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Tampere University

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Grid Connection of Power Electronics

Stability and Sensitivity Analysis

Roni Luhtala

PhD Student

Introduction

Roni Luhtala

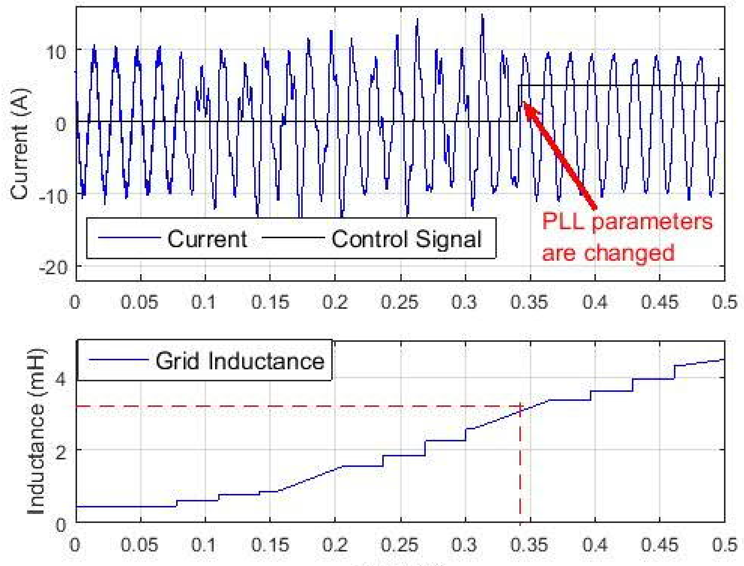
Doctoral Student

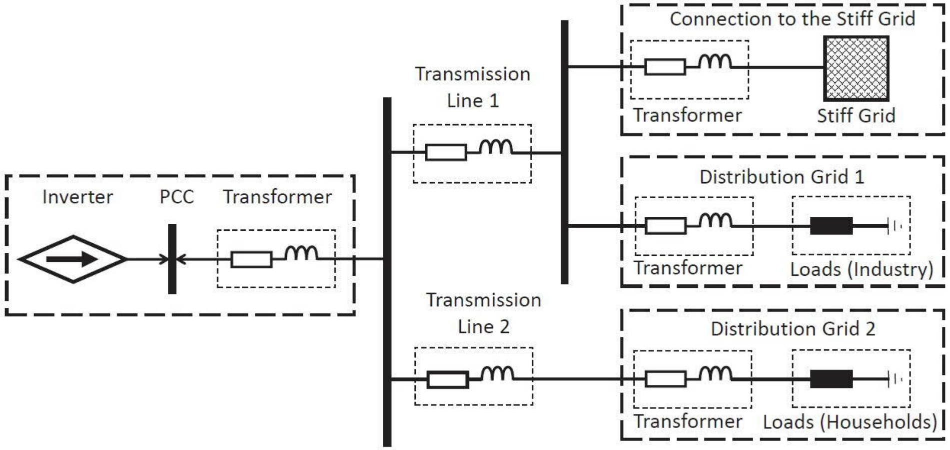
Department of Automation Science
(and Electrical Engineering)

Power electronics group

Research topics:

- **Identification of power grids**
- **Intelligent power electronics**
    - Adaptive control
    - Real-time measurements
    - Real-time performance optimization

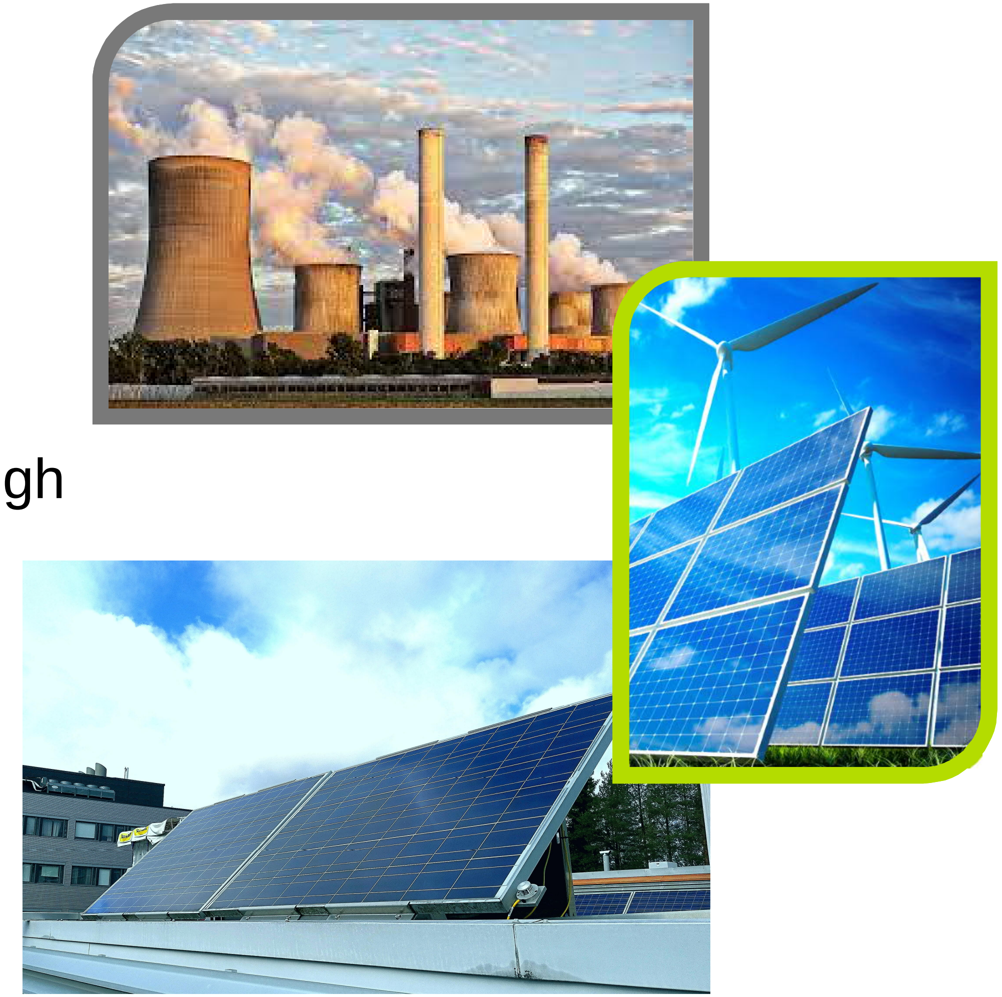




Background of Power Electronics in Grid

- Increased amount of renewable-energy sources are connected to the grid
    - Connected to the grid through power electronic inverters
- Loads
    - Laptop through swithcing converter
    - Increasing amount of machines through frequency converter
- Decreased inertia
- Faster dynamics

More prone to stability issues



Renewable Energy Sources

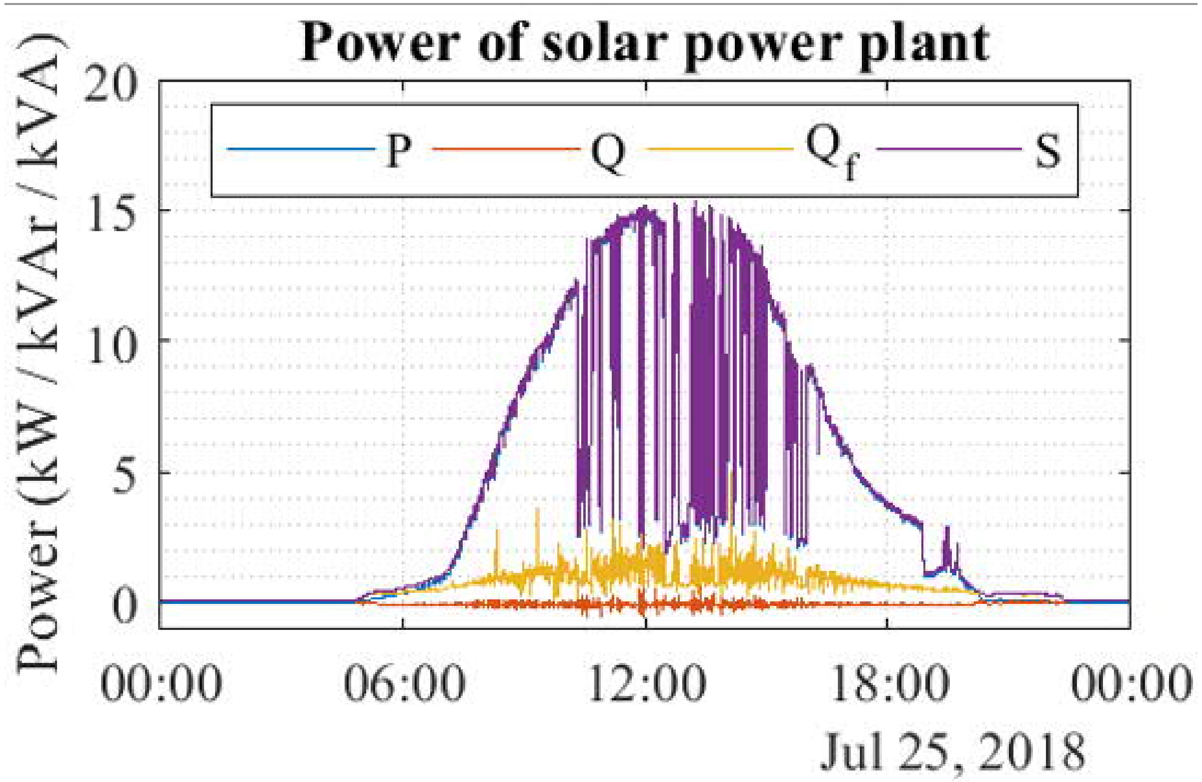
- Amount of renewables is rapidly increasing due to climate change and reduction in price
- Weather denpendent
  - Produced power vary over time
    - Wind/Sun
  - Hard to forecast
  - Power can not be controlled similar to for example gas turbines
- Photovoltaics produce DC, Wind generators usually have controlled DC link

→ Needs DC/AC conversion when connected to power grid (50 (or 60) Hz AC)

Power Production of PV (Solar) plant

- Power is produced from sun irradiance
- Highly weather depended

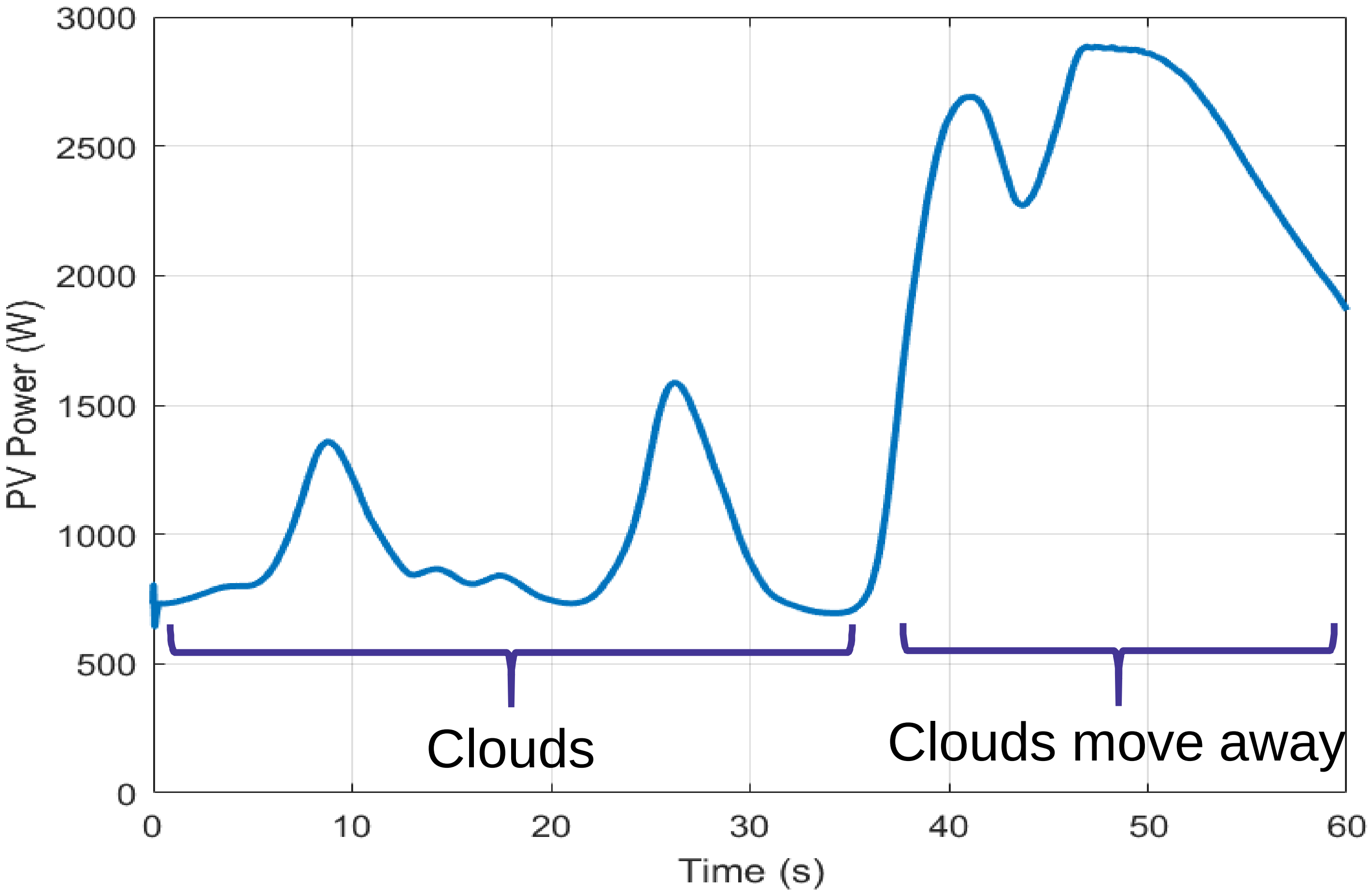
- Measurement from a sunny summer day in Finland



Real measurement by MSc. Antti Hilden in Tampere

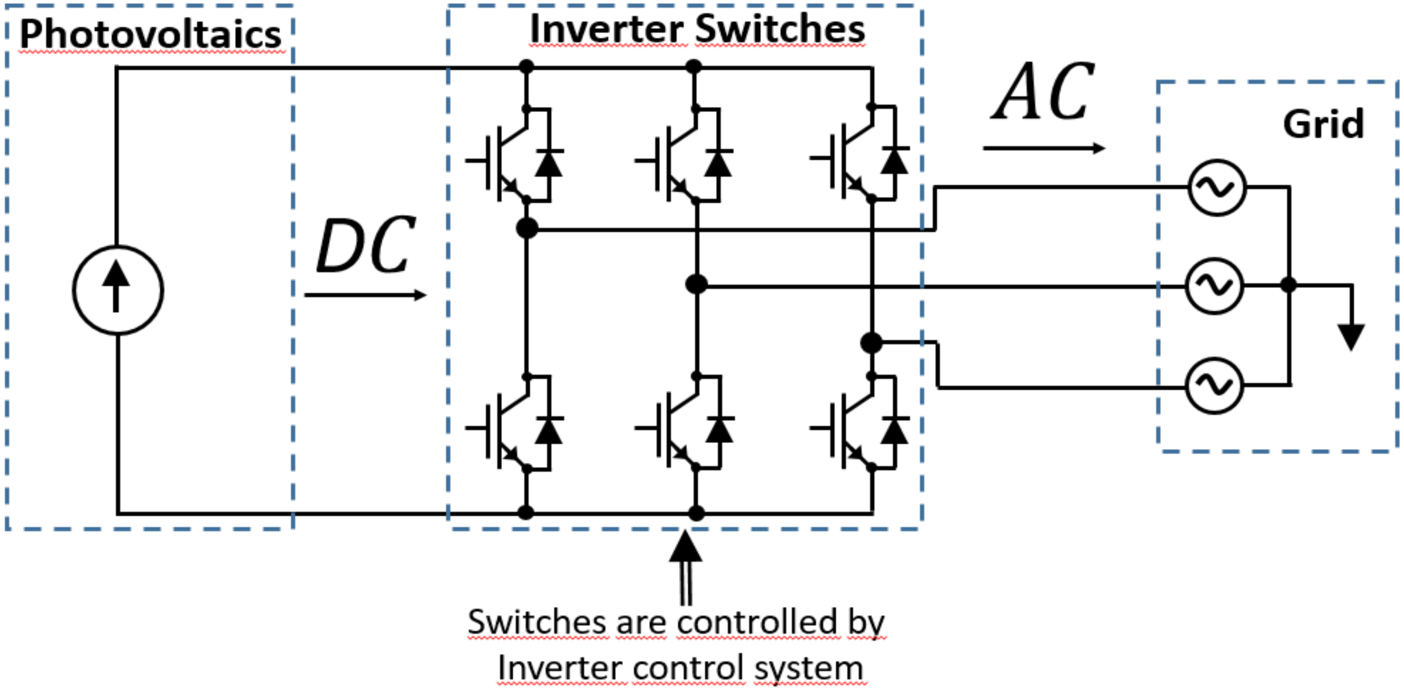
PV Power

- Nominal power of the PV panel is 2.7 kW
- Measurement over one minute
  - Moving clouds



Inverter (DC/AC converter)

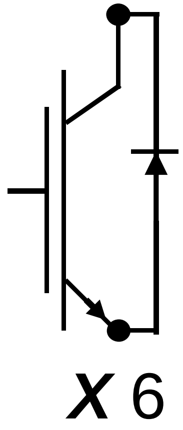
- Inverter transforms direct current (DC) to alternative current (AC)
- Power flows trough fast switching components
  - Requires carefully tuned control system to ensure good power quality
- Big PV systems include all three phases of power system, two switches per phase



Control of PV Inverter

- Control system basically produces duty cycle reference for modulator
  - Controls when switches are on conductive or non-conductive state
  - Switches can change their state about 5 000 – 20 000 times in one second (= switching frequency)
- Three basic controllers:
  - Phase-locked loop (PLL) syncronizes inverter to grid voltages
  - AC-current controller determines produced power to grid
  - DC-voltage control finds maximum power point (MPP) from photovoltaic source by affecting to DC-voltage

Switching pulse from the inverter control system →



Separate pulses for every six switches

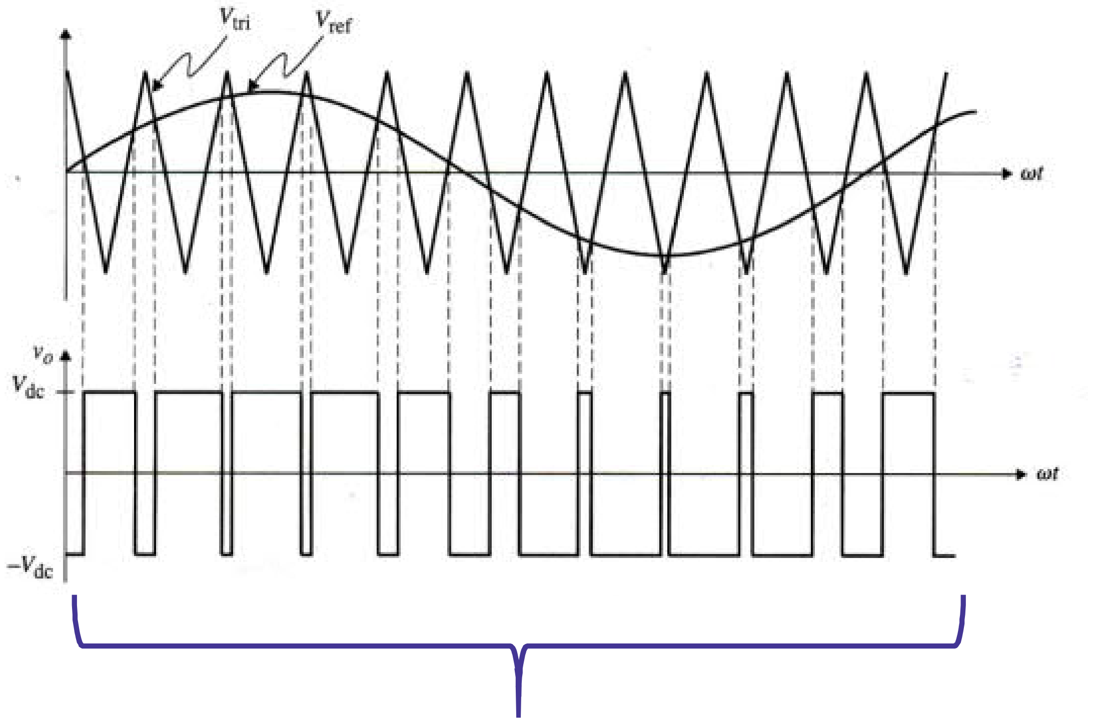
Pulses are generated by pulse-width modulator

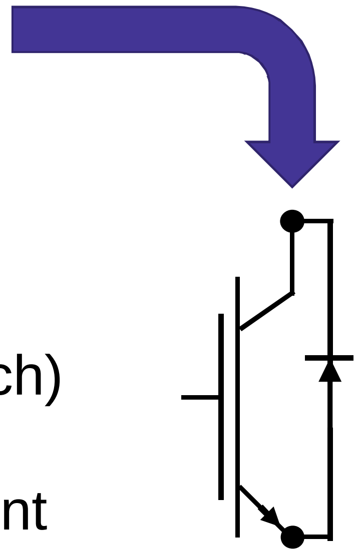
Produced currents have to be synchronized with grid voltages

Pulse-Width Modulator (PWM)

Reference
- Generated by control system
- Here the sinusoidal signal

Triangular (saw tooth) wave is generated by PWM

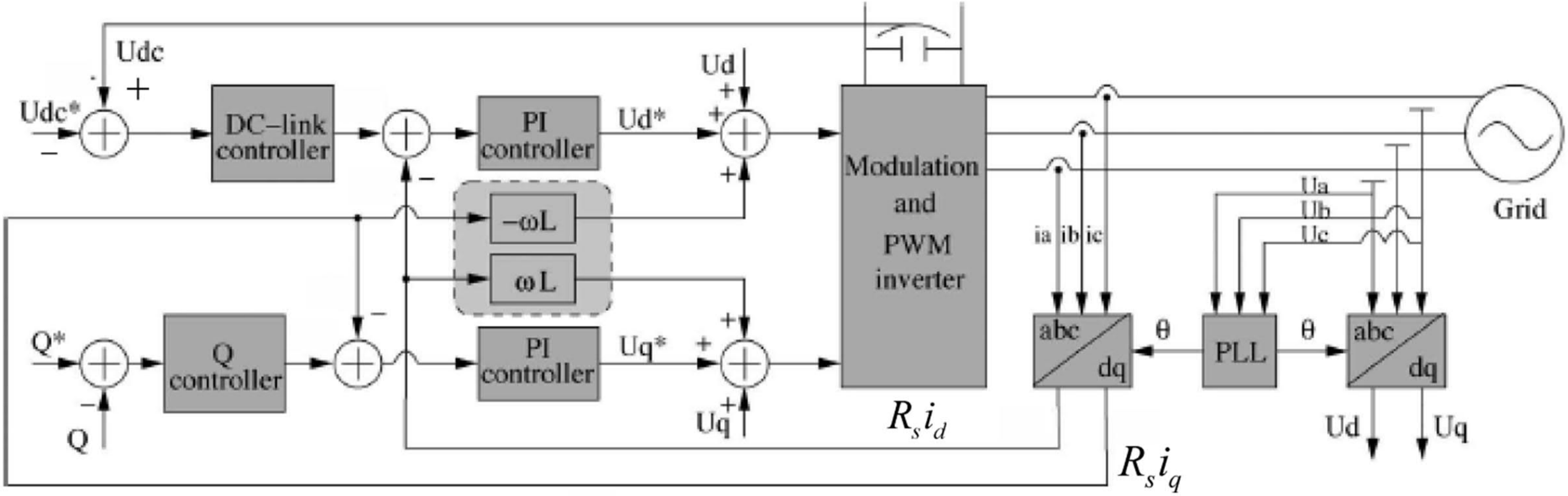




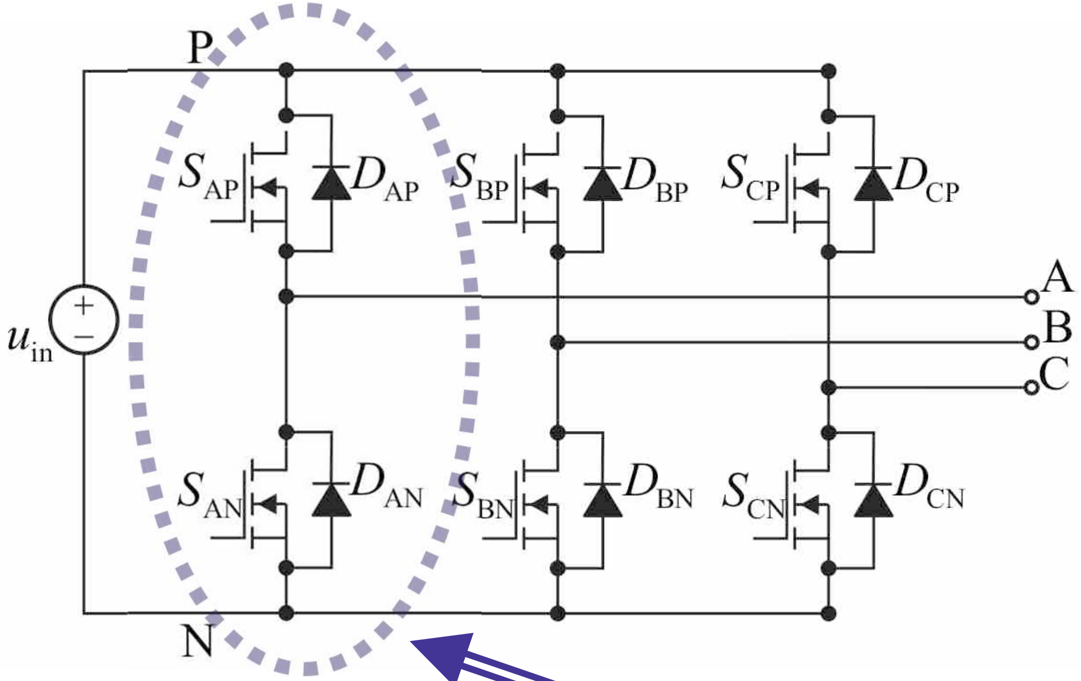
Switching pulses for switch (different for each switch)
- Positive value → switch conducts current
- Negative value → switch does not conduct current

Short Introduction to PV-Inverter Control

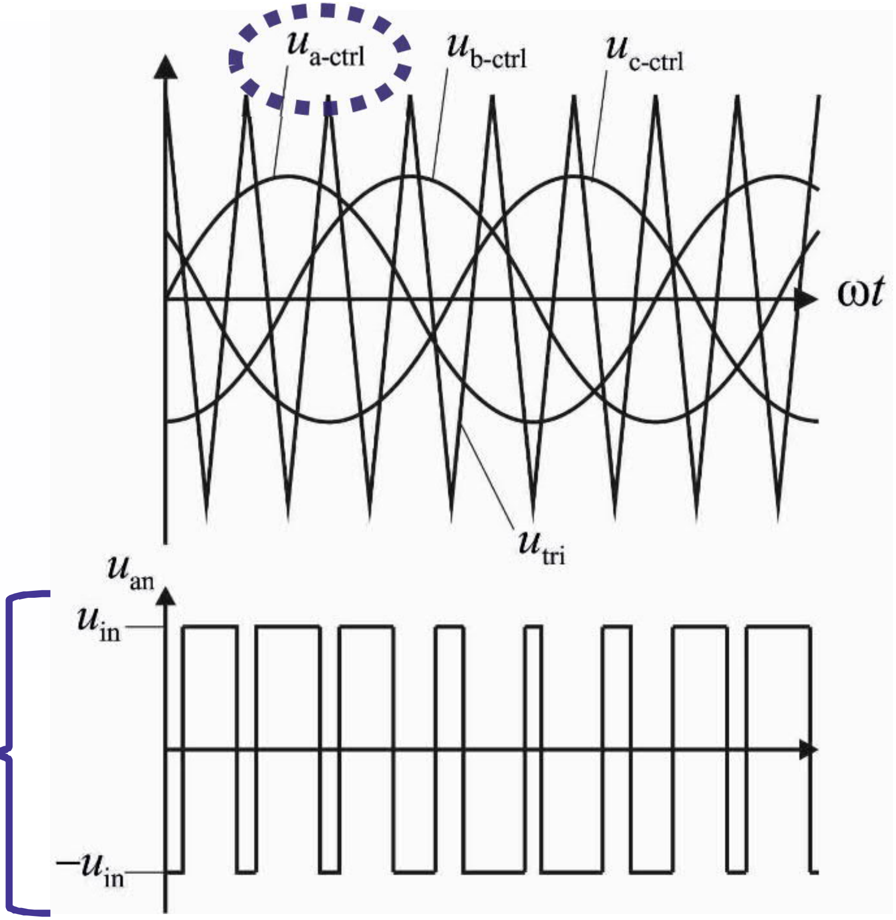
- Control system produces the reference signal to PWM
  - Synchronized to grid voltages by PLL
  - Amplitude of reference is determined by current controller
    - Active and reactive power can be controlled separately
  - DC-voltage control maintains the DC-voltage (MPP of PV-panels)



PWM for Three-Phase Inverter



Phase A



Switching pulses
for phase A

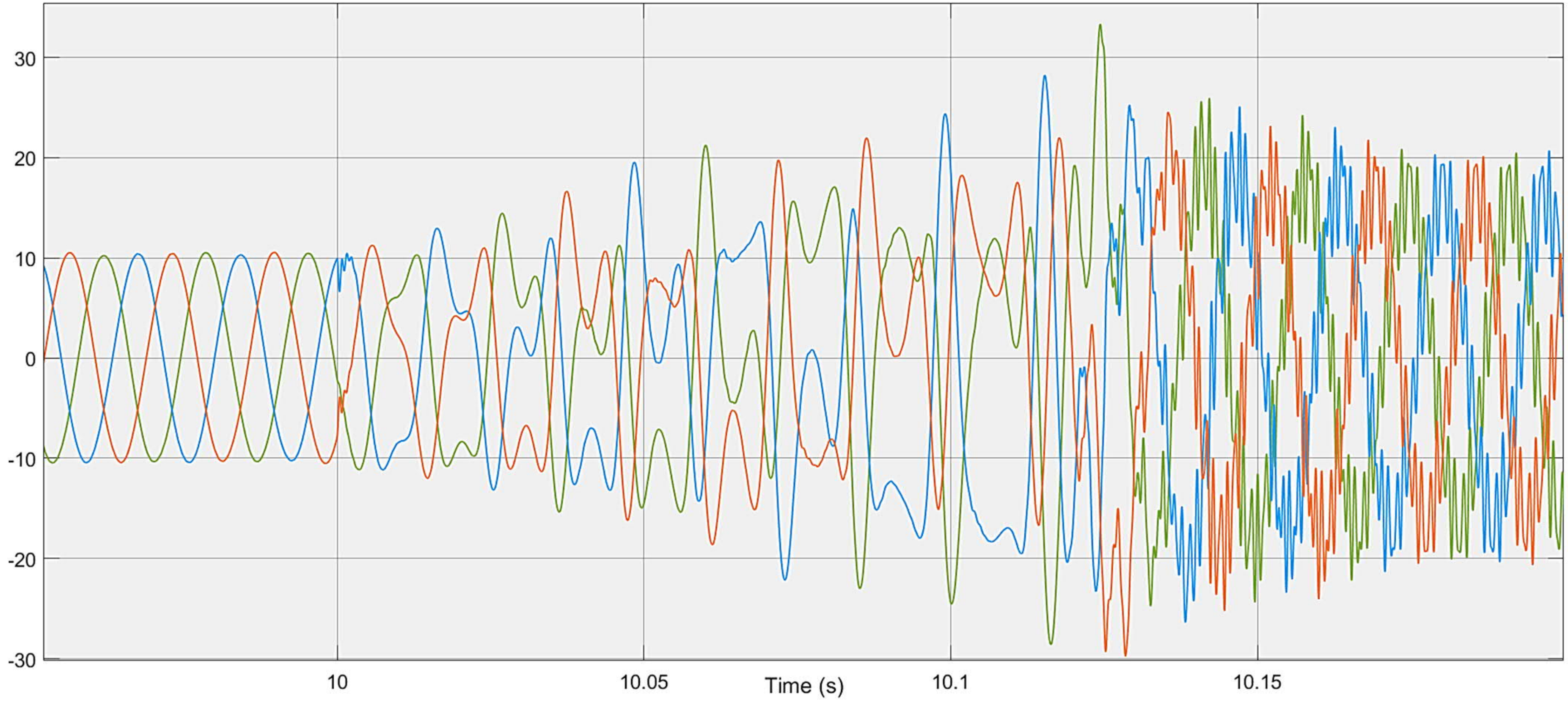
Same kind of pulses for Phases B and C

- 120 degree difference in phase angle

Stability Issues

- Little changes (for example in grid) may cause instability
  - Faster dynamics than in conventional generators

  → More sensitive for stability issues



Power Quality

- Power-elecronic inverters may cause power-quality issues that big rotating machines doesn’t

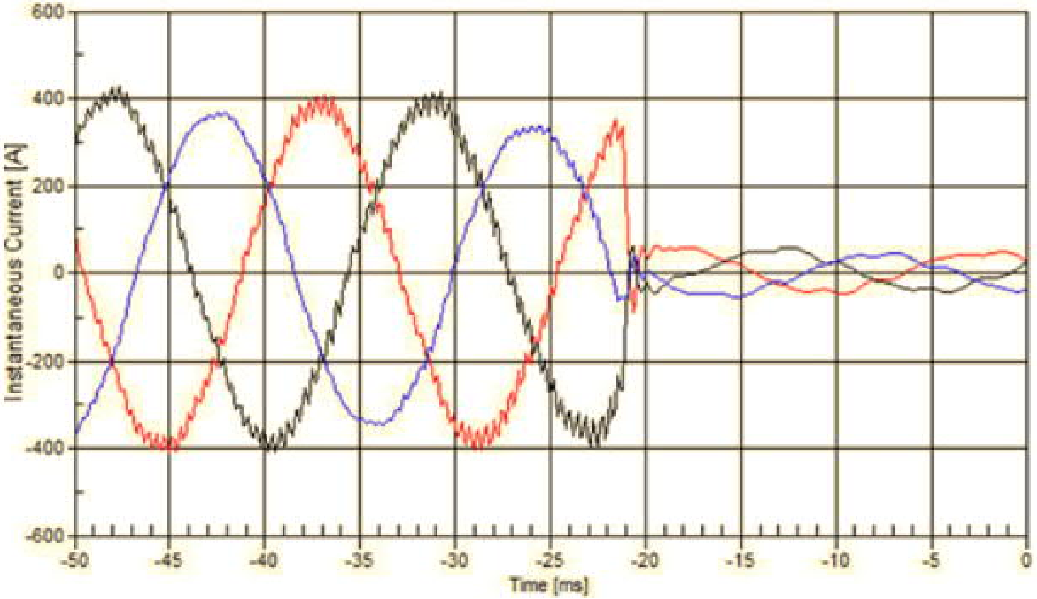


Fig. 4. PV current waveforms with high-frequency oscillations.

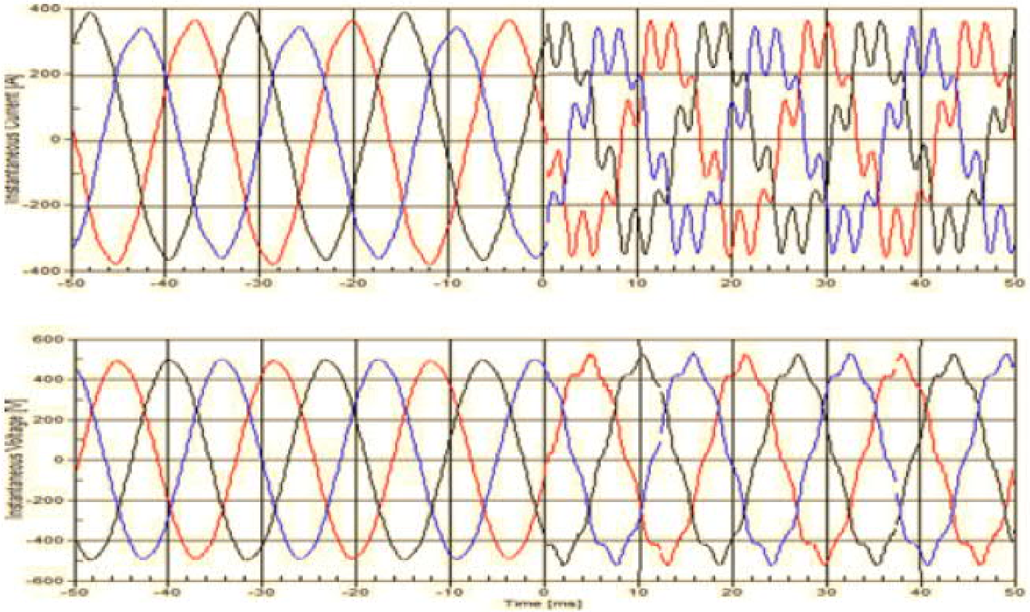
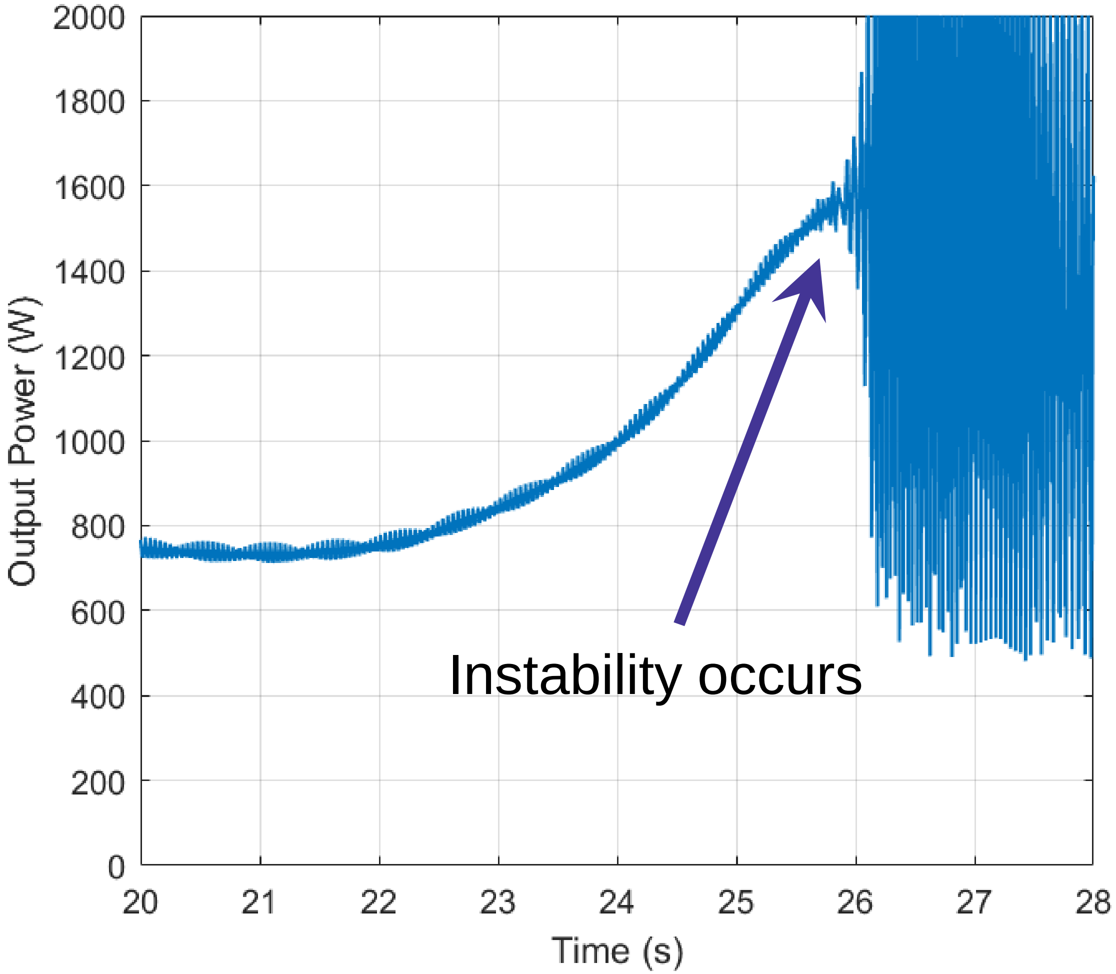


Fig. 1. Current and voltage waveforms under normal and unstable operations.

C. Li, "Unstable Operation of Photovoltaic Inverter from Field Experiences," in IEEE Transactions on Power Delivery, vol. 33, no. 2, pp. 1013-1015, 2018.

Unstable Operation due to Increased Power

- Poor control performance
  - System goes unstable as power increases

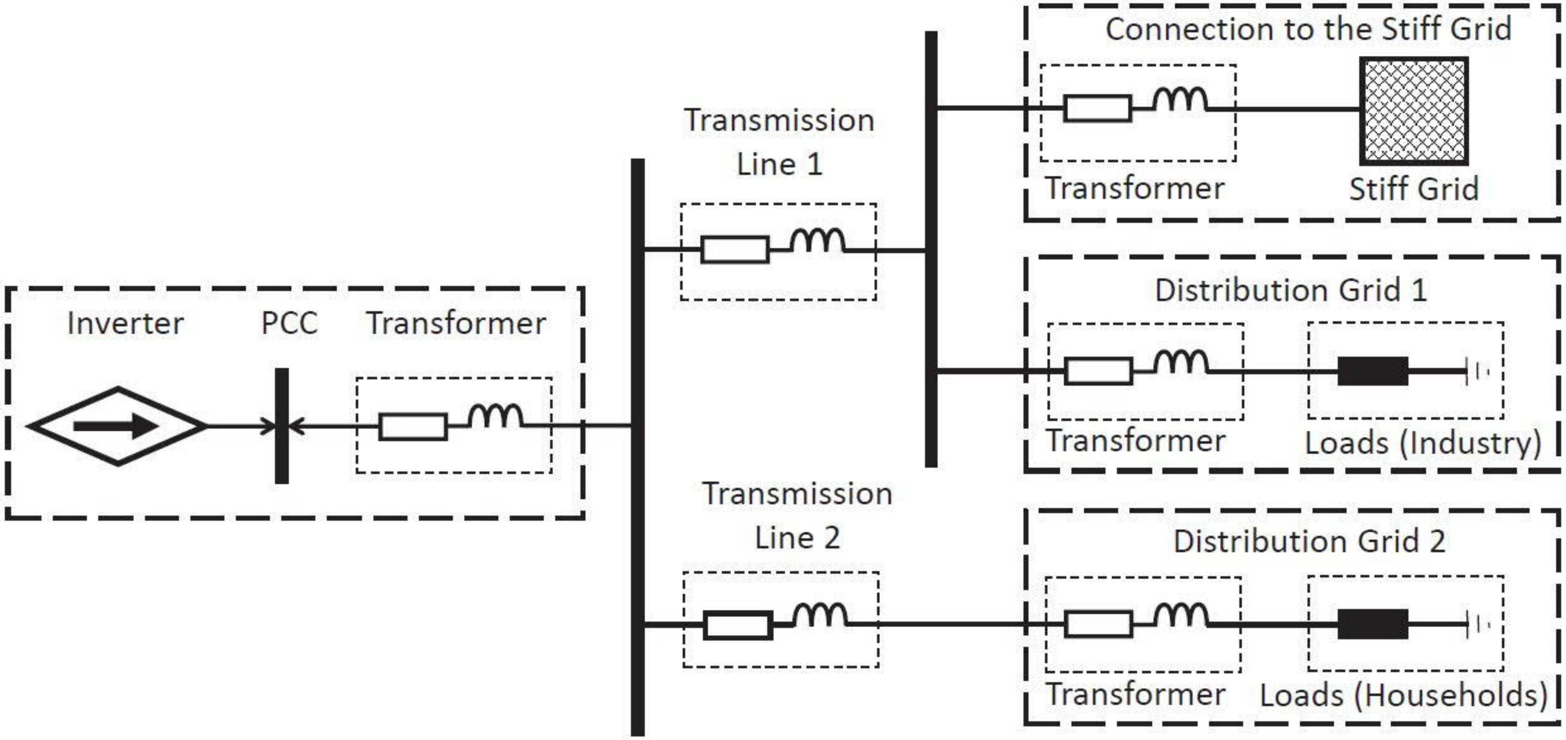


Power Grid

- Renewable energy resources are located in various places
  - Requires lot of space
  - Distributed generation
  - Long distances
- Power grid affects to the power quality and stability
  - Voltage harmonics
  - Voltage stability
  - Grid impedance → reactive power

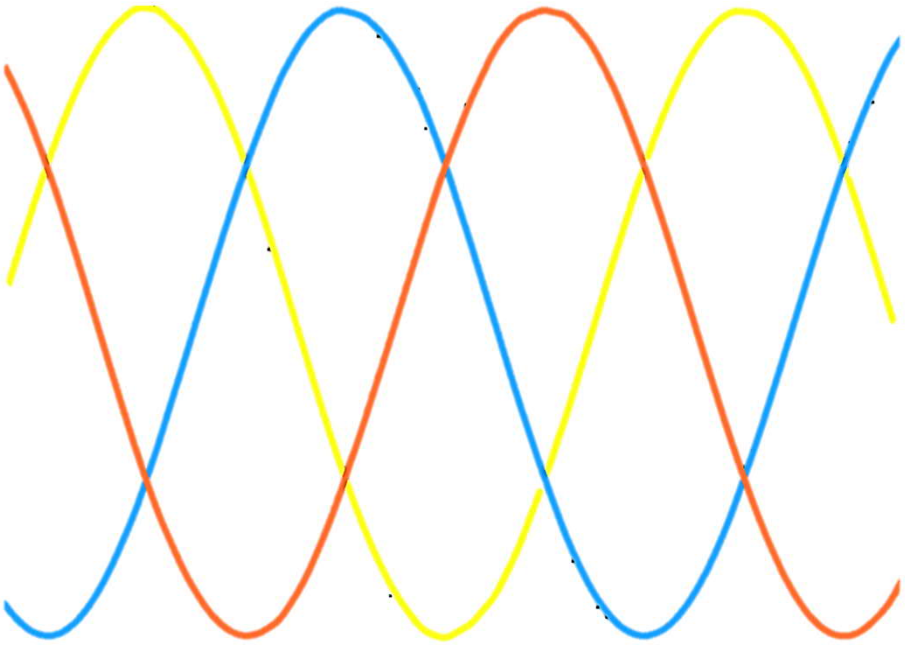
Power Grid

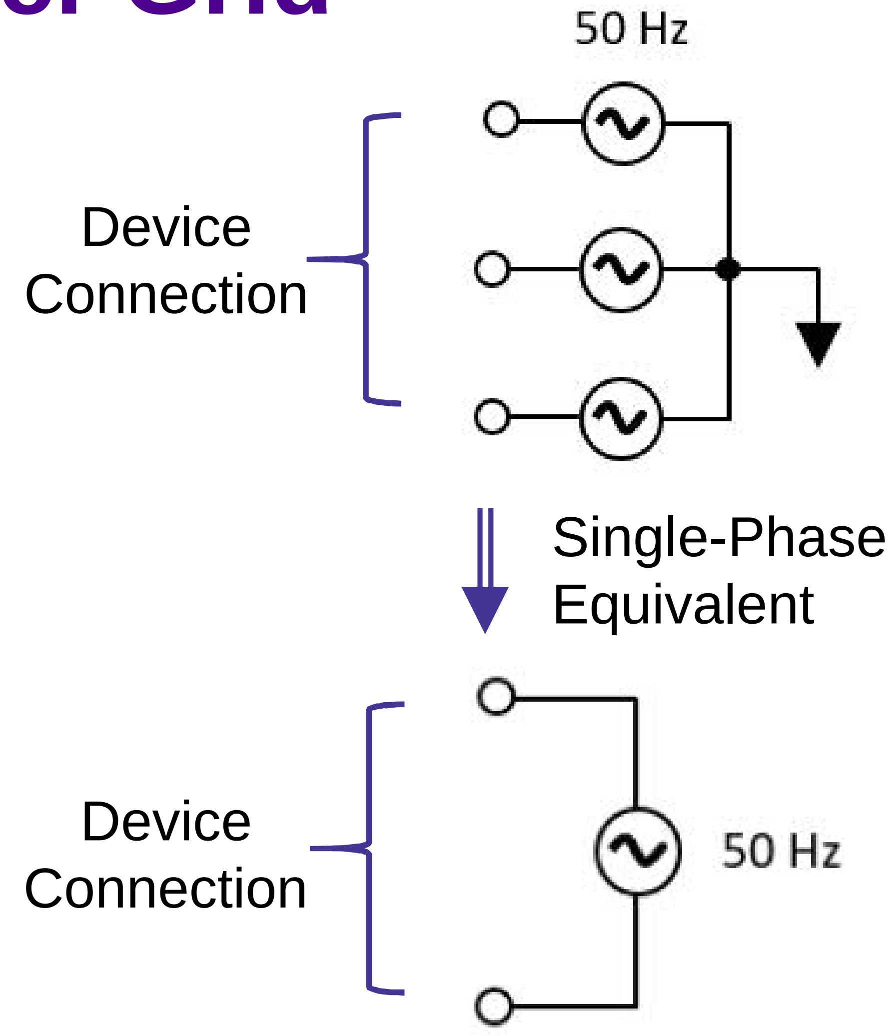
- Single inverter ”sees” the power grid as a load
- Depends on the connection point, point-of-common coupling (PCC)



Ideal Power Grid

- The ideal power grid can be represented by three 50 Hz voltage sources
- Voltage amplitude depends on the voltage level





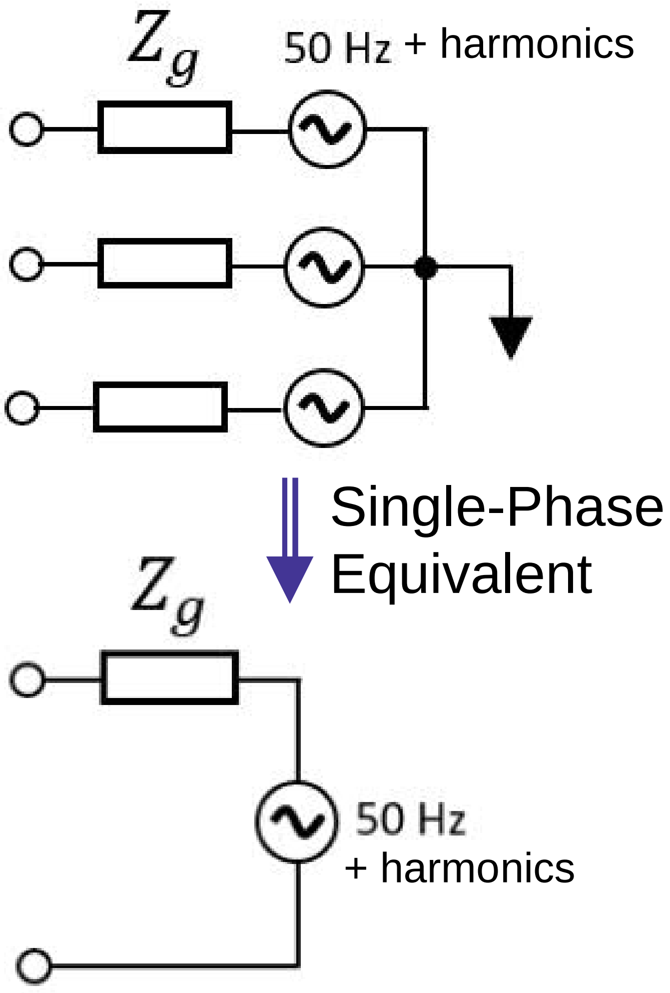
Device Connection

Single-Phase Equivalent

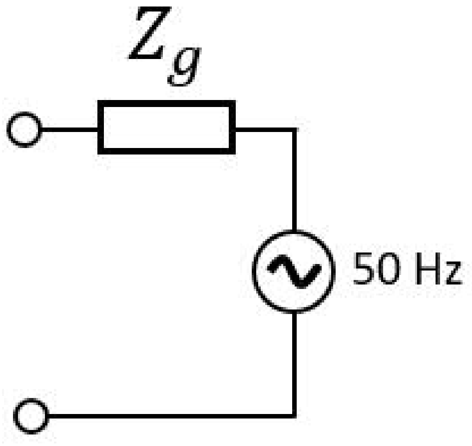
Device Connection

Realistic Power Grid

- The non-idealities of the power grid can be represented by voltage harmonins, frequency variations and grid impedance (Z_g)
- Thevenin equivalent
    - Ideal voltage source
    - Non-idealities as an series impedance
- Low grid impedance is more robust



Grid Impedance

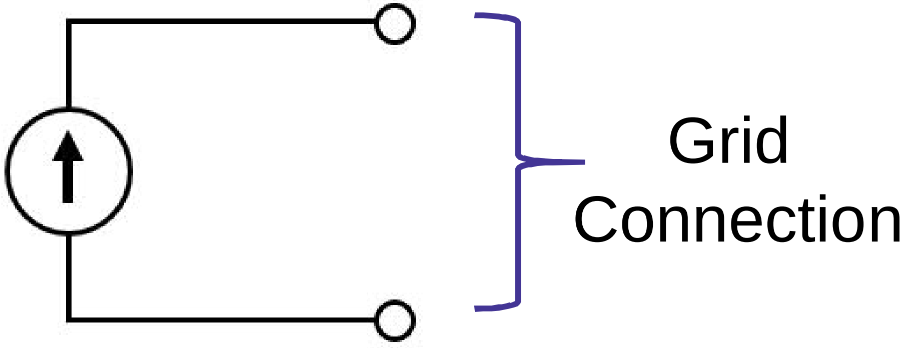


- The grid impedance consist of:
    - Power lines (resistance and inductance)
    - Cabling (resistance, capacitance, inductance)
    - Transformers (Inductance and resistance)
    - Loads
    - Possible compensation (capacitance)
- Low grid impedances (thick power lines and short lengths) are most robust
- High grid impedance is usually a problem
    - Long distances and thin lines usually causes problems

Ideal Inverter

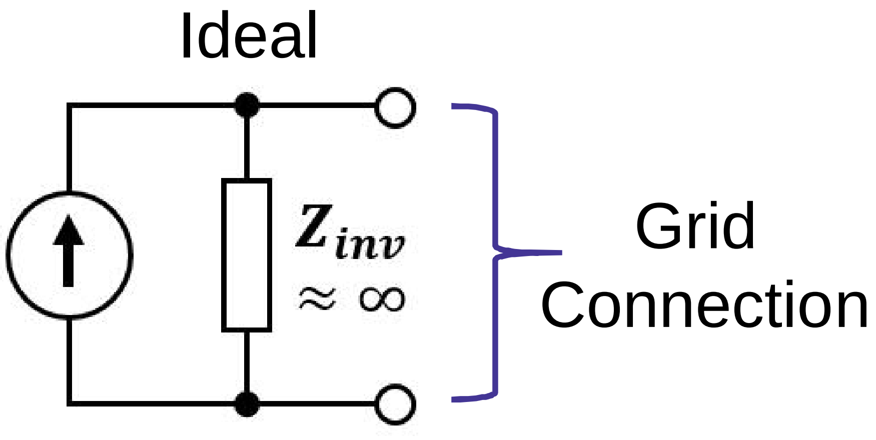
- Inverter feeds power to the grid
  - Amount of power depend on the produced current

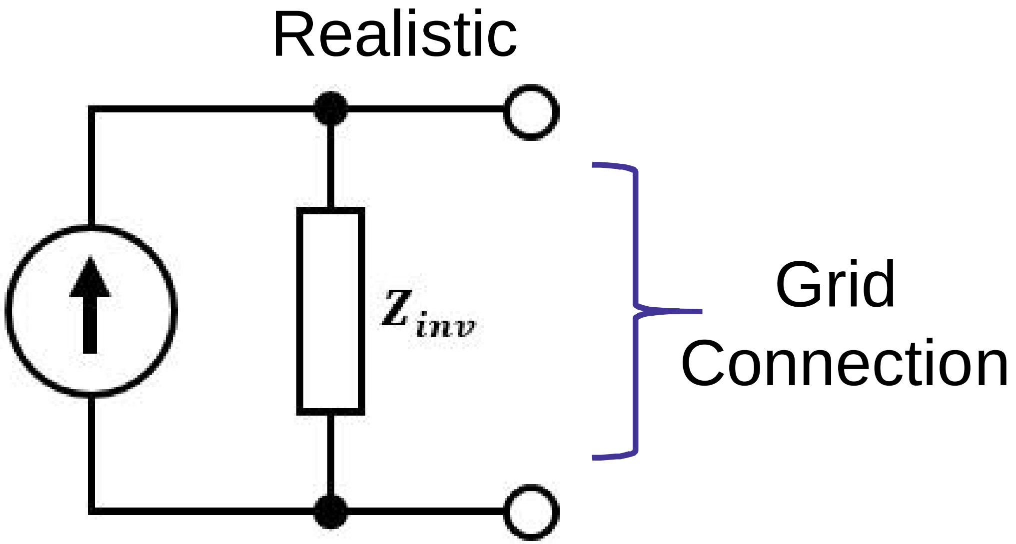
  → Ideal inverter can be represented by a current source
  - Active and reactive power



Realistic Inverter

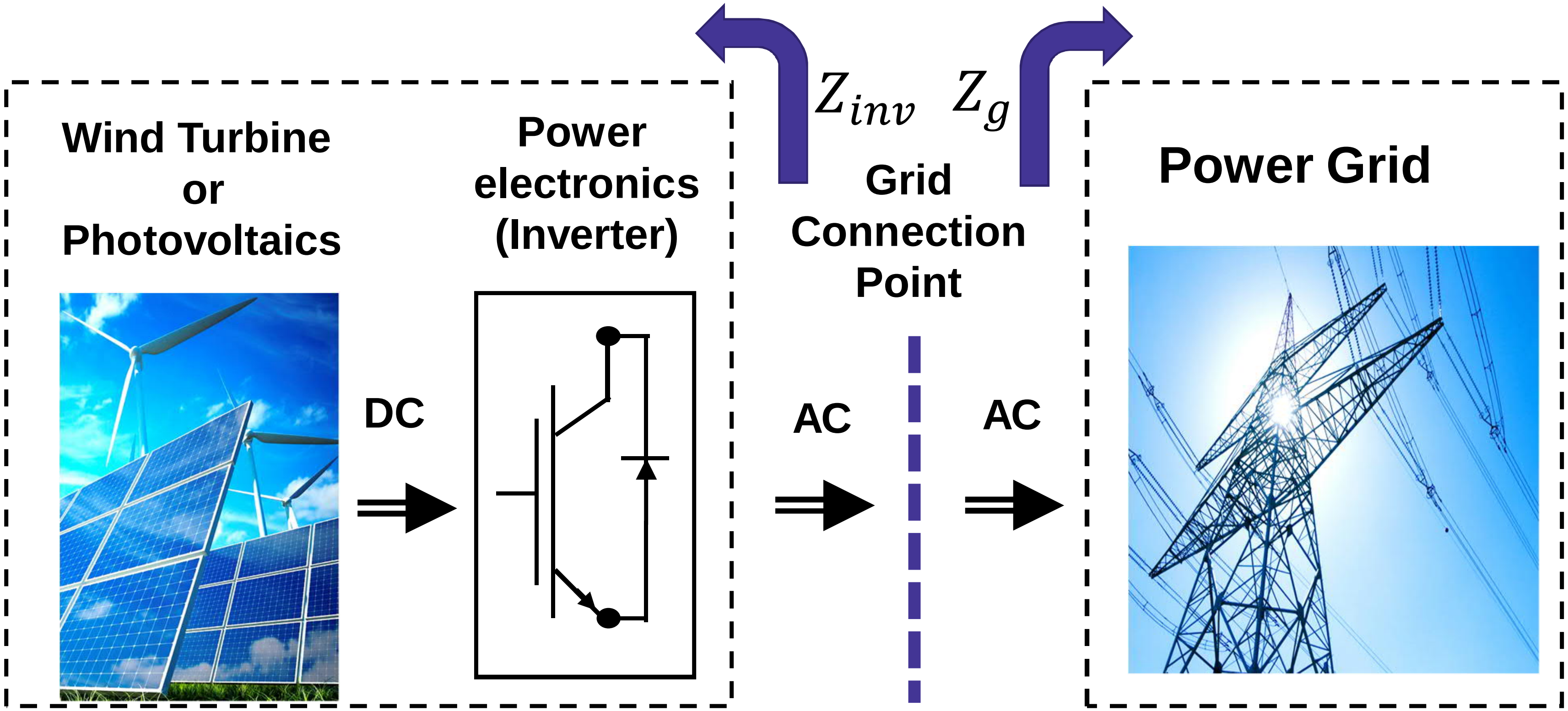
- The non-idealities can be represented by an output impedance
- Norton equivalent
  - Ideal current source
  - Finite parallel impedance
- Output impedance consists of
  - Components
  - Power source
  - Most improtantly: control system
- Higher output impedance is more robust





Grid Connection

- Renewable energy sources are usually connected to the power grid through an inverter
- Non-ideal characteristics can be analysed through they impedances Z_g and Z_{inv}



Z_{inv} Z_g

Wind Turbine or Photovoltaics

Power electronics (Inverter)

DC

Grid Connection Point

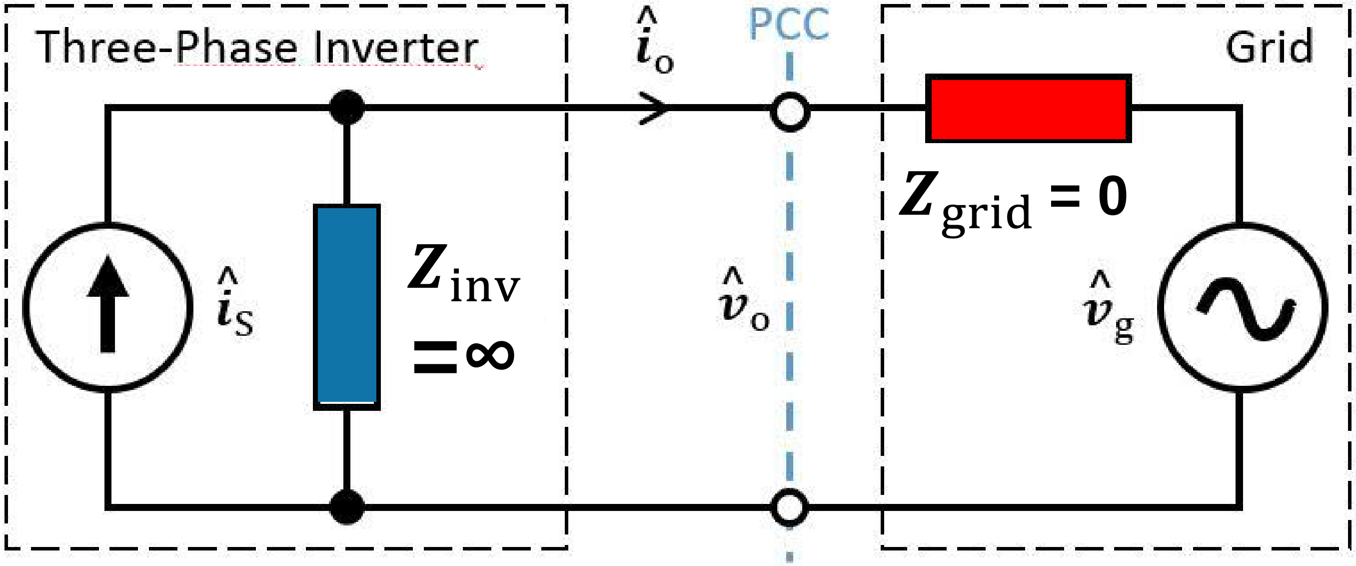
AC

AC

Power Grid

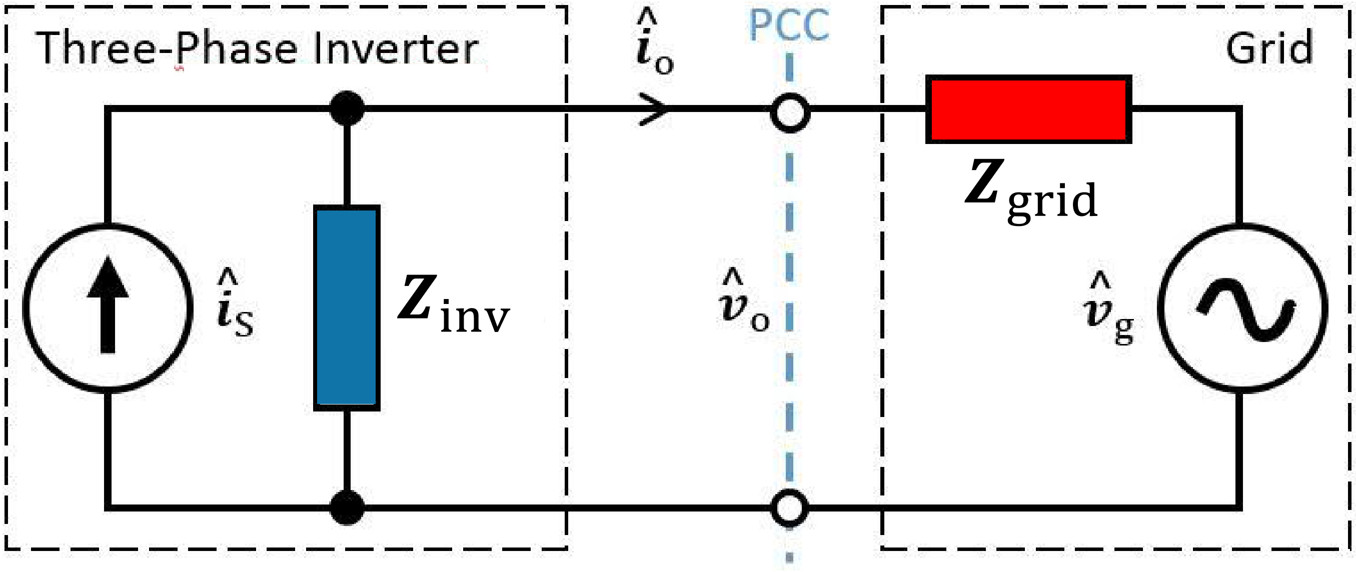
Ideal Grid Connection

- The previously presented inverter and grid models are connected
- Inverer (current source) and grid (voltage source) determine voltage and current of the circuit; $P = UI$
- Connection point is usually called as ”Point of Common Coupling (PCC)”



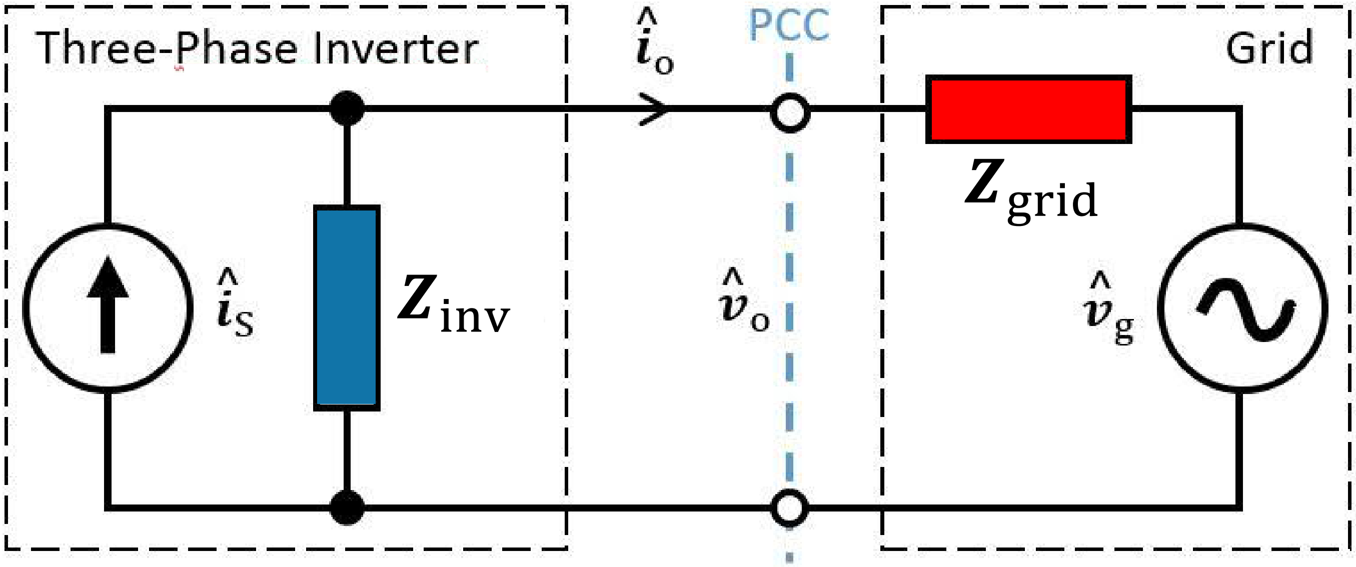
Grid Connection

- Non-idealities can be represented by inverter output and grid impedances
  - Losses and phase shifts
- Stability of the grid-connection point can be assessed with those impedances
  - **Impedance-Based Stability Analysis (small-signal stability)**
  - Determines the controllability/stability of the inverter output current (i_o)



Grid Connection

- Grid impedance usually have inductive characteristics
  - Phase close to 90 degrees
- Inverter impedance is non-passive in some frequencies
  - Which here means that the phase may be below -90 degrees
  - Cannot be represented by passive components (R, L and C)

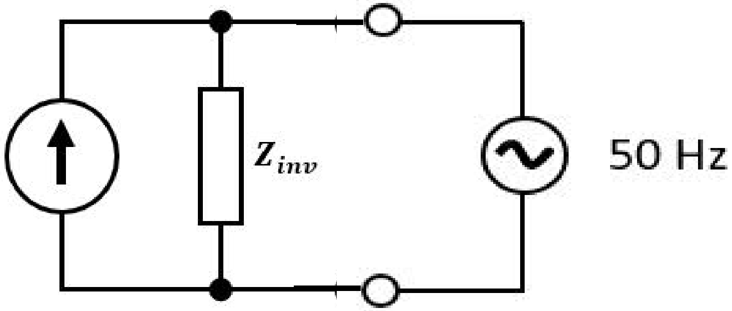


Impedance-Based Stability

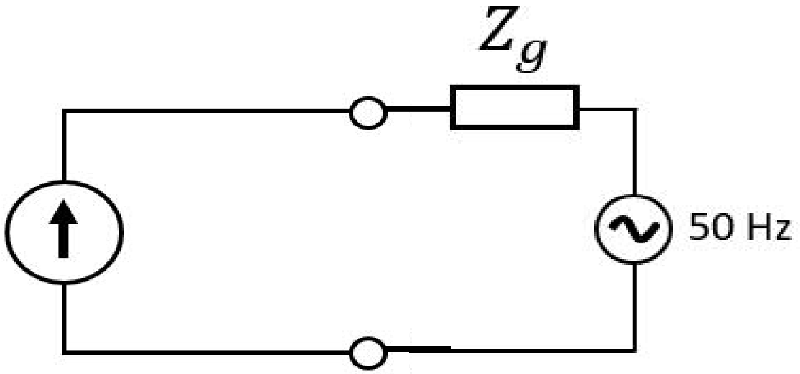
Assumptions:

- Inverter is designed properly and is internally stable (1)
  - Stable when connected to ideal (strong) grid
- Grid is stable powered when from a ideal source (2)
  - Voltages are stable

STABLE



STABLE



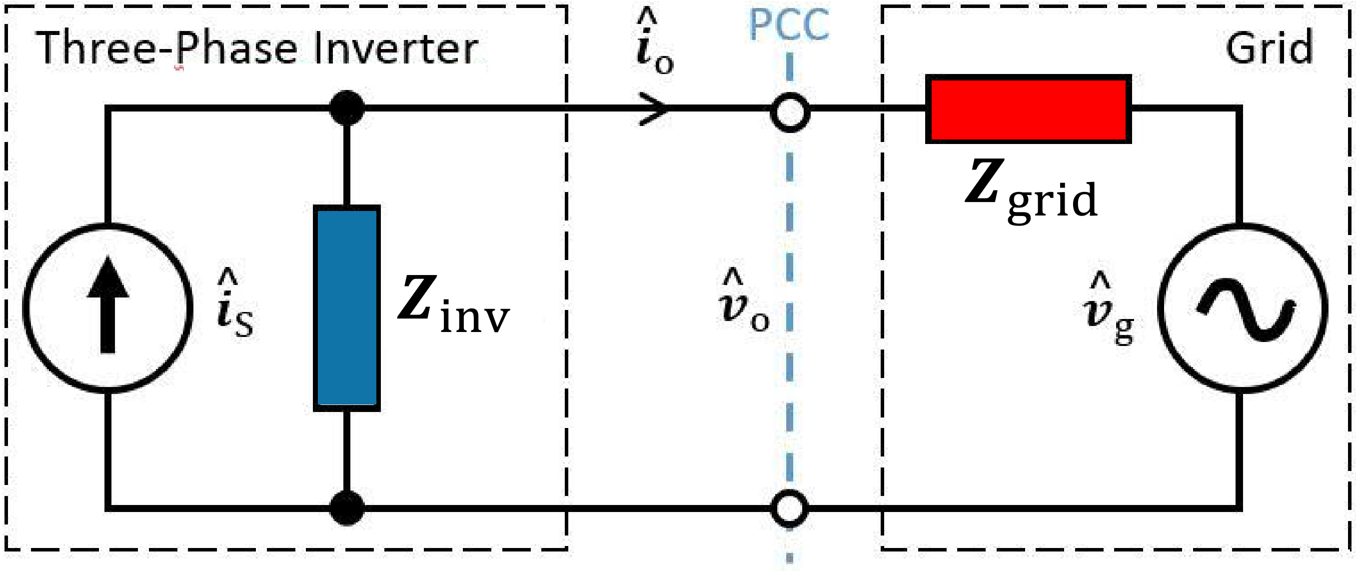
Is the connection of the grid impedance (Z_g) and inverter output impedance (Z_{inv}) stable

$\approx$

Impedance-Based Stability Analysis

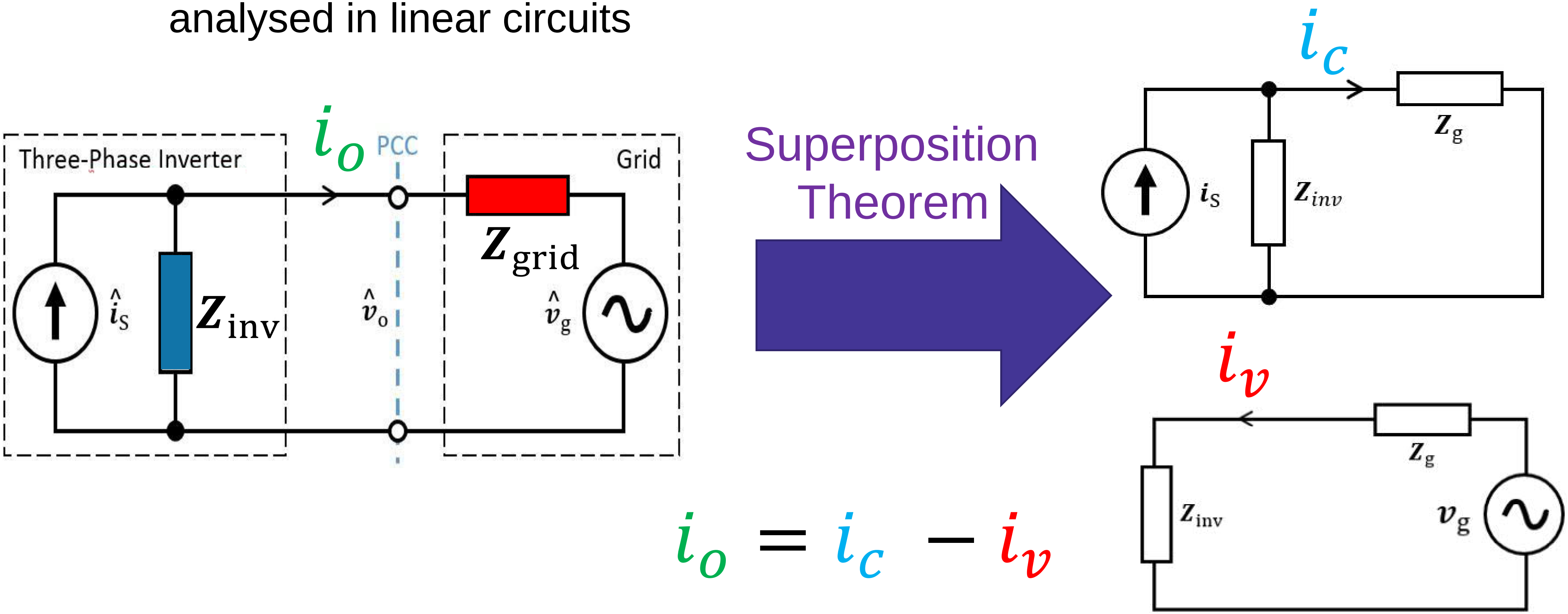
Impedance-Based Stability Analysis

- Small-signal stability → small disturbances can magnify too much → instability
- Impedance-based stability analysis determines, is the output current (i_o) stable
- If these two impedances are mismatching, harmonic resonance occurs in the output current → impedance-based instability
    - AC-current controller loses its controllability → bad current quality or compelete instability (small signal becomes large signal)



Determinig Impedance-Based Analysis

- Based on the basic Kirchoff’s current and voltage laws; and superposition theorem
  - Superposition theorem: current and voltage sources can be separately analysed in linear circuits



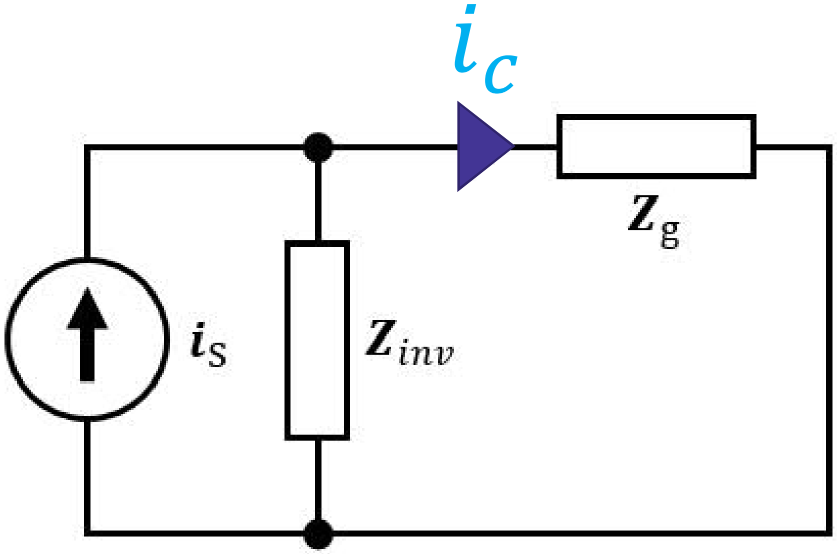
Superposition Theorem

$$i_o = i_c - i_v$$

Superposition

- Kirchoff’s current law:

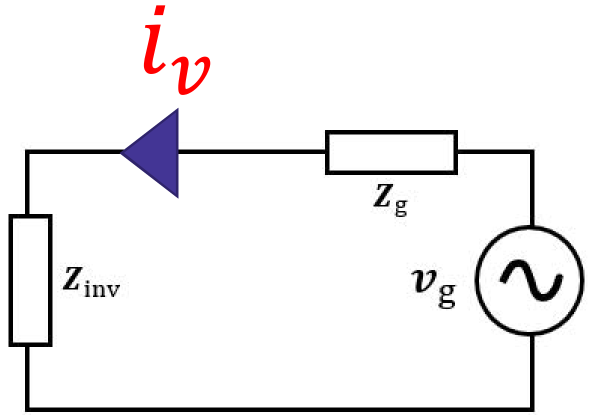
$$i_c = \frac{i_s Z_{inv}}{Z_{inv}+Z_g}$$



Superposition

- Kirchoff's voltage/current law:

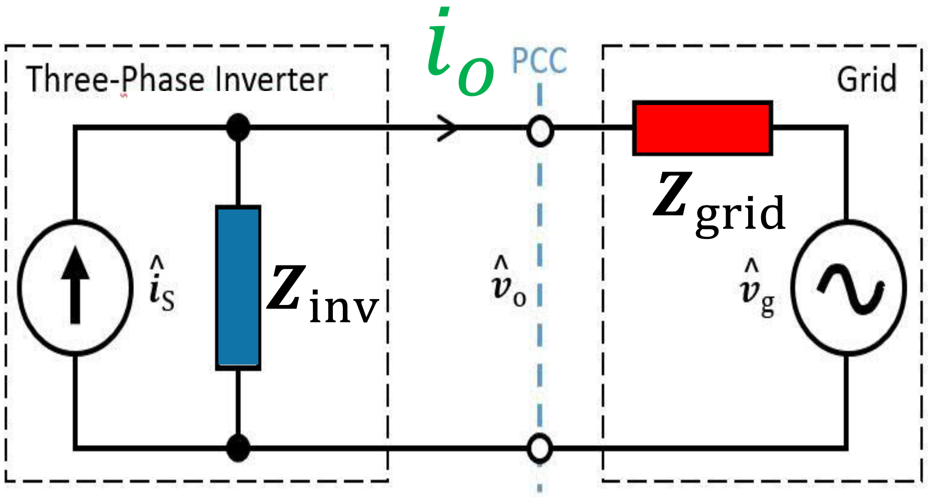
$$i_v = \frac{v_g}{Z_{inv}+Z_g}$$

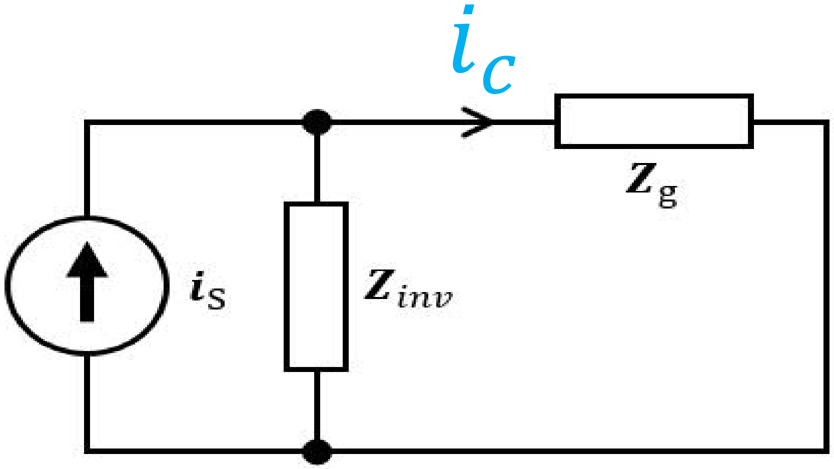


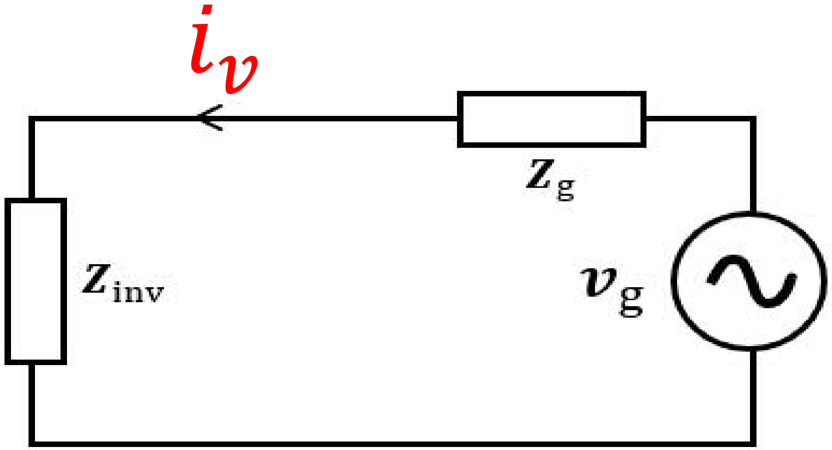
Superposition

$$i_o = i_c - i_v$$

$$= \frac{i_s Z_{inv}}{Z_{inv}+Z_g} - \frac{v_g}{Z_{inv}+Z_g}$$







Impedance-Based Stability Analysis

$$i_o = \frac{i_s Z_{inv}}{Z_{inv} + Z_g} - \frac{v_g}{Z_{inv} + Z_g}$$

$$= (i_s Z_{inv} - v_g)(\frac{1}{Z_g + Z_{inv}})$$

$$= \underbrace{\left(i_s - \frac{v_g}{Z_{inv}}\right)}_{\text{Previously assumed to be stable ”Inverter in ideal grid”}} \left.\left(\frac{1}{1+\frac{Z_g}{Z_{inv}}}\right)\quad\right\} \text{Applied for the impedance-based stability analysis}$$

Impedance-Based Stability Analysis

$$G = \frac{1}{1 + \frac{Z_g}{Z_{inv}}}$$

⇓

$$G(s) = \frac{1}{1 + \frac{Z_g(s)}{Z_{inv}(s)}}$$

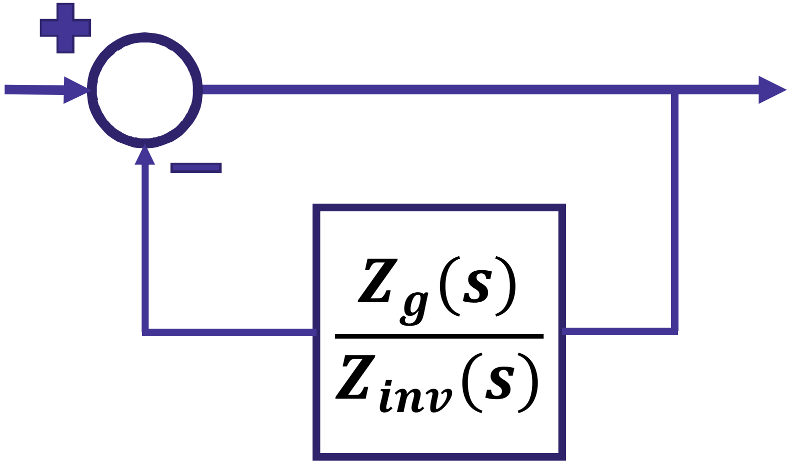
- Small disturbances are located in wide frequency range
- In the impedance-based stability analysis, all frequencies must be taken into account
  - Not only 50 Hz frequency as done in the power system stability analysis
  - Analysis is executed in frequency domain (Laplace domain)
  - Must be stable at every frequency

$$s = j\omega = j2\pi f$$

Feedback-System Equivalent

$$G(s) = \frac{1}{1+\frac{Z_g(s)}{Z_{inv}(s)}}$$

- Resembles a transfer function of a negative feedback system, with a gain $\frac{Z_g(s)}{Z_{inv}(s)}$ in a feedback.
- System eigenvalues depends on the $\frac{Z_g(s)}{Z_{inv}(s)}$ and thus can be applied for the stability analysis

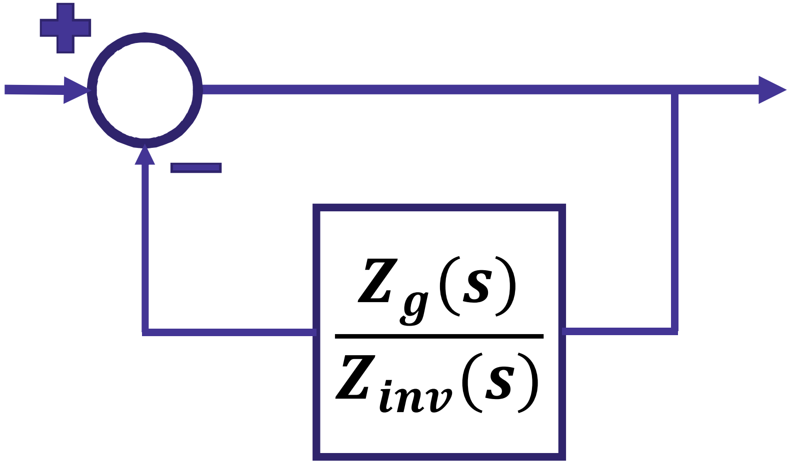


- Basic control theory can be applied
  - Feedback system stability

Feedback-System Equivalent

$$G(s) = \frac{1}{1+\frac{Z_g(s)}{Z_{inv}(s)}}$$

- Stability issues arise from the shape of the impedances
- Line lengths, transformers, compensation and loads shape the grid impedance
  - Low value of Z_g is more robust
- Effect of delays and control system shape the inverter output impedance
  - High Z_{inv} is more robust



- Low Z_g and high Z_{inv}

$\rightarrow \frac{Z_g(s)}{Z_{inv}(s)}$ is very low

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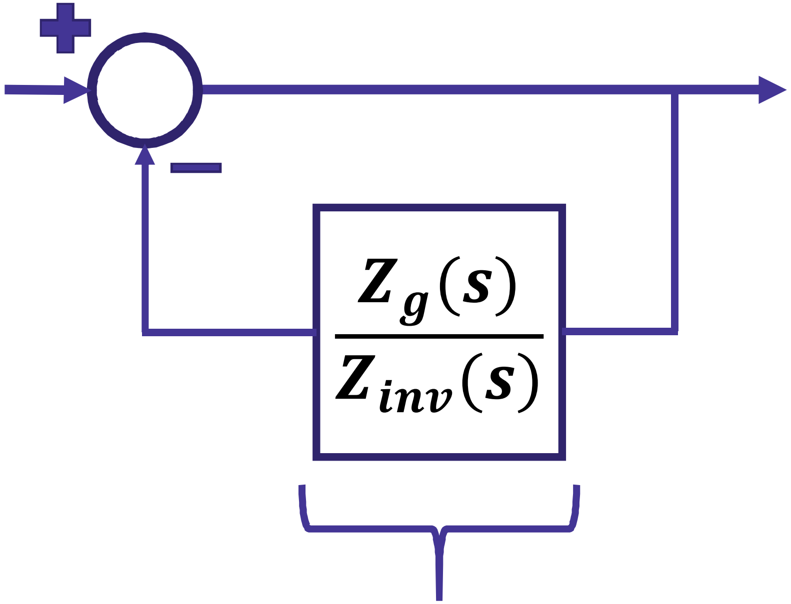
Feedback-System Equivalent

$$G(s) = \frac{1}{1+\frac{Z_g(s)}{Z_{inv}(s)}}$$

- Z_{inv} can be shaped by control design
- Z_g depends on the grid-connection point and may vary over time

- Grid connection can destabilize the system
  - ”Mismatch” between Z_{inv} and Z_g



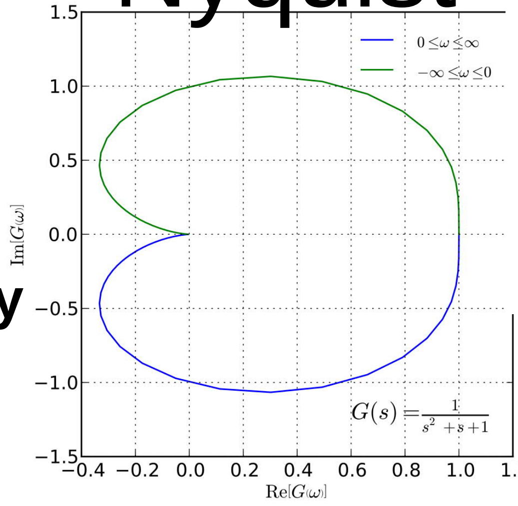
”Load Effect”

- Starts to affect when the inverter is connected to the grid
- Grid is load for the inverter

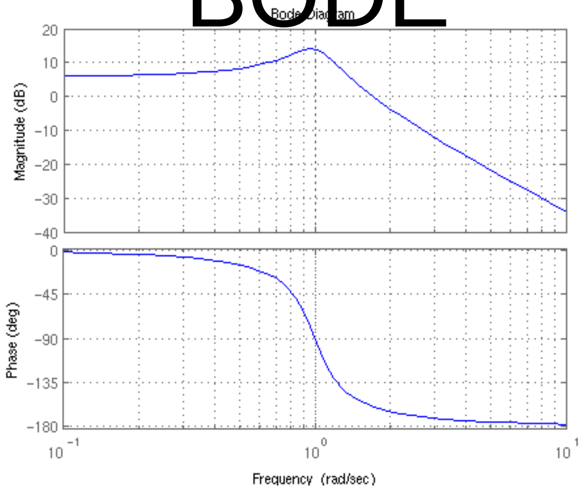
Impedance-Based Stability

- The impedance ratio $\frac{Z_g(s)}{Z_{inv}(s)}$ must satisfy the stability criterion which can be analysed for example by:
  - **Bode plots**
  - **Nyquist plots**
  - **Sensitivity Function**
- System should have sufficient **Stability Margins** for robust performance
  - Stability margins may change if the grid conditions vary over time
  - Low stability margins causes distortions to produced currents

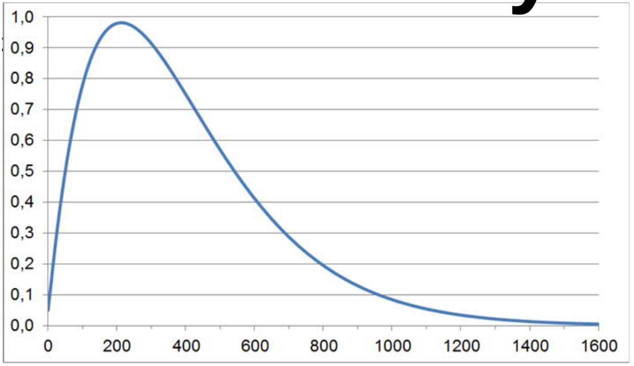
Nyquist



BODE



Sensitivity



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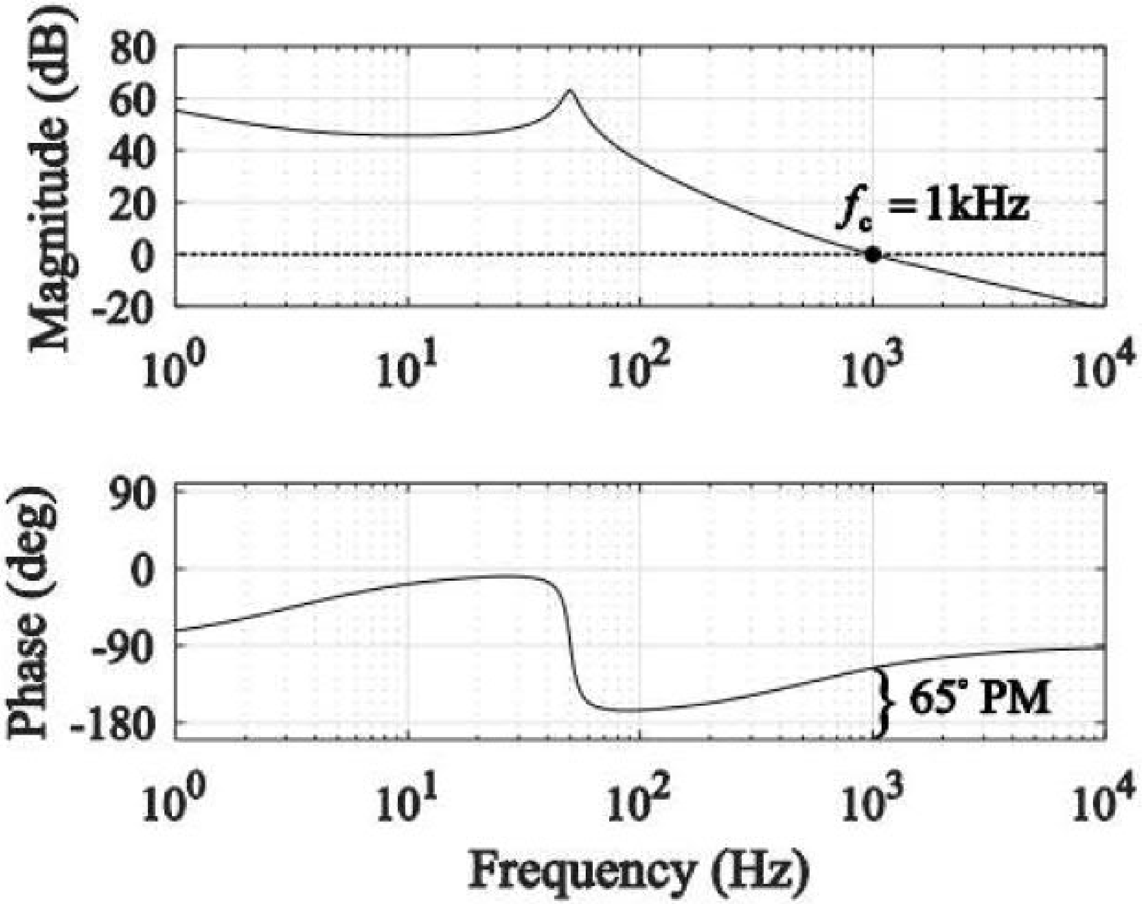
Bode Plot

- Illustrates transfer functions as its magnitude and phase shift in function of frequency
- **Crossover frequency**, where Magnitude = |G| = 0 dB = 1 (abs)
  - **Phase margin** is the phase difference to -180 (180) degrees at system crossover frequency
- Usually it is important to know the frequencies of specific dynamics
  - They are easy to see from Bode plots



Phase shift at 1 kHz is -115 degrees
→ -115 – (-180) = 180 - 115 = 65 (degree PM)

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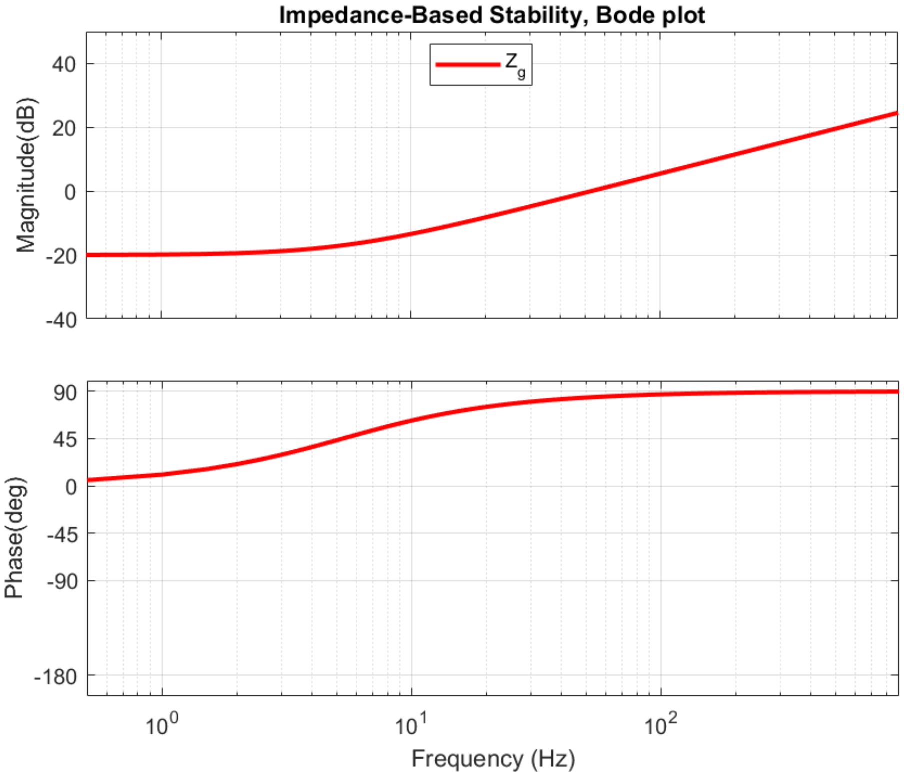
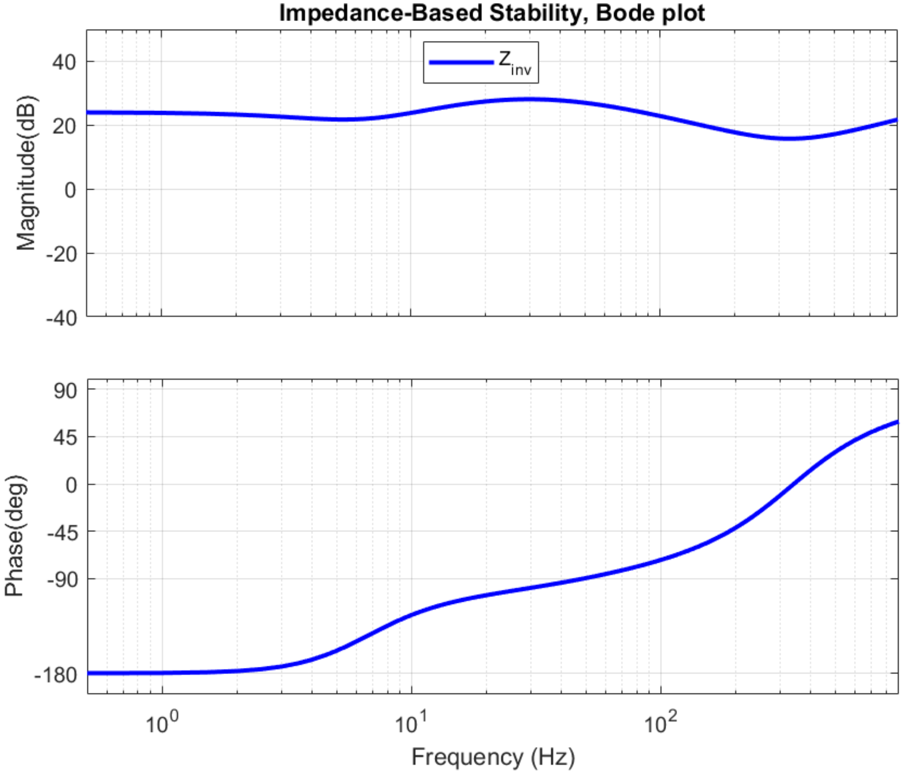
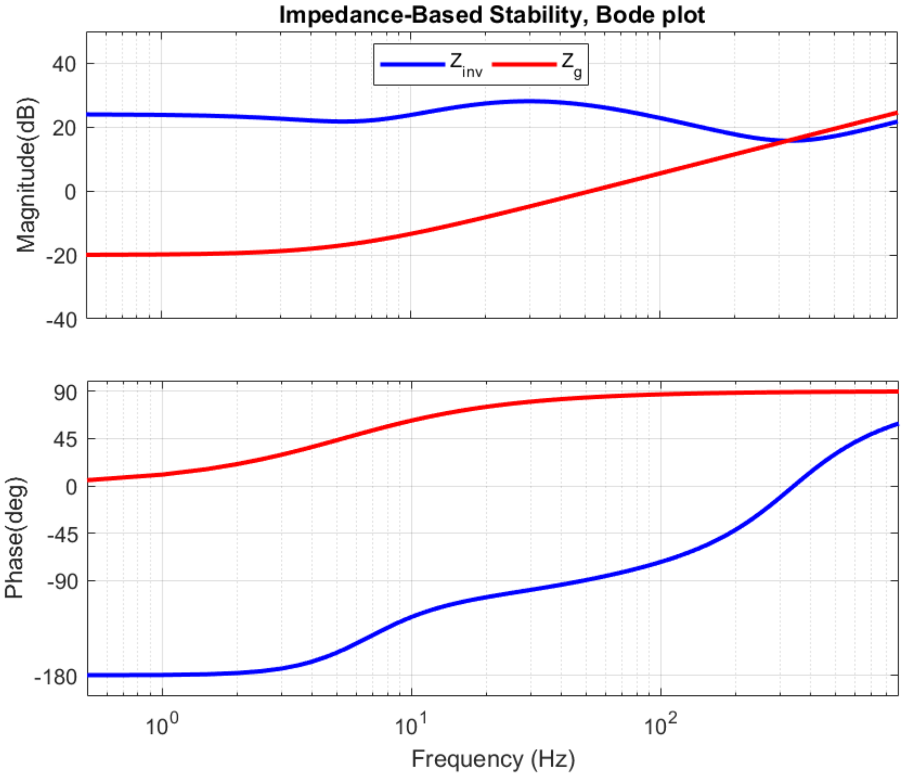
Impedance-Based Stability Assessment as Bode plot



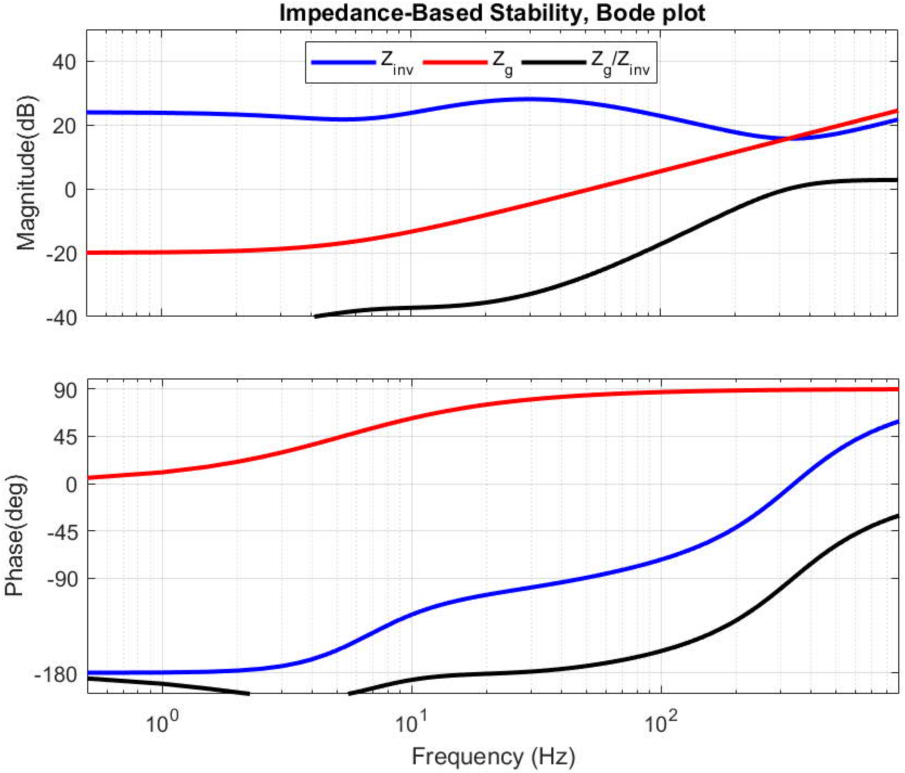
Impedance-Based Stability Assessment as Bode plot



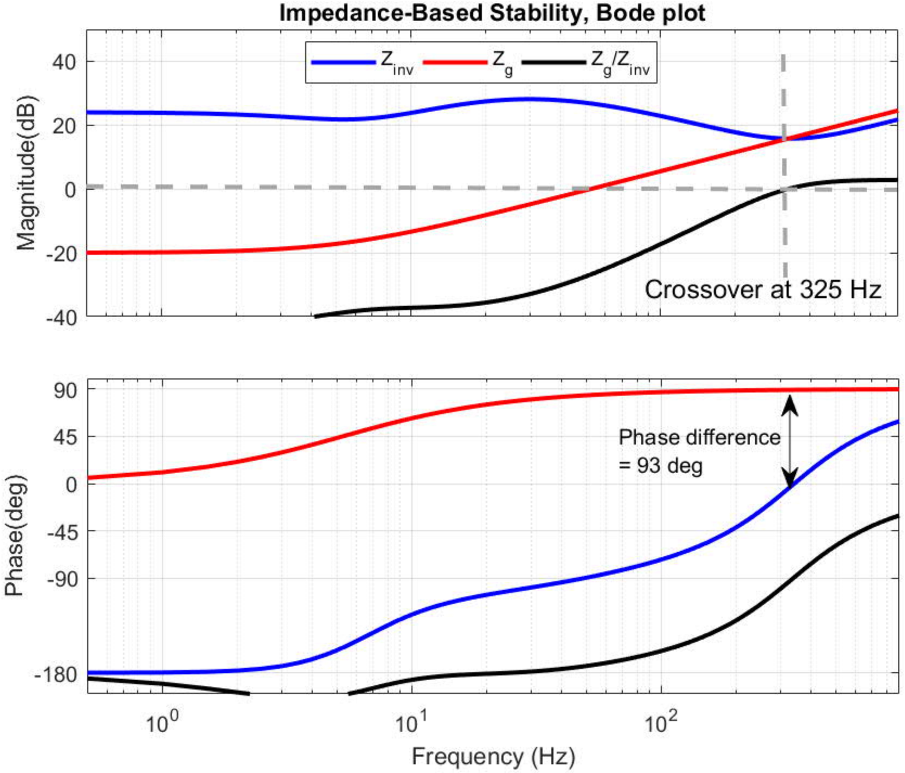
Impedance-Based Stability Assessment as Bode plot



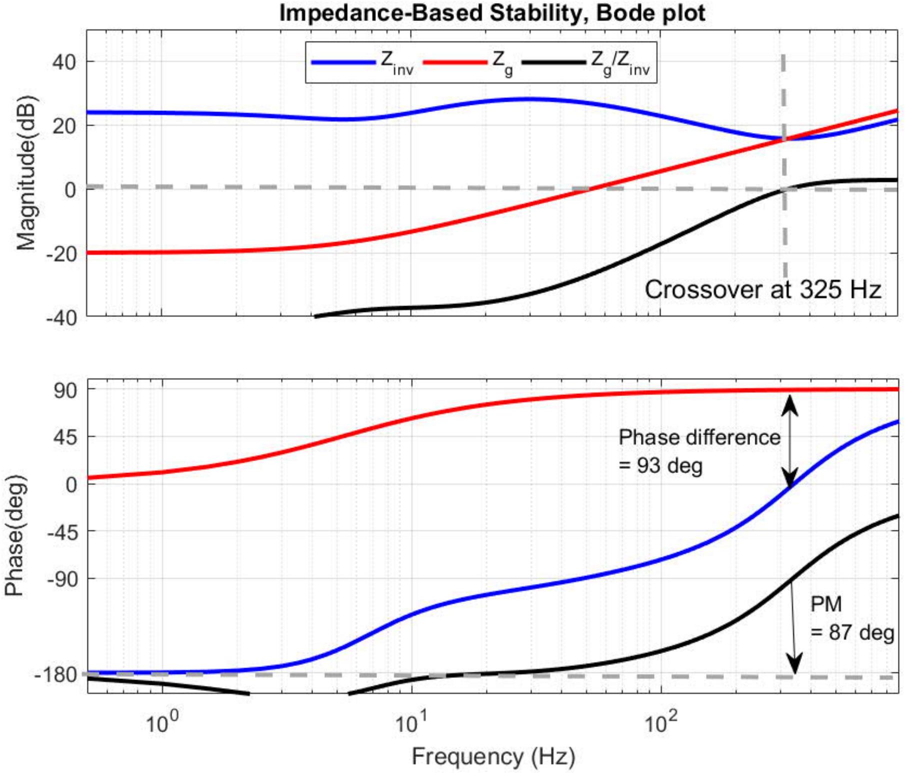
Impedance-Based Stability Assessment as Bode plot



Impedance-Based Stability Assessment as Bode plot



Impedance-Based Stability Assessment as Bode plot



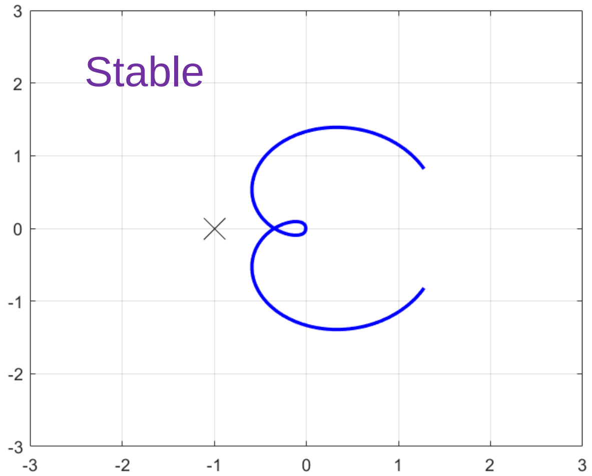
Nyquist

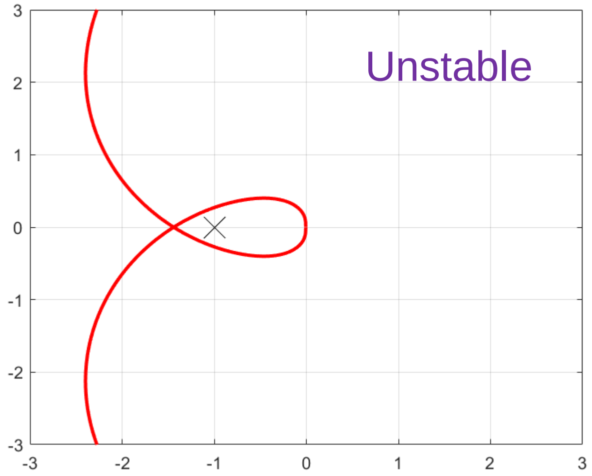
Determines poles of

$$G(s) = \frac{1}{1+\frac{Z_g(s)}{Z_{inv}(s)}}$$

Stability analysis can be monitored by plotting $\frac{\boldsymbol{Z_g(s)}}{\boldsymbol{Z_{inv}(s)}}$ **to complex plane**

- The stability is preserved if curve does not encircle **the critical (-1+j0) point** clockwise (simplified)
- Which ensures that the system does not have unstable poles, which are poles with positive real part
- Curve’s distance to the critical point can be handled as **stability margin**





Stability can be easily seen!

Sensitivity

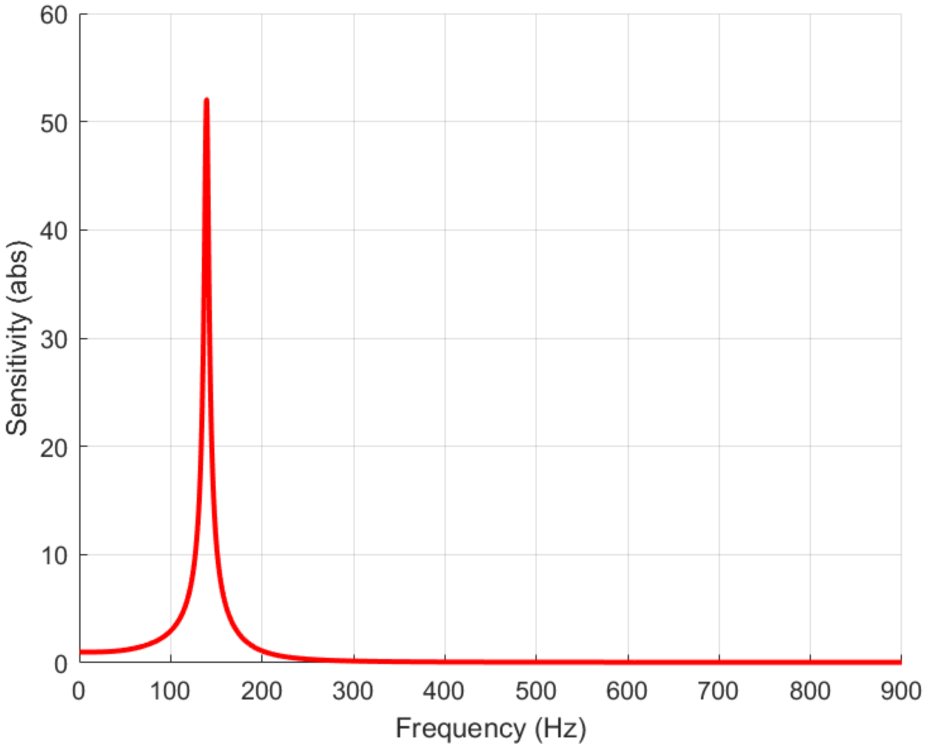
Absolute value of the

$$G(s) = \frac{1}{1+\frac{Z_g(s)}{Z_{inv}(s)}} = S(s)$$

Can be handled as **the system sensitivity function $\boldsymbol{S(s)}$**

- High values means sensitivity for disturbances
- Highest absolute value is called as **sensitivity peak** which is the most sensitive frequency

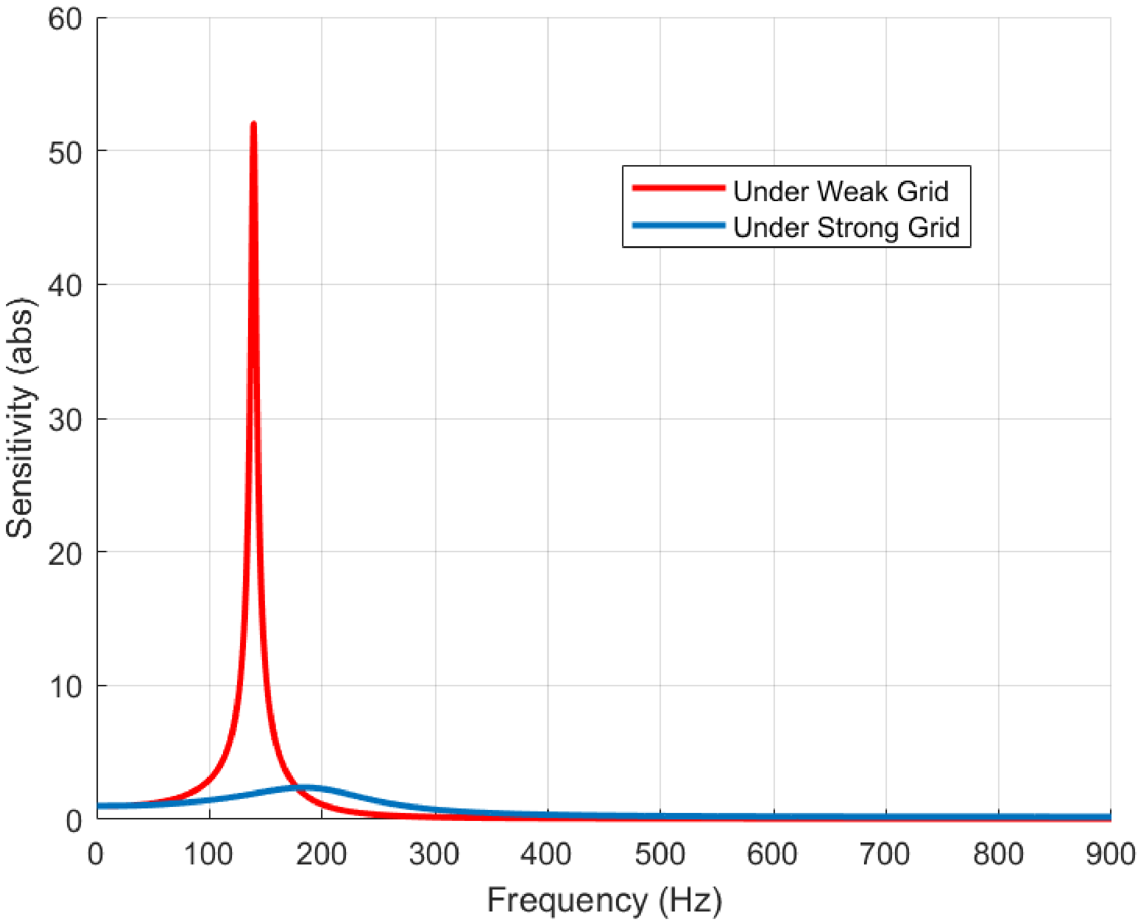
$$S_{peak} = \max_{0\,\leq s\,\leq\,\infty} \frac{1}{\left|1+\frac{Z_g(s)}{Z_{inv}(s)}\right|}$$



- Forecaste distorted frequencies
- Sensitivity peak is indicator for robustness
  - Values below 2 are usually desired

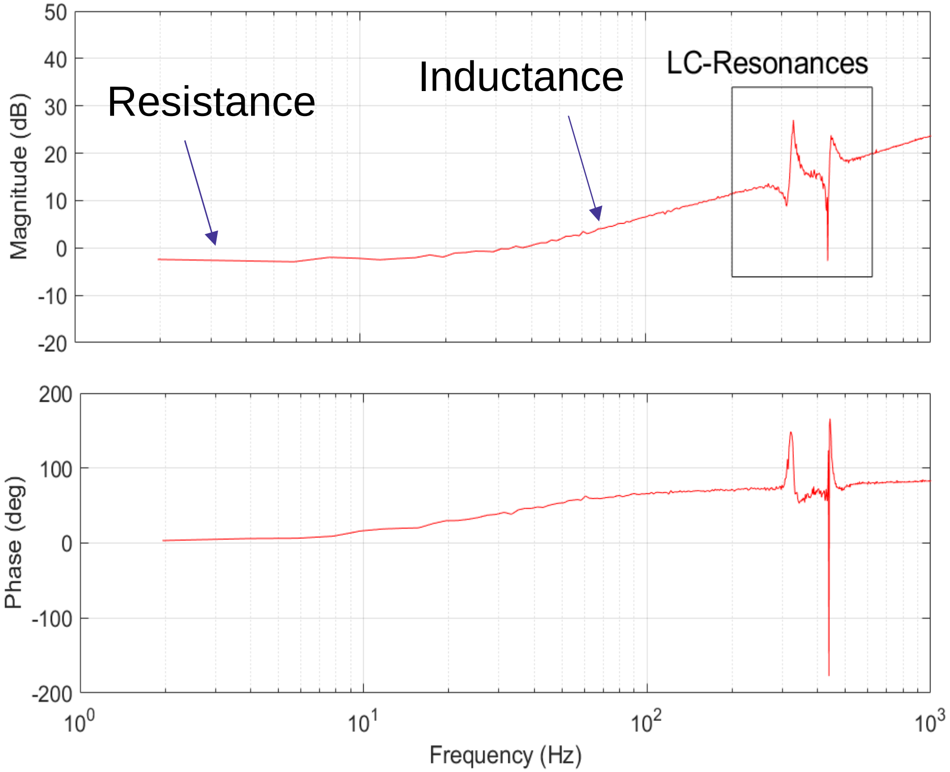
Sensitivity

- High values in sensitivity function forecast increased disturbances
  - Maximum value determines the most sensitive frequency
    →most likely there is disturbances in that frequency
- By knowing the most sensitive frequencies
  - The source of issues can be usually identified



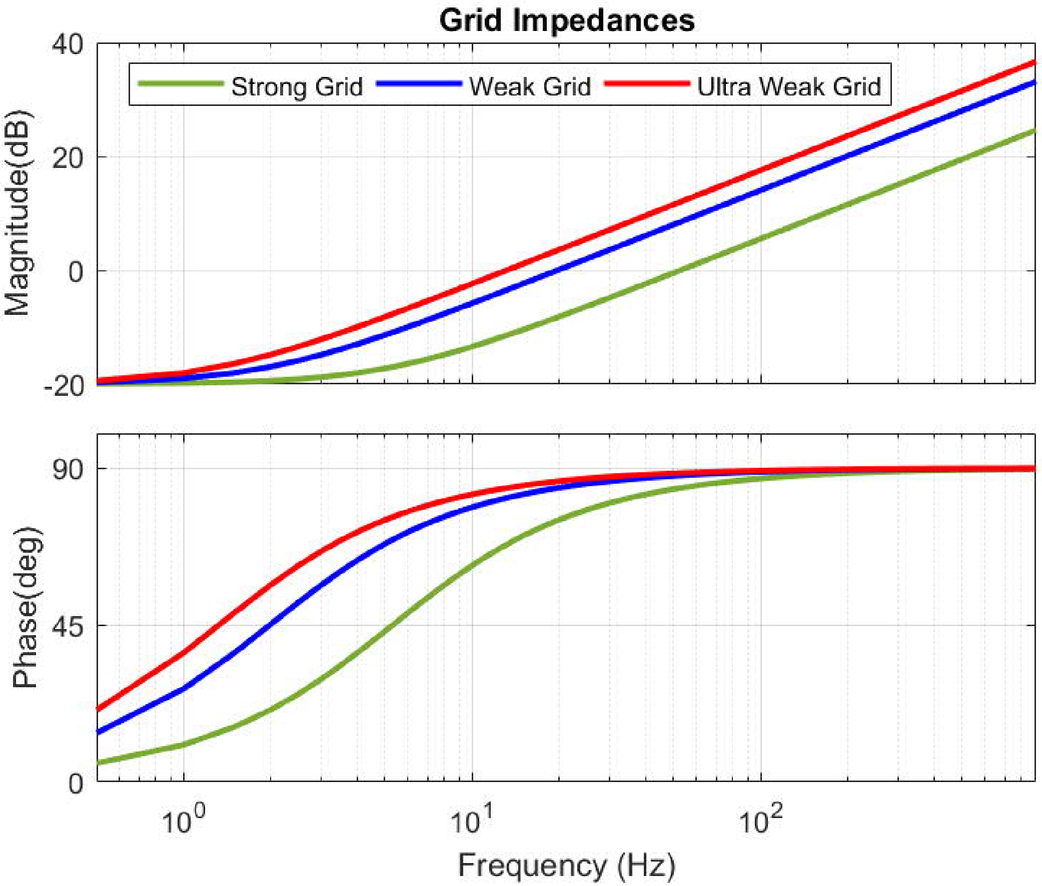
Grid Impedance Characteristics

- Resistance
  - Especially in low-voltage lines
- Inductance
  - Especially in medium(and high)-voltage lines
  - Transformers
  - Consumes reactive power
  - Phase response rises close to 90 degrees
- Capacitance
  - Reactive power compensation
  - Cablings
  - Introduces LC-resonances in otherwise inductive grids



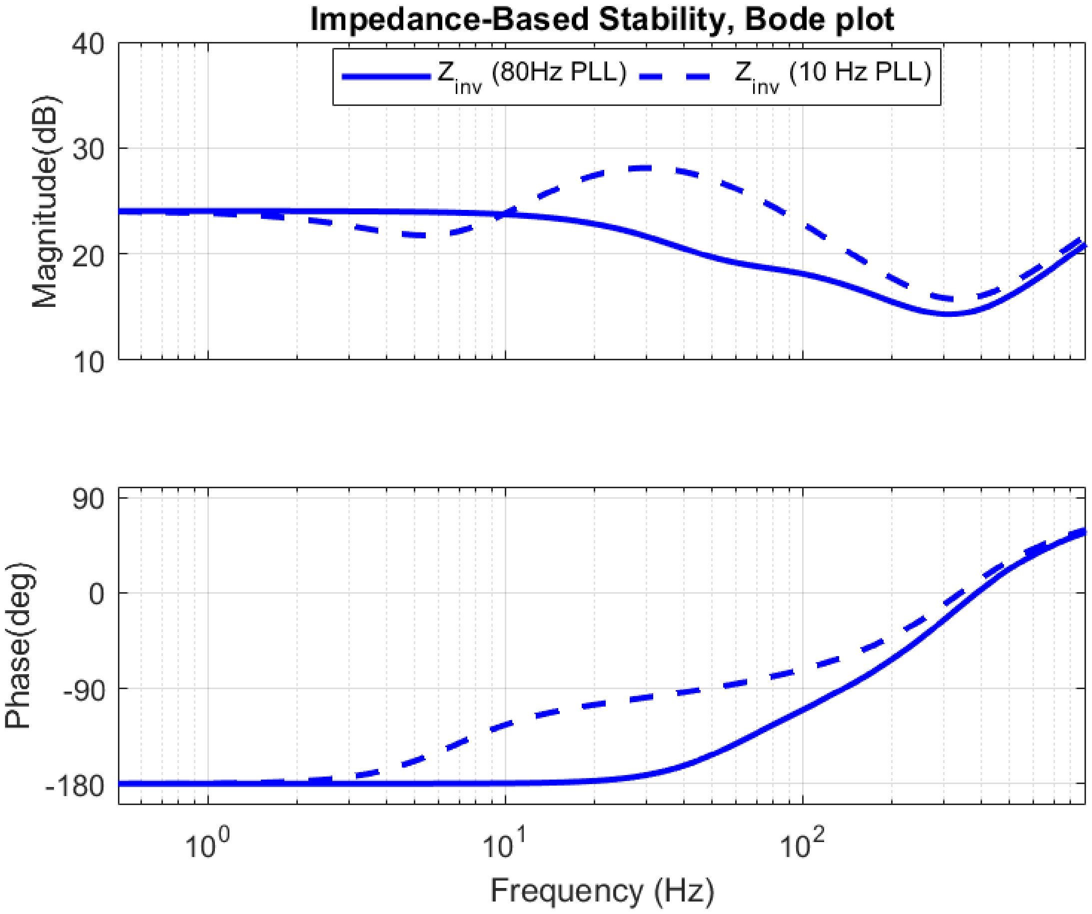
Weak Grid (very inductive grid)

- The grid goes weaker as its impedance increases
  - Here inductance increases
    - Usually the case in MV-lines
- Three different grids for test scenarios
  - **Strong, 3 mH (inductance)**
  - **Weak, 8 mH**
  - **Ultra weak, 12 mH**
- Weak grid ≈ high-impedance grid



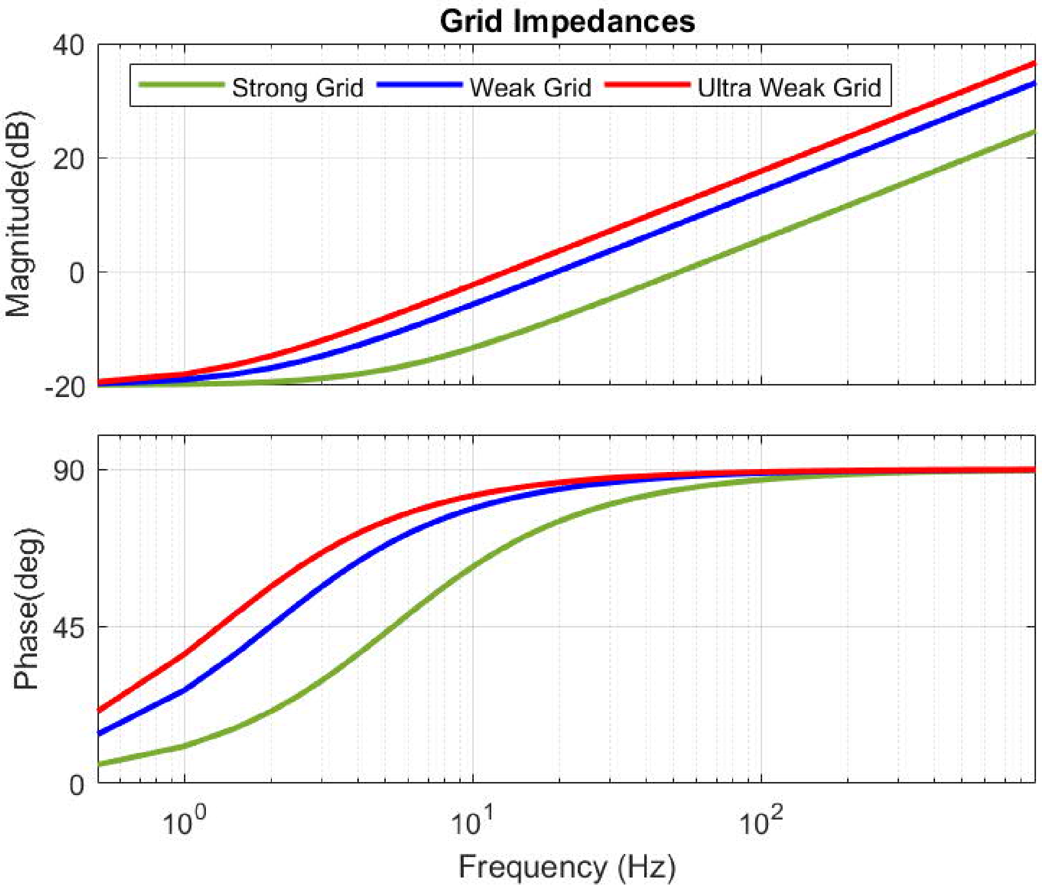
Inverter Impedance Characteristics

- Shape of the inverter output impedance depends on
  - **Used components**
  - **Used control system**
    - Control parameters, bandwidths…..
    - Additional control strategies such as grid-voltage feedforward
- Can be re-shaped by different control tuning
- Dynamic modeling requires linearized state-space modeling (differential equations) and modeling of closed-loop control system…



Simulations examples

- Simulation examples show how the grid impedance affect to system stability
  - Weak (high-impedance) is usually a problem
- Performance of single inverter in different grids are compared
  - How the performance can be improved by re-tuning the control system
  - → Different control tuning
  - → Re-shaped inverter impedance

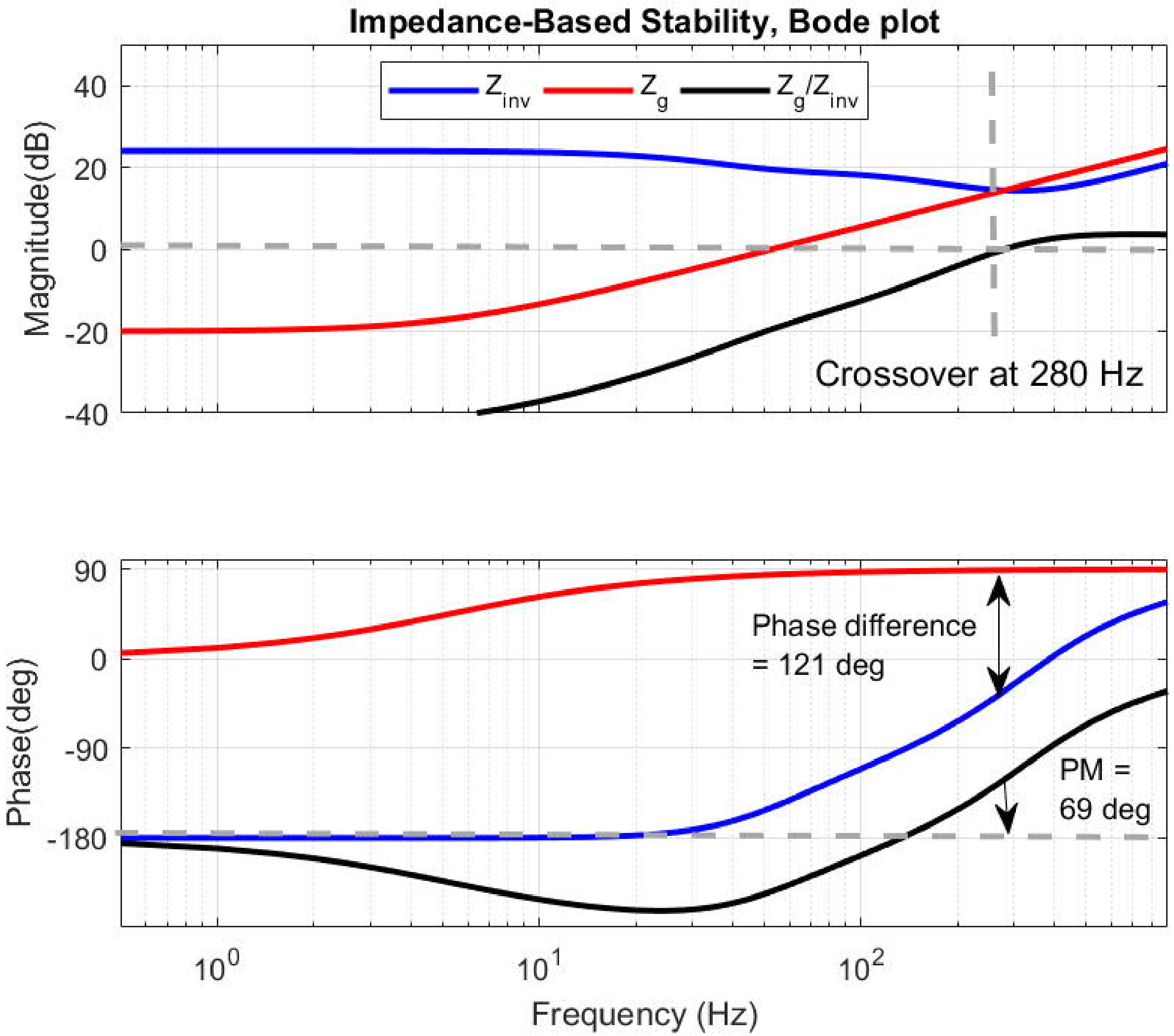


Strong Grid

- Stability issues doesn’t usually appear when grid is relatively strong
- Sufficient stability margins

→ Good control performance

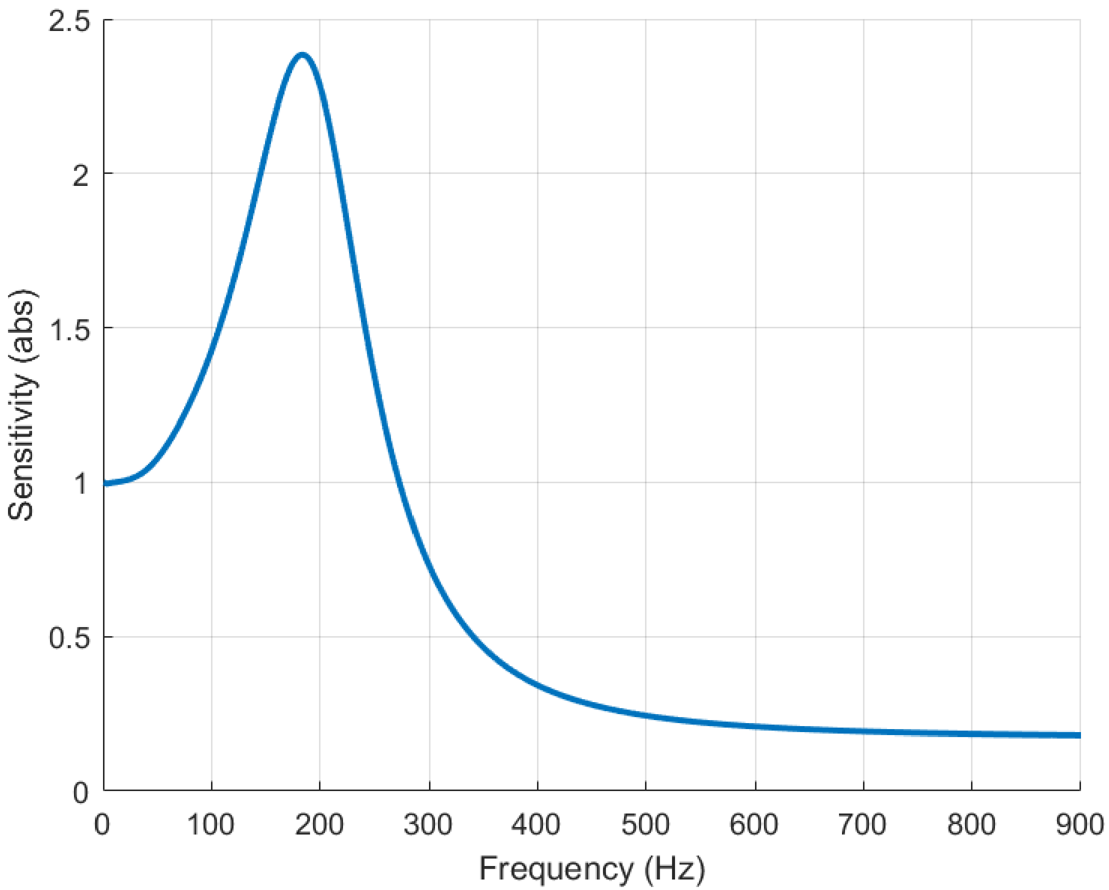
→ Good power quality



Strong Grid

- Sensitivity function have low values

  → Low amount of distortions are expected



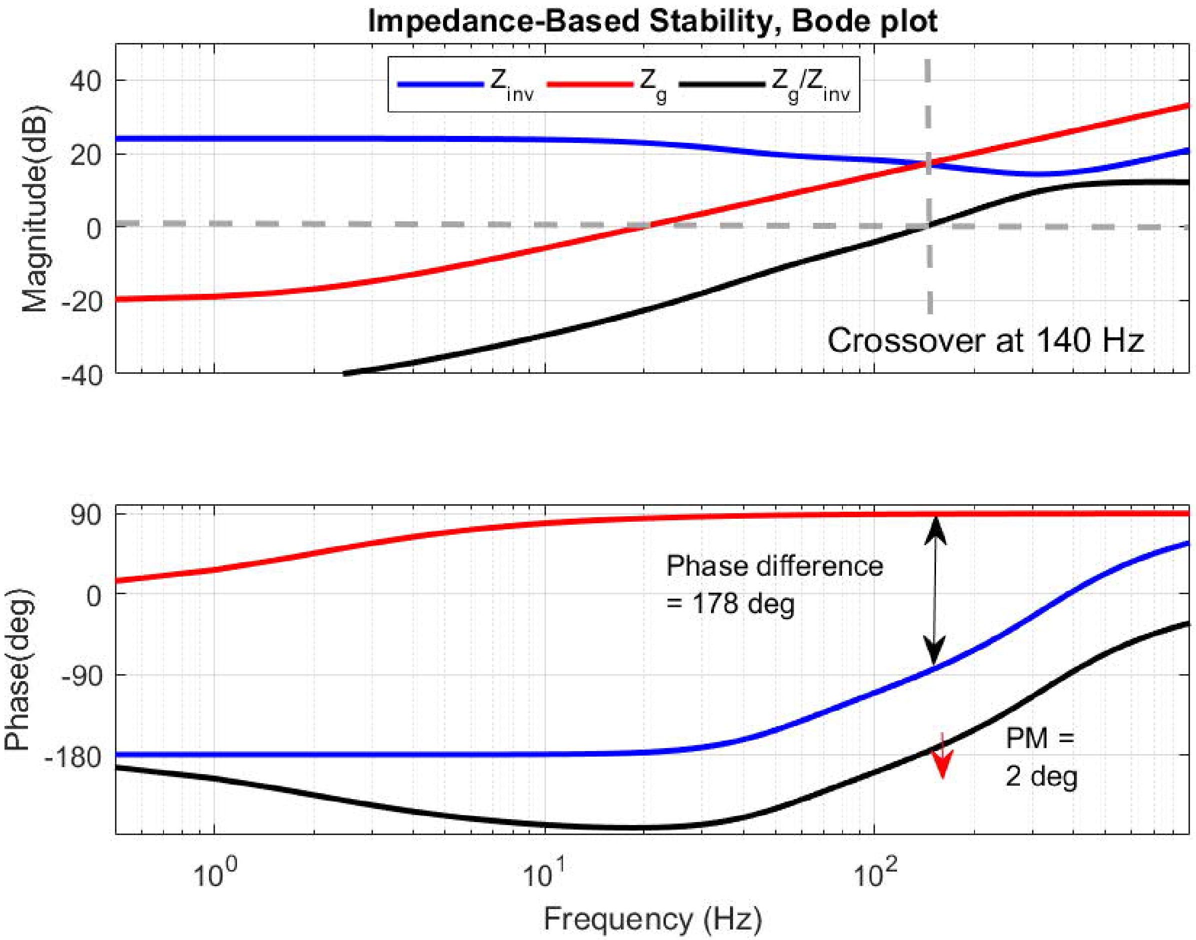
Weak Grid

- Stability issues may occur in weak grids
- Poor stability margins

→ Not so optimal control performance

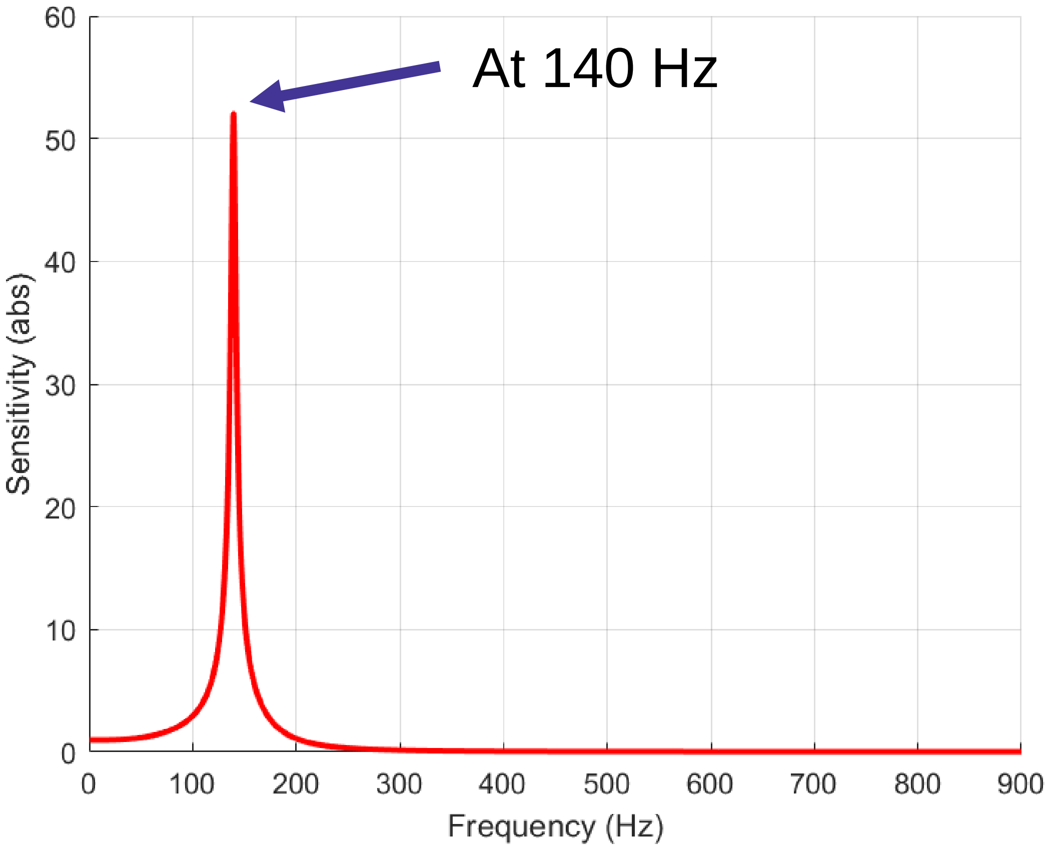
→ Bad power quality and even instability

- Phase margin of 2 degrees is **very low**!
    - Small change in system may cause unstable operation

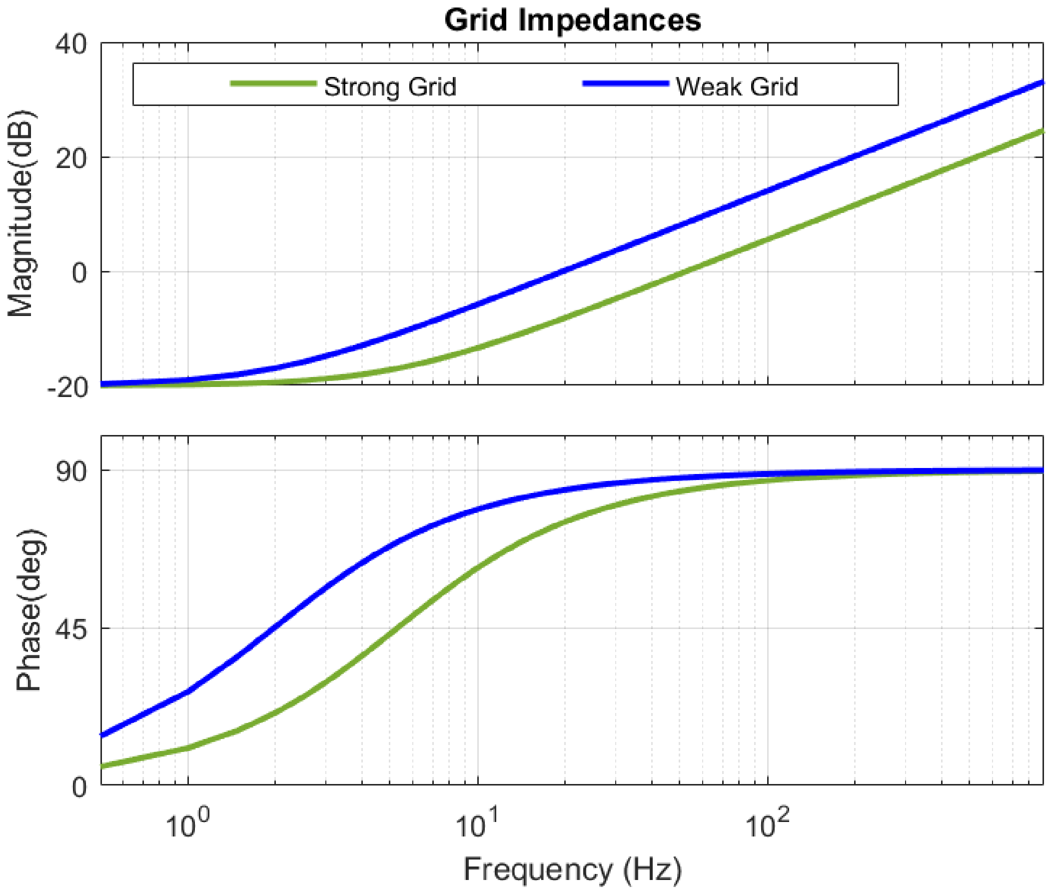


Weak Grid

- Very high maximum value of sensitivity function
    - Located at 140 Hz
    - High value of distortions are expected at 140 Hz

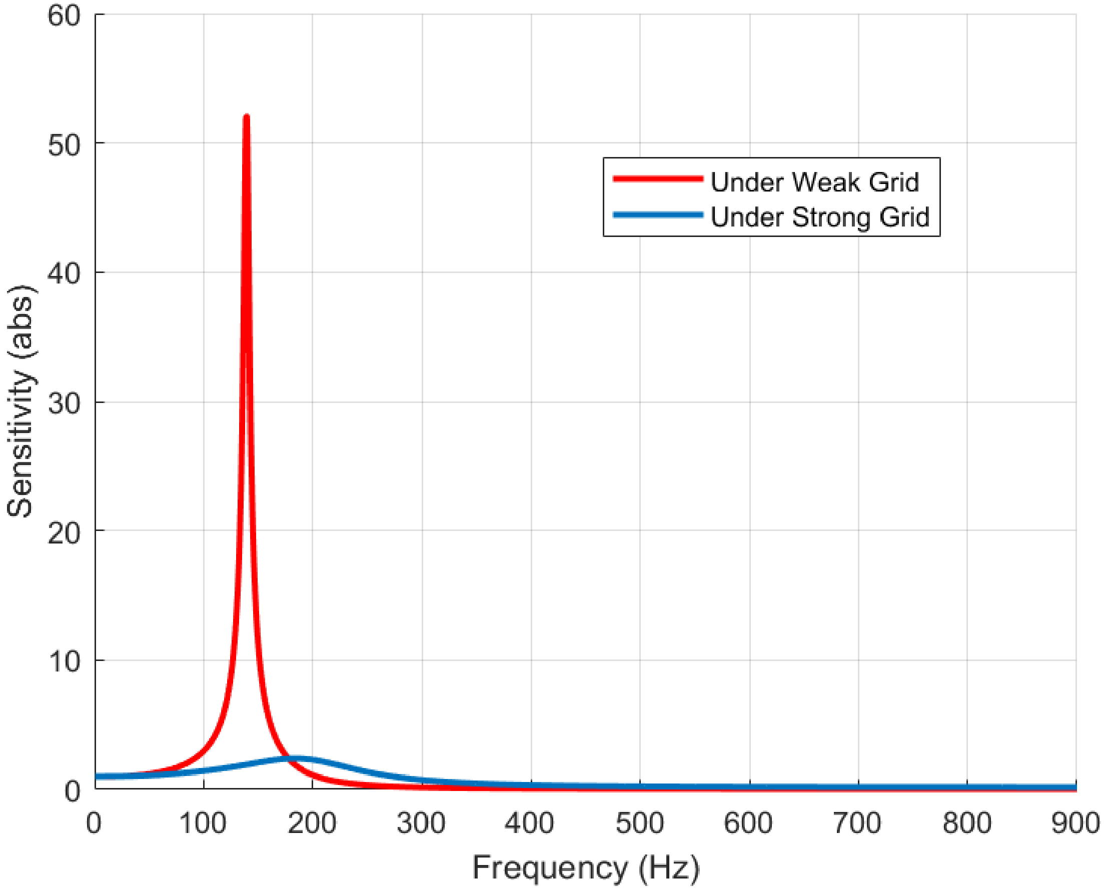


Strong and Weak Grids



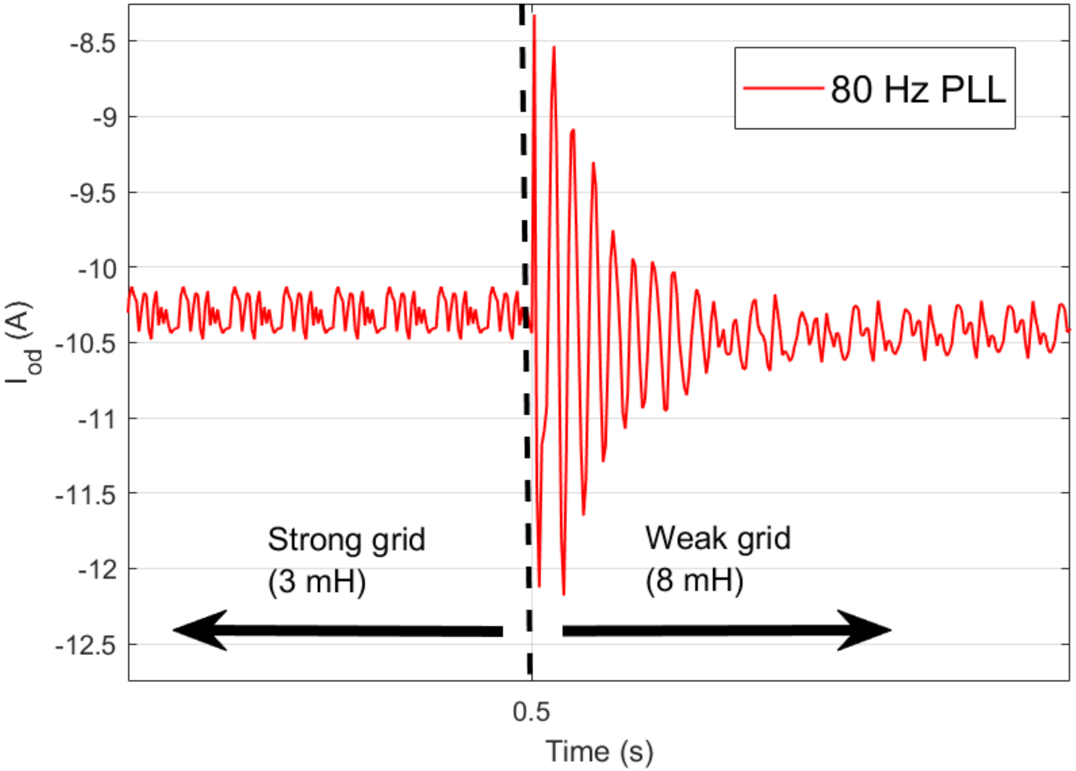
Strong and Weak Grids

- Sensitivity function under strong and weak grids are drawn in same figure
  - Huge difference!



Transient from strong to weak grid

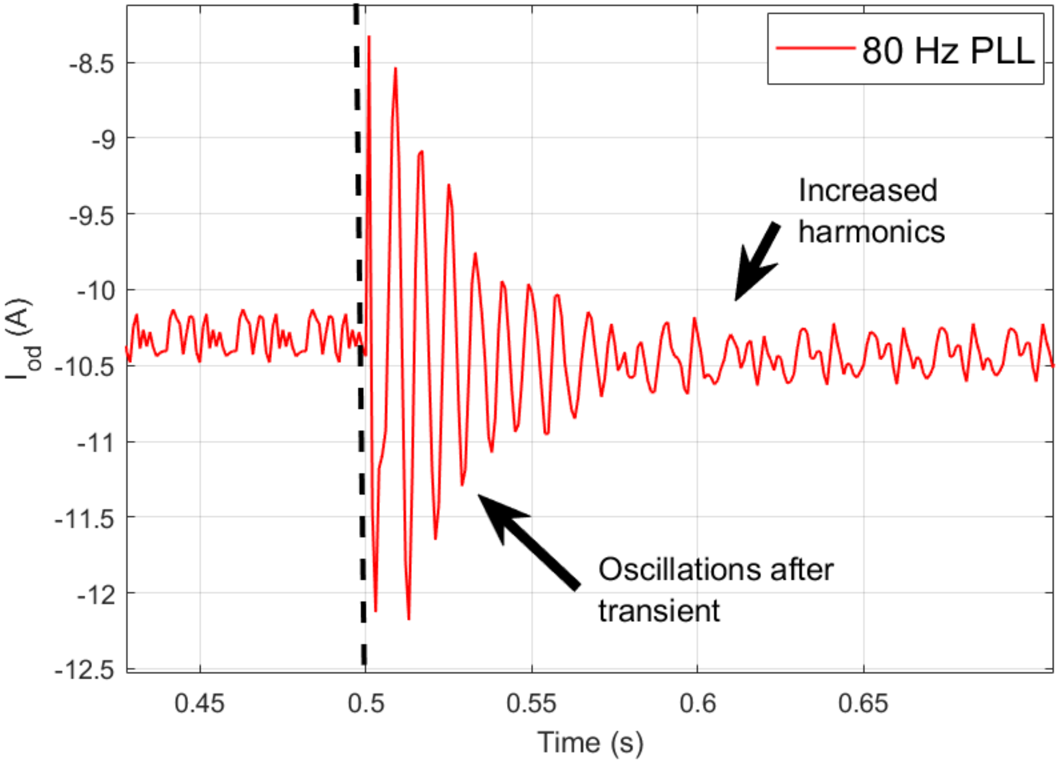
- Now the grid suddenly changes from strong grid to weak
- Stability margins are significantly decreased
- Great amount of oscillations occurs, as expected
    - System is still stable as the oscillation are mitigated



Transient from Strong to Weak Grid

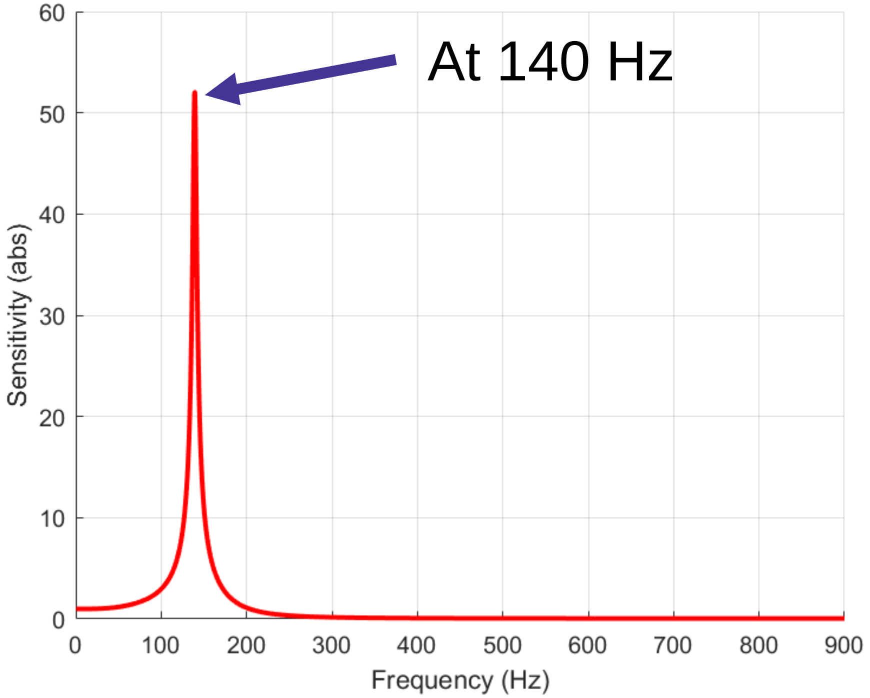
- Damped oscillation occurs after transient

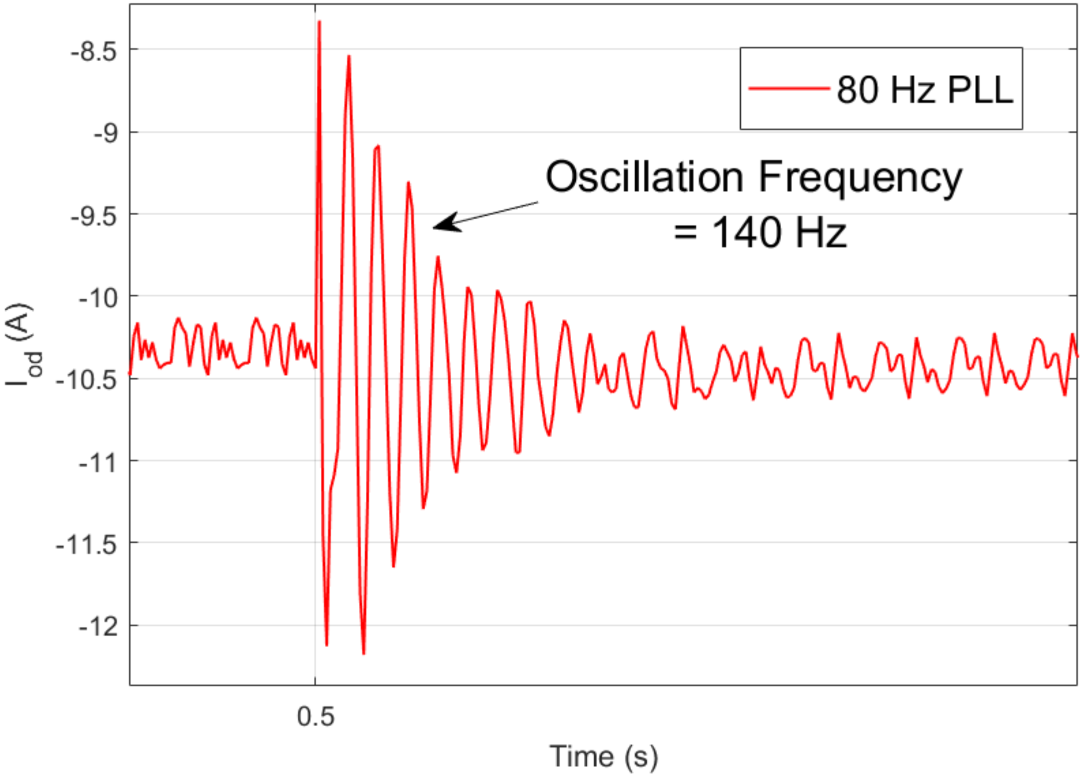
- The system harmonics (disturbances) are increased in weak grid



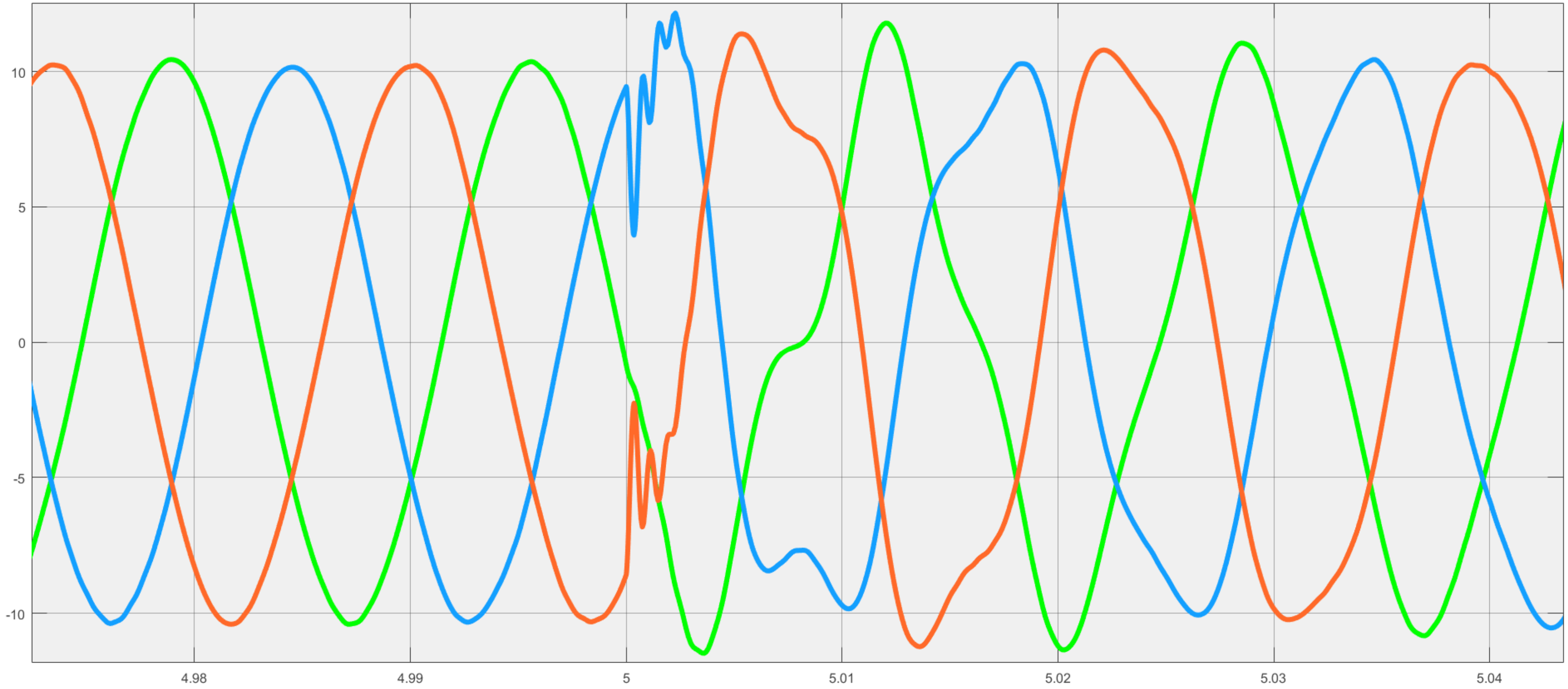
Transient from strong to weak grid

System sensitivity function
during weak grid





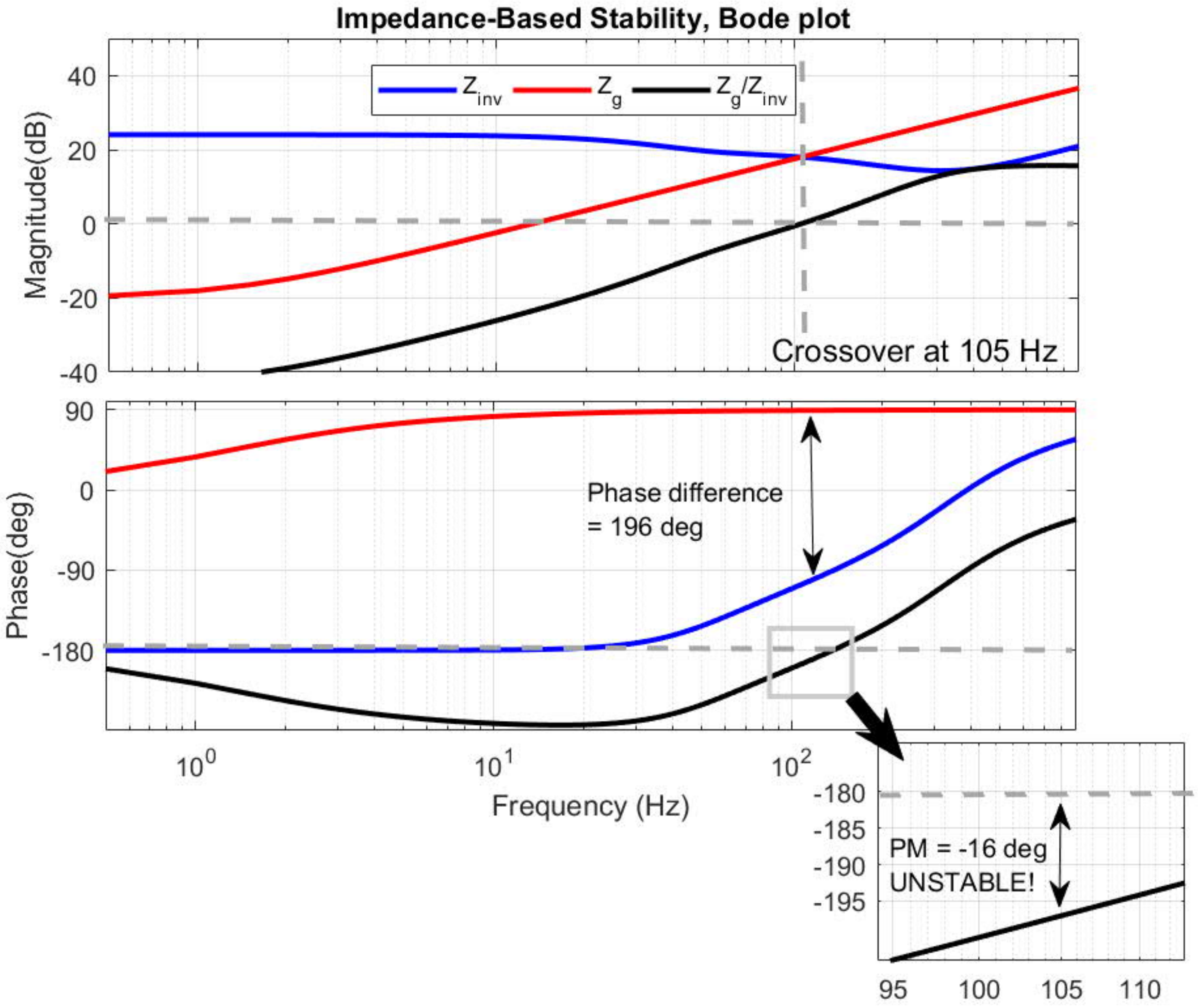
Transient from strong to weak grid



Oscillations after transien

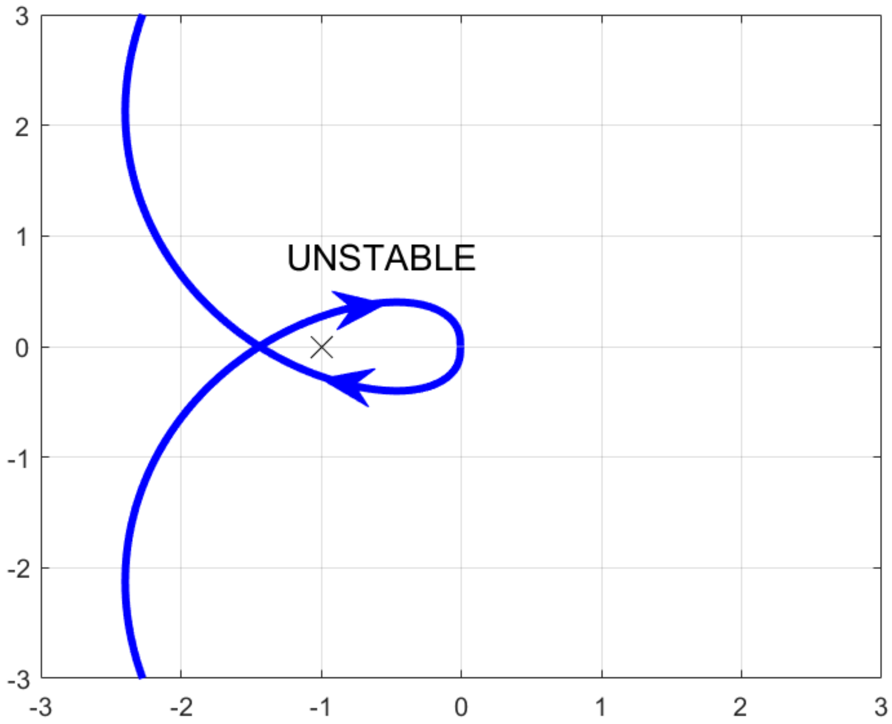
Ultra Weak Grid

- Now the grid have very high impedance
- Crossover frequency = 105 Hz
- Negative (-16 degrees) phase margin forecasts unstable operation
  → System phase lag over 180 degrees
  → Oscillations with increasing amplitude



Ultra Weak Grid

- Instability is easy to see from Nyquist plot
    - **Loci encircles the critical point clockwise**



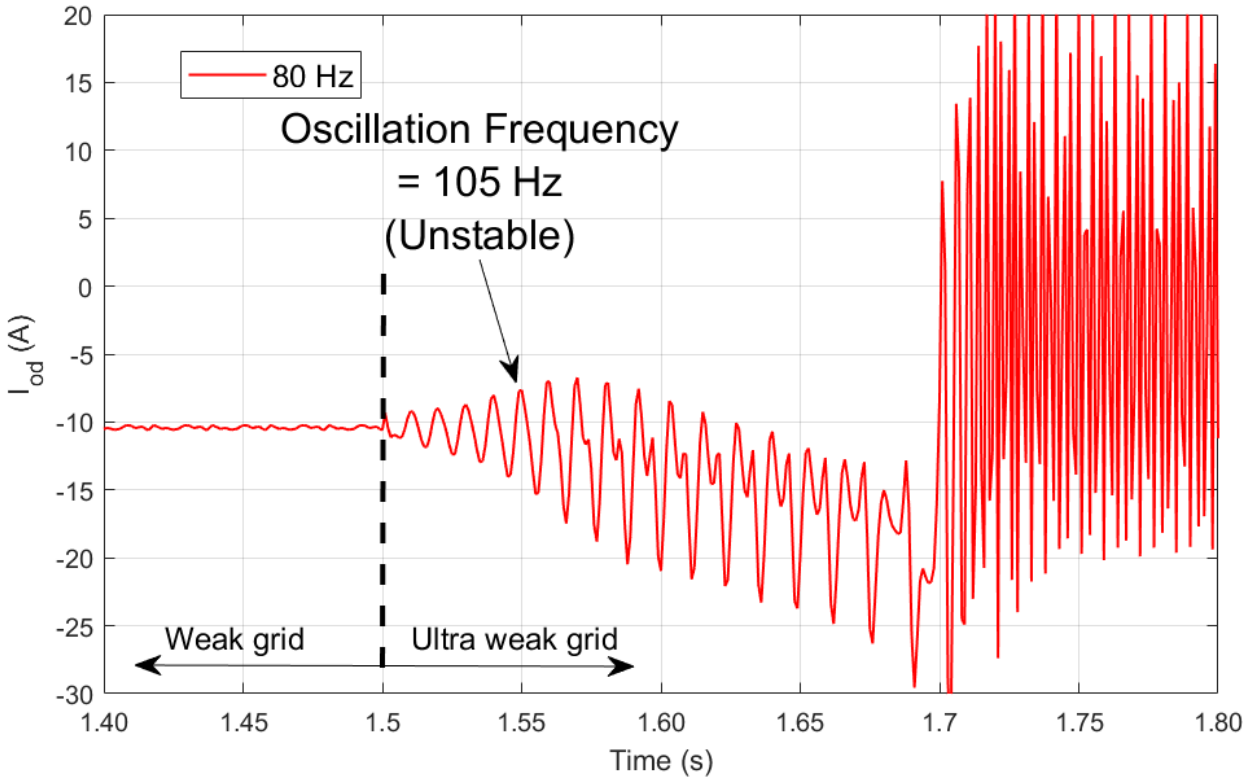
Transient to Ultra Weak Grid

- After grid transient, the instability occurs
  - The oscillation at 105 Hz magnifies over time
- This kind of operation may break the device
  - Need for protection system

→ over-current and over-voltage protection

→ The inverter is disconnected from the grid as the protection system reacts

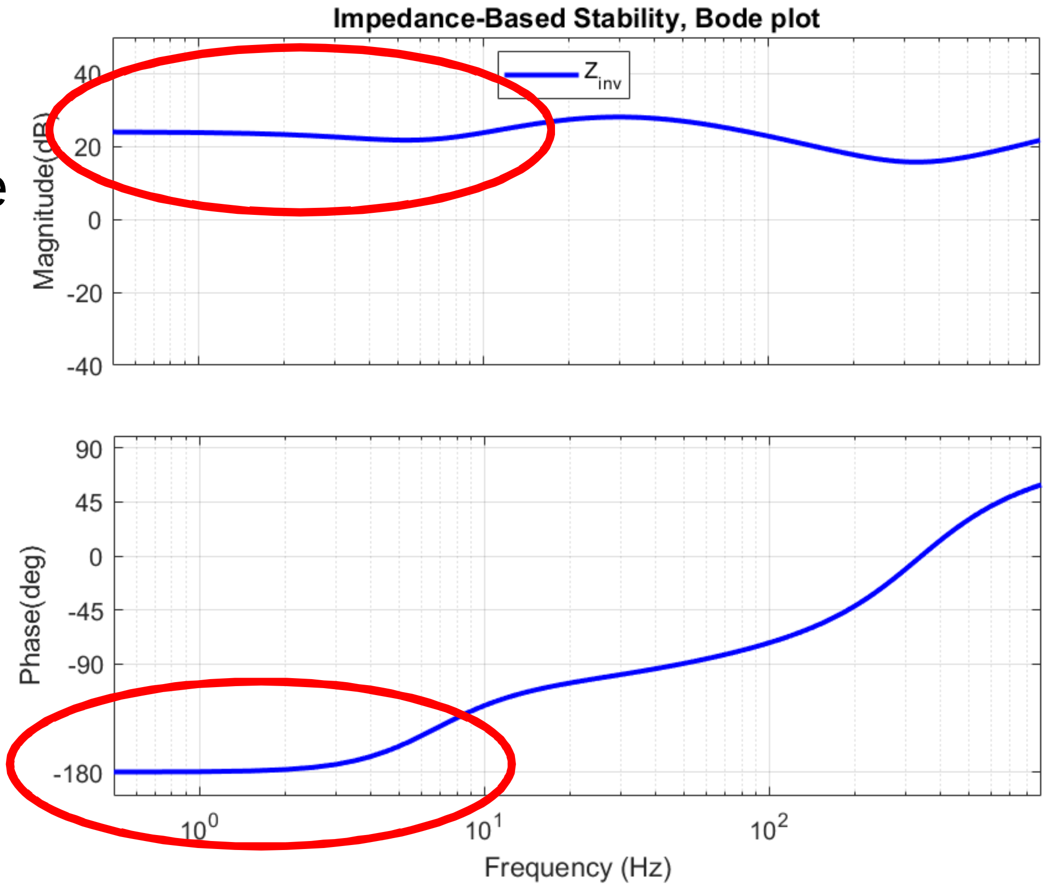
→ The inverter is protected



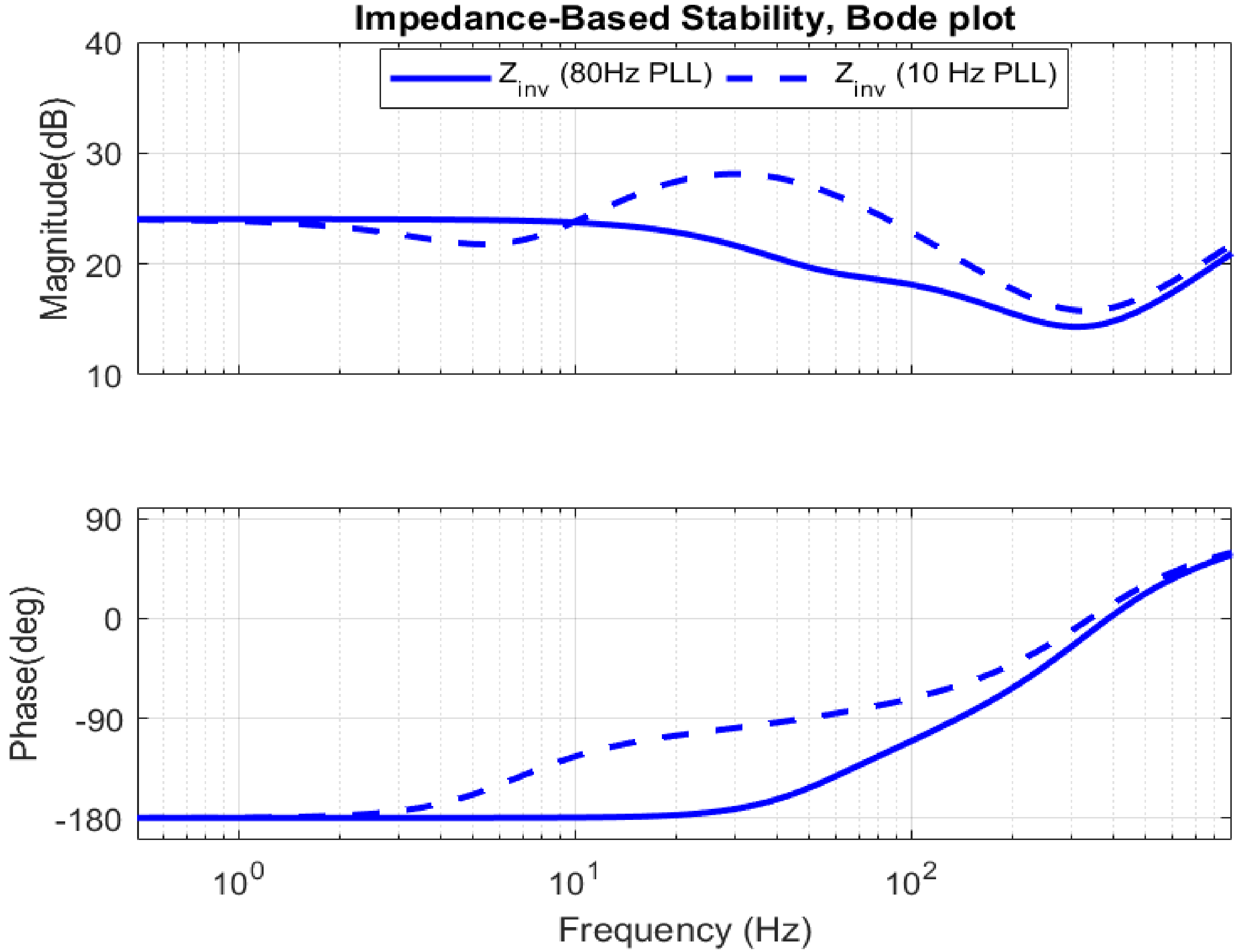
Reason for Instability

The grid-syncronization method in control system (PLL) introduce ”negative-resistance like behaviour” to inverter output impedane

- Appears below control bandwidth of PLL
  - Phase -180 degrees with constant magnitude
- When phase of the inverter impedance is below -90 degrees, there is possibility for instability



Inverter Impedance with Different PLL Control Bandwidths



Reason for Instability

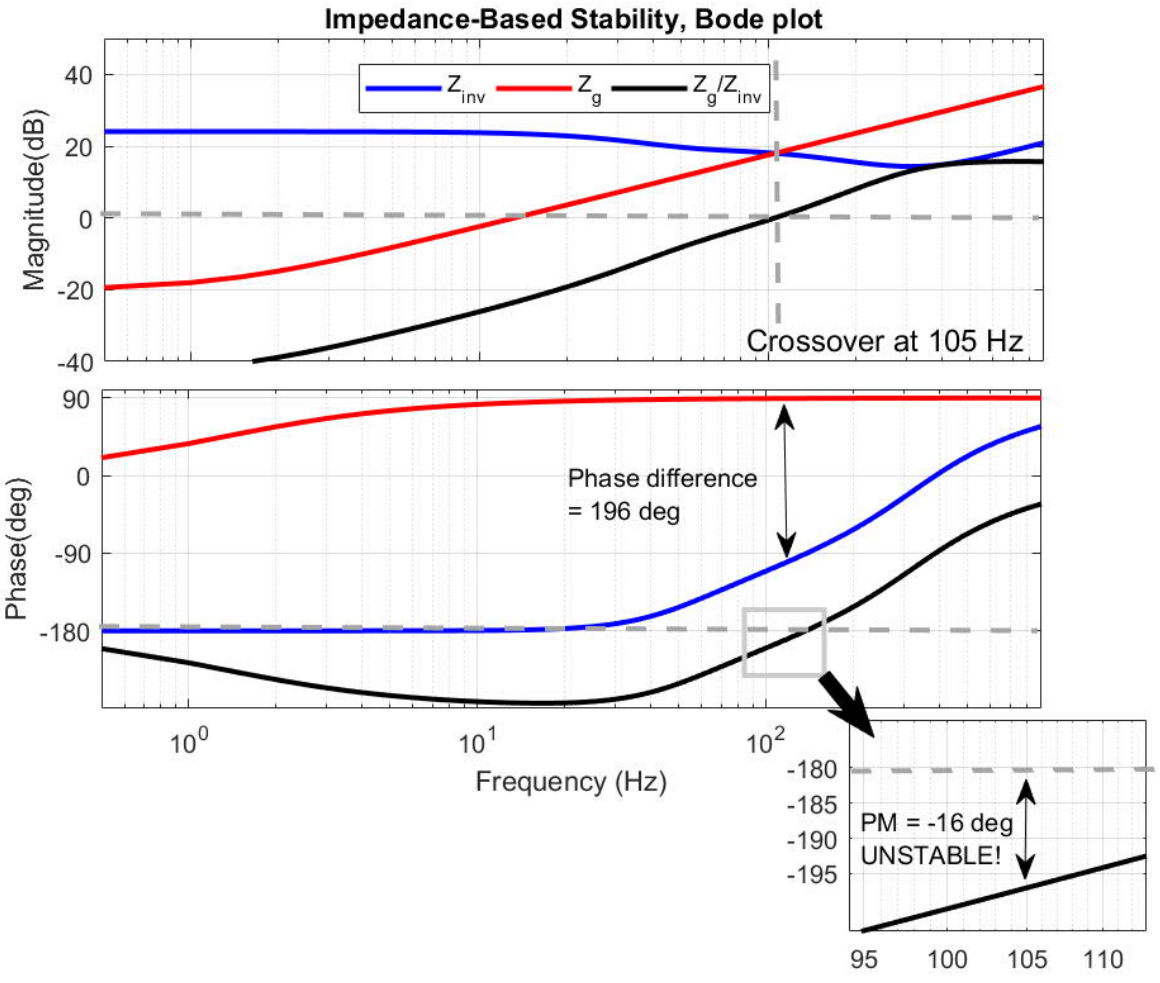
Impedance of the weak grid has phase close to 90 degrees

→ Possibility to over 180 degree phase difference → Negative phase margin

- Inverter phase below -90 degree
- Grid phase is 90 degrees

→ Phase difference over 180

→ Problem if crossover of the system is located in that frequency range

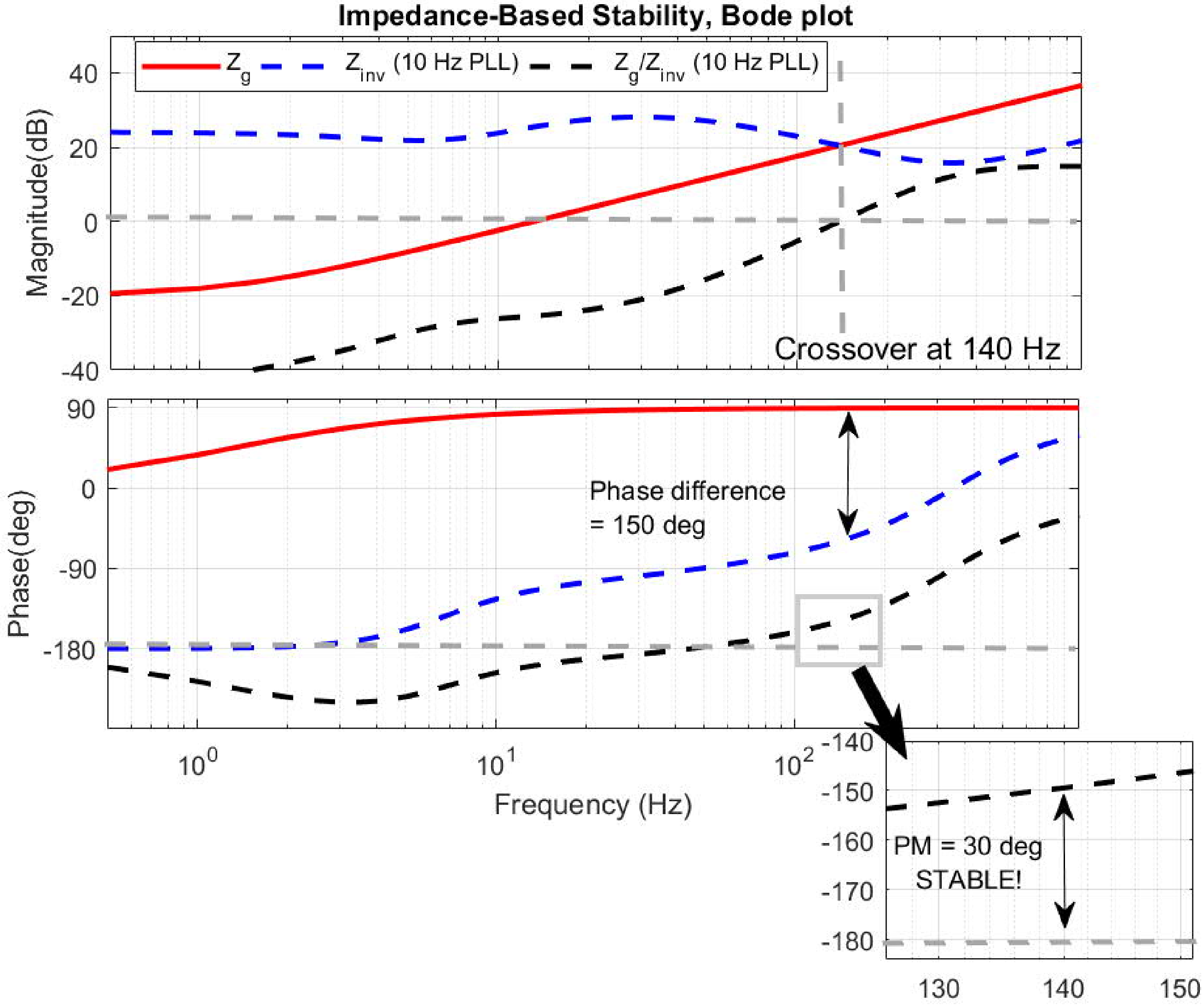


There are many more possible reasons, this is just one example

Solution

- The PLL control bandwidth can be limited

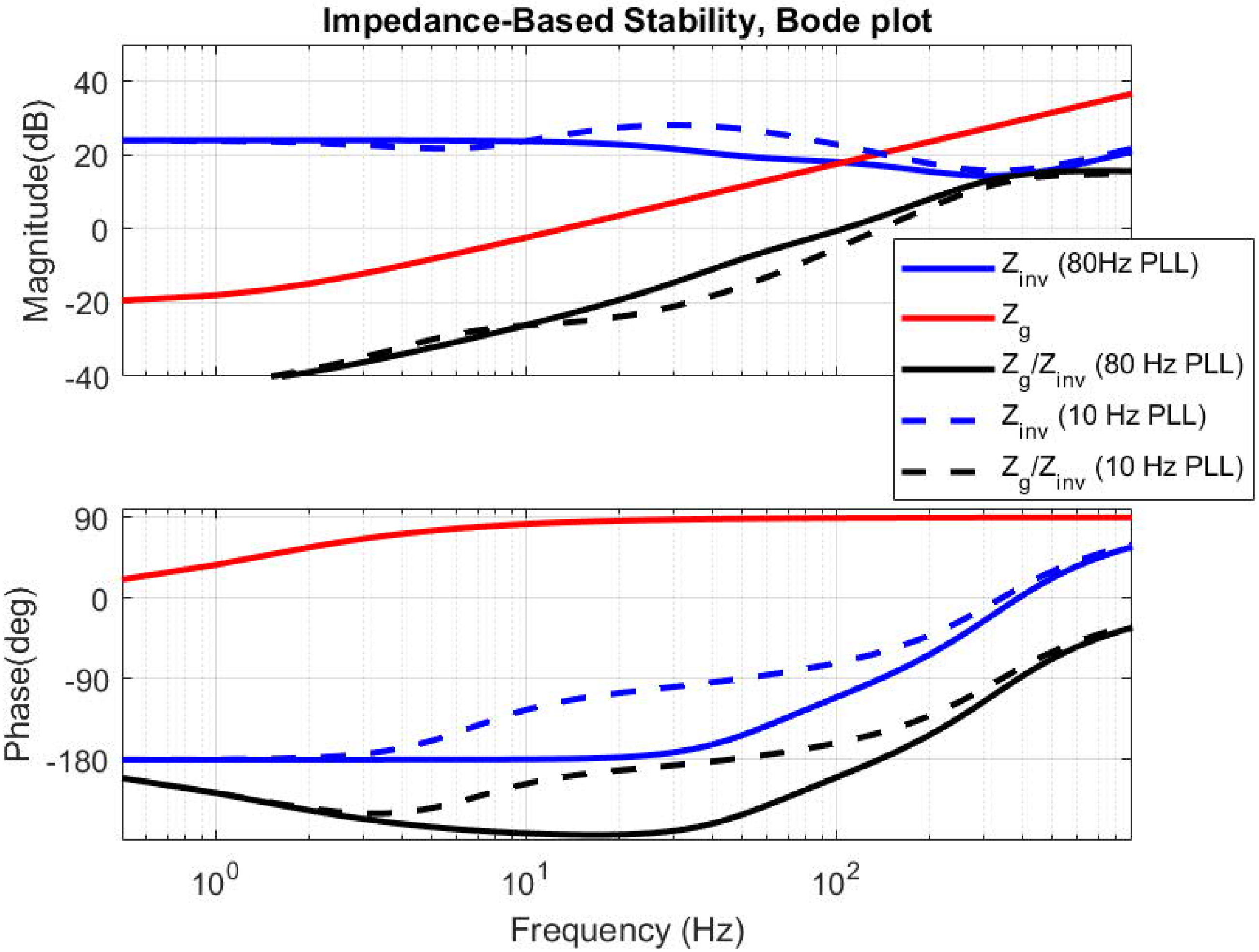
→ Re-shapes inverter impedance
→ System becomes stable with 30 degree phase margin in similar grid (where 80 Hz PLL was unstable)
→ Crossover frequency moves from 105 Hz (80 Hz PLL) to 140 Hz (10Hz PLL)



Comparison

- Limiting the PLL bandwidth from 80 Hz (solid blue) to 10 Hz (dashed blue)
    - Gain and phase boost at low frequencies
    - ”Non-passive” (phase below -90 degrees) frequency range is limited to lower frequencies
        - Inside non-passive range the stability issues may occur

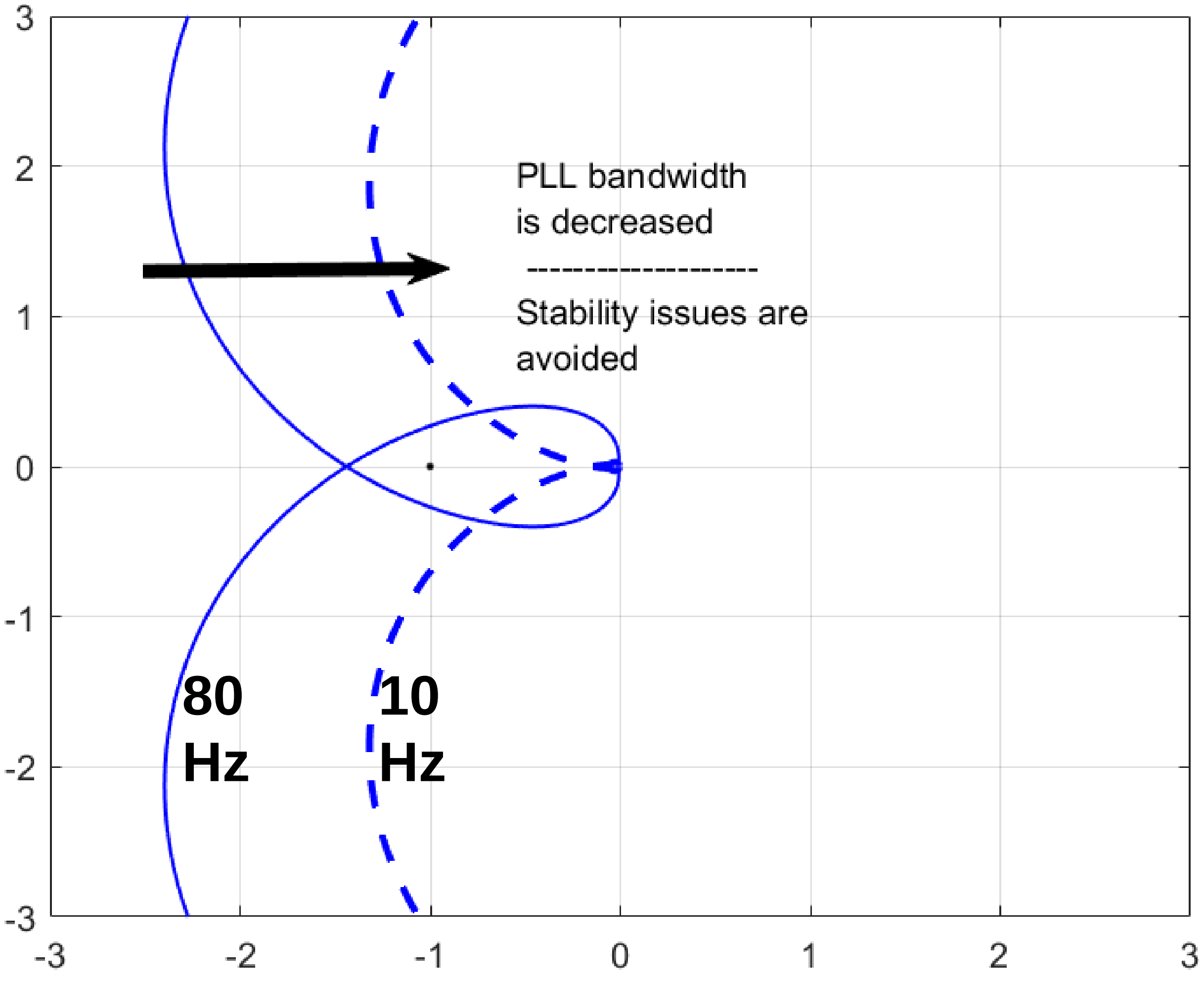
However, limiting the control bandwidths are not always the best solution!



Limiting the PLL Bandwidth

Similar conclusion can be made from Nyquist plot

- Inverter with **80 Hz PLL is unstable** in this test grid
- Inverter with **10 Hz PLL is stable** in similar grid

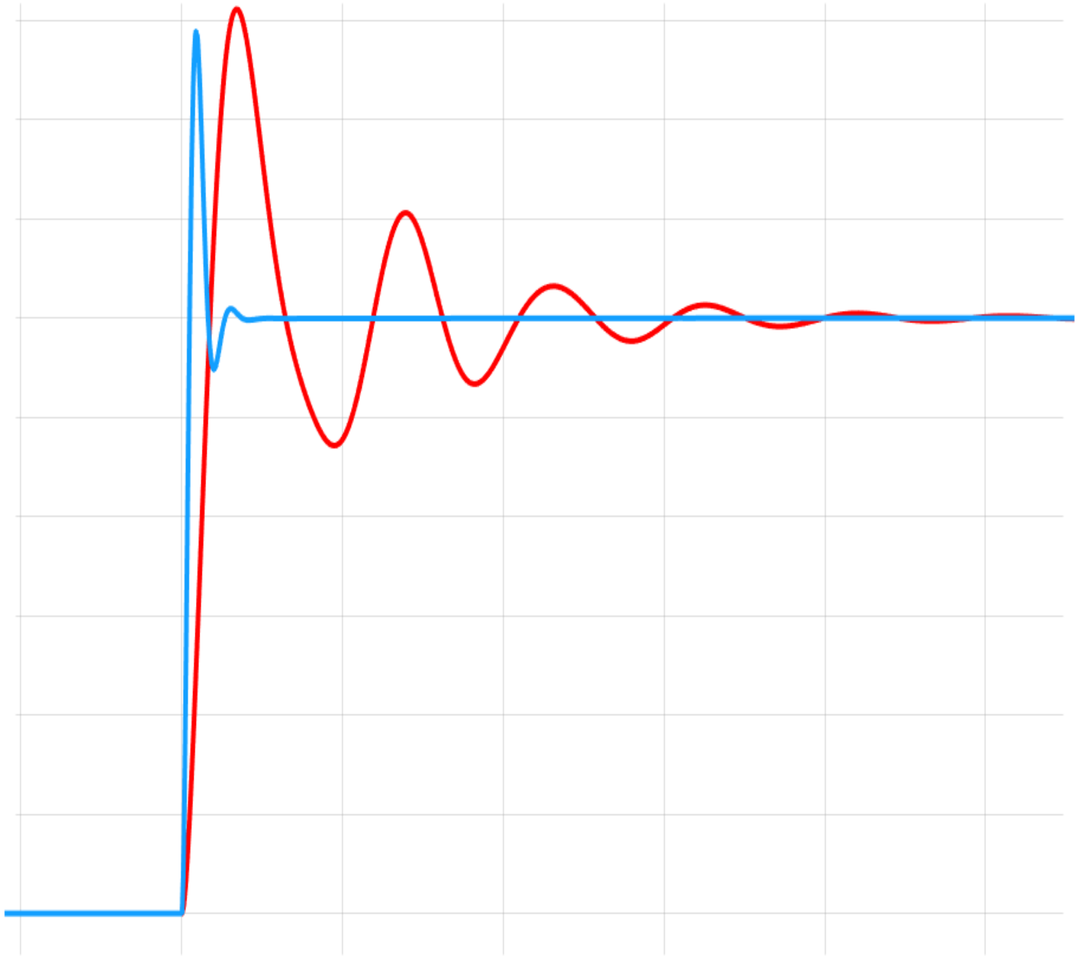


Tampereen yliopisto
Tampere University

Problem with Limited Bandwidth

- Decreased control performance
  - More oscillation
  - Increased settling time
  - May affect to other controllers

- PLL syncronizes inverter to grid
  - Slow PLL produces unintented flow of reactive power during grid transients



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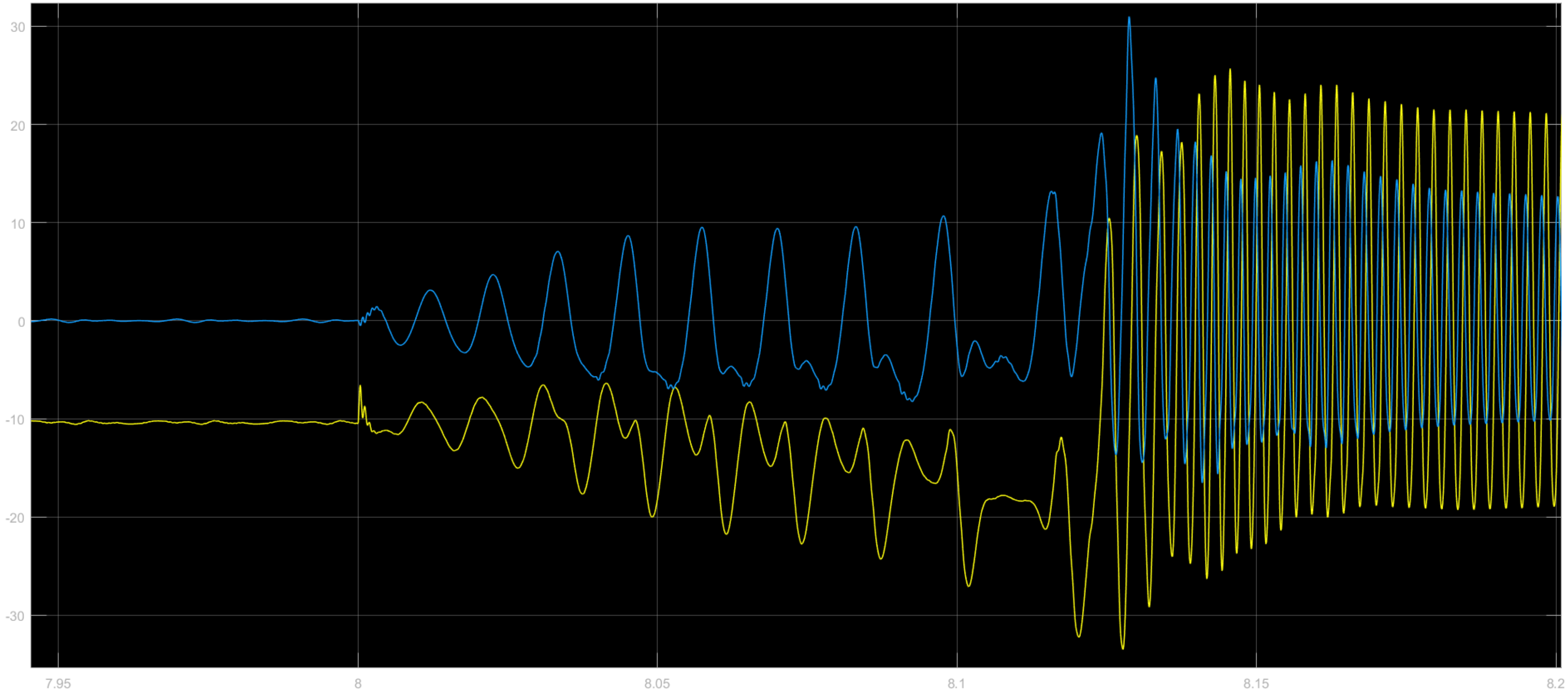
Simulations with MATLAB/Simulink

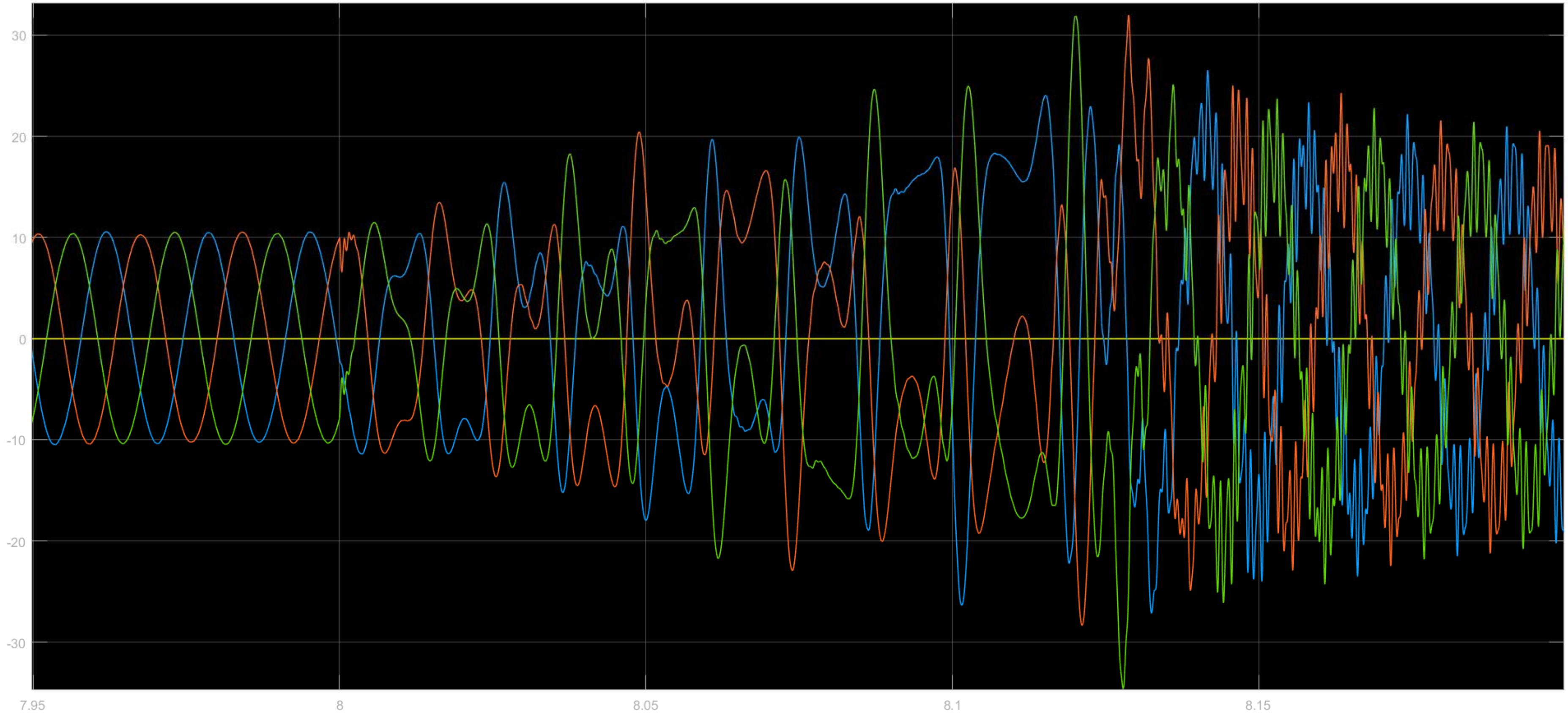
Simulation Results (80 Hz PLL)

- Transient from weak to ultra weak grid (DQ-domain currents)
- Instability occurs



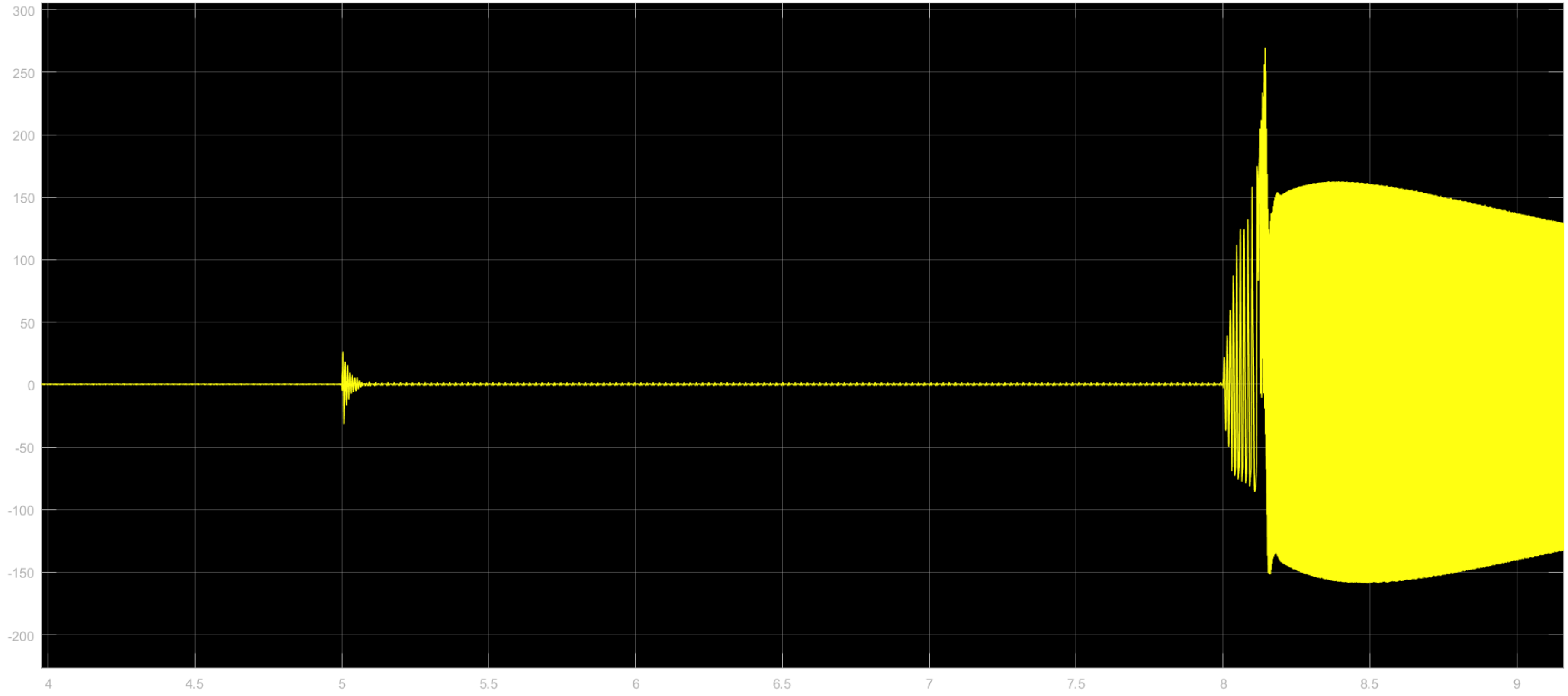
Simulation Results (80 Hz PLL)

- Transient from weak to ultra weak grid (time-domain currents)
- Instability occurs



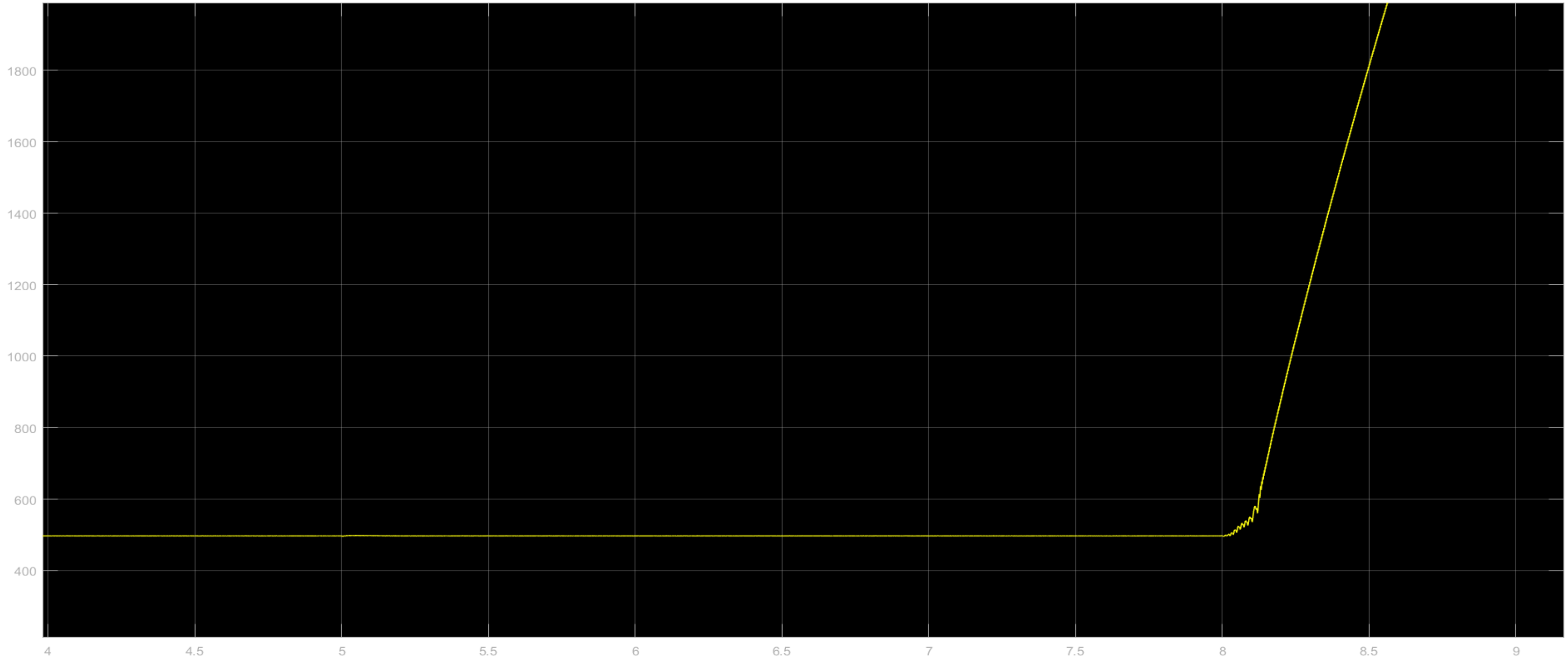
Simulation Results (80 Hz PLL)

- Transient from strong to weak and then to ultra weak grid (Observed voltage q-component)
- Instability occurs in transient to ultra weak grid



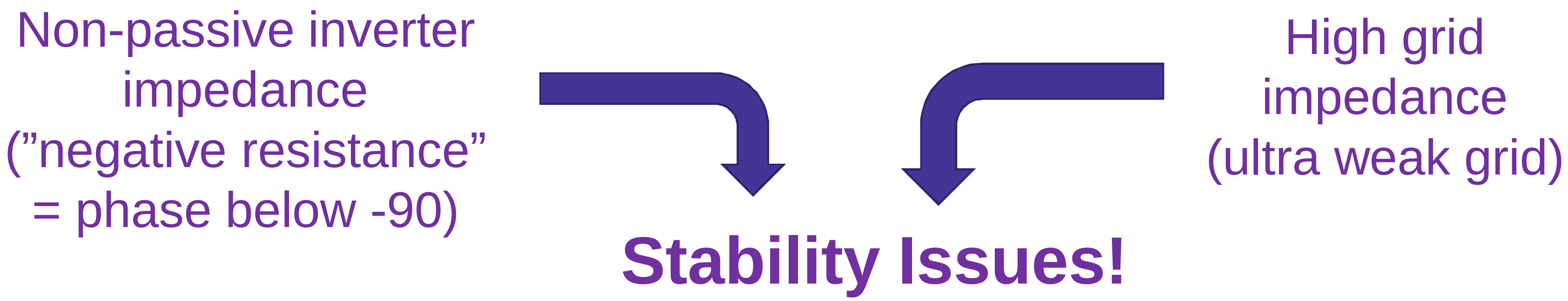
Simulation Results (80 Hz PLL)

- Transient from strong to weak and then to ultra weak grid (DC voltage)
- Instability occurs in transient to ultra weak grid
- This kind of performance will break also the PV panels



High PLL Bandwidth and Ultran Weak grid

- The impedance-based stability issues occurs
- The system is totally unstable
- Unstable operation may break the devices
- Should be connected off from the grid
    - By protection system



Non-passive inverter impedance (”negative resistance” = phase below -90)

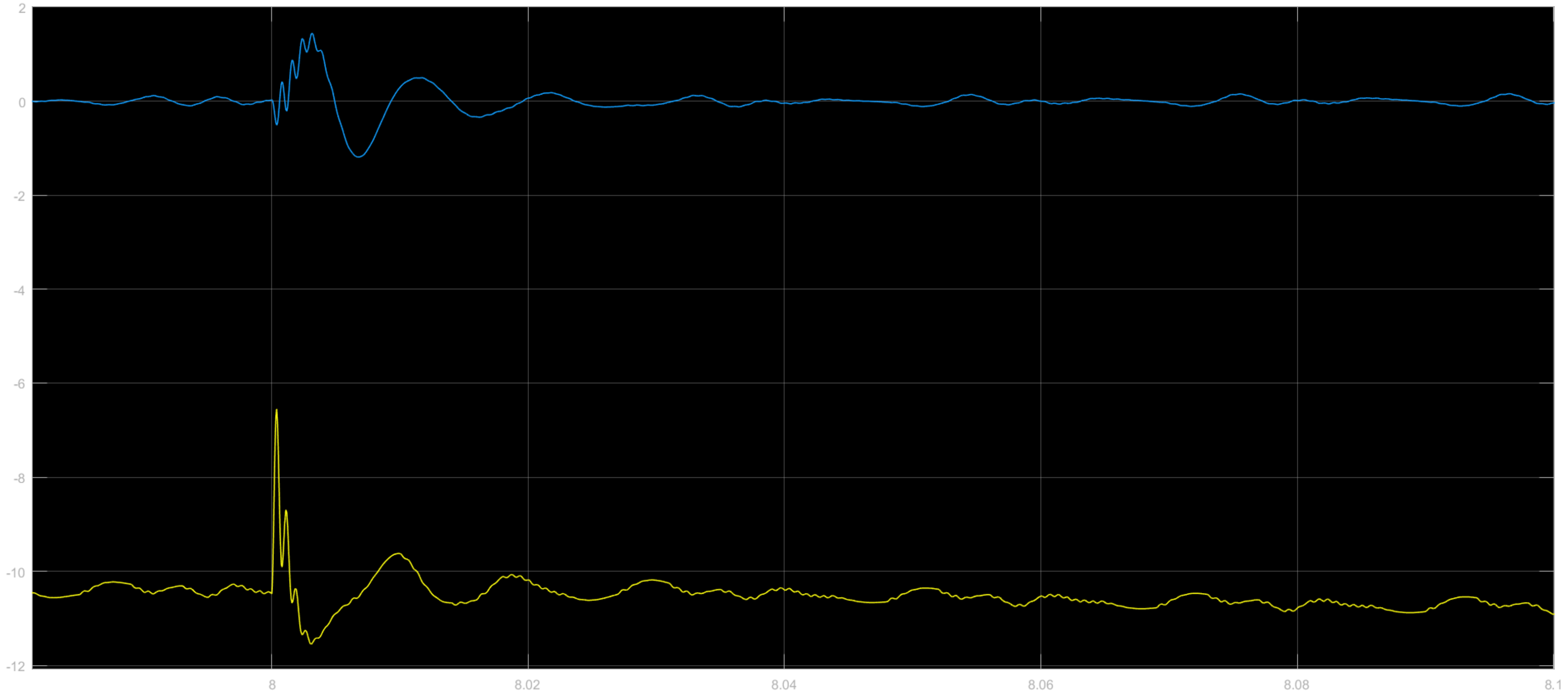
High grid impedance (ultra weak grid)

Stability Issues!

Similar simulations with 10 Hz PLL (Limited PLL bandwidth)

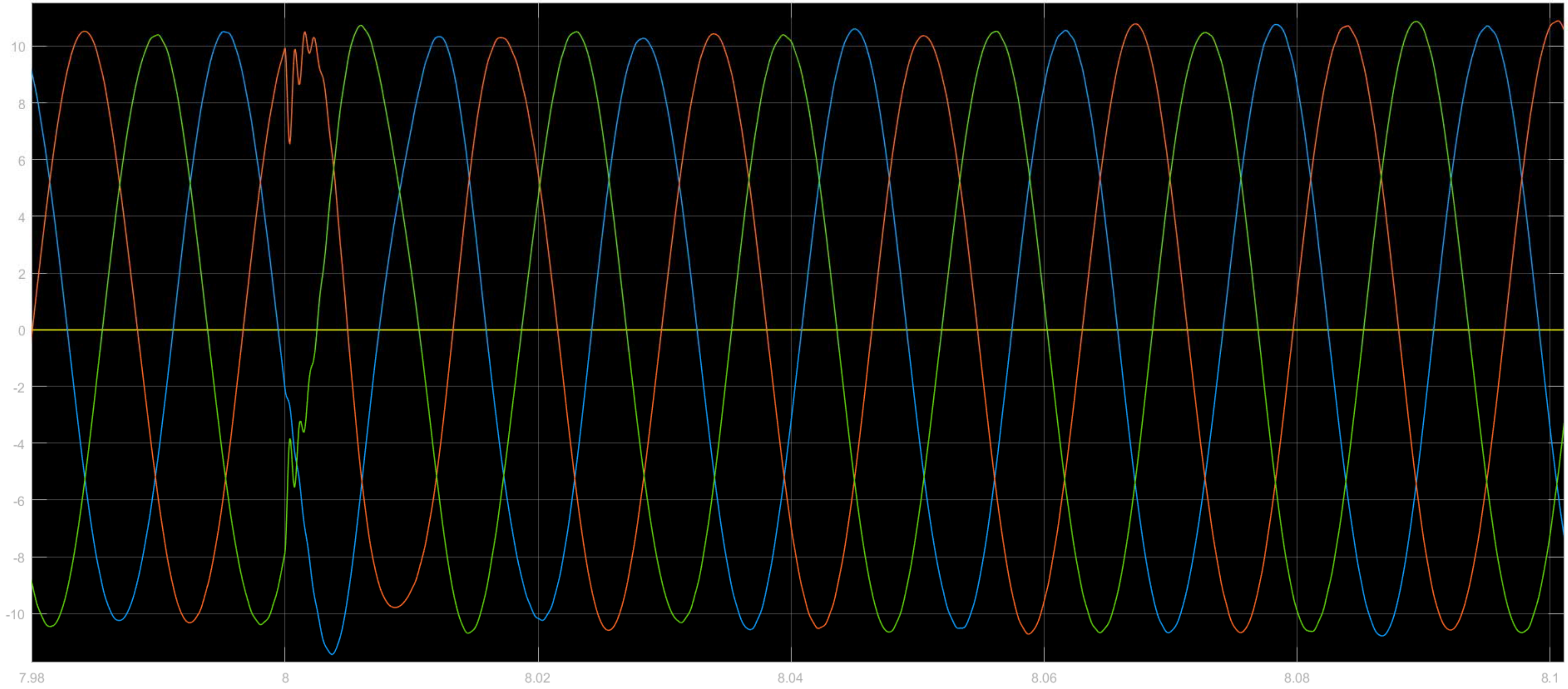
Simulation Results (10 Hz PLL)

- Transient from weak to ultra weak grid (time-domain currents)
- Stable, good performance



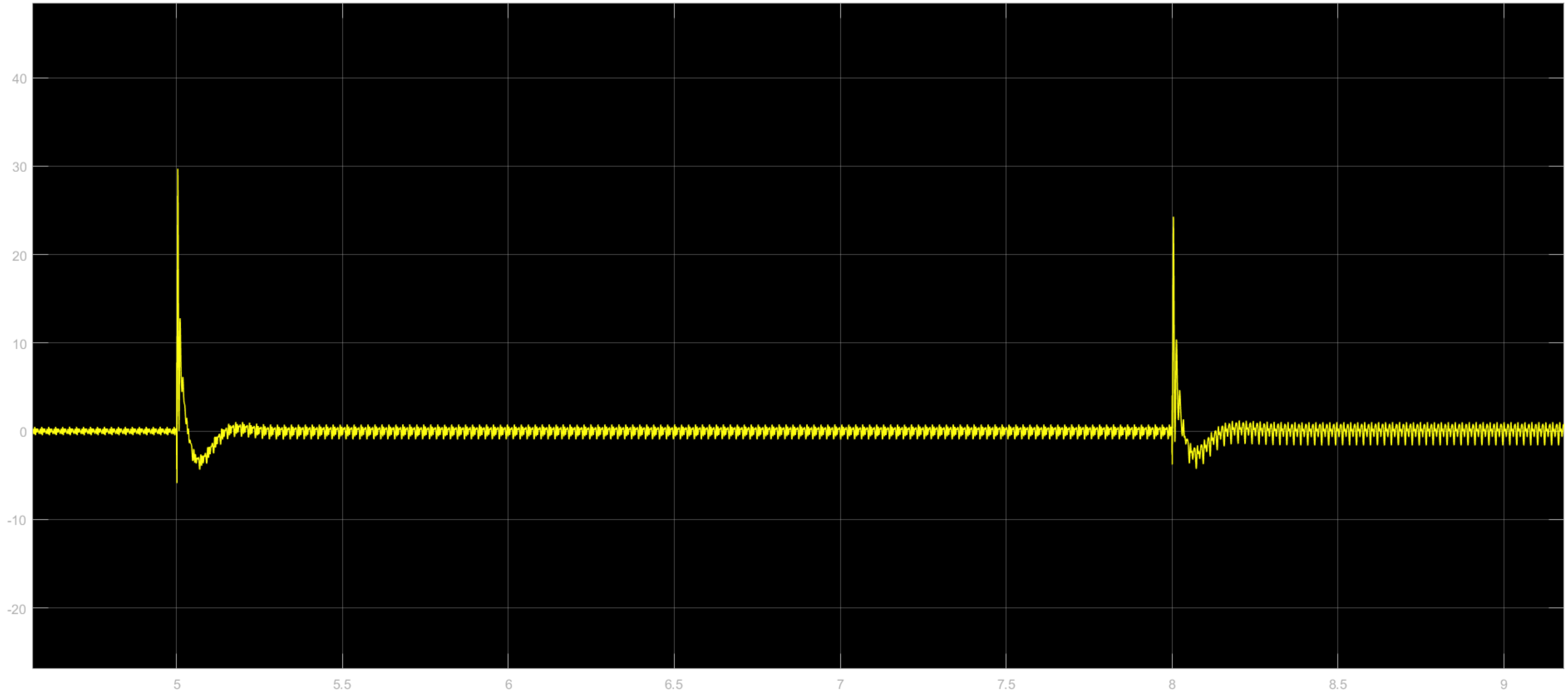
Simulation Results (10 Hz PLL)

- Transient from weak to ultra weak grid (time-domain currents)
- Stable, good performance



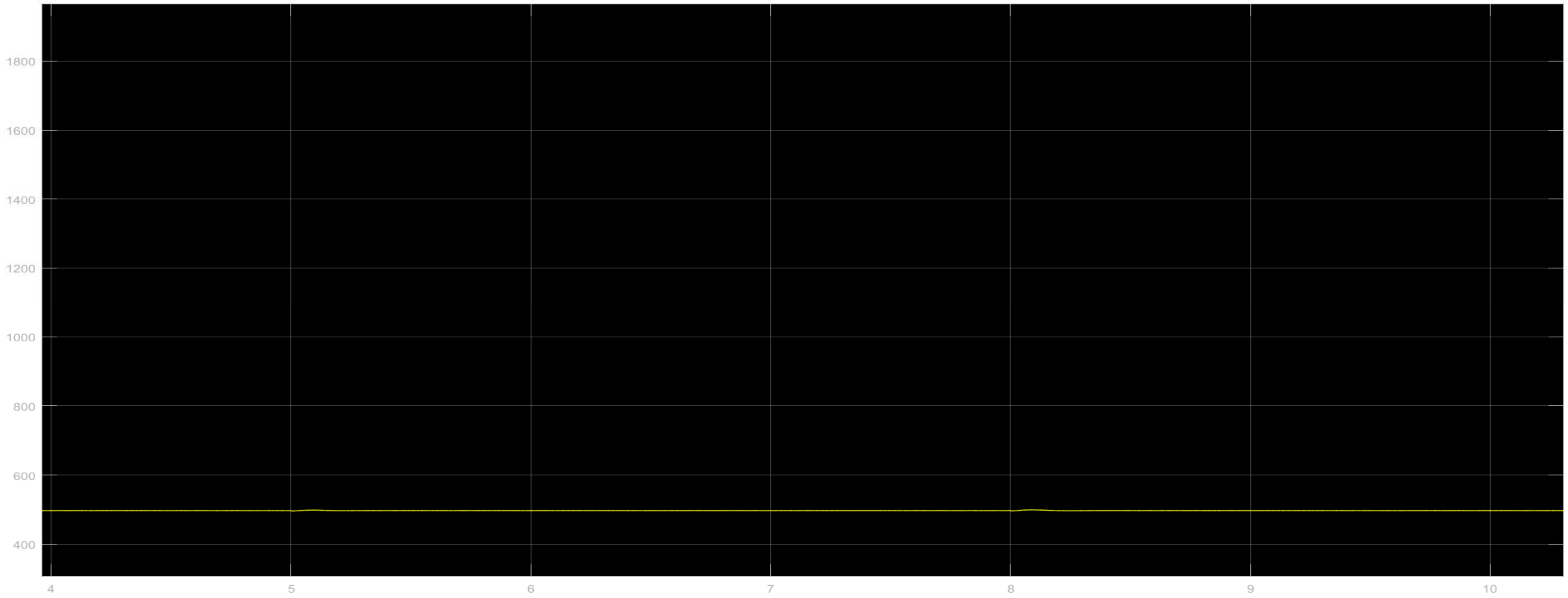
Simulation Results (10 Hz PLL)

- Transient from strong to weak and then to ultra weak grid (Observed voltage q-component)
- Stable operations in both transients



Simulation Results (10 Hz PLL)

- Transient from strong to weak and then to ultra weak grid (DC voltage)
- Transients are so low that they can be neglected → optimal performance



Conclusion

Co-funded by the
Erasmus+ Programme
of the European Union

- Renewable-energy inverters are more sensitive for stability issues than the big rotating generators
- Grid impedance has major impact on the control performance and stability
- By using impedance-based stability analysis, the possible issues can be forecasted and located
- One very common source for instability is the connection of inverter with high PLL bandwidth to weak grid

- These stability issues do not often occur
  - When they do, impedance-based stability analysis is effective tool to identify them!