IMPEDANCES IN DC-MICROGRIDS
FROM OFFLINE TO ONLINE MEASUREMENTS

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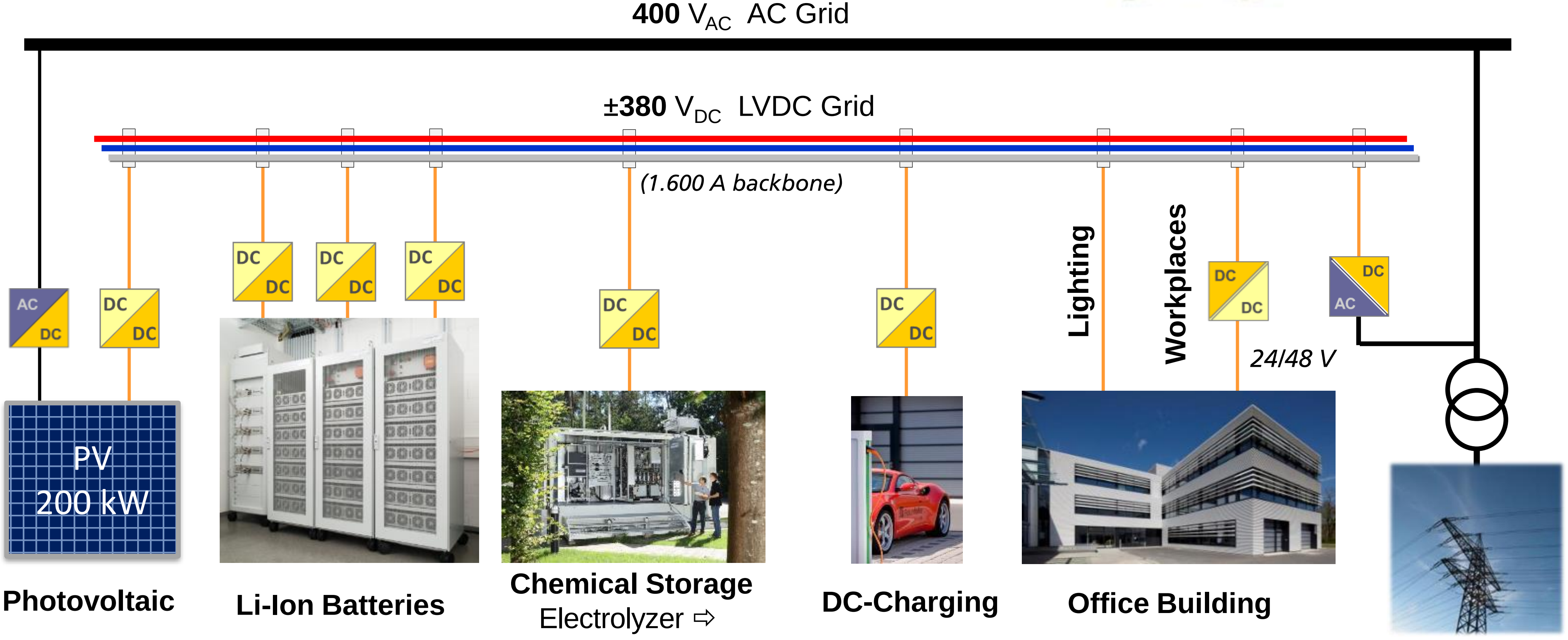
Agenda

- *Introduction to the DC-Mircrogrid*
- *Opportunities for Impedance Measurements in DC-Microgrids*
- *Droop-Controlled DC-Microgrids*
- *Stability Investigation through Impedance Measurements*
- *Bode 100 Testbench*
  - *Output-impedance of a constant-current source*
  - *Output-impedance of a constant-voltage source*
  - *Output-impedance of a droop-controlled converter*
  - *Input-impedance of a constant-power load*
- *Online Measurement with Pseudo-Random-Binary-Sequences*
- *Advanced Data Analytics for Grid Layout and Stability Optimization*
- *Stabilization of DC Networks Applying Artificial Intelligence*
- *Summary*

Introduction to the DC-Mircrogrid



400 V$_{AC}$ AC Grid

±380 V$_{DC}$ LVDC Grid

(1.600 A backbone)

Photovoltaic

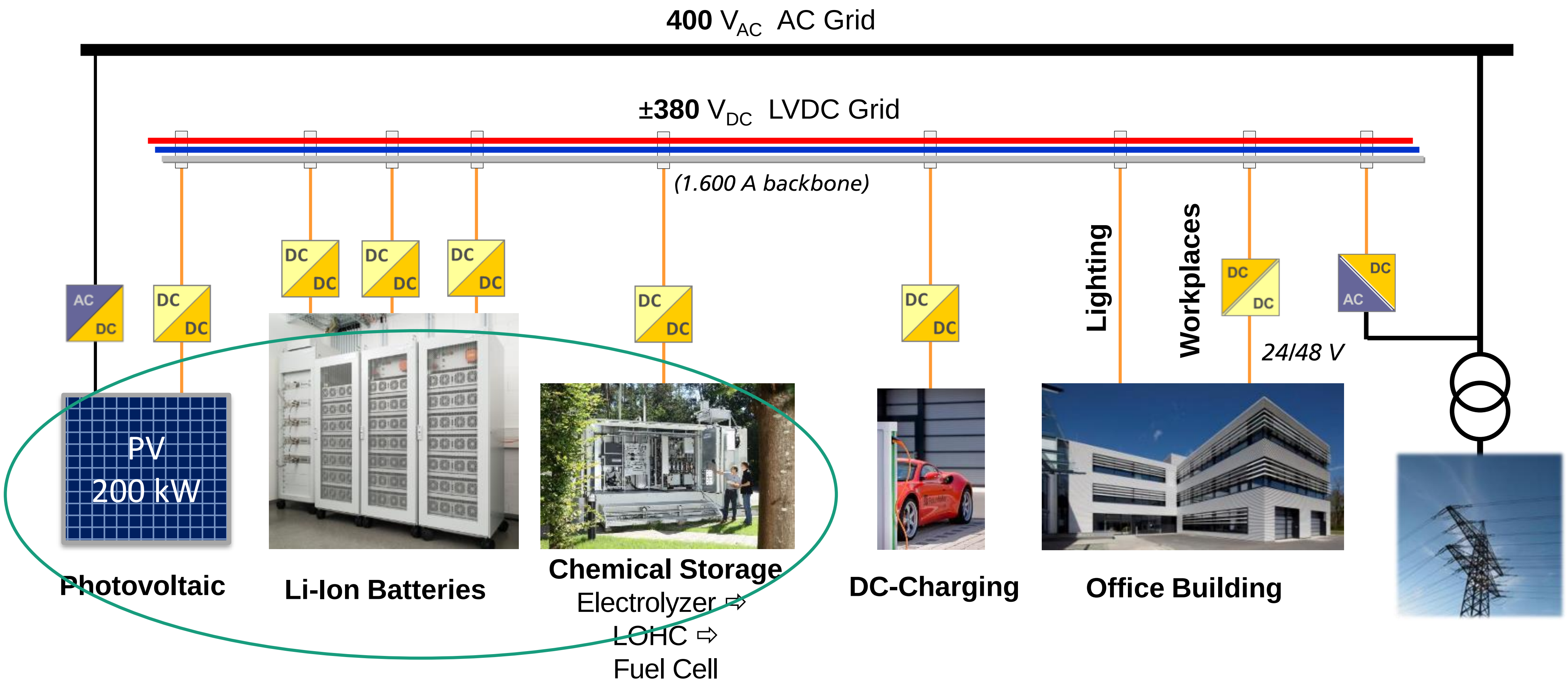
Li-Ion Batteries

Chemical Storage
Electrolyzer ⇨
LOHC ⇨
Fuel Cell

DC-Charging

Office Building

Opportunities for Impedance Measurements in DC-Microgrids



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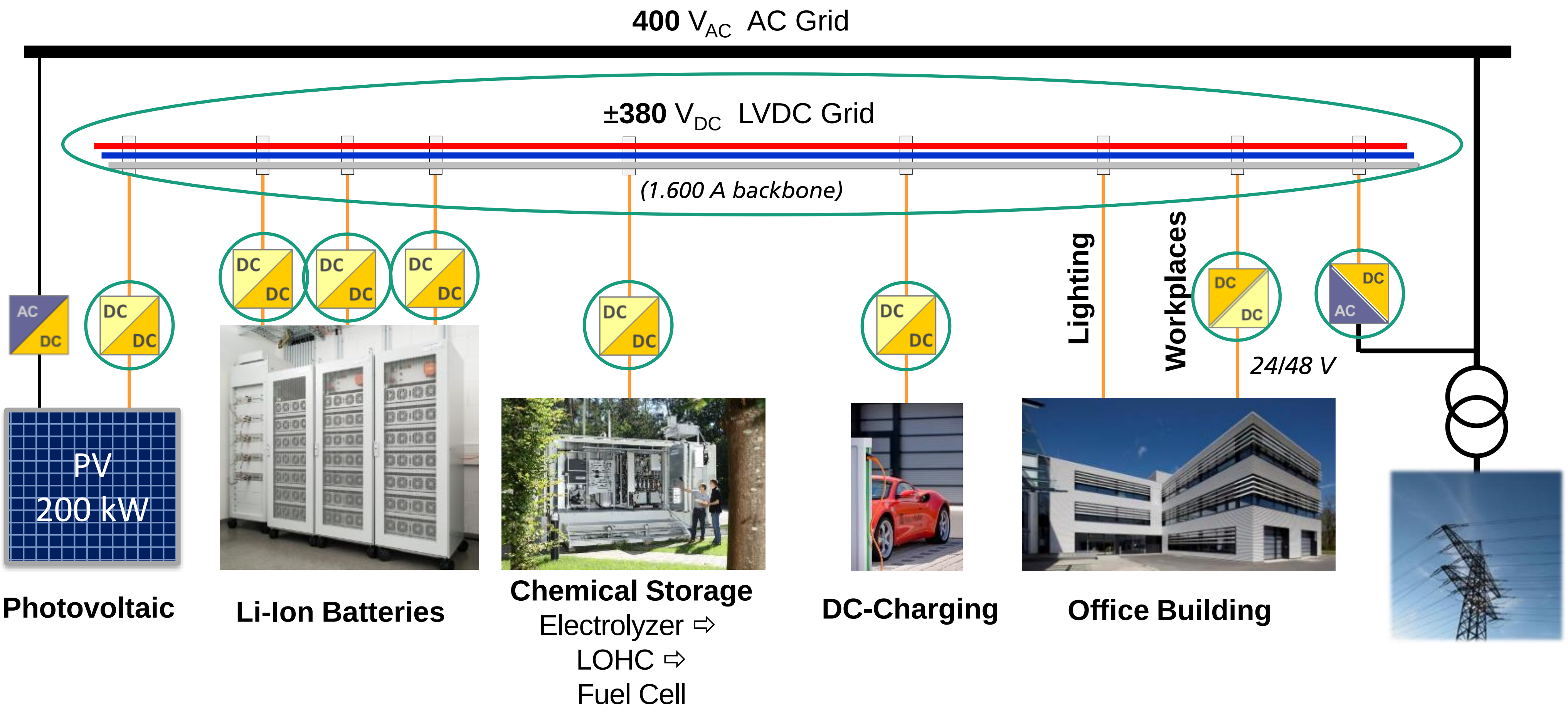
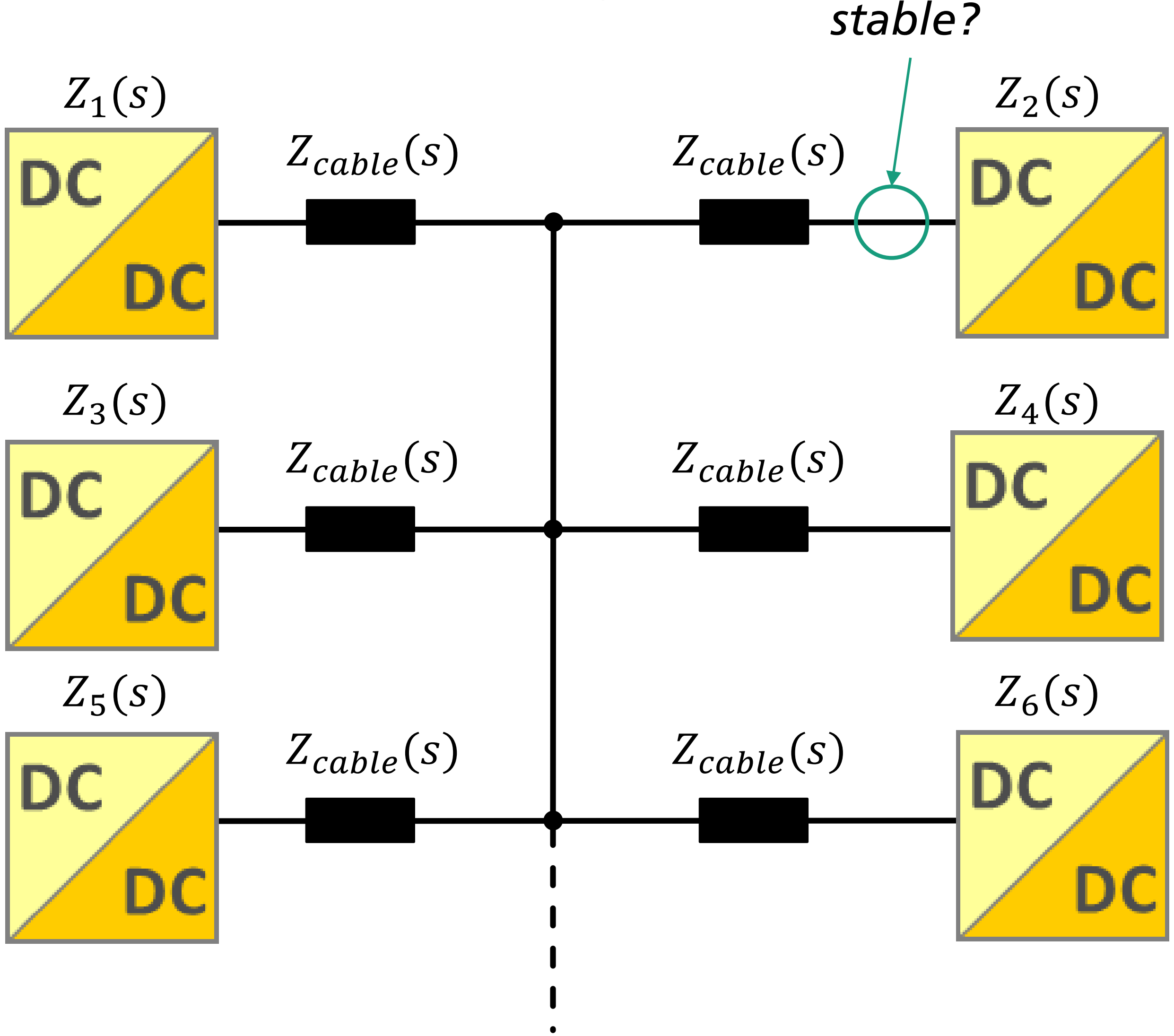
Opportunities for Impedance Measurements in DC-Microgrids



Opportunities for Impedance Measurements in DC-Microgrids

- *Why online measurements?*
  - *Real grids are complex*
  - *Converters are nonlinear*
  - *Adjustable parameters:*
    - *Control*
      - *Mode of operation*
      - *Controller*
      - *Digital filter*
    - *Droop-curve*
      - *Slope*
      - *Shape*
      - *Offset*



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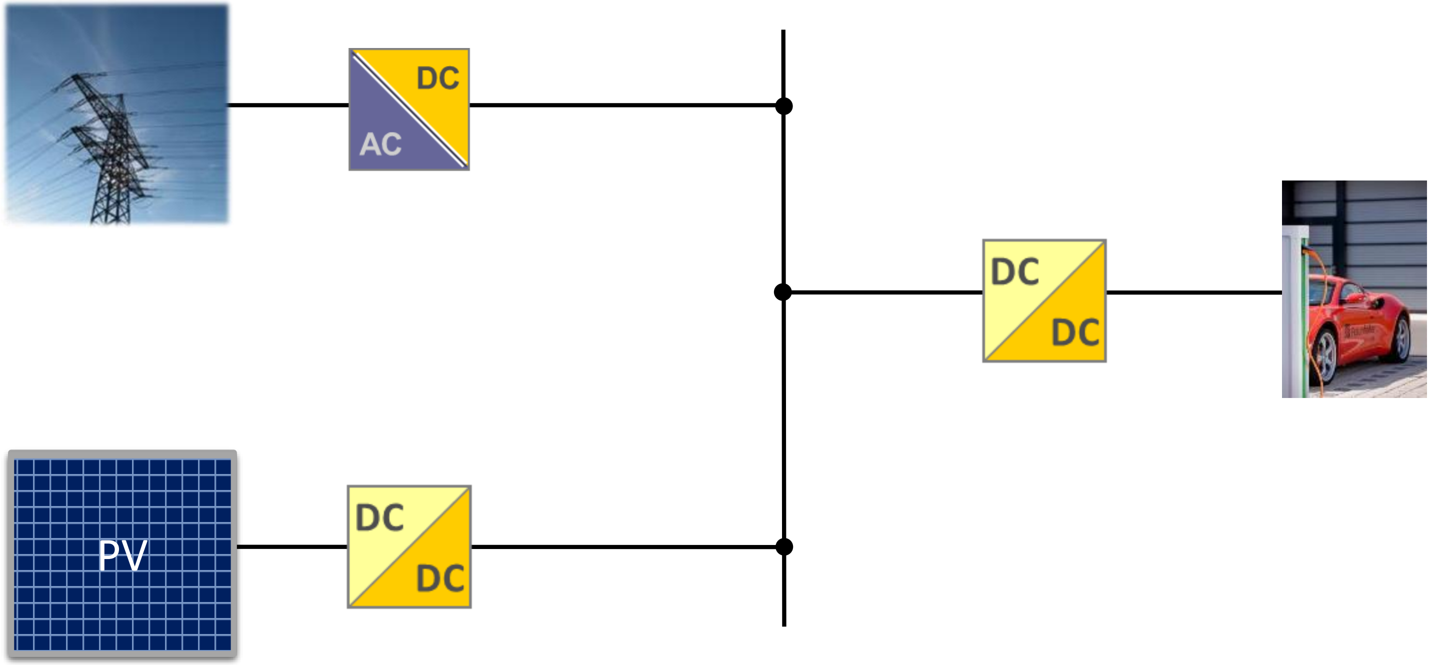
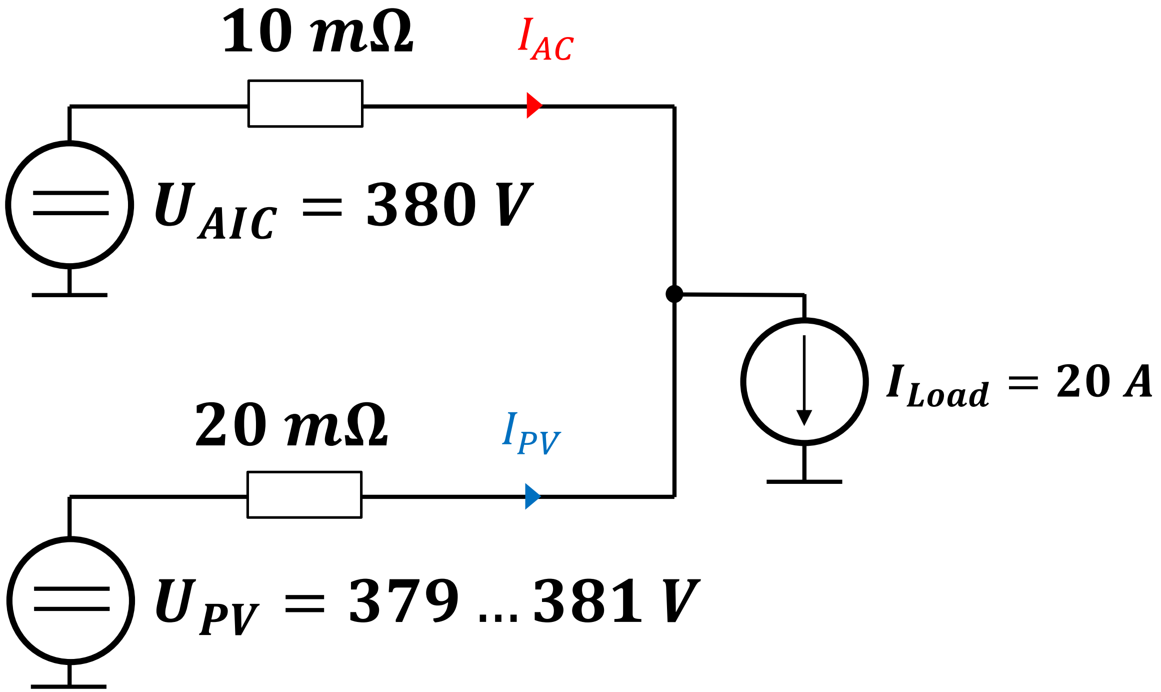
Droop-Controlled DC-Microgrids

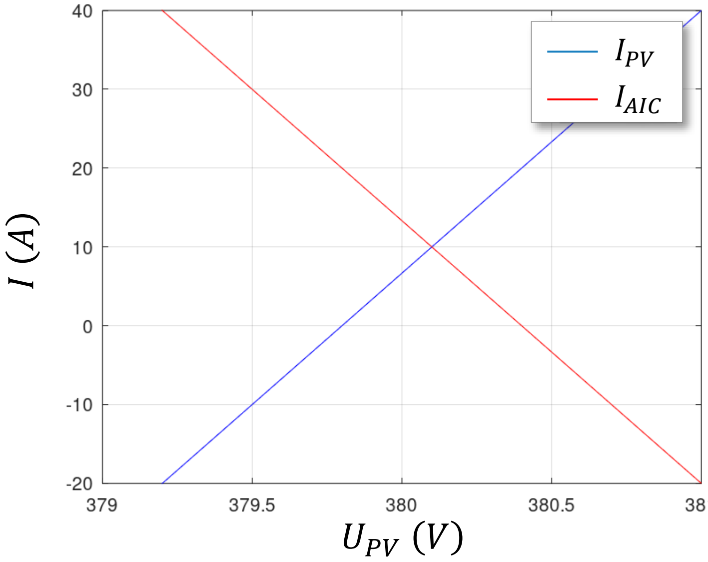


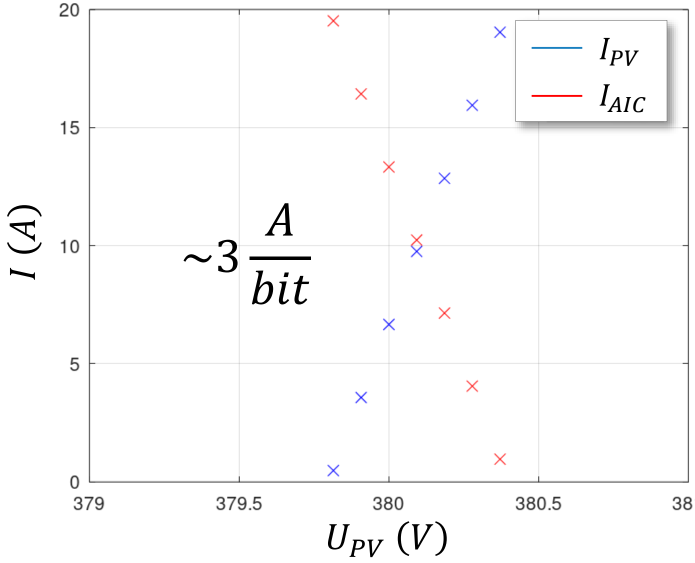
Droop-Controlled DC-Microgrids

- *Voltage Control:*



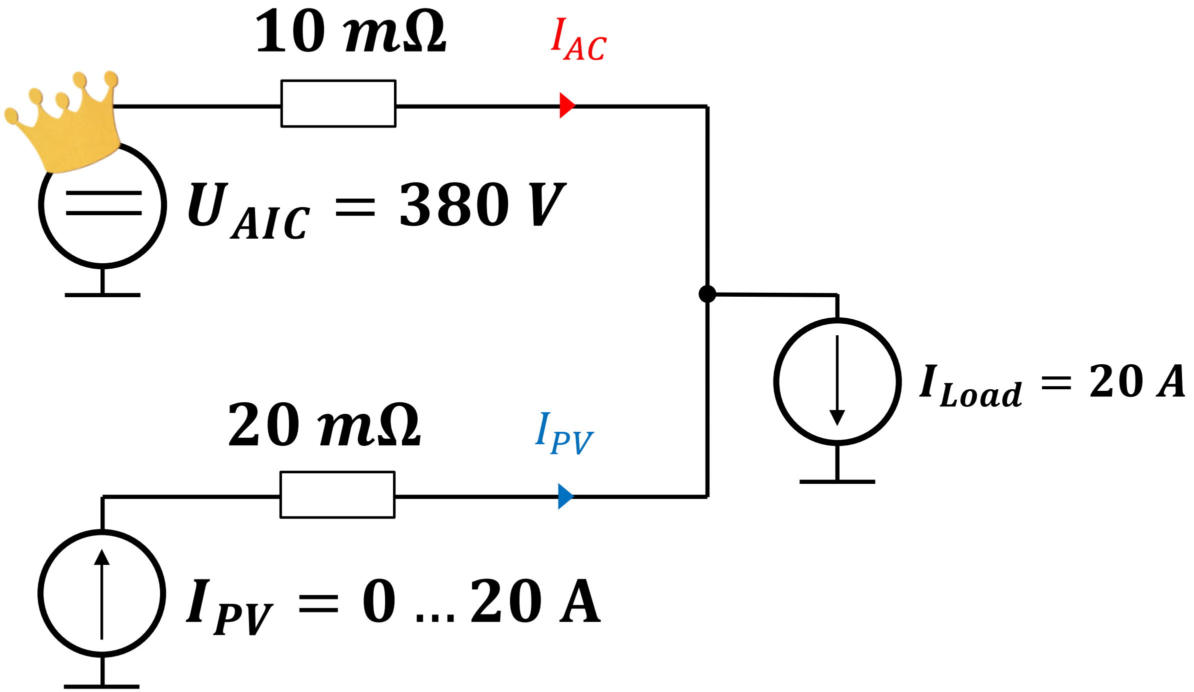
- *Voltage sources need fine tuning*
- *Load sharing is nearly impossible with a 12-bit ADC*





Droop-Controlled DC-Microgrids

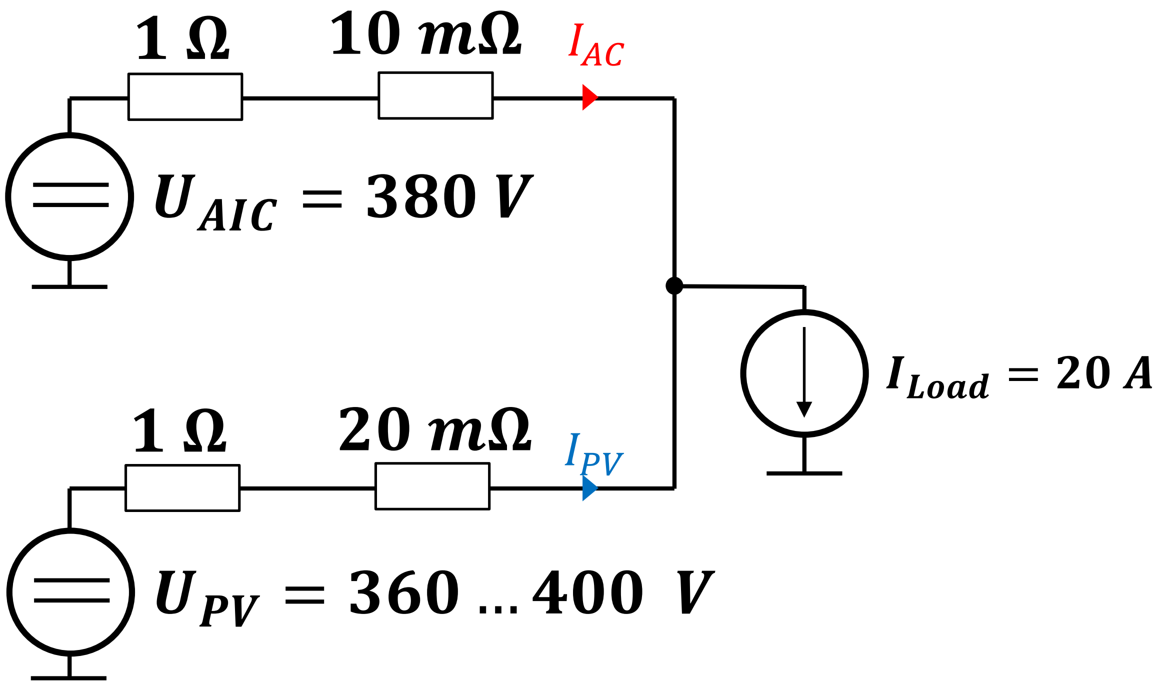
- *Master-Slave Control:*

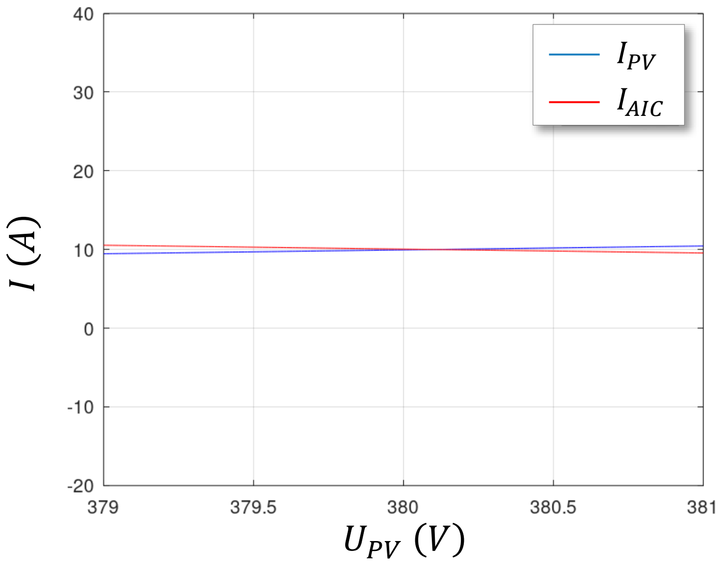


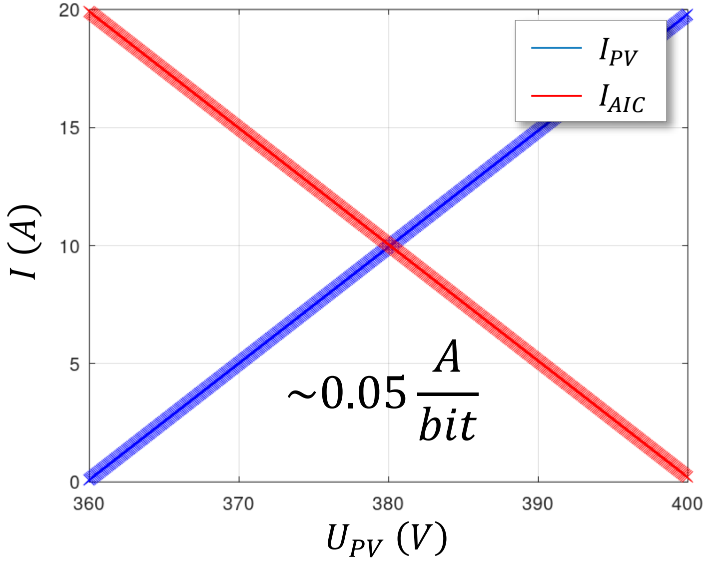
- *Less communication is required*
- *Master must be a bidirectional source*
- *Master must not be turned off*

Droop-Controlled DC-Microgrids

- *Transition to droop-control:*





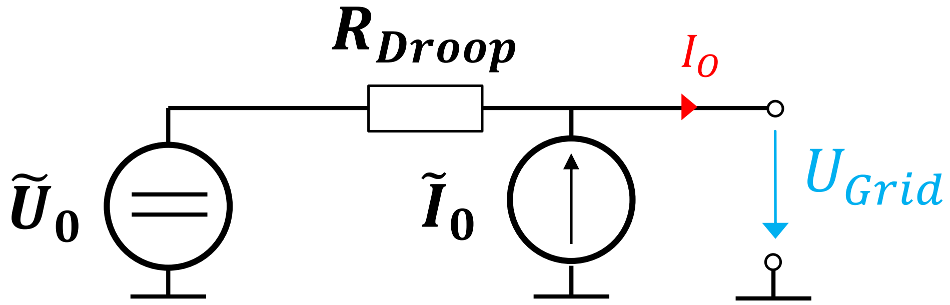


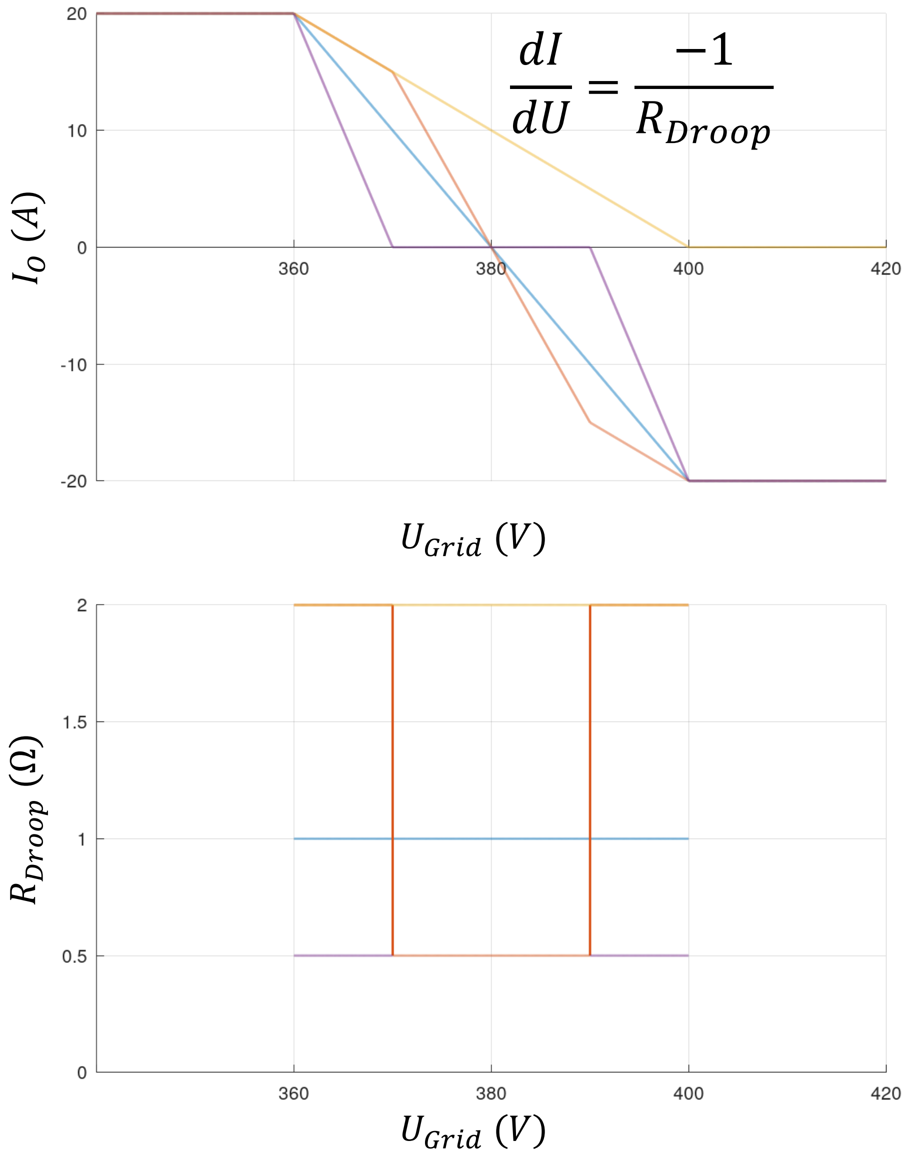
- *No communication is required*
- *A defined additional resistance helps with load sharing*

➢ *Use a virtual droop-resistance*

Droop-Controlled DC-Microgrids

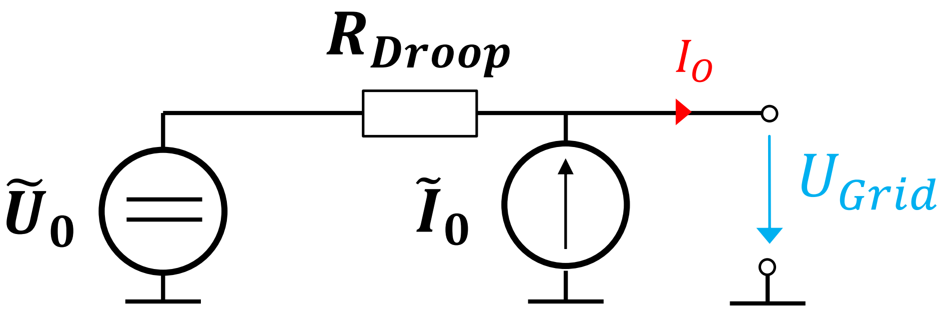
- *Load sharing can be accomplished by droop-curves*
- *The droop-curve is defined by a small signal* R_{Droop}
- *For each linear interval* I_O *can be expressed as:*
  - $I_O = \frac{U_{Grid} - \tilde{U}_O}{R_{Droop}} + \tilde{I}_O$
- *Example (blue curve from 360 V to 400 V)*
  - $I_O = \frac{U_{Grid} - 380\,V}{1\,\Omega}$

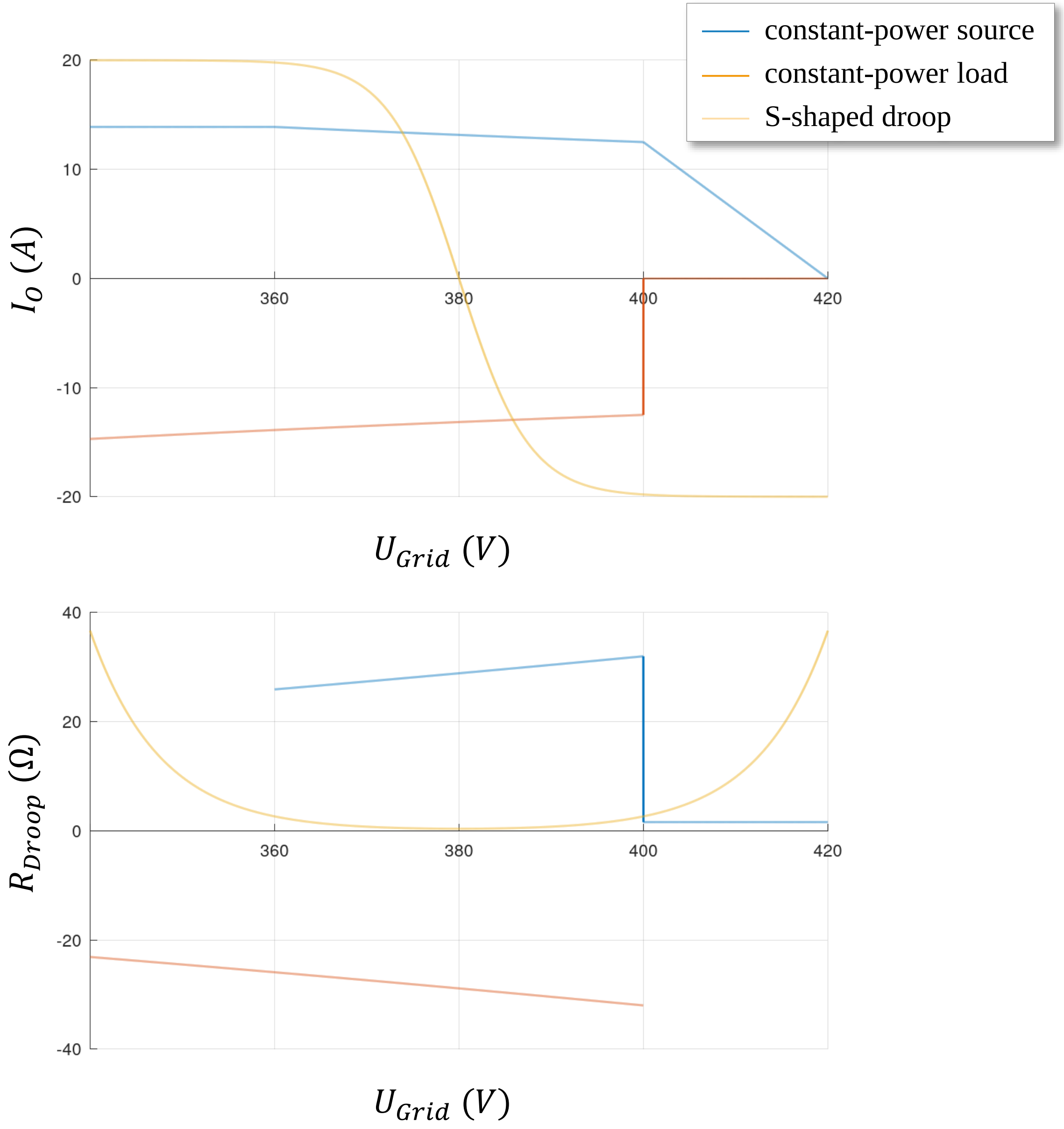




Droop-Controlled DC-Microgrids

- *Load sharing can be accomplished by droop-curves*
- *The droop-curve is defined by a small signal* $\mathrm{R_{Droop}}$
- *Droop-curves can also be nonlinear*
- *Constant-power-loads have a negative* $\mathrm{R_{Droop}}$
- *Example (blue curve at 380 V):*
  - $$I_O = \frac{P_O}{U_{Grid}} = \frac{5\ kW}{380\ V}$$
  - $$R_{Droop} = \frac{U_{Grid}^2}{P_O} = \frac{(380\ V)^2}{5\ kW} = 28.88\ \Omega$$

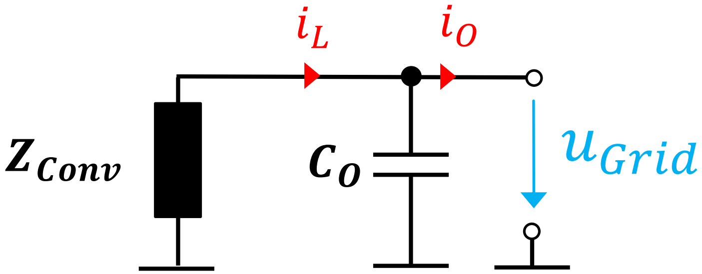




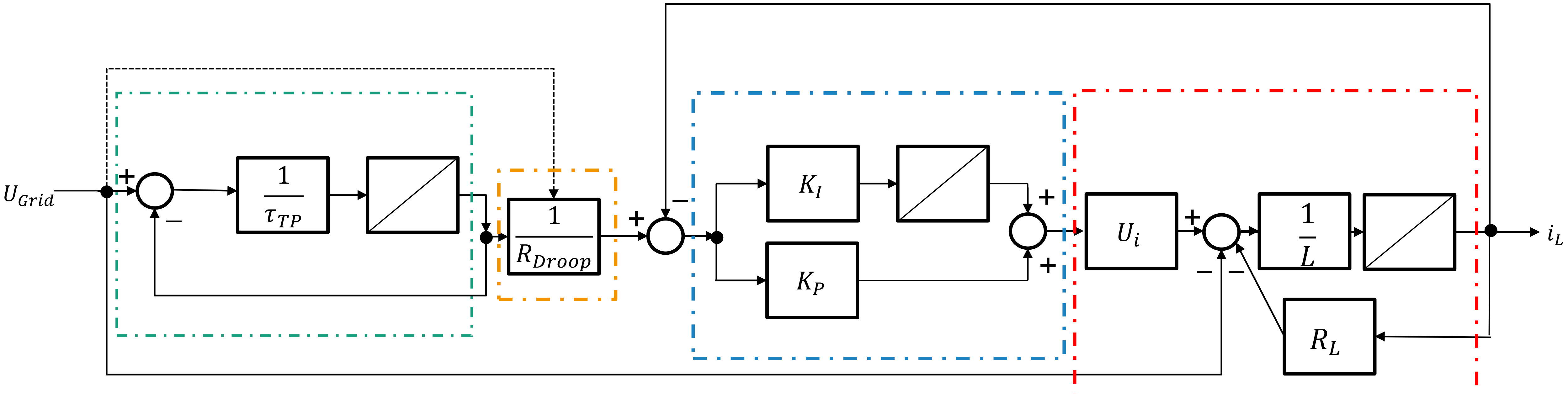
Droop-Controlled DC-Microgrids

Small-signal modeling:

- *Converter is current controlled*
- *Converters impedance Z_{Conv} can be separated from C_O*



Droop-Controlled DC-Microgrids



Simplified block diagram of a droop controlled converter:

- *Measurement filter*
- *Droop-resistance*
- *PI-controller*
- *Buck-converter*

Droop-Controlled DC-Microgrids

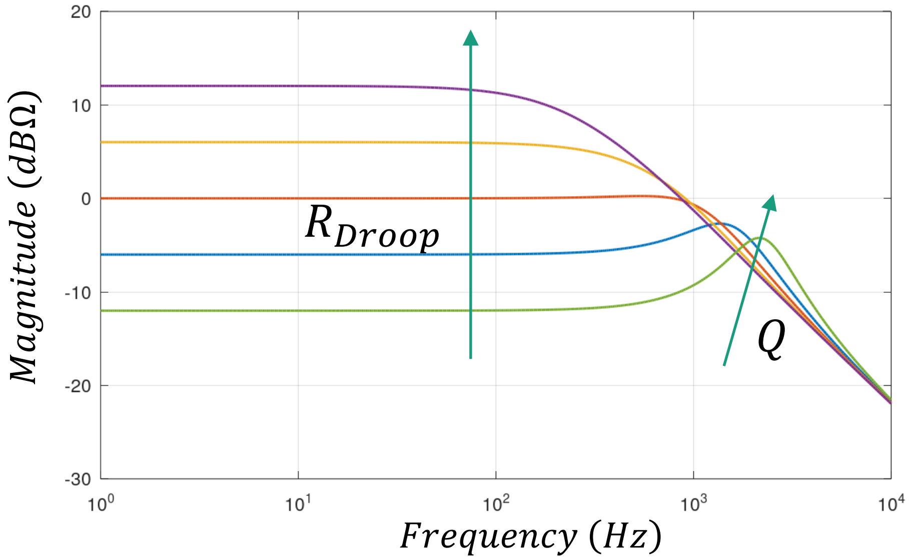
Small-signal modeling:

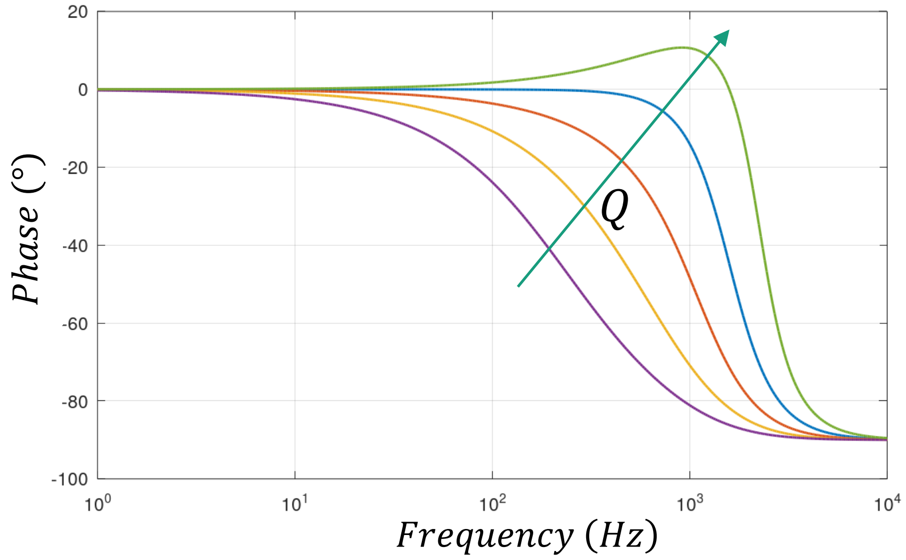
- *Converter is current controlled*
- *Converters impedance can be separated from* C_O
- *In many cases the current control acts like a low pass of 1st order*
- *Converter can be modeled as R-L-C*

Droop-Controlled DC-Microgrids

Small-signal modeling:

- *Converter can be modeled as R-L-C*
  - *L is part of the low pass $L_{LP} = \frac{R_{Droop}}{2\pi \cdot f_c}$*
  - *Resonant circuit has a Quality factor $Q = \frac{1}{R_{Droop}} \sqrt{\frac{L_{LP}}{C_O}} \sim \frac{1}{\sqrt{R_{Droop}}}$*





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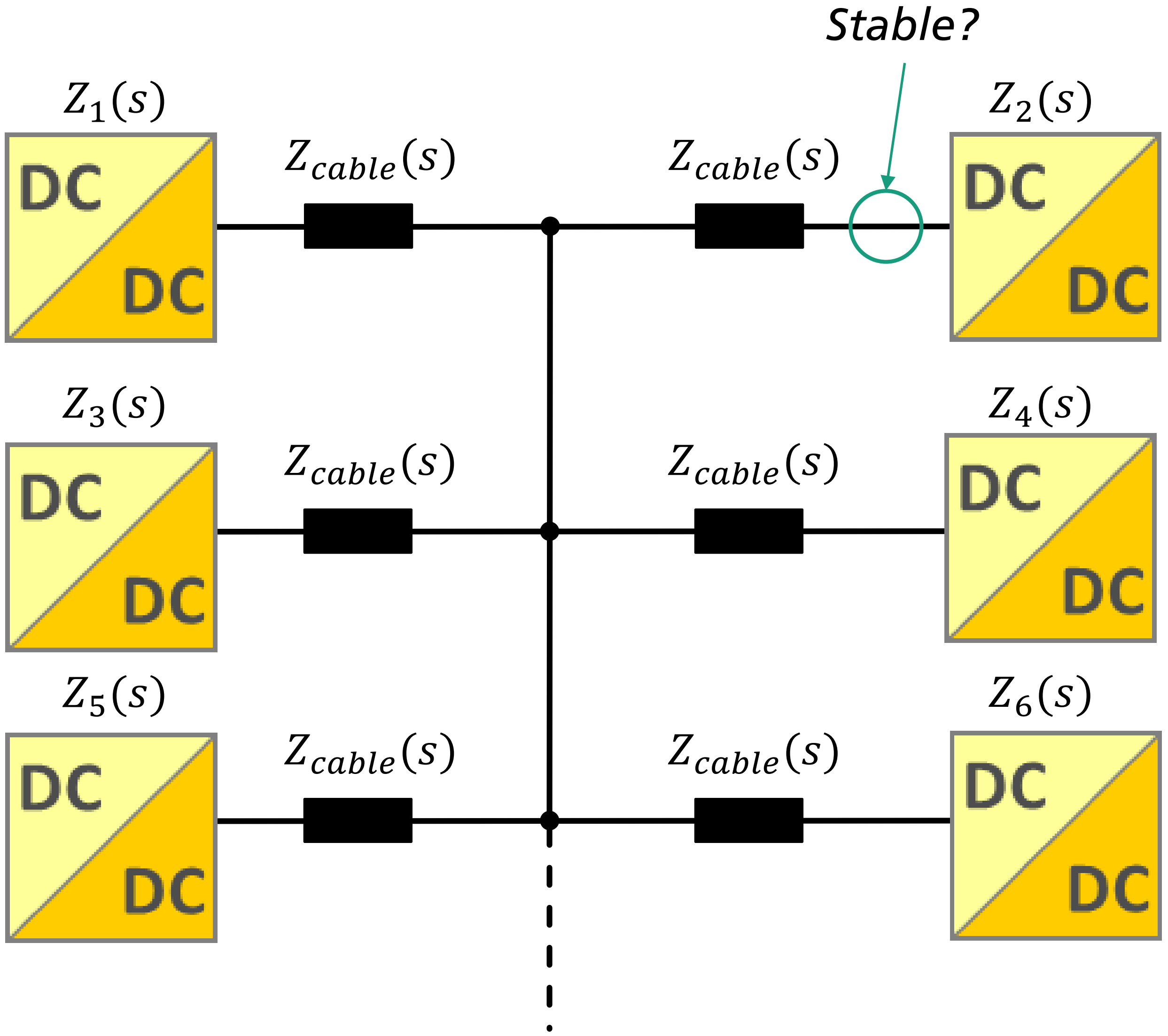
Stability Investigation through Impedance Measurements

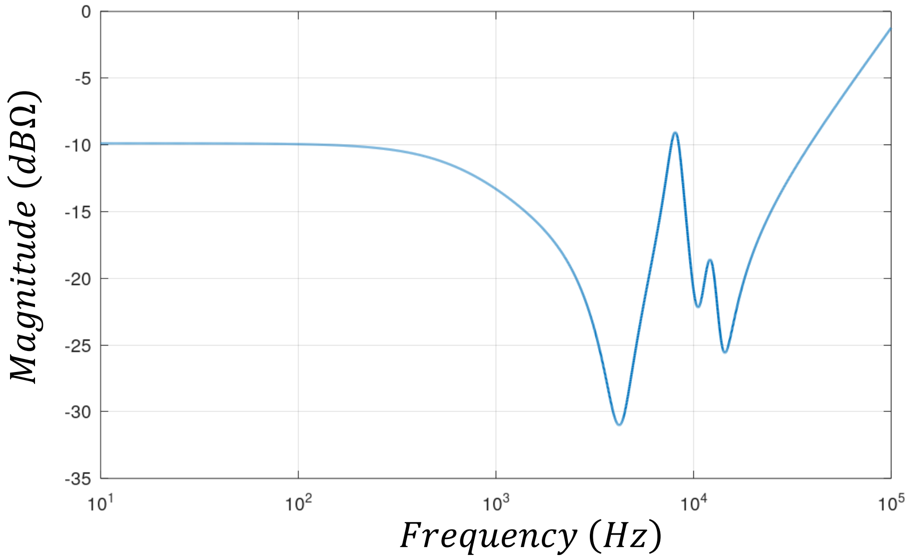
Stability Criteria

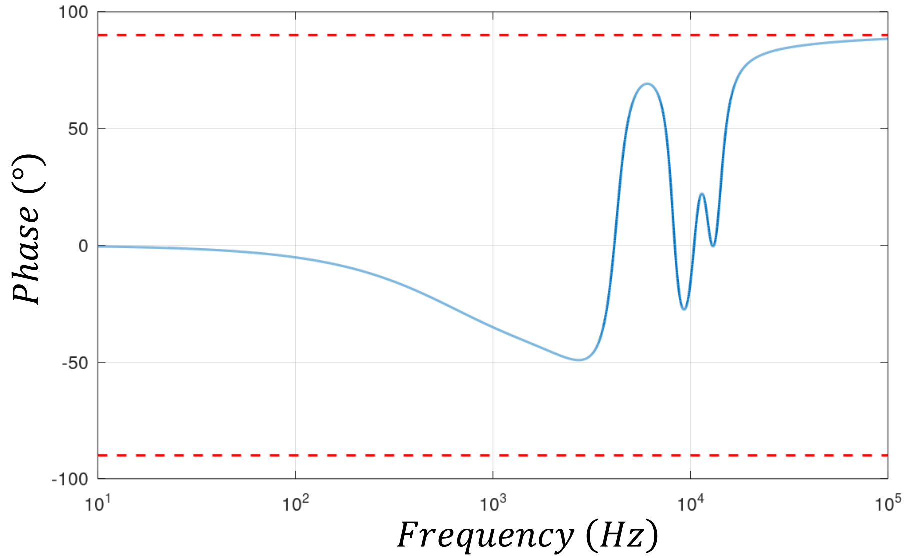
- *Passivity Criterion*
- *Minor Loop Gain Criterion*
  - *Middlebrook Criterion*
  - *Gain-Margin-Phase-Margin*
  - *Opposing Argument Criterion*
  - *ESAC Criterion*
  - *RESC Criterion*
  - …



Stability Investigation through Impedance Measurements

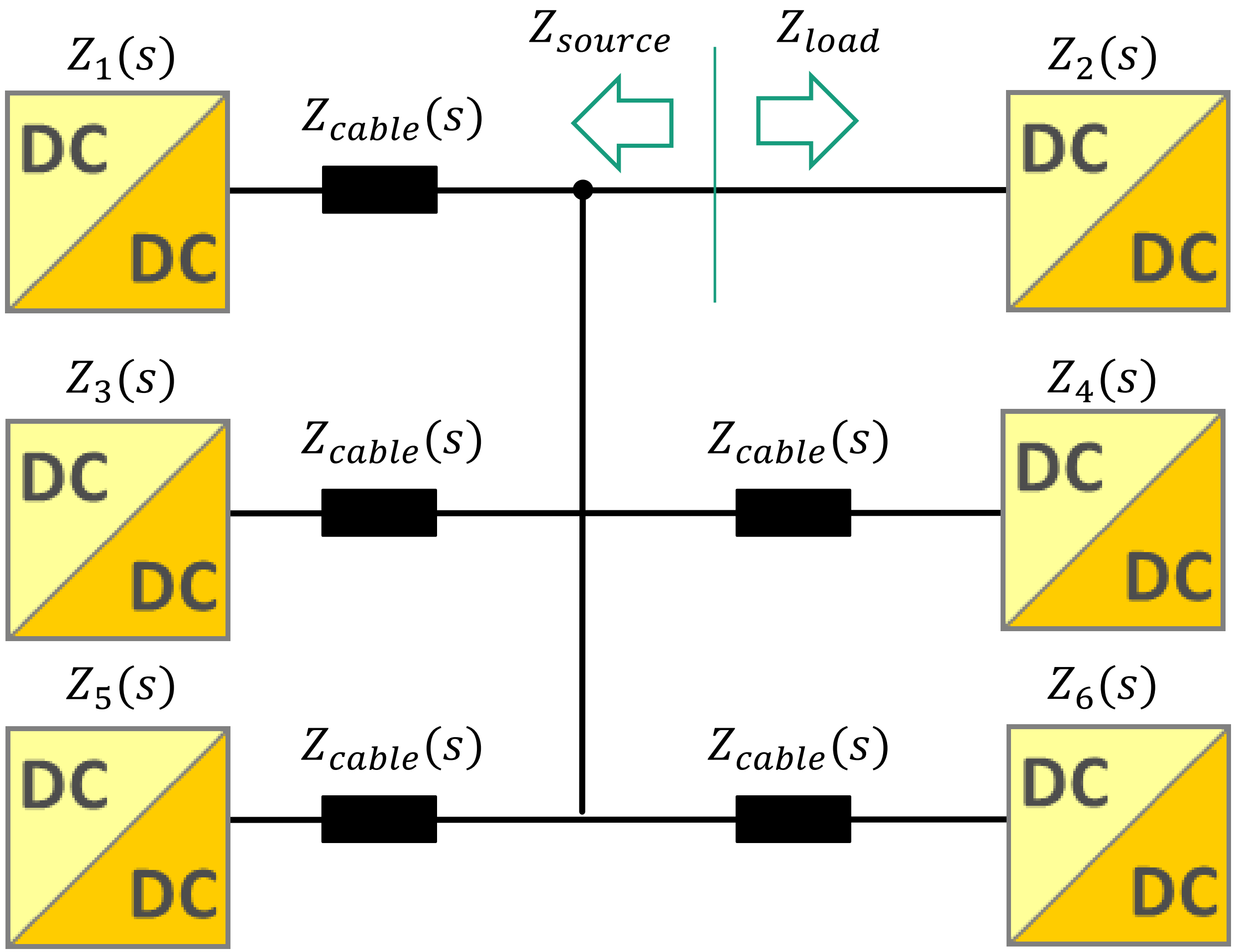
- *Passivity Criterion*
  - *A passive system must have no RHP-poles*
  - *The phase φ of a passive system must be $-90° \leq \varphi \leq 90°$*
  - *Can be used for design of a converter or the whole system*





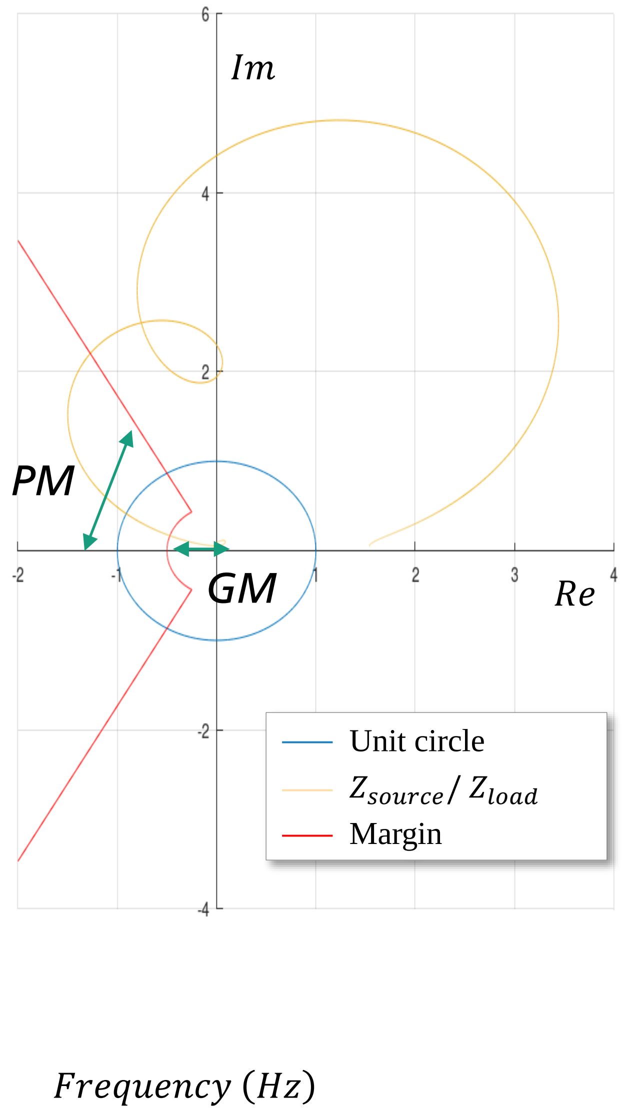
Stability Investigation through Impedance Measurements

- *Minor Loop Gain Criterion*
  - *Take an initially stable grid*
  - *Add a new load converter*
  - *Measure Z_{source} and Z_{load}*
  - *We apply a MLGC*
  - *Repeat for every new load*



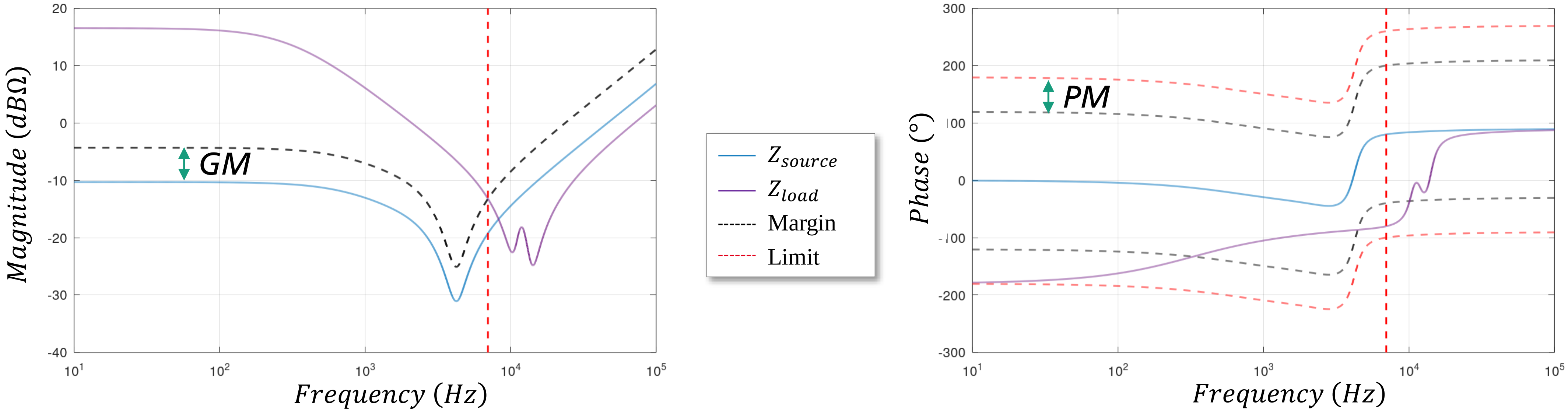
Stability Investigation through Impedance Measurements

- *Gain-Margin-Phase-Margin*
  - *To form the whole grid Z_{source} and Z_{load} are paralleled*
  - $Z_{Grid} = \frac{Z_{source} \cdot Z_{load}}{Z_{source} + Z_{load}} = \frac{Z_{source}}{1 + \frac{Z_{source}}{Z_{load}}}$
  - Z_{source} is stable
  - $1 + \frac{Z_{source}}{Z_{load}}$ *must not destabelize*



Stability Investigation through Impedance Measurements

- *Gain-Margin-Phase-Margin (GM-PM)*
  - *Compare both Z_{source} and Z_{load}*
  - *For each frequency <u>one</u> of two conditions must apply*
    - $|Z_{source}| \cdot GM \leq |Z_{load}|$
    - $\arg(Z_{source}) - (180° - PM) \leq \arg(Z_{source}) \leq \arg(Z_{source}) + (180° - PM)$



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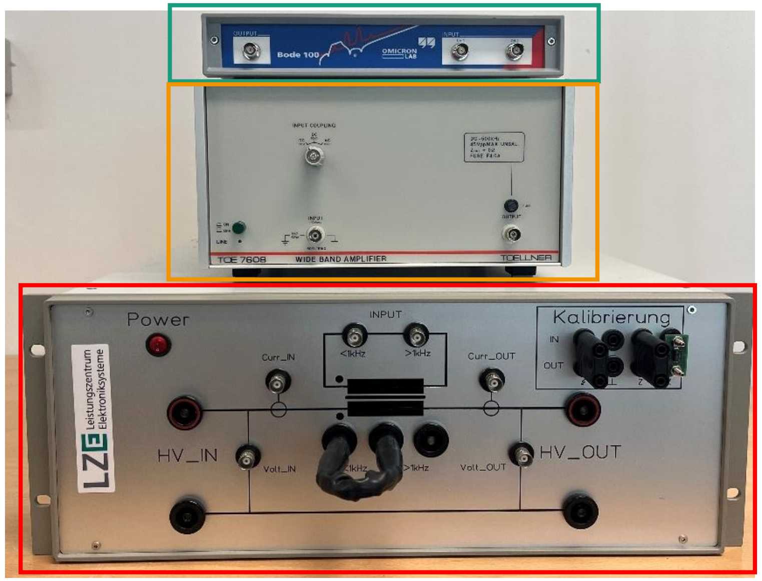
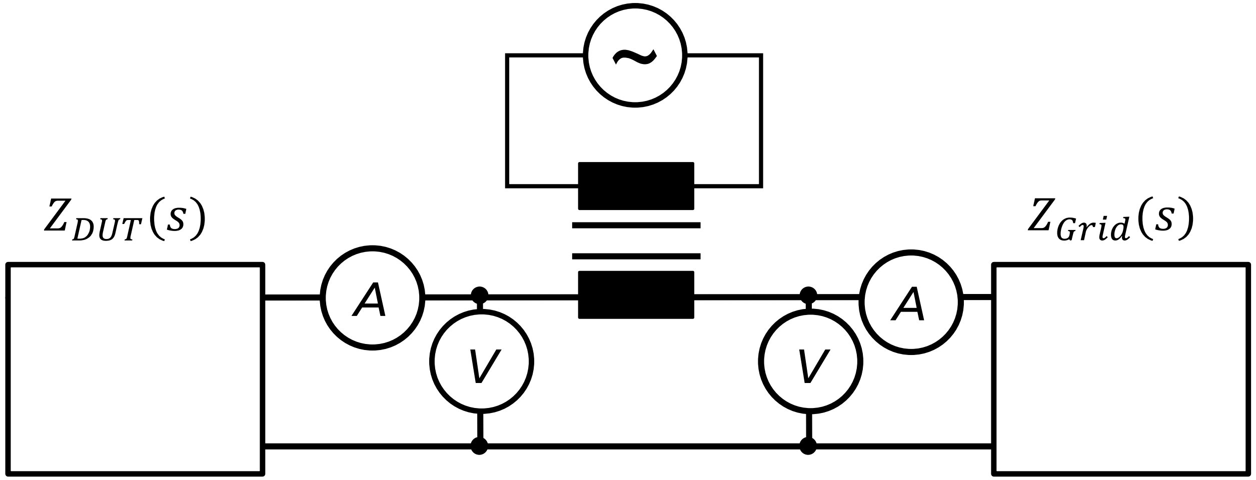
Bode100 Testbench

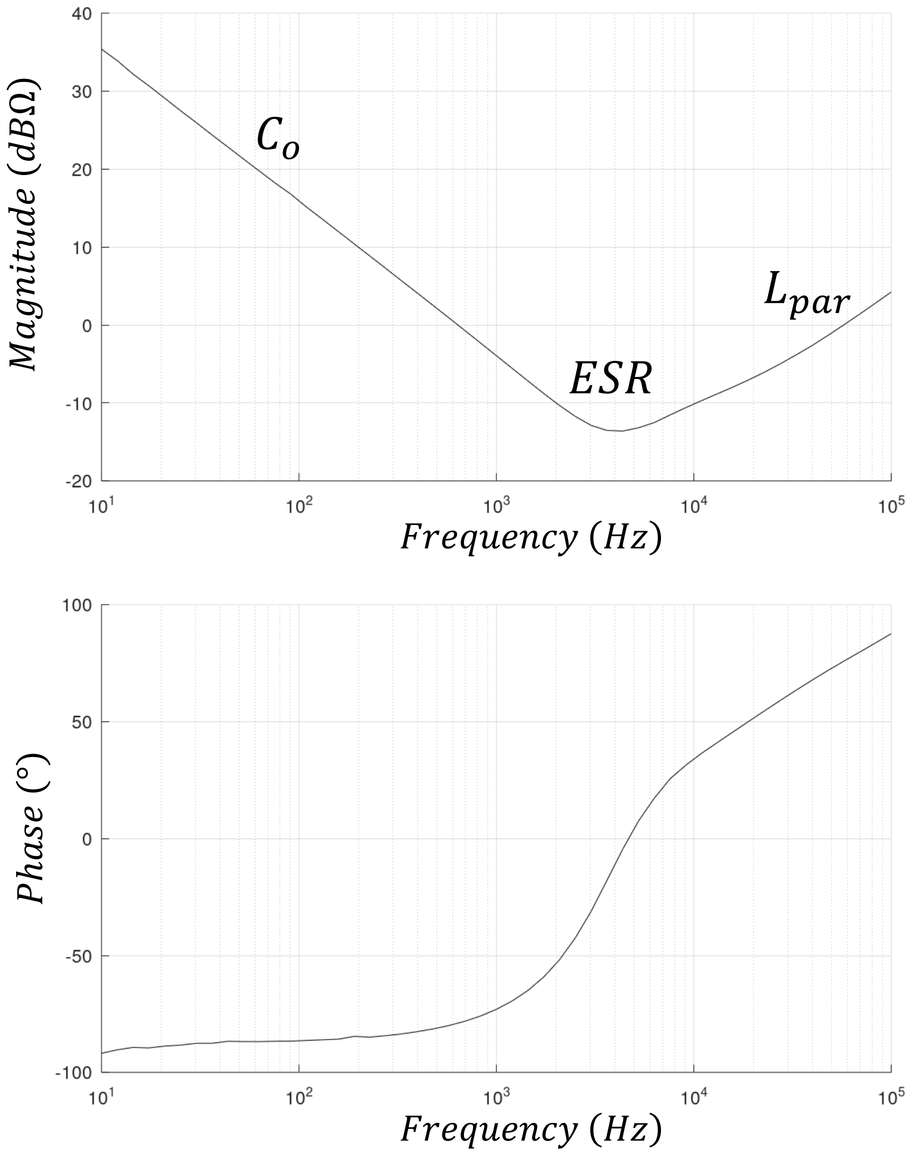
- *Bode 100*
    - *Generation of the test signal (max 13dBm)*
    - *Gain-Phase measurement*
- *Wide Band Amplifier*
    - *Amplification by 13 dB*
    - $0.2\ \Omega$ *ouput resistance*
- *Coupling Transformers*
    - *Isolated coupling*
    - *Isolated measurement*
    - *Maximum DC-current:*
        - *25 A for 10 Hz-Transformer*
        - *50 A for 100 Hz-Transformer*





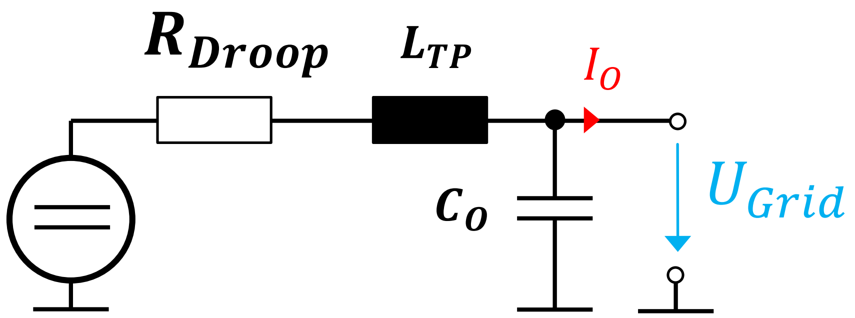
Bode 100 Testbench

- *Passive converter:*
  - $C_O \approx 260\ \mu F$
  - $ESR \approx 20\ m\Omega$

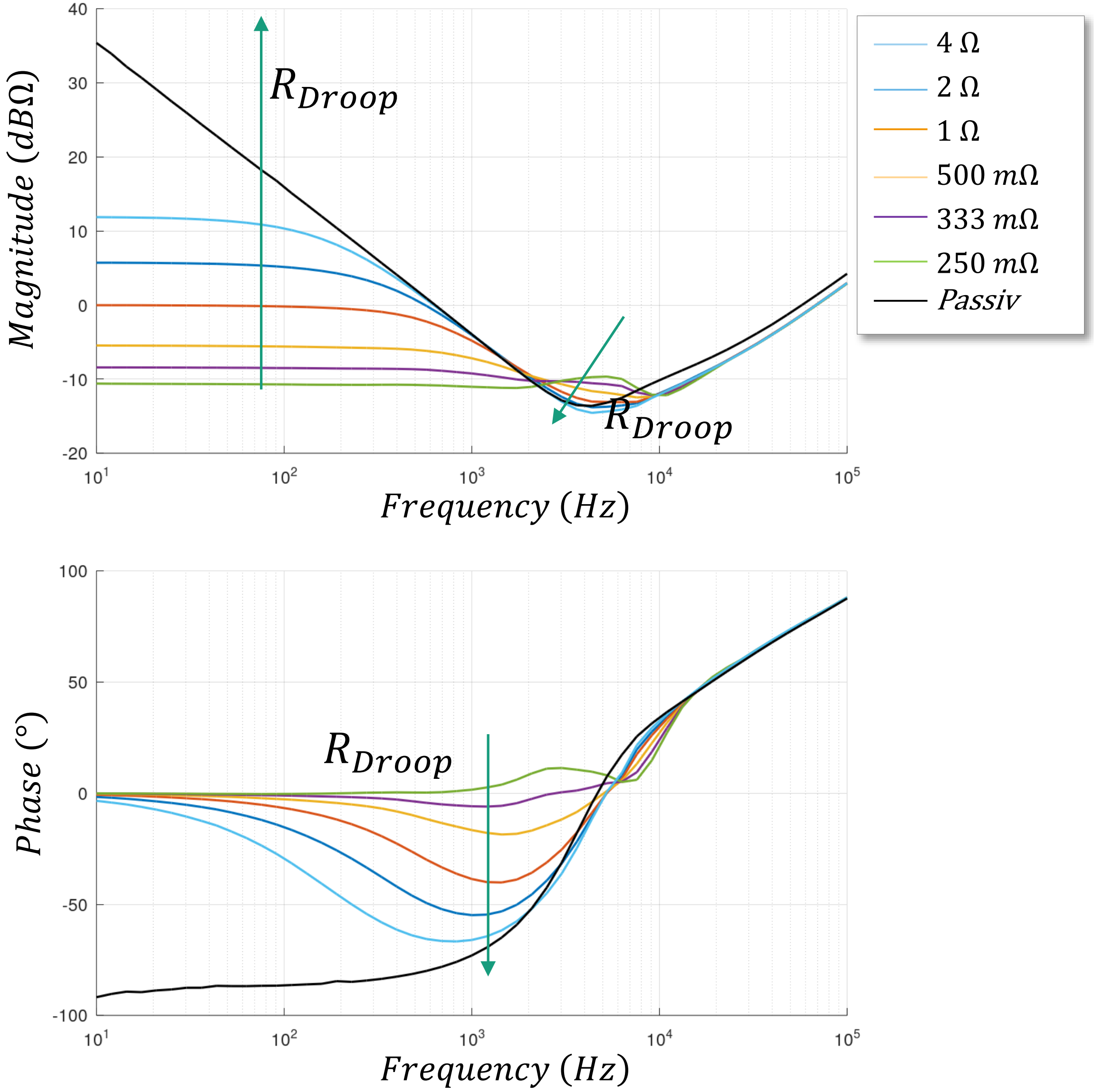


Bode 100 Testbench

- *Droop-controlled converter*
  - *Converter can be modeled as R-L-C*

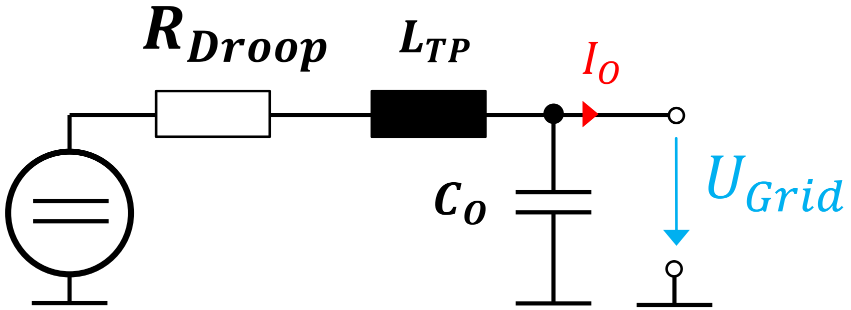


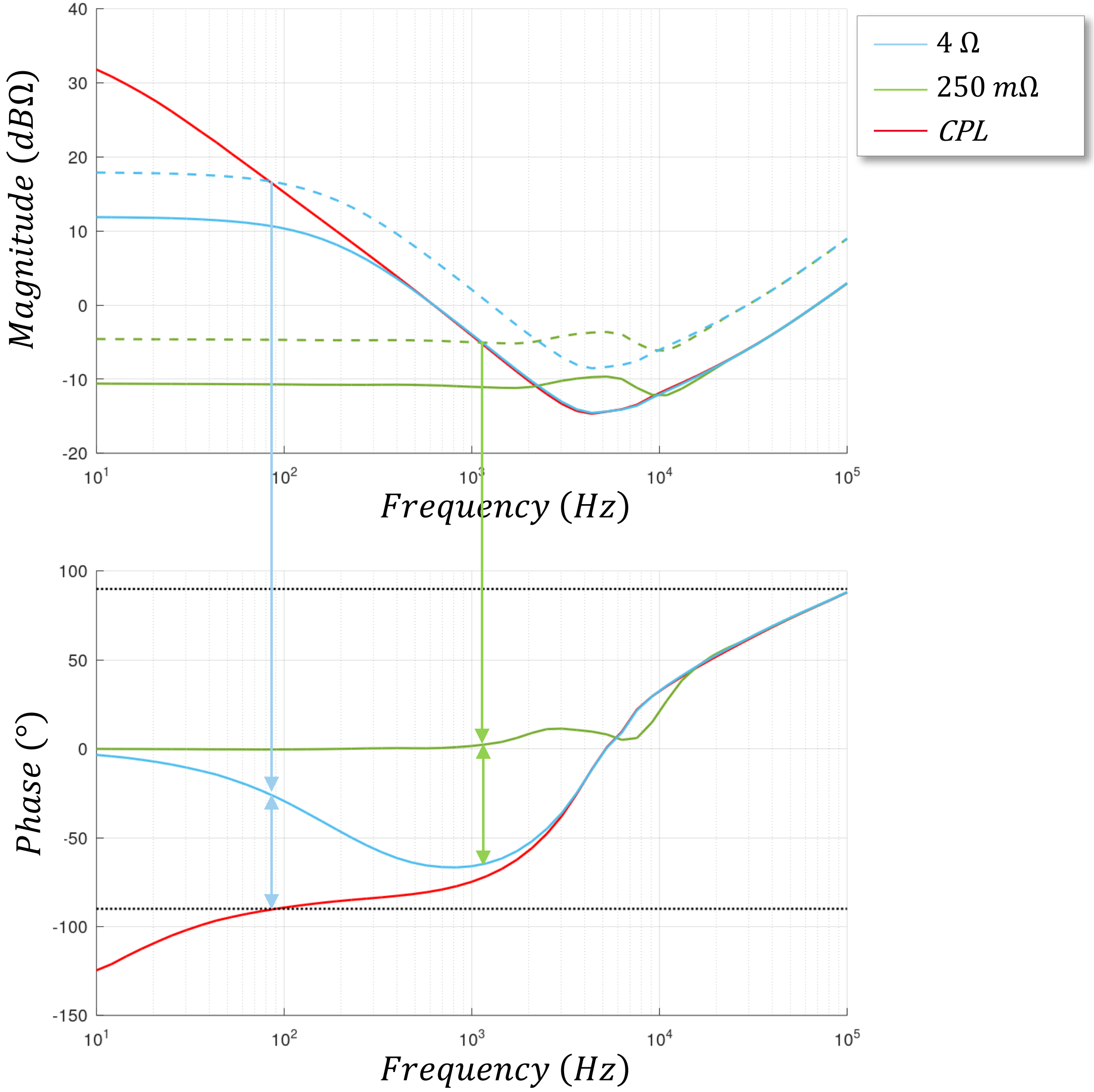
  - *Increase in R_{Droop} leads to:*
    - *Higher Z at low frequencies*
    - *Lower Z at „resonance frequency“*



Bode 100 Testbench

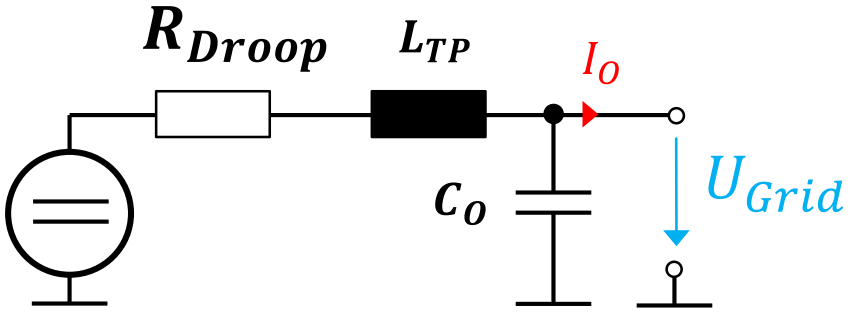
- *Constant-power load (CPL)*
  - *Typically high R_{Droop}*
  - *Violates passivity at low frequencies*

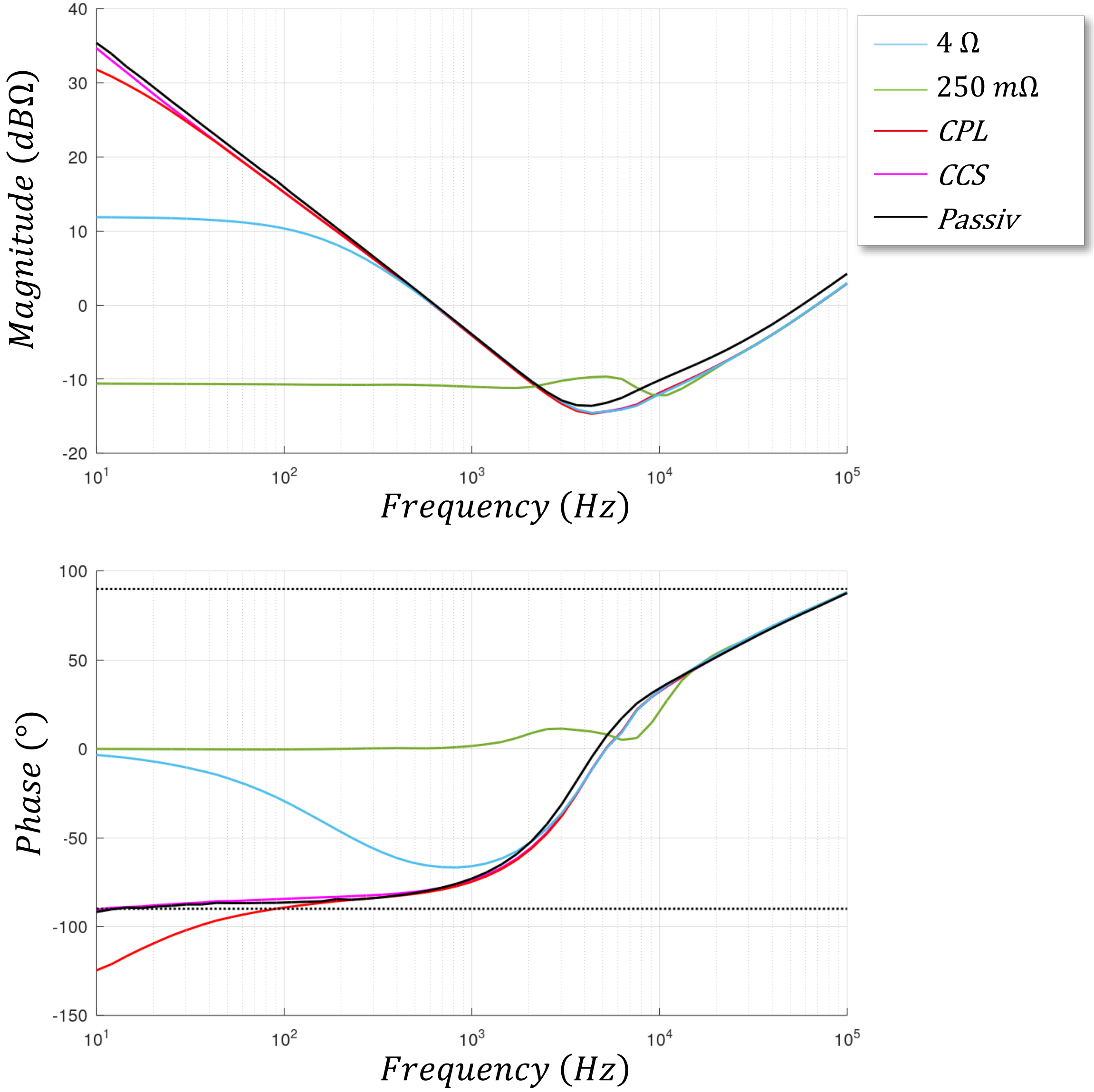




Bode 100 Testbench

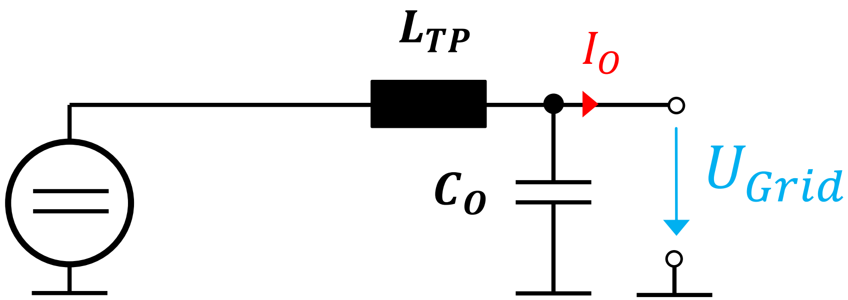
- *Constant-current source (CCS)*
  - *Acts like a passive converter* ($R_{Droop} = \infty$)
  - *Can not stabilize a constant power load*

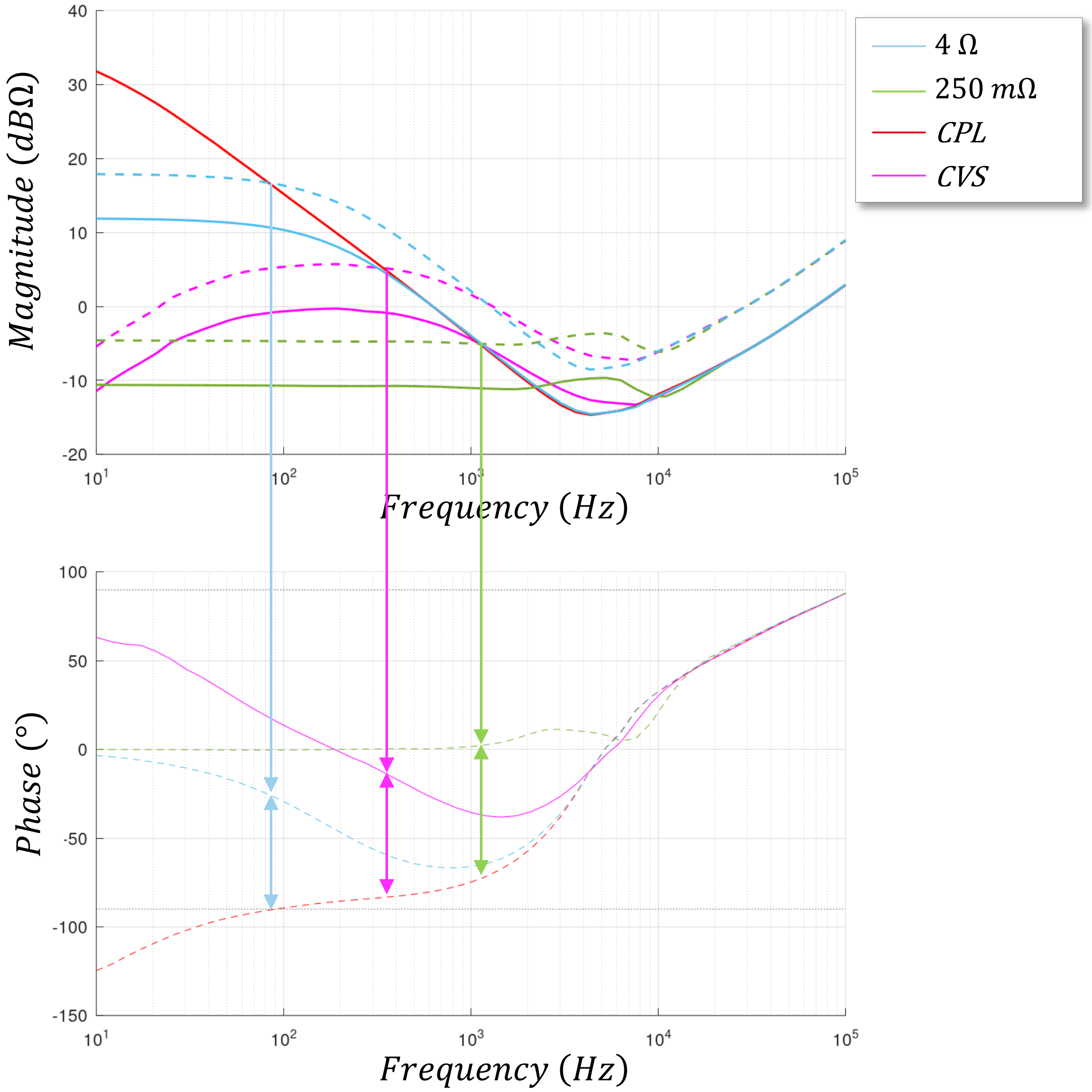




Bode 100 Testbench

- *Constant-voltage source (CVS)*
  - *No droop-resistance*
  - *“Resonance“ at lower frequencies*





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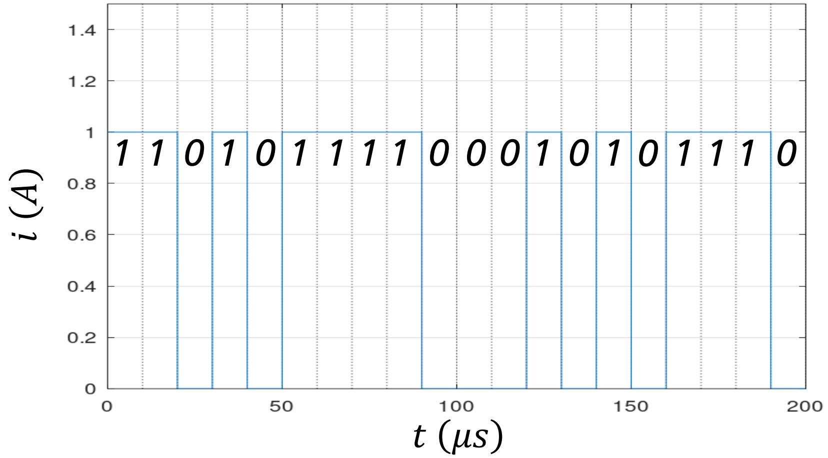
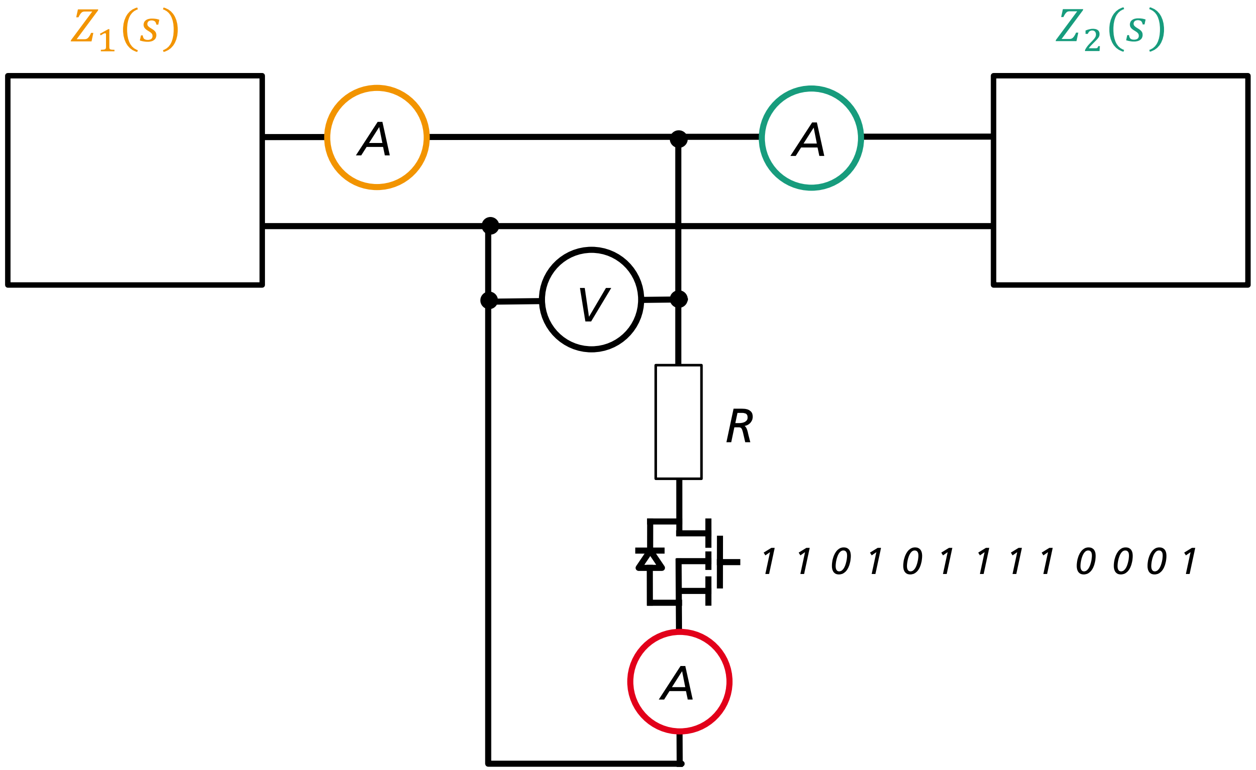
Online measurement with Pseudo-Random-Binary-Sequences

- *Pseudo-Random-Binary-Sequences (PRBS)*
  - *Length* L
  - *Bit-Duration* τ_B
  - *White noise Approximation*
    - $f_{min} = \frac{1}{\tau_B \cdot L} = \Delta f$
    - $f_{max} \approx \frac{1}{3\,\tau_B} \dots \frac{1}{2\,\tau_B}$





Online measurement with Pseudo-Random-Binary-Sequences

- *Pseudo-Random-Binary-Sequences (PRBS)*
  - *Length* L
  - *Bit-Duration* τ_B
  - *White noise Approximation*
    - $f_{min} = \frac{1}{\tau_B \cdot L} = \Delta f$
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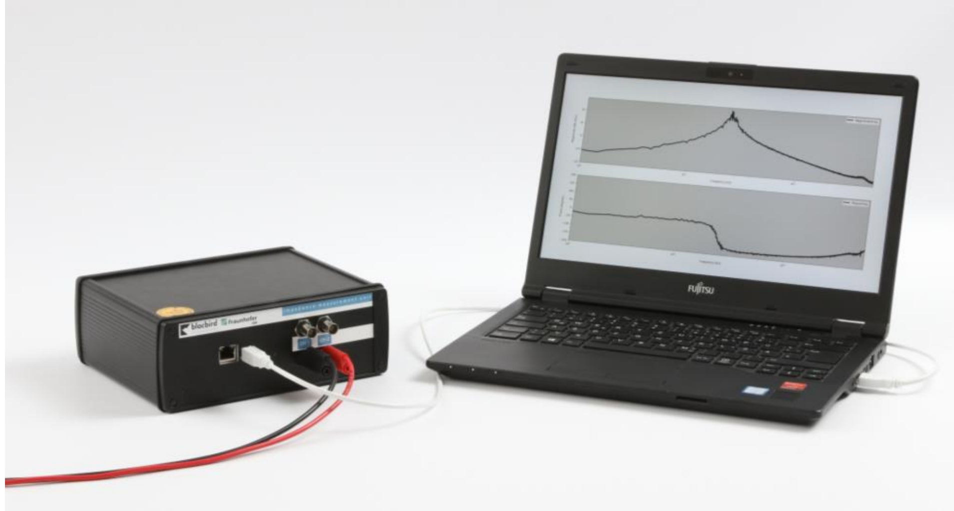
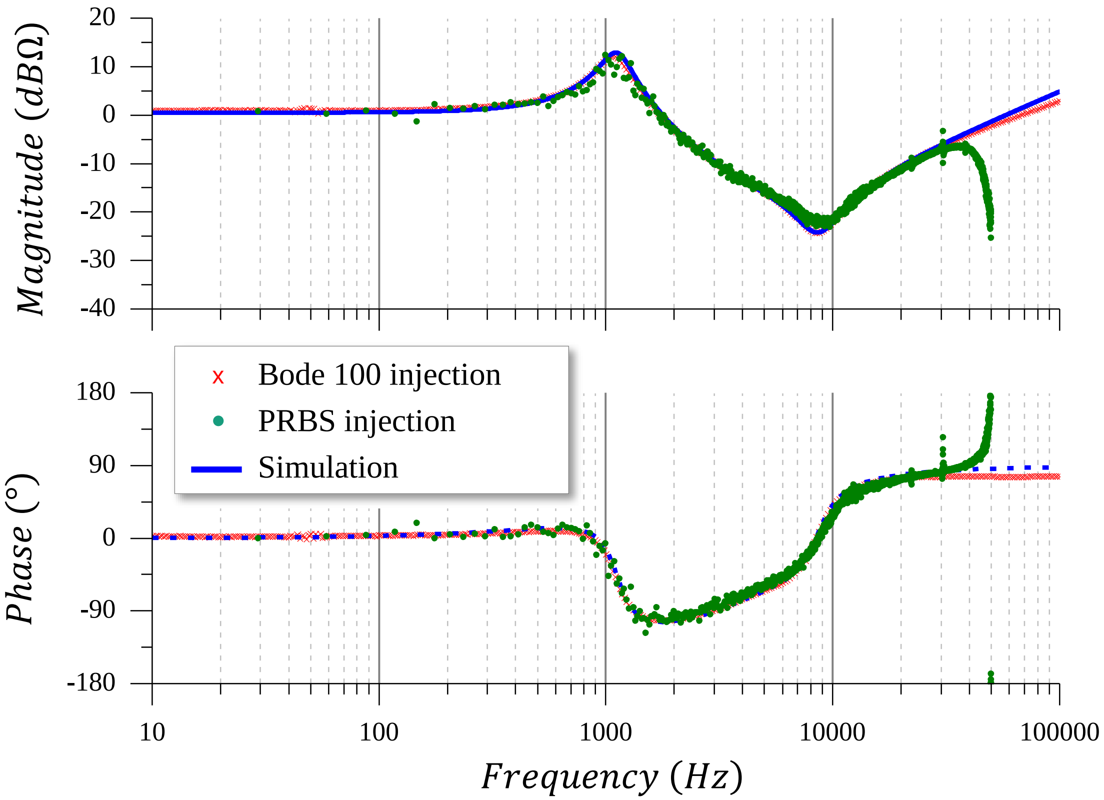
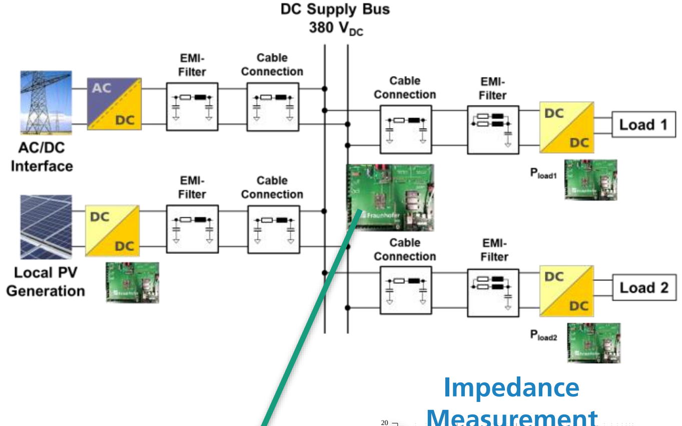




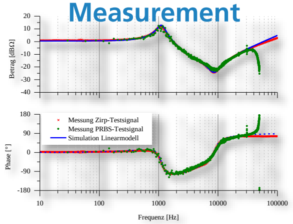
Advanced Data Analytics for Grid Layout and Stability Optimization

Setup of the Example DC Network

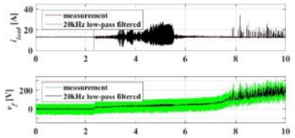


Data acquisition hardware

Impedance Measurement



IV-Measurement

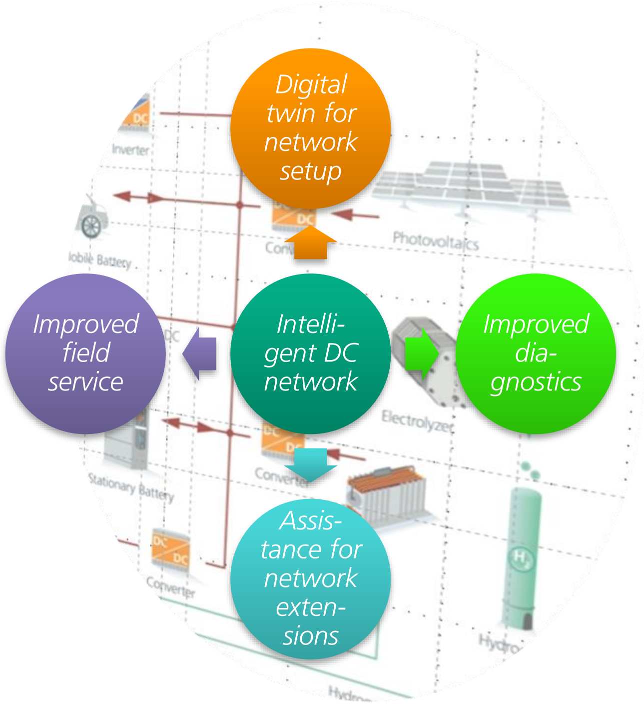


AI Use Cases

Identification, localization, prediction, root cause analysis, prevention, presentation

- *Grid stability*
- *Network branch overload*
- *Faults with long time constant (e.g., shorts)*
- *Faults with short time constant (e.g., arcing)*
- *Energy network map*

Applications and Benefits



Digital twin for network setup

Improved field service

Intelligent DC network

Improved diagnostics

Assistance for network extensions

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Stabilization of DC Networks Applying Artificial Intelligence

ADA LOVELACE CENTER

Digital Network Twin

- *Automated calculation of the small signal DC network impedance for many input parameter settings*
- *Stability assessment according to the minor loop gain criterion*
- *Refinement of the circuit model based on PRBS-measurements*

Surrogate Model DC Network

- *Modeling the relationship between network parameters and stability using random forests*
- *Determination of the relevance of the input parameters of network*
- *Base model for optimization*

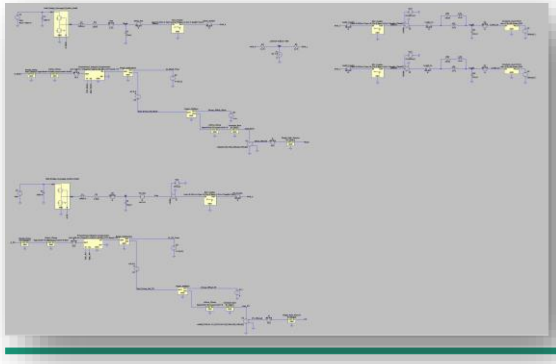
Stability Optimization

- *New optimization method using classification decision trees as surrogate model and ensemble methods (random forests)*
- *Adjustment of network parameters for stability optimization or the design of new networks*

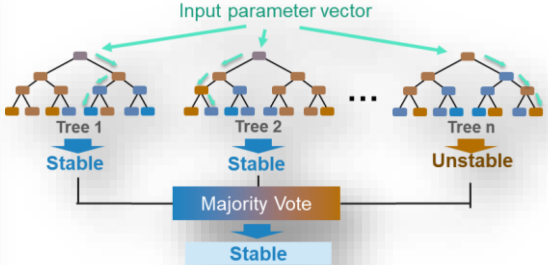
Implementation

- *Implementation of PRBS measurement*
- *Adjustments for power coupling*
- *Testing and improvement of procedures*
- *Integration into an IISB test bench*

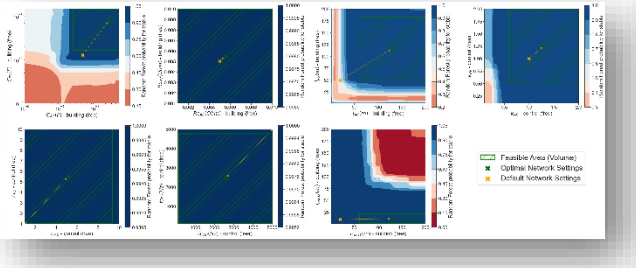
SPICE Model



Random Forest Model



New Optimization Algorithm for Classification Models



Test Bench

Summary

- DC-Microgrids
  - Power electronics dominated
  - Droop-controlled
  - Decentral load sharing
- Droop-Control
  - Current controlled converter
  - Droop curves can be linear or nonlinear
  - Constant-power converters have negative droop resistances
- Stability
  - Passivity-Cirterion
  - MLGC-Criterion
- Bode 100 Testbench
  - Bode 100
  - Wide band amplifier
  - Coupling transformer
- PRBS
  - Injection of bit streams
  - Multiple frequencies in one measurement
- Data-Analytics & AI
  - Digital Twin
  - Stability optimization
  - Intelligent DC-Microgrid