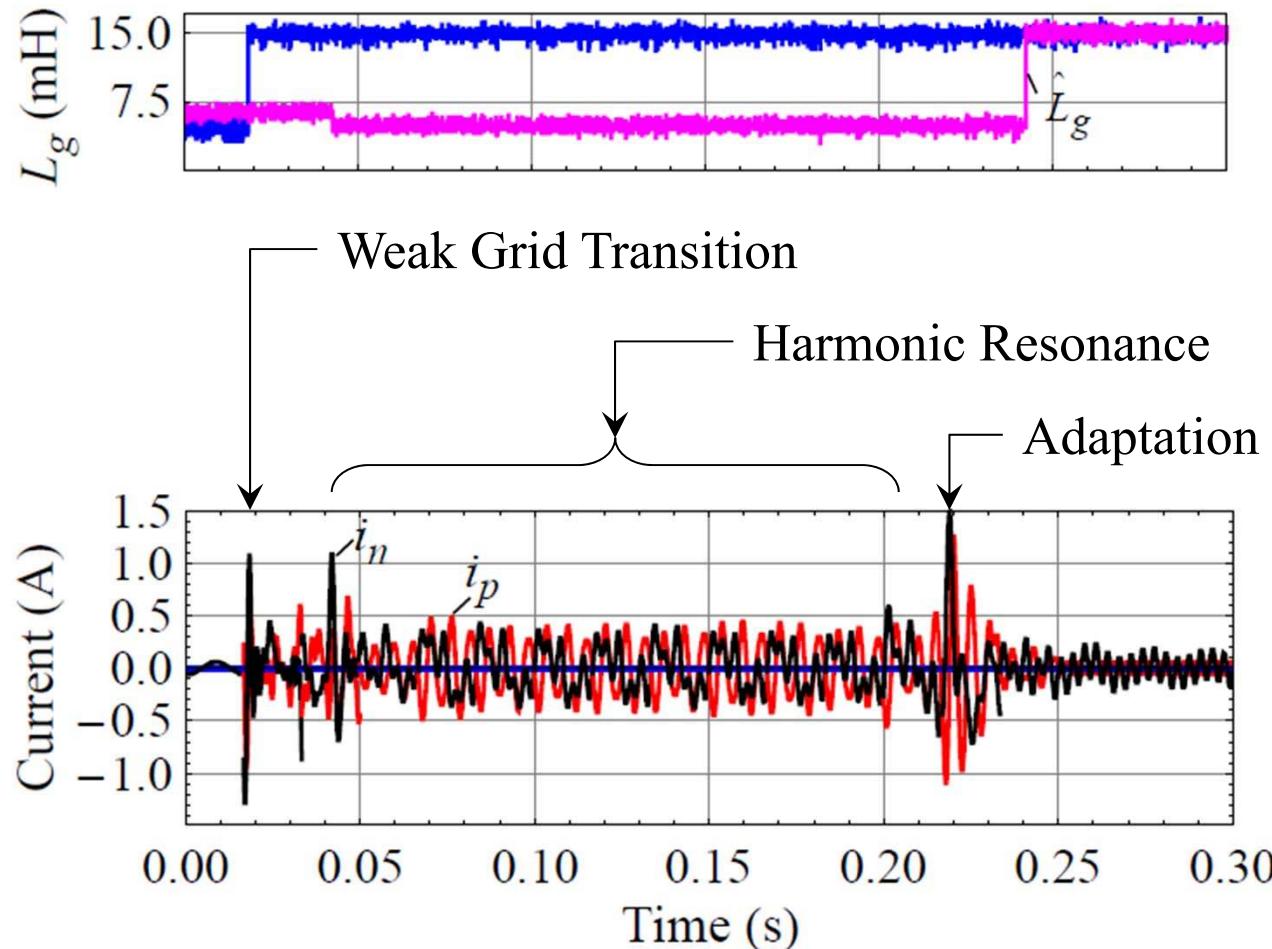
Rensselaer



imagination at work

19

Summary of Adaptation Transient



Estimate Is Updated
Every 200 ms (12
Fundamental Cycles)



Rensselaer



imagination at work

20

Conclusions

- Proposed and Demonstrated Adaptation of PLL Bandwidth to Guarantee System Stability Using Online Grid Impedance Identification
 - Adaptation Using Routh-Hurwitz Criterion
- Developing Conditions for Constant Damping Ratio Involve Complex-Valued Coefficients in the Characteristic Polynomial
 - Adaptation Uses Generalized Routh-Hurwitz Criterion



Rensselaer



imagination at work

21

End of Presentation

This work was supported in part by GE Global Research Center (GE GRC). The authors thank Dr. Z. Jiang of GE GRC for his technical inputs.



Rensselaer



imagination at work

22