DFG SPP 1984

# Control of Smart Transformer-fed Grid

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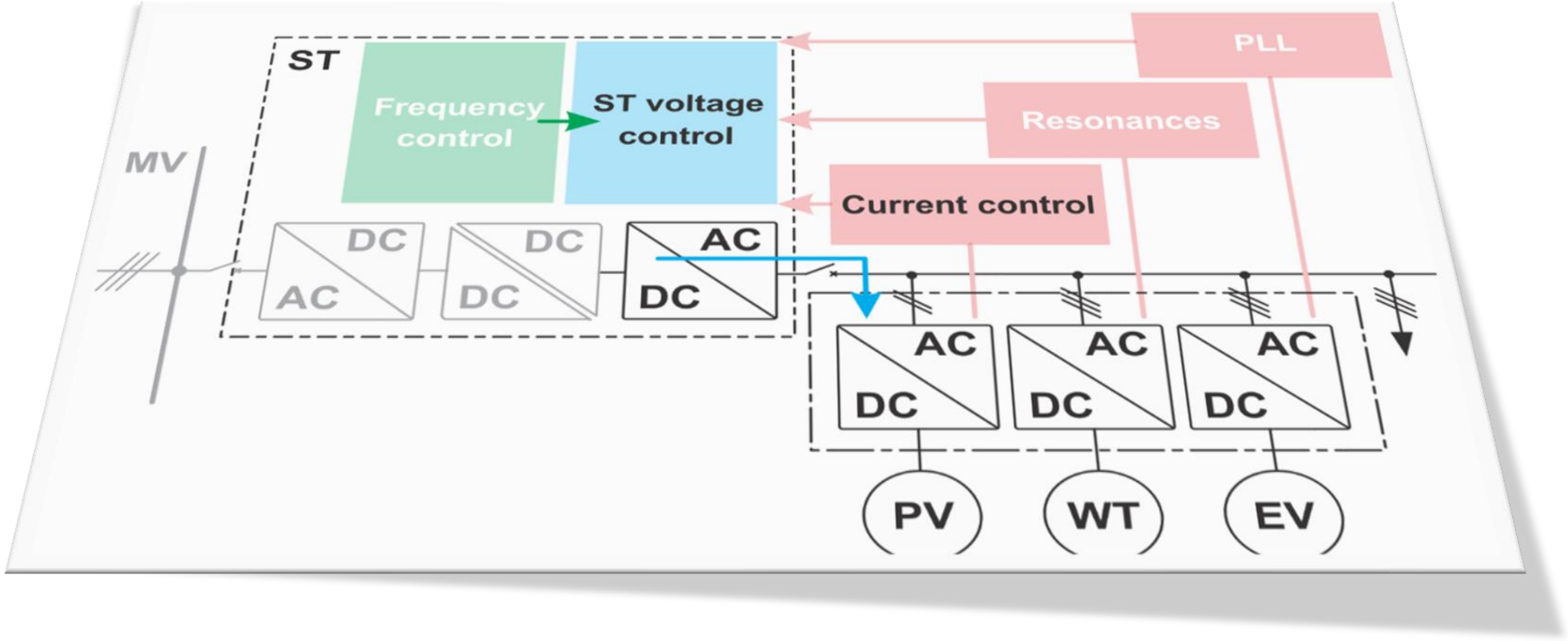
# Outline

- Control of Smart Transformer (ST) and its challenges
- Analysis and stabilization of ST-fed grid
- Influences of grid synchronization on ST-fed grid
- Conclusions

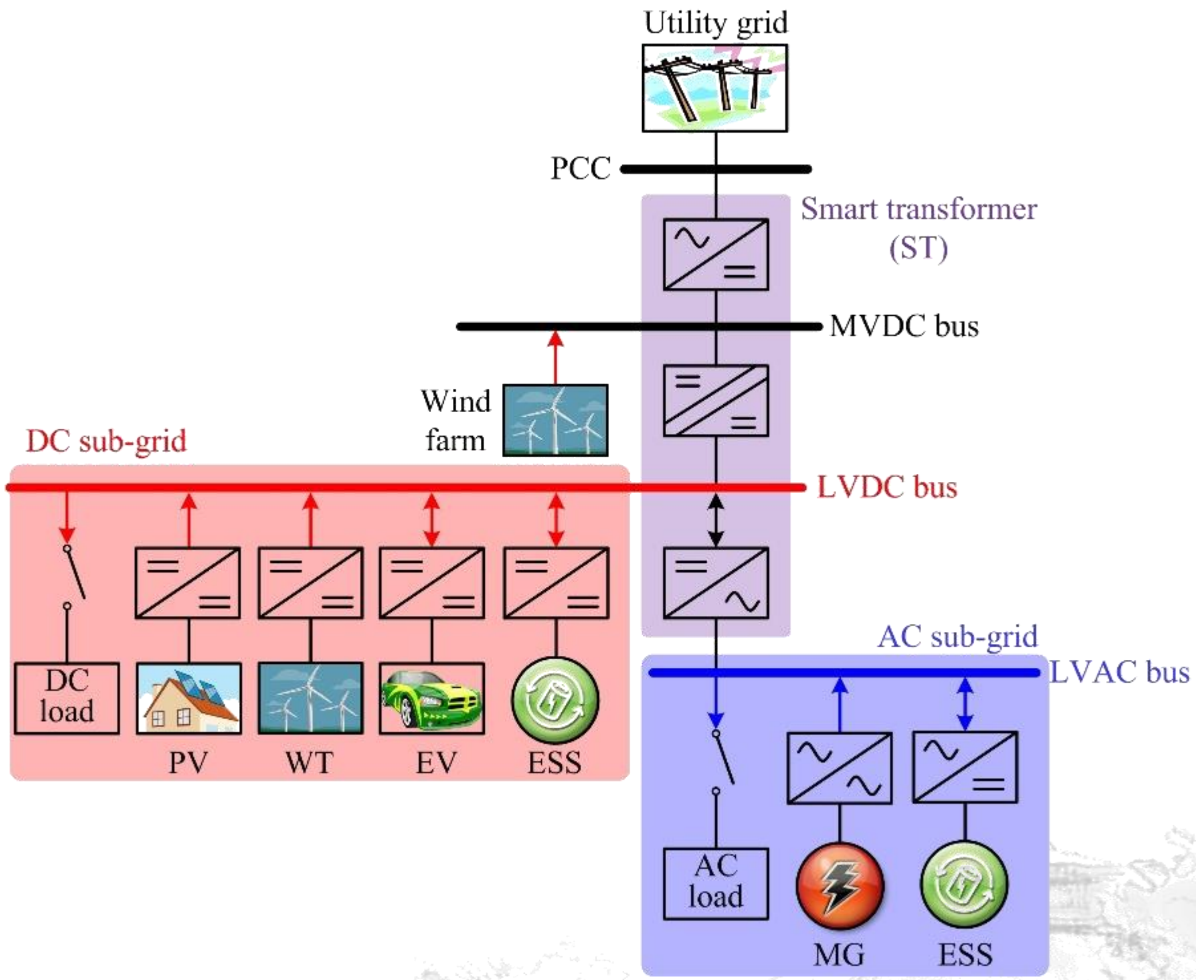



# Control of Smart Transformer and its challenges

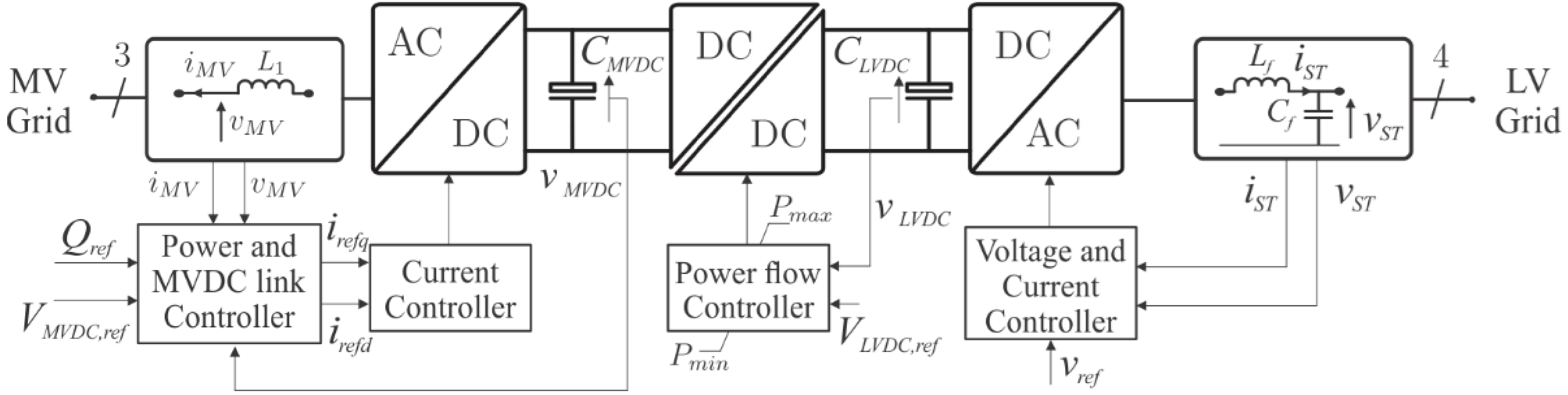
# The Smart Transformer

**The Smart Transformer features shall be:**

- LV and MV dc-links available
- Advanced control of all the three-stages
- The system should be able to work even with faulty modules
- During partial loading conditions it should be able to fully use its rating for other services



# Control of Smart Transformer




**MV Converter**

**Inner loop:** MVAC current control

**Outer loop:** MVDC link total voltage control

**DC/DC Converter**

MV cell balancing

LVDC link voltage control

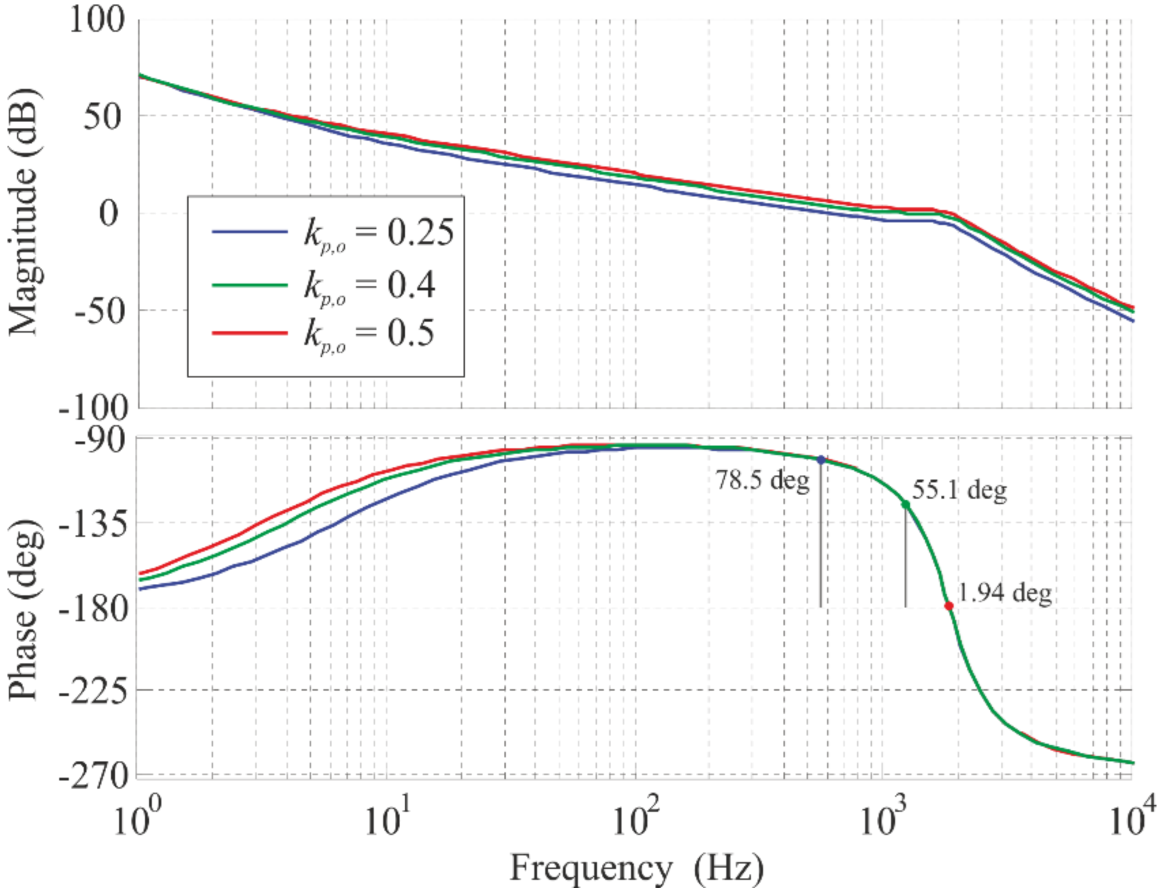
**LV Converter**

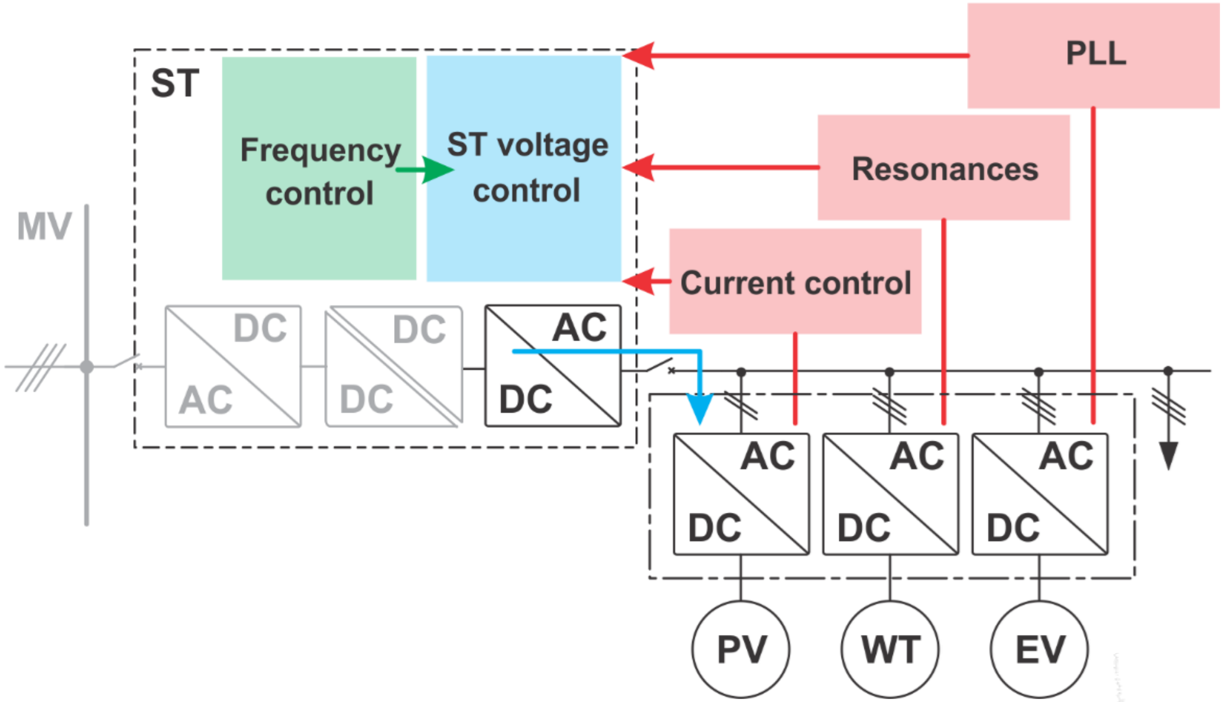
LVAC voltage control

Ancillary services

# Challenges of ST LV Control

## Limited control bandwidth

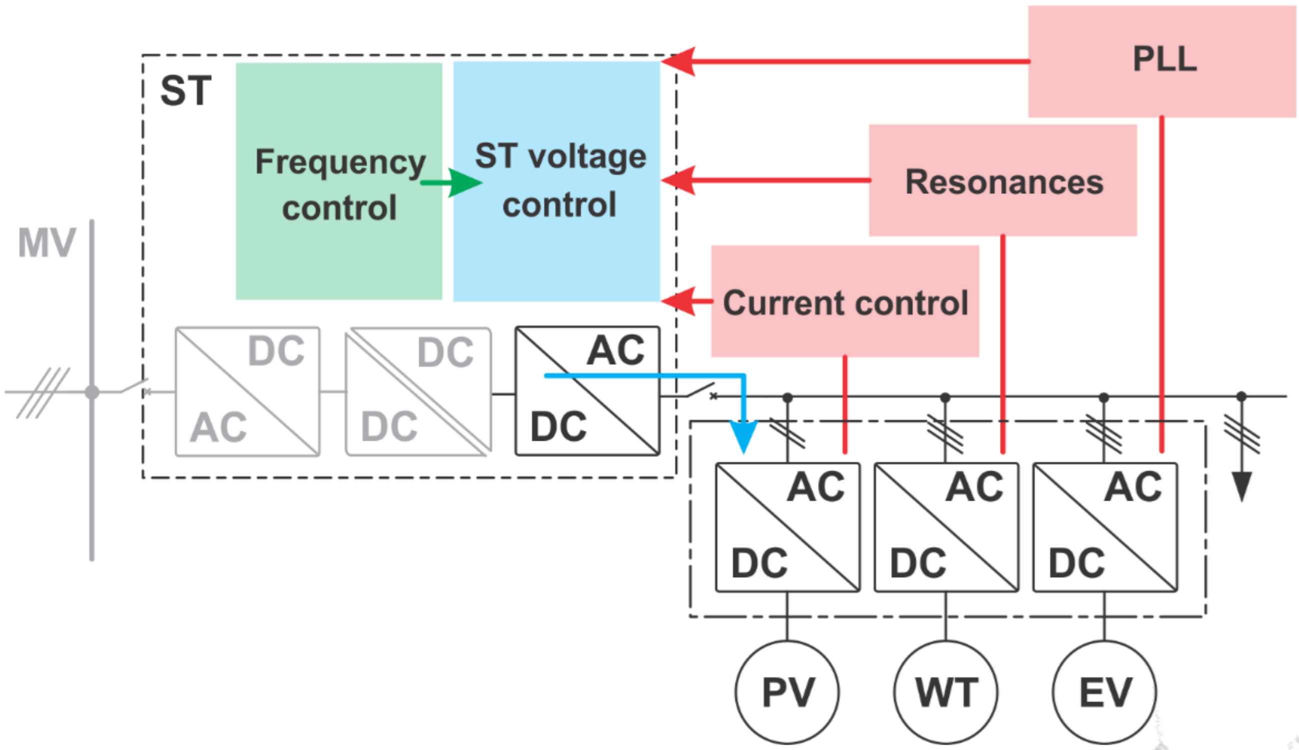


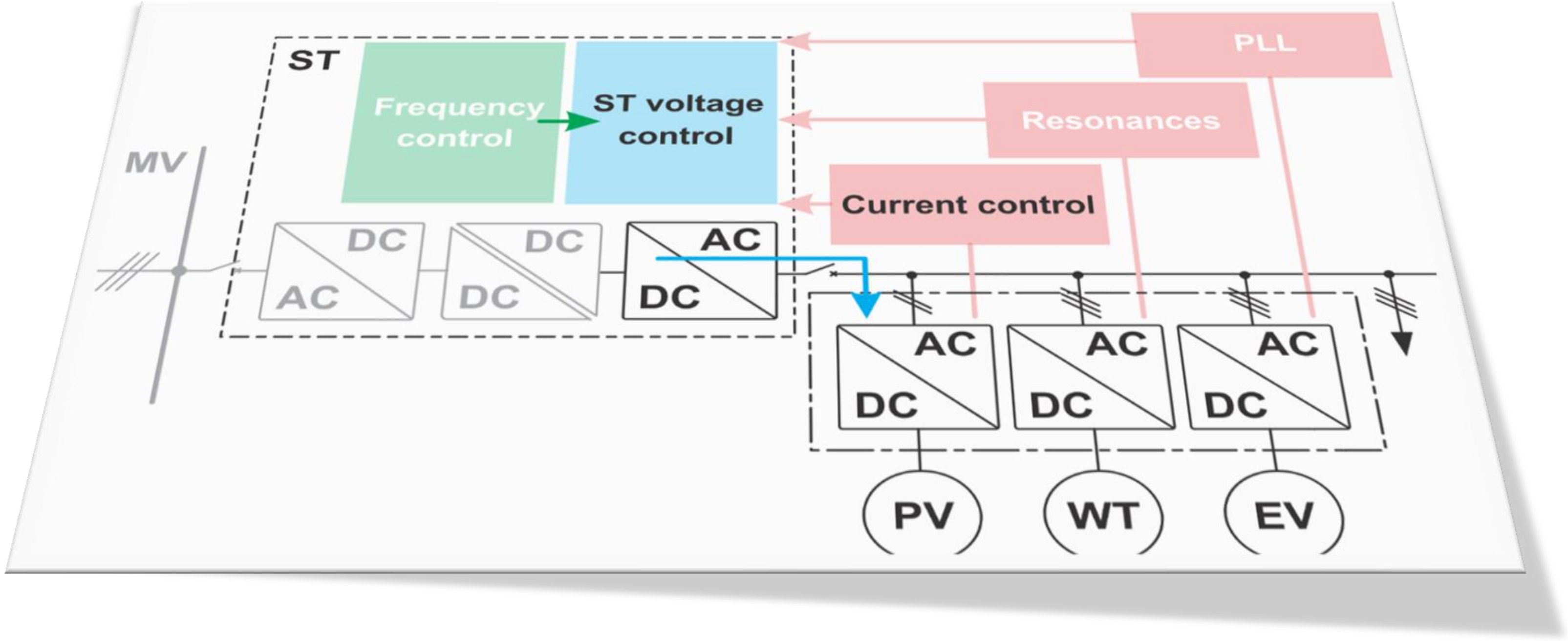



# Challenges of ST LV Control

**Control issues for ST-fed grid:**

- Control interactions and instability;
- Resonance and power quality violation;
- Stability issues associated with PLL；
- Power quality violation during frequency control.

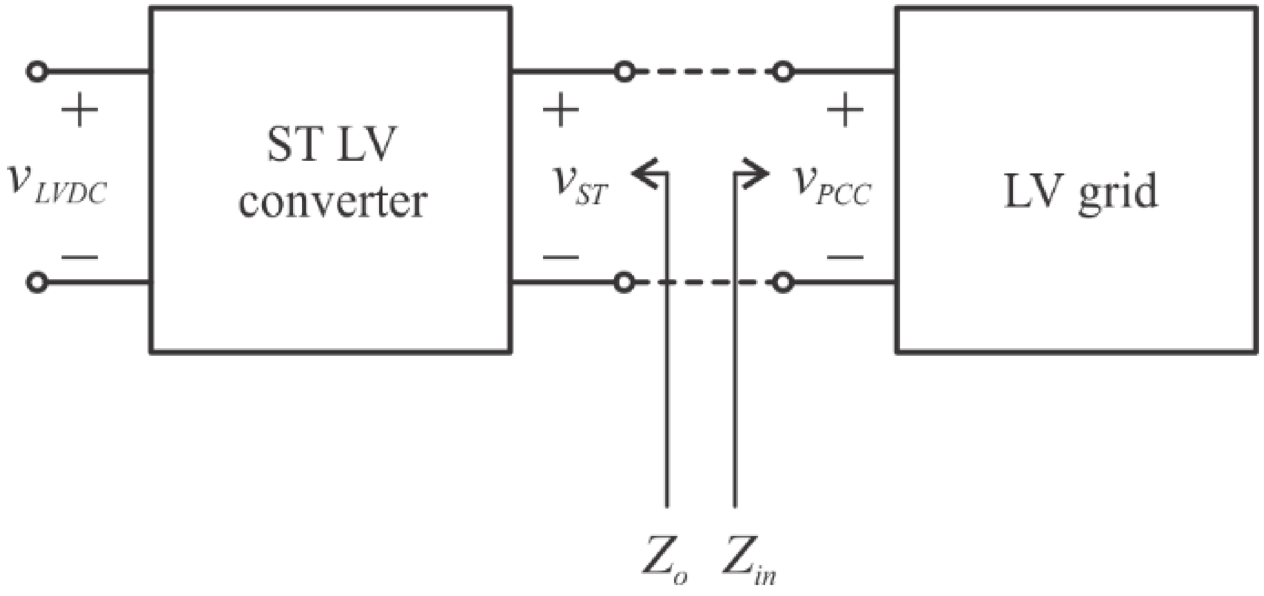





# Analysis and Stabilization of ST-fed Grid

# Interactions between ST and LV Grid

**Equivalent ST-fed grid**

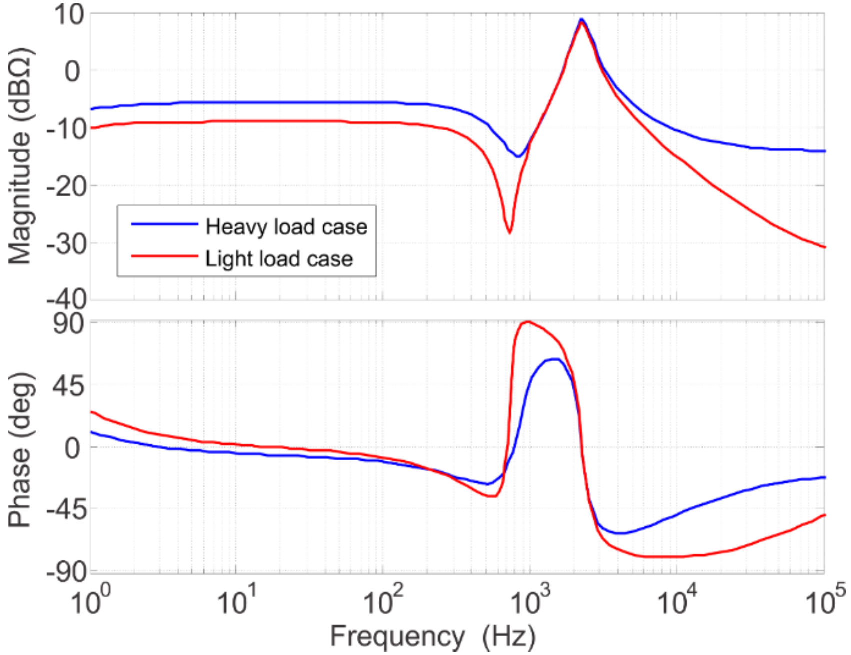



$Z_o$: output impedance of LV converter
$Z_{in}$: input impedance of LV grid

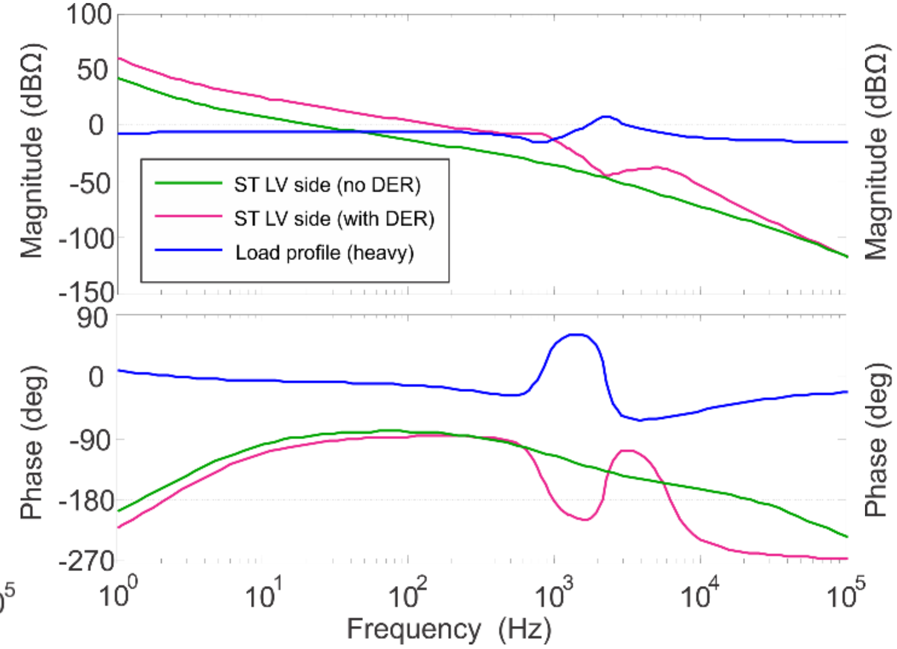
- System stability is determined by $T_m = Z_o / Z_{in}$;
- If $|Z_{in}| >> |Z_o|$ for all frequencies, the effect of LV grid is negligible, the system stability will depend on the stability of LV converter;
- In an actual grid, due to the utilization of „plug-and-play“ devices (e.g., grid converters), $|Z_{in}| >> |Z_o|$ is not always valid.

# Impacts of High-order Filter

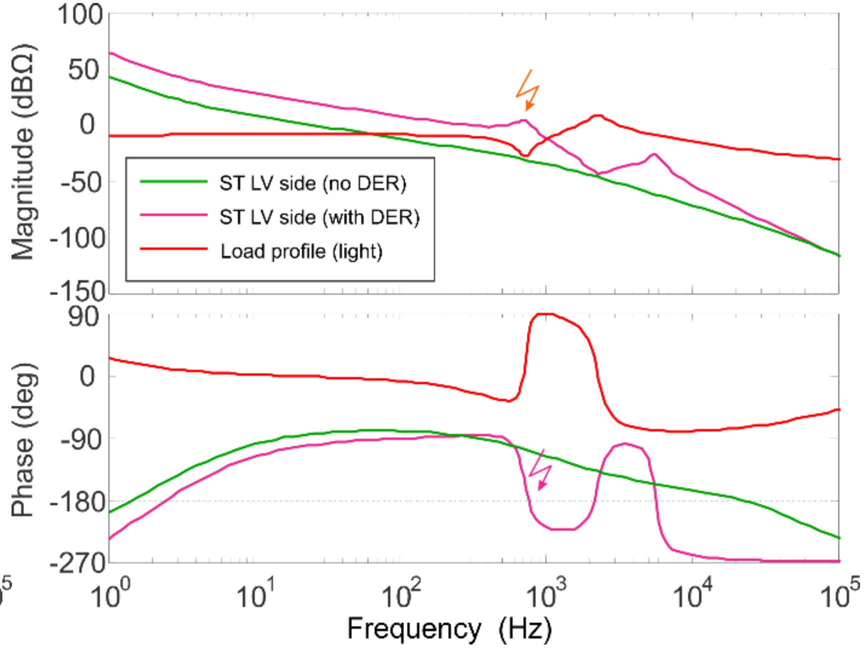
## Admittance of LV grid




## Heavy load case



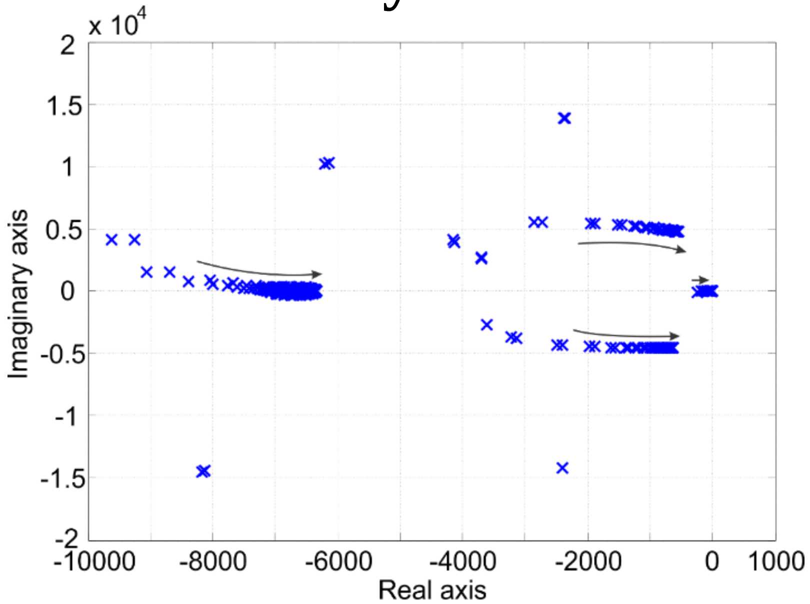

## Light load case



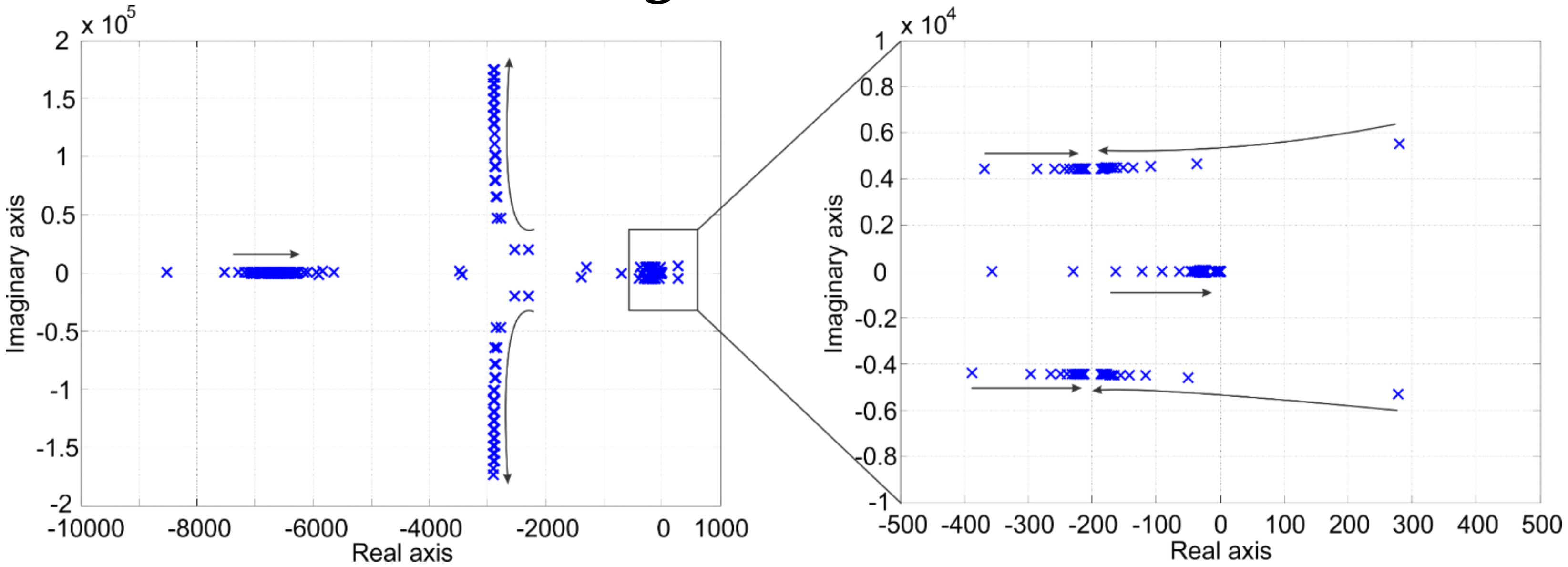

- Shunt-connected passive loads can alleviate resonant peak;
- In case of light load, the high-order filters (e.g., LCL filter) can compromise system stability.

# Impacts of Higher Penetration

## Heavy load case




## Light load case

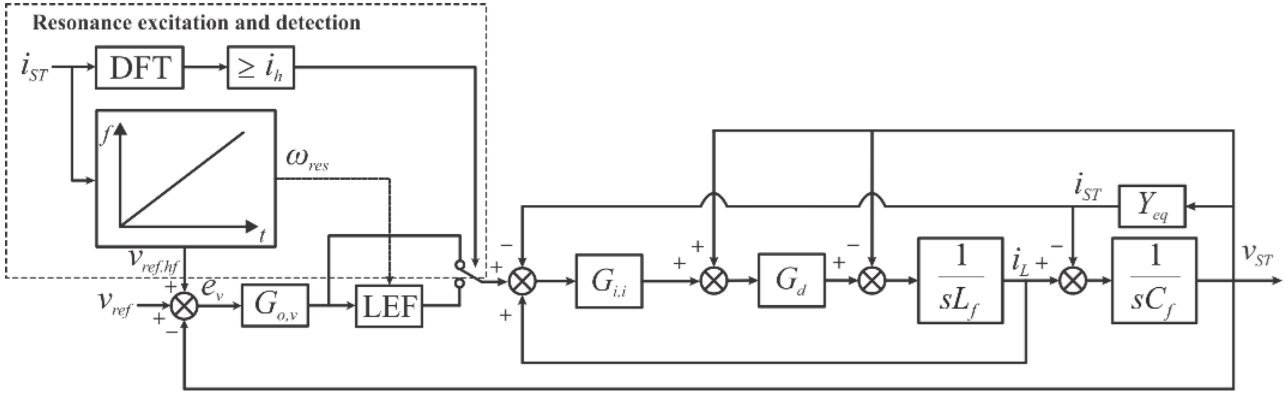


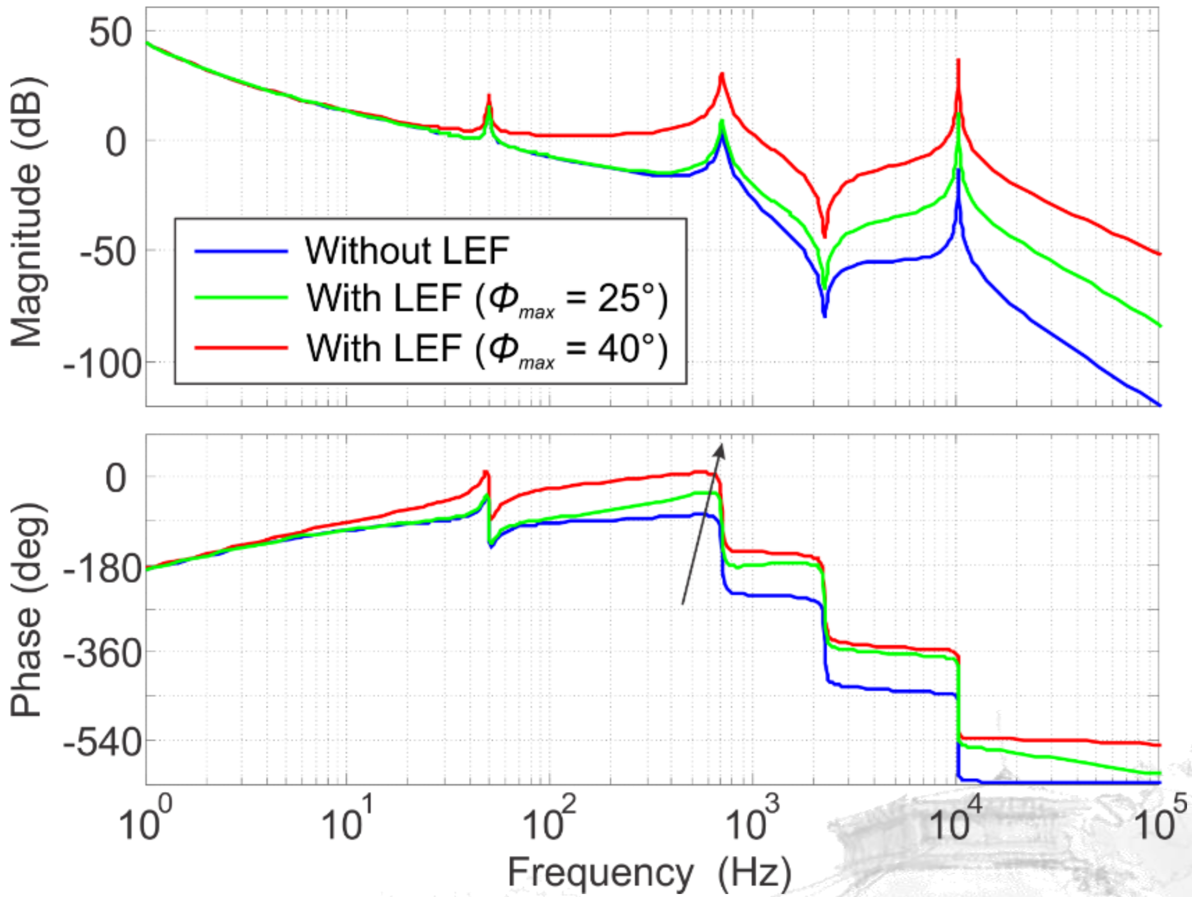

- In case of heavy load, the pair of dominant poles move towards the imaginary axis with the increasing of grid converters;
- In case of light loads, the pair of poles shift leftwards when converters increase.


Z. Zou, G. Buticchi and M. Liserre, "Grid identification and adaptive voltage control in a smart transformer-fed grid," *IEEE Transactions on Power Electronics*, vol. 34, no. 3, pp. 2327-2338, March 2019.

# Stabilization Approaches

## Using lead-element filter (LEF)




- Magnitude and phase property at critical point being changes;
- Phase compensating frequency is based on online resonance indentifiation.

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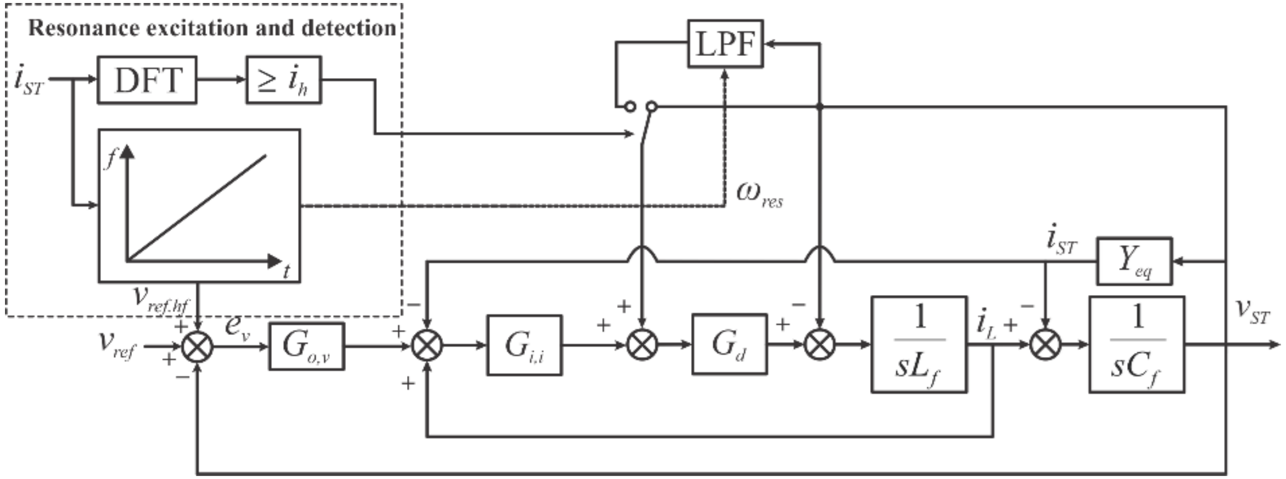
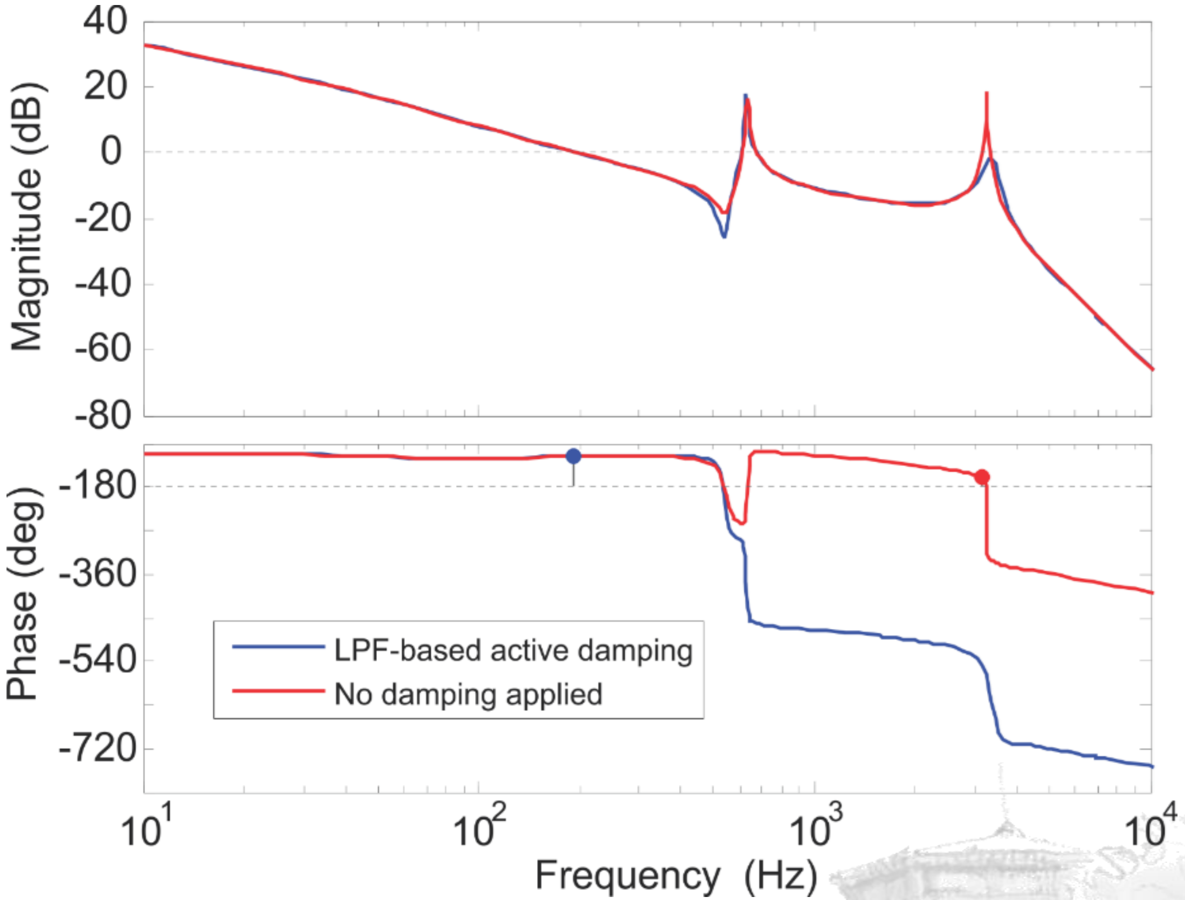
# Stabilization Approaches

## Using low-pass filter (LPF)




- Magnitude and phase property at critical point being changes;
- Cut-off frequency is based on online resonance indentifiation.

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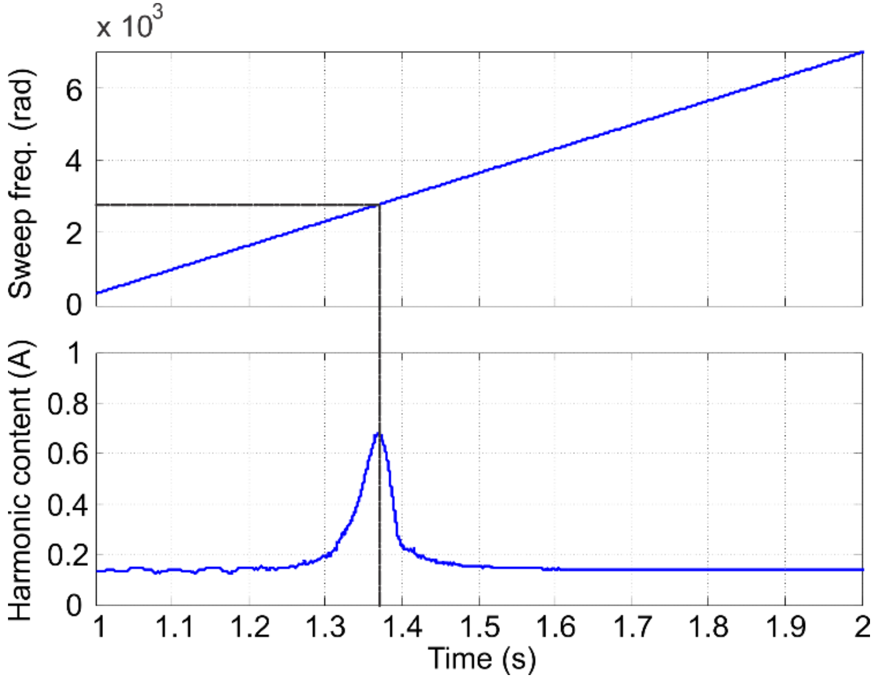
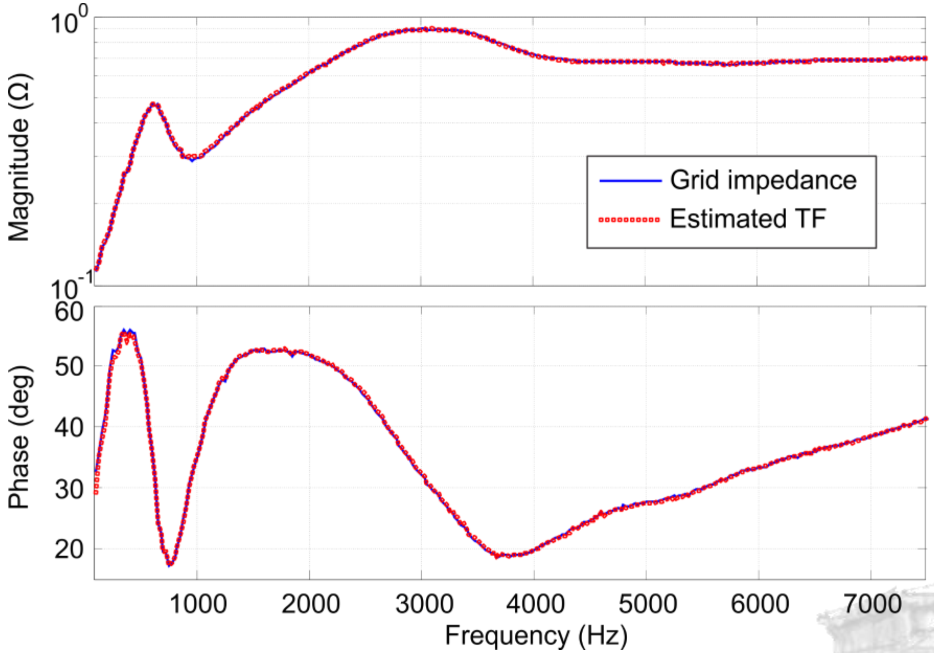
# Resonance Identification

- Mono-frequency excitation ranging from 150 Hz to 1500 Hz is implemented together with voltage control and active damping;
- By using time-domain data, the transfer function of impedance can be obtained by **vector fitting** method.

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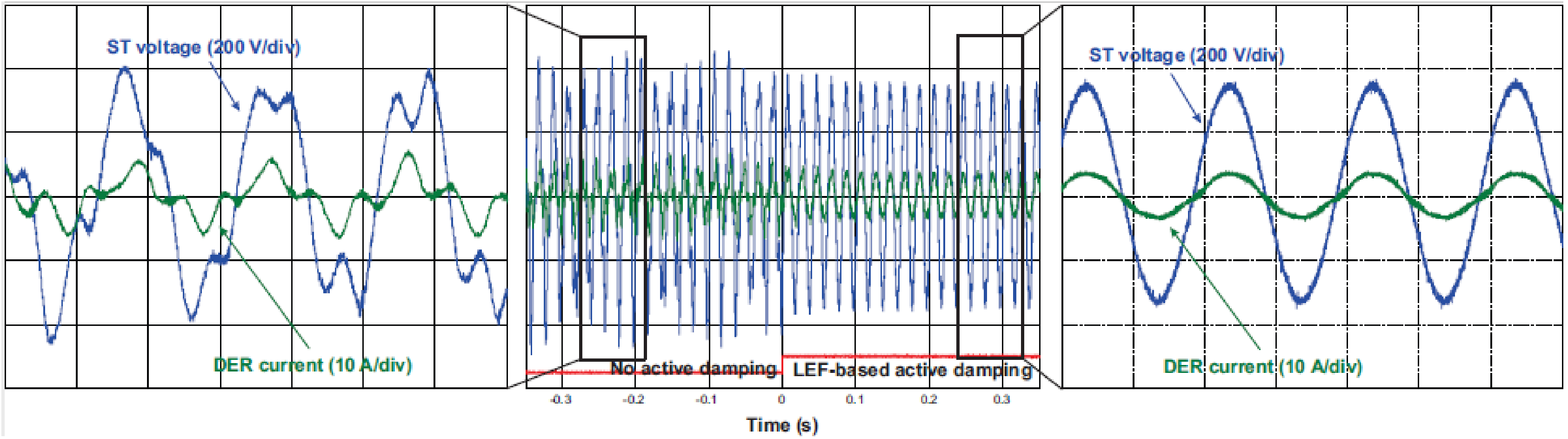
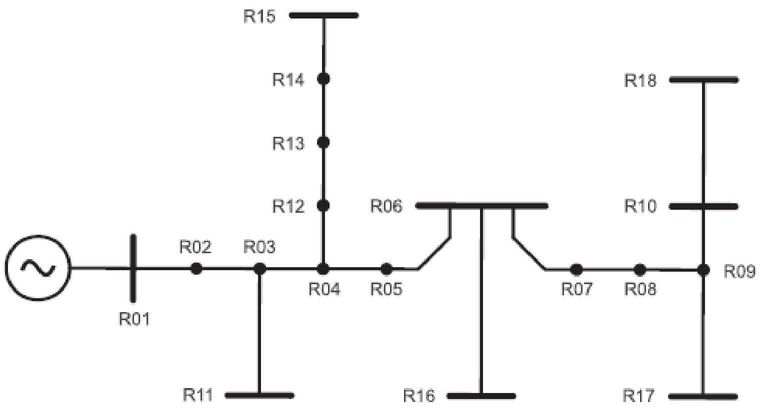
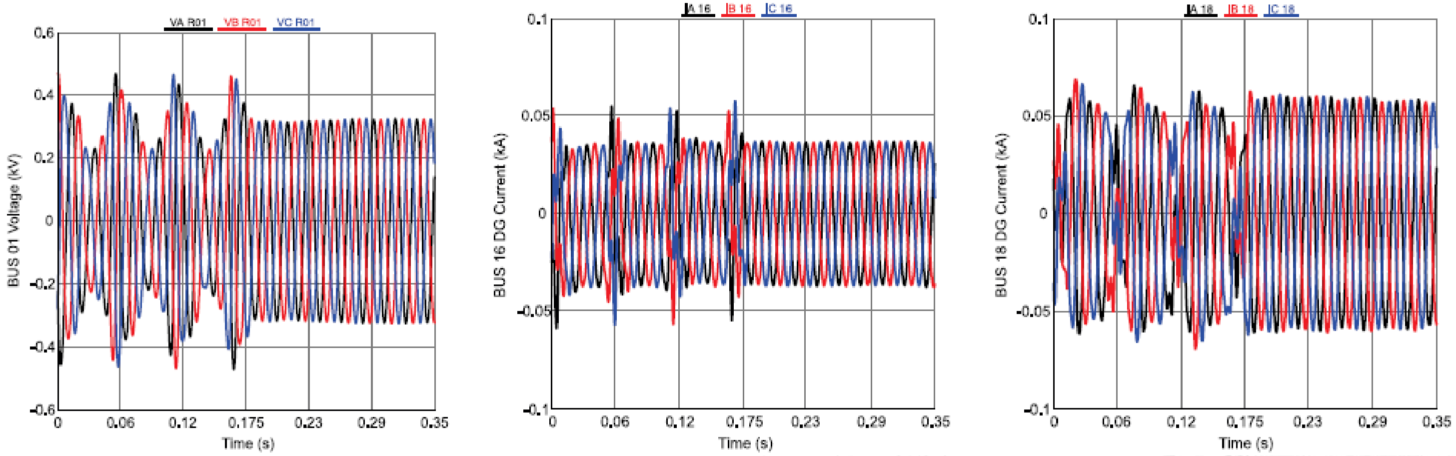
# Experimental Results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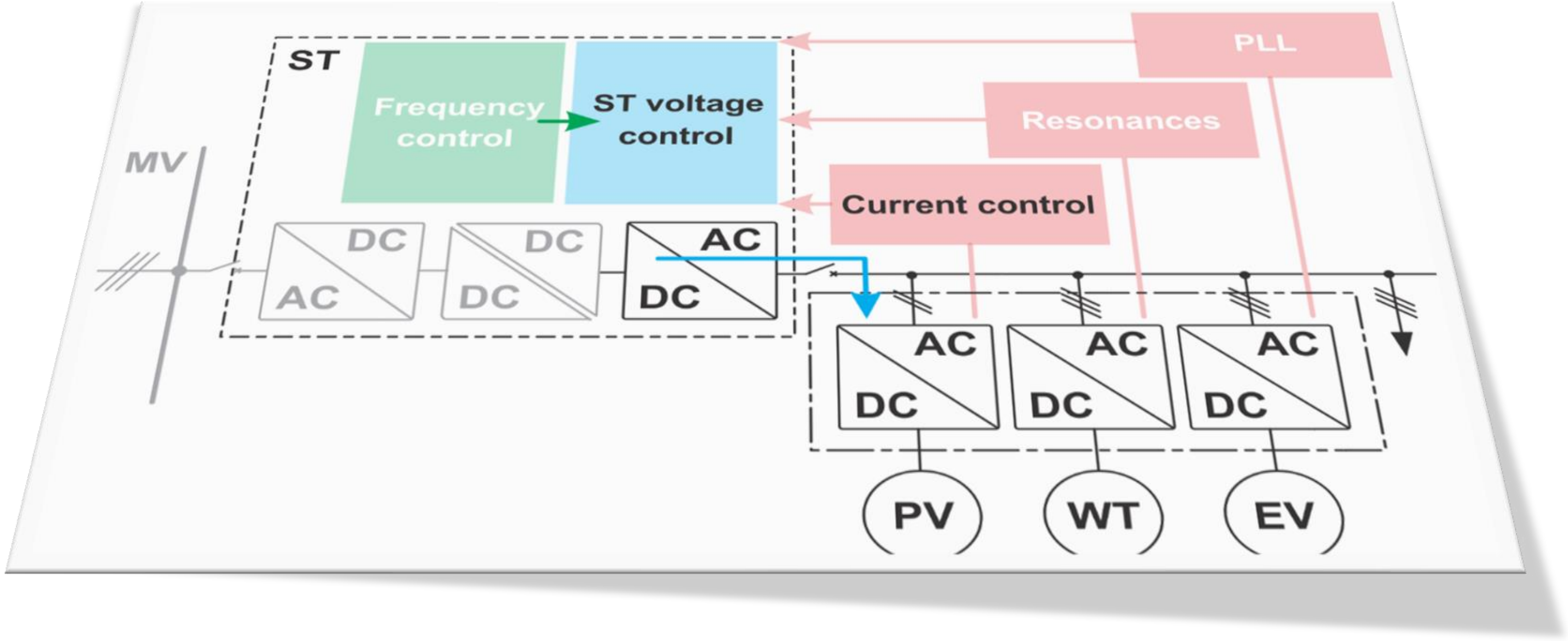
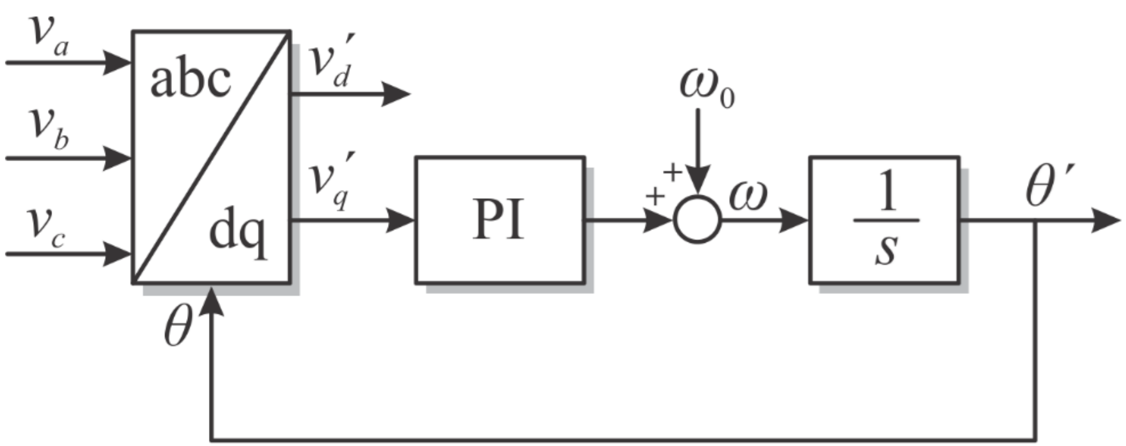
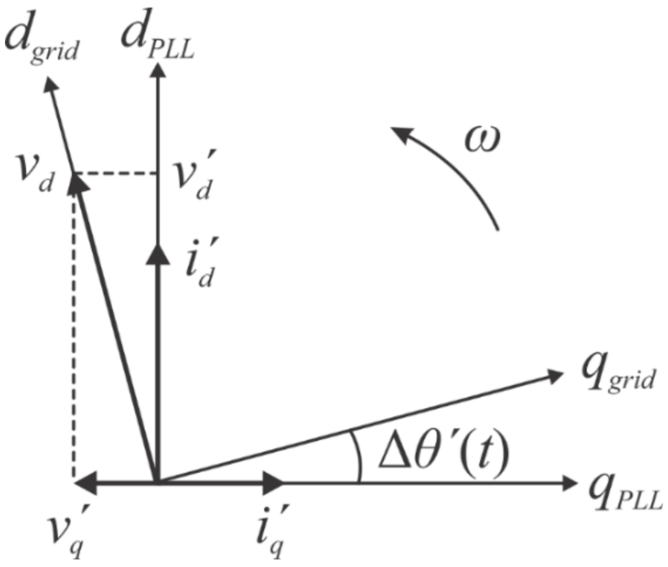



# Influence of Synchronization on ST-fed Grid

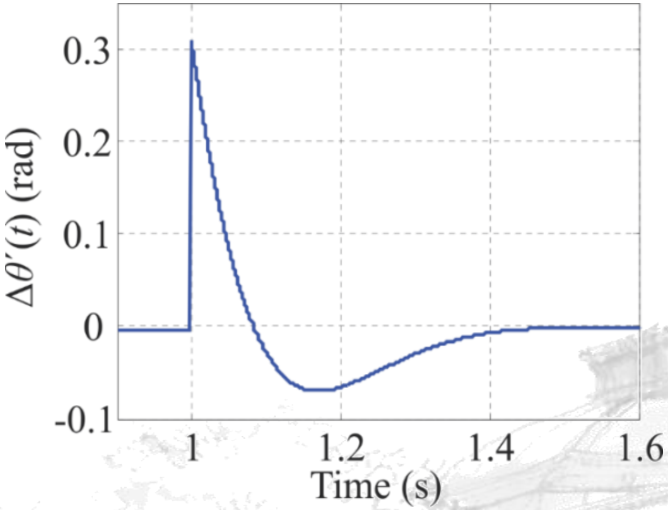
# Quasistationary behaviors of PLL




Phasor diagram

- SRF-PLL is one of the most extended synchronization
- During phase perturbation, the PLL exhibits oscillatory behaviors
- Converter current and power would be oscillatory during disturbance




Angle waveform

Z. Zou, R. Rosso and M. Liserre, "Modeling of the Phase Detector of a Synchronous-Reference-Frame Phase-Locked Loop based on Second-Order Approximation," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 8, no. 3, pp. 2534-2545, Sept. 2020.

**Park transform:**

$$\mathbf{T}(\theta') = \begin{bmatrix} cos\Delta\theta' & sin\Delta\theta' \\ -sin\Delta\theta' & cos\Delta\theta' \end{bmatrix} \mathbf{T}(\theta_0)$$

**During small phase perturbation (<7 deg):**

$$\begin{bmatrix} 1 & \Delta\theta' \\ -\Delta\theta' & 1 \end{bmatrix}$$

Small-angle approximation

**During large phase perturbation:**

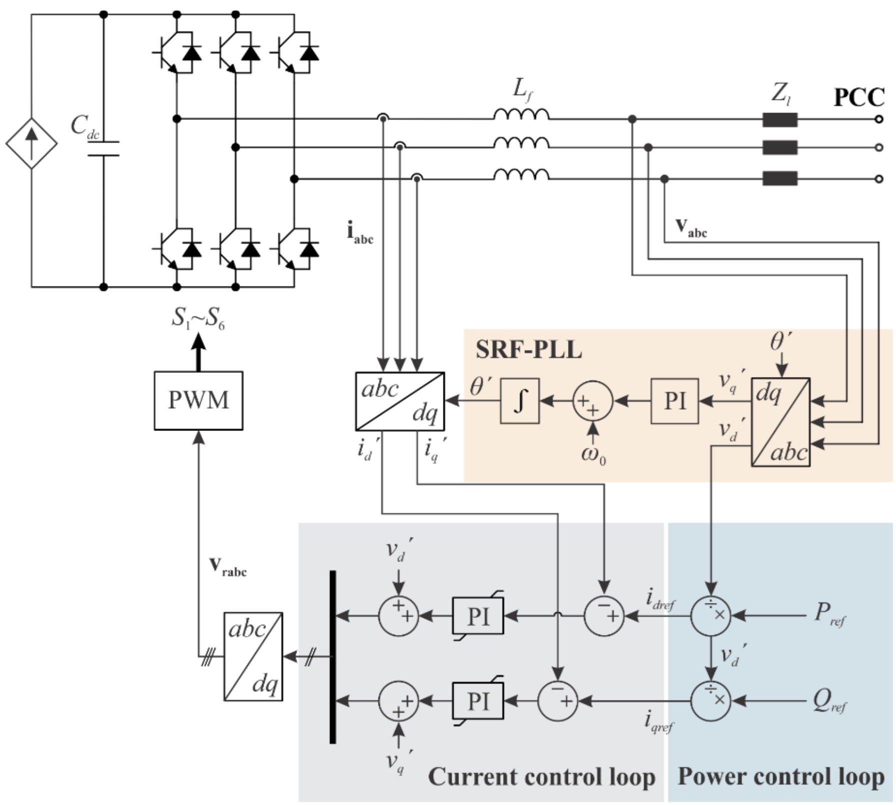
$$\begin{bmatrix} \sum_{n=0}^{\infty} \frac{(-1)^n}{(2n)!}(\Delta\theta')^{2n} & \sum_{n=0}^{\infty} \frac{(-1)^n}{(2n+1)!}(\Delta\theta')^{2n+1} \\ -\sum_{n=0}^{\infty} \frac{(-1)^n}{(2n+1)!}(\Delta\theta')^{2n+1} & \sum_{n=0}^{\infty} \frac{(-1)^n}{(2n)!}(\Delta\theta')^{2n} \end{bmatrix}$$

Large-angle approximation (Maclaurin expansions)

Z. Zou and M. Liserre, "Modeling Phase-locked Loop-based Synchronization in Grid-interfaced Converters," *IEEE Transactions on Energy Conversion*, vol. 35, no. 1, pp. 394-404, 2020.

# More Accurate Model of Grid Converter

## PLL-synchronized converter




## Average model:

$$\begin{bmatrix} L_f s & -\omega L_f \\ \omega L_f & L_f s \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} = G_d \begin{bmatrix} v_{rd} \\ v_{rq} \end{bmatrix} - \begin{bmatrix} v_d \\ v_q \end{bmatrix}$$

## Updating model with second-order terms:

Grid voltage:

$$\begin{bmatrix} v_d' \\ v_q' \end{bmatrix} = \begin{bmatrix} \frac{2-\Delta\theta'^2}{2} & \Delta\theta' \\ -\Delta\theta' & \frac{2-\Delta\theta'^2}{2} \end{bmatrix}\begin{bmatrix} v_d \\ v_q \end{bmatrix}$$

Grid current:

$$\begin{bmatrix} \Delta i_d \\ \Delta i_q \end{bmatrix} = \begin{bmatrix} \Delta i_d' \\ \Delta i_q' \end{bmatrix} + \begin{bmatrix} -I_q \\ I_d \end{bmatrix}\Delta\theta' + \begin{bmatrix} -\frac{1}{2}I_d \\ -\frac{1}{2}I_q \end{bmatrix}\Delta\theta'^2$$

Voltage reference:

$$\begin{bmatrix} \Delta v_{rd} \\ \Delta v_{rq} \end{bmatrix} = \begin{bmatrix} \Delta v_{rd}' \\ \Delta v_{rq}' \end{bmatrix} + \begin{bmatrix} -V_{rq}' \\ V_{rd}' \end{bmatrix}\Delta\theta' + \begin{bmatrix} -\frac{1}{2}V_{rd}' \\ -\frac{1}{2}V_{rq}' \end{bmatrix}\Delta\theta'^2$$

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# More Accurate Model of Grid Converter

## Compete model of PLL-synchronized grid converter (second-order):

$$\begin{bmatrix}\Delta i_d \\ \Delta i_q\end{bmatrix} = \begin{bmatrix}Y_{dd} & 0 \\ 0 & Y_{qq}\end{bmatrix}\begin{bmatrix}\Delta v_d \\ \Delta v_q\end{bmatrix} + \begin{bmatrix}I_{dd} & 0 \\ 0 & I_{qq}\end{bmatrix}\begin{bmatrix}\Delta i_{dref} \\ \Delta i_{qref}\end{bmatrix} + \begin{bmatrix}\Theta_{d1} \\ \Theta_{q1}\end{bmatrix} G_{PLL\_cl}\Delta\theta + \begin{bmatrix}\Theta_{d2} \\ \Theta_{q2}\end{bmatrix} (G_{PLL\_cl})^2(\Delta\theta)^2$$

| Accuracy | Problem | Grid condition | Modeling type |
|---|---|---|---|
| A | Transient stability | Weak grid with large phase pertutbation | Impedance-based model with higher-order PLL terms |
| B | Harmonic stability using small-signal analysis | Weak grid (SCR < 3) | Impedance-based model with first-order PLL terms |
| C | | Strong grid (SCR > 10) | Impedance-based model |
| D | Linear analysis | Strong grid (SCR > 10) | Current source model |
| E | Scheduling and optimization | Stiff grid | Phasorial model |

- Each model can reveal certain phenomenon, though has limitation
- The model deepness has to be decided depending on the studied problems and required accuracy.

Z. Zou and M. Liserre, "Modeling Phase-locked Loop-based Synchronization in Grid-interfaced Converters," *IEEE Transactions on Energy Conversion*, vol. 35, no. 1, pp. 394-404, 2020.

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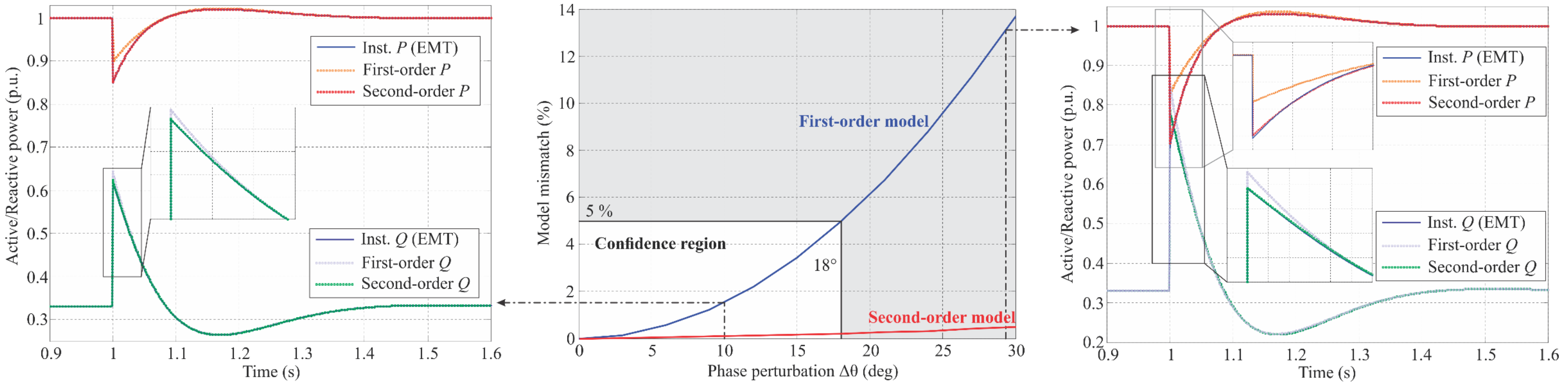
# Model Evaluation: Time-domain Responses

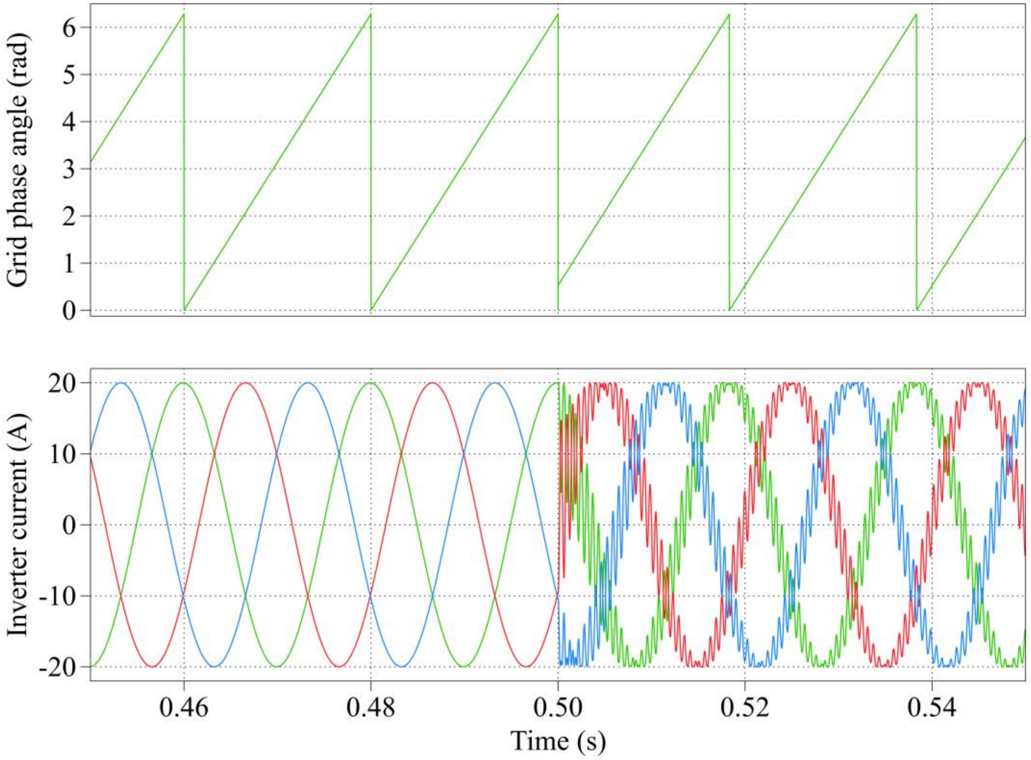



- When the phase perturbation is small, the small-signal model (first-order) is able to represent the system behavior and be used for stability analysis
- When the phase perturbation is large, i.e., out of confidence region, the second-order model has to be used for the analysis

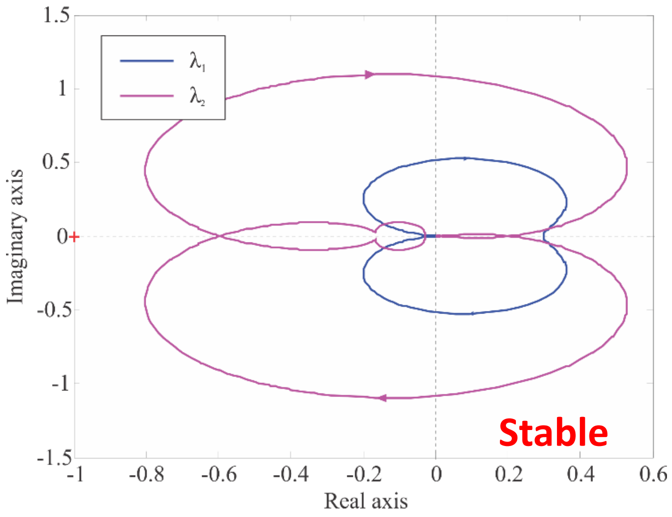
Z. Zou, R. Rosso and M. Liserre, "Modeling of the Phase Detector of a Synchronous-Reference-Frame Phase-Locked Loop based on Second-Order Approximation," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 8, no. 3, pp. 2534-2545, Sept. 2020.

# Stability Analysis with Different Models

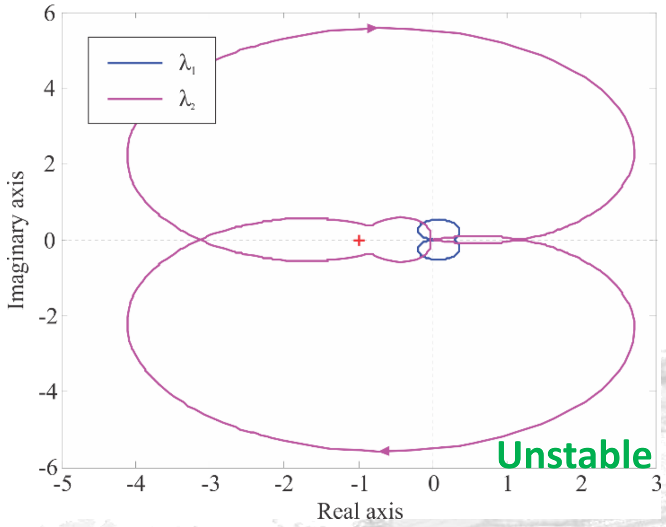
## An unstable case of grid converter due to phase jump




Small-signal (1st-order) model




More accurate (2nd-order) model





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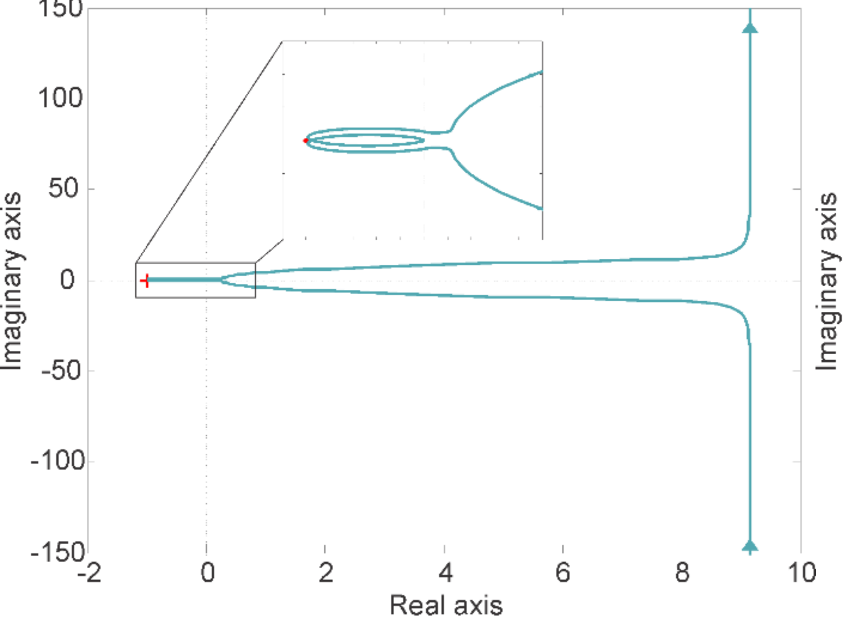
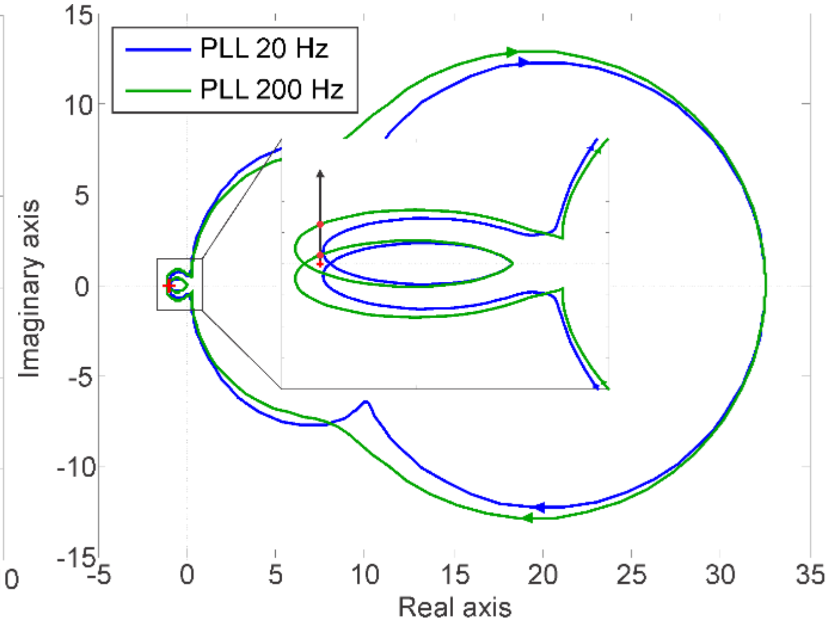
# Impacts of SRF-PLL

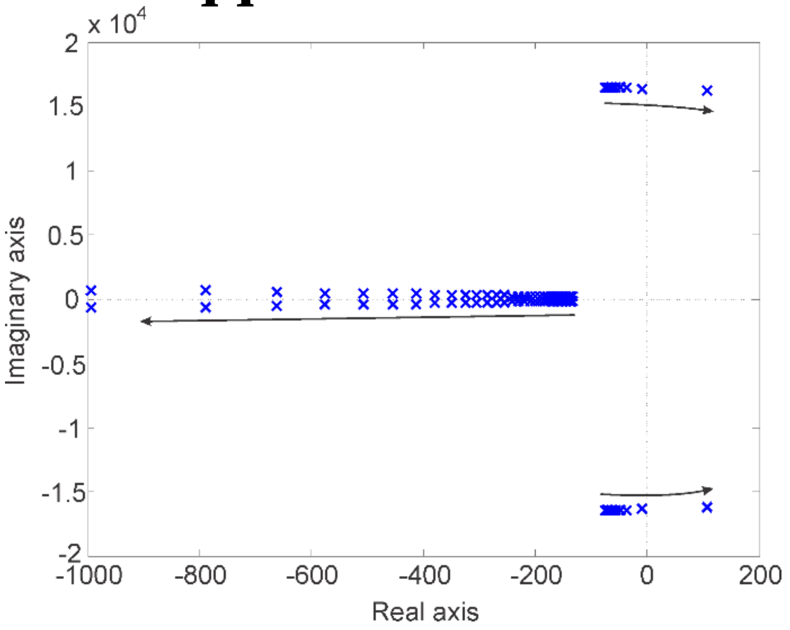
$\lambda_1$




$\lambda_2$



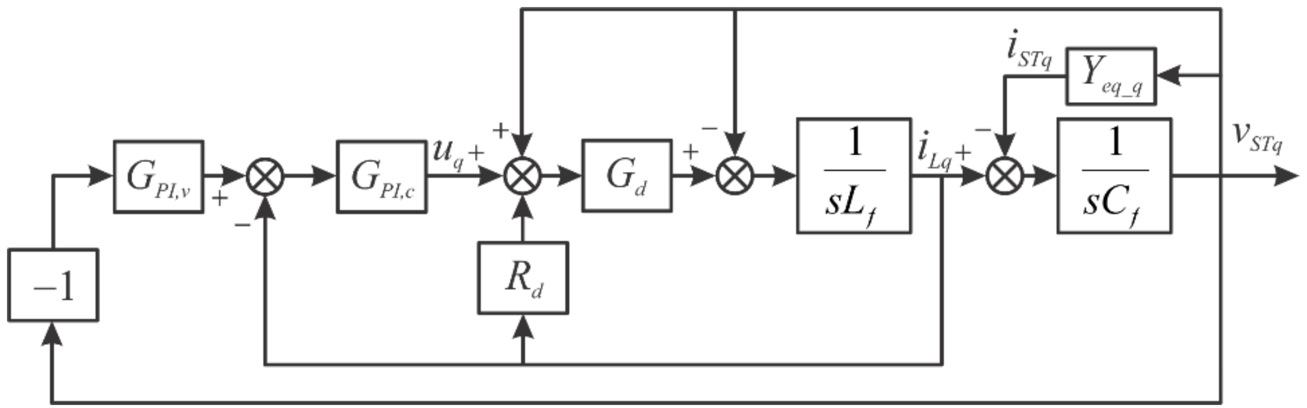

**qq-axis root locus**



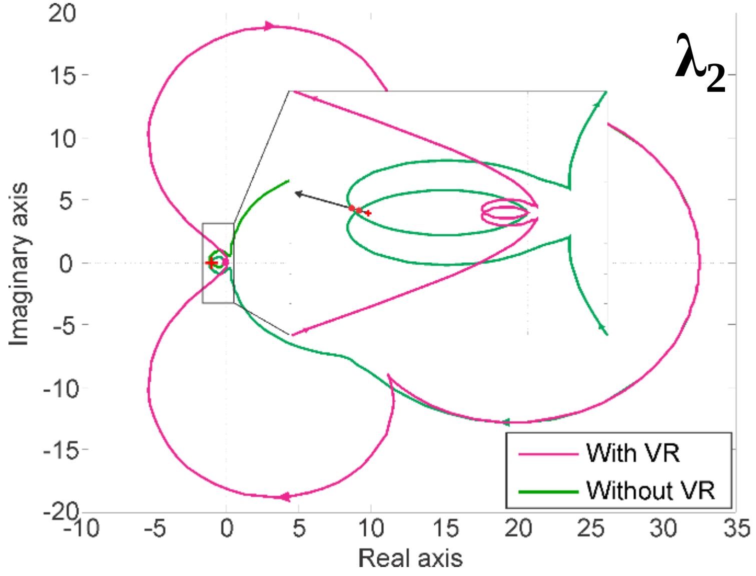

- Nyquist plot of the second eigenvalue ($\lambda_2$) is determined by the PLL bandwidth;
- In case of high PLL bandwitdh, the system is less likely to be stable, the dominant poles of the qq-axis closed-loop system move towards right-half plane.


Z. Zou, M. Liserre, Z. Wang and M. Cheng, "Modeling and Stability Analysis of a Smart Transformer-Fed Grid," *IEEE Access*, vol. 8, pp. 91876-91885, 2020.

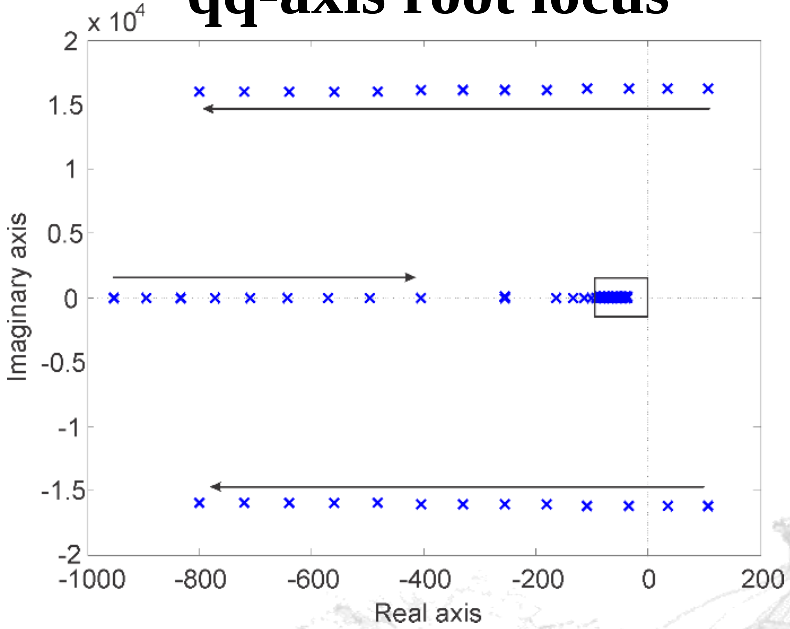
# Stabilization Approach




- *d*-axis voltage control strategy remains the same;
- Virtual resistor being introduced in *q*-axis improves system stability.




**qq-axis root locus**

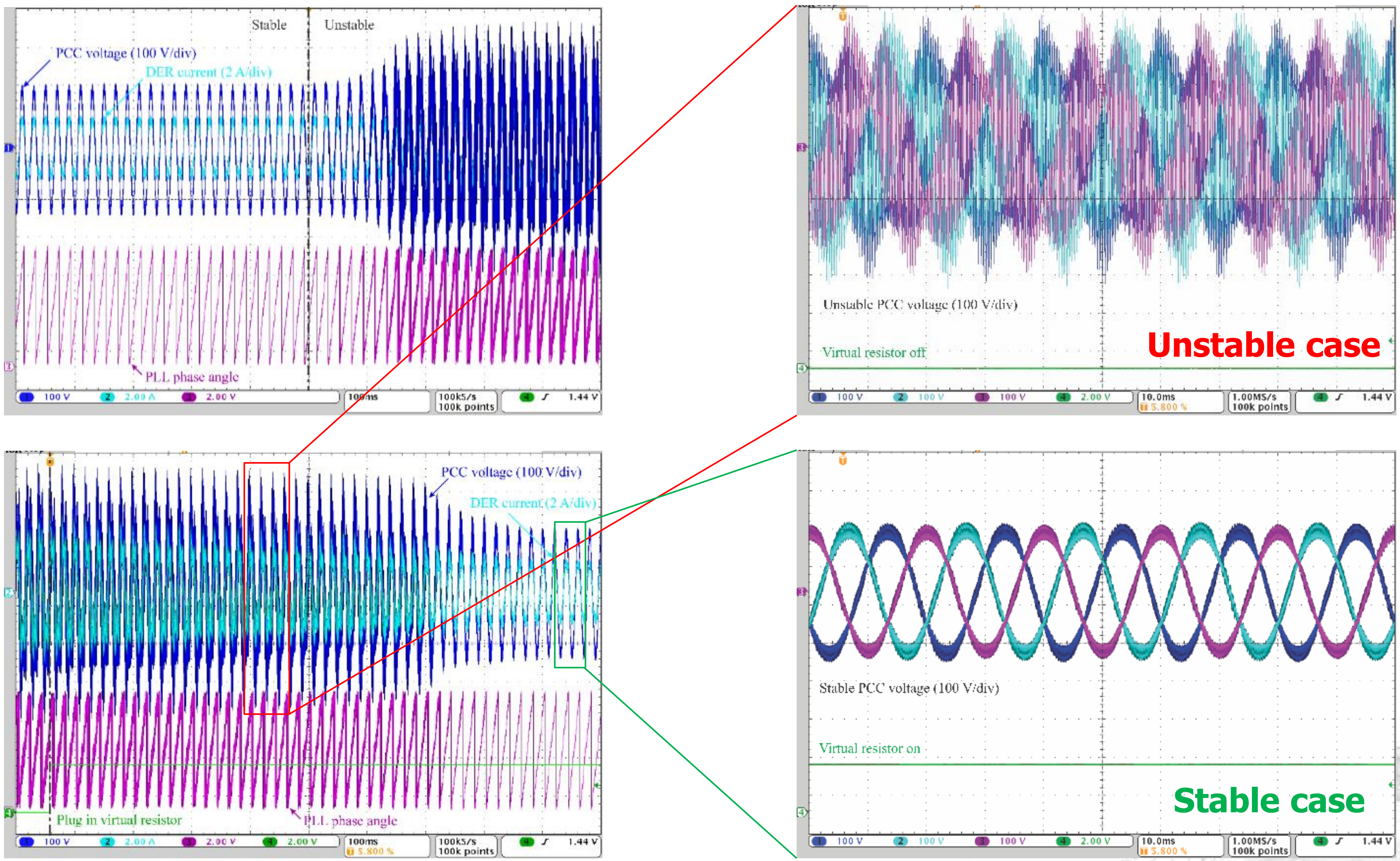



Z. Zou, M. Liserre, Z. Wang and M. Cheng, "Modeling and Stability Analysis of a Smart Transformer-Fed Grid," *IEEE Access*, vol. 8, pp. 91876-91885, 2020.

# Experimental Results

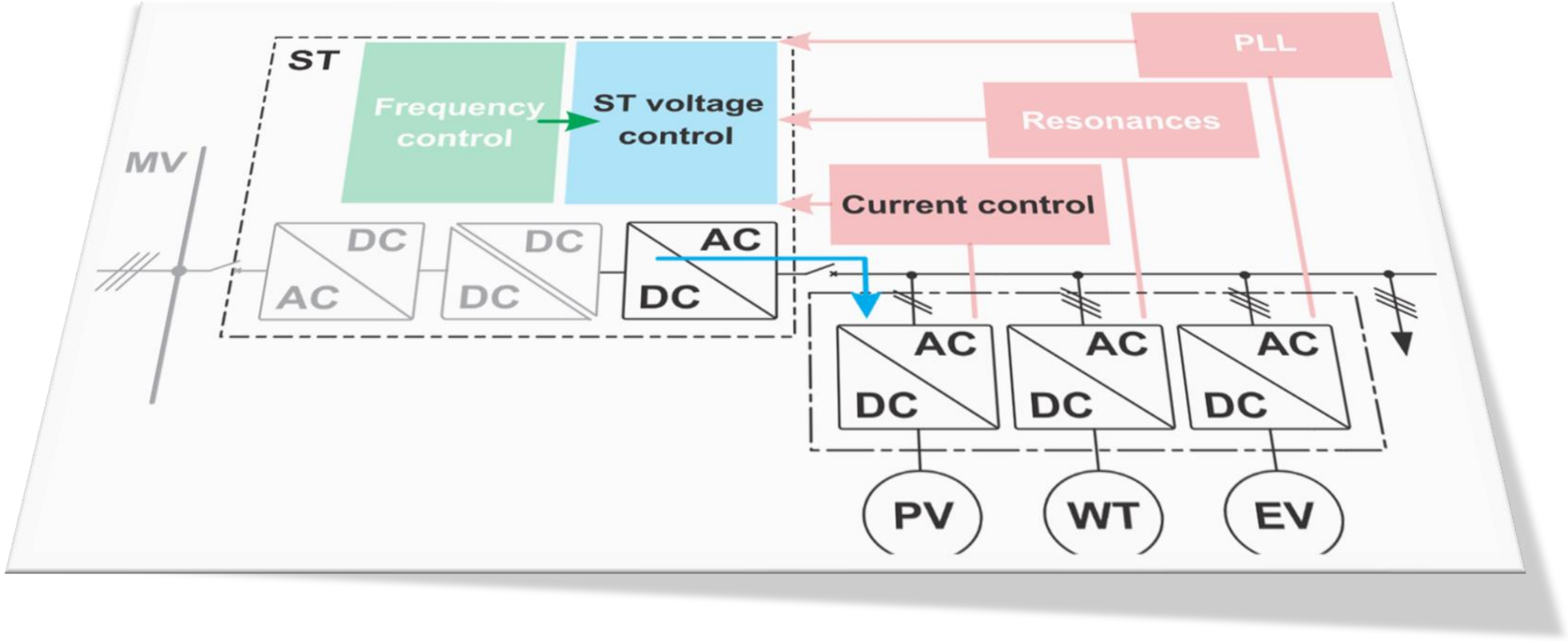
**Jump from low bandwidth to a higher one:**

**Before & after the plug-in of virtual resistor:**





Z. Zou, M. Liserre, Z. Wang and M. Cheng, "Modeling and Stability Analysis of a Smart Transformer-Fed Grid," *IEEE Access*, vol. 8, pp. 91876-91885, 2020.




# Conclusions

# Conclusions

- Smart transformer can provide better controbility of modern power system, but it has local control challenges as well;
- The ST LV converter can use filter-based active damping to stabilize the LV grid caused by filter resonances; the system robustness can be further improved by employing online resonance identification;
- High bandwidth SRF-PLL can incur instability of a ST-fed grid, while the system can be stabilized by using virtual resistor in q-axis of voltage control of ST LV converter.

DFG SPP 1984

# Thank you for the attentions!

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