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Power system

Grid-connected power electronics

Power grid for grid-connected power electronics

Power grid for grid-connected power electronics

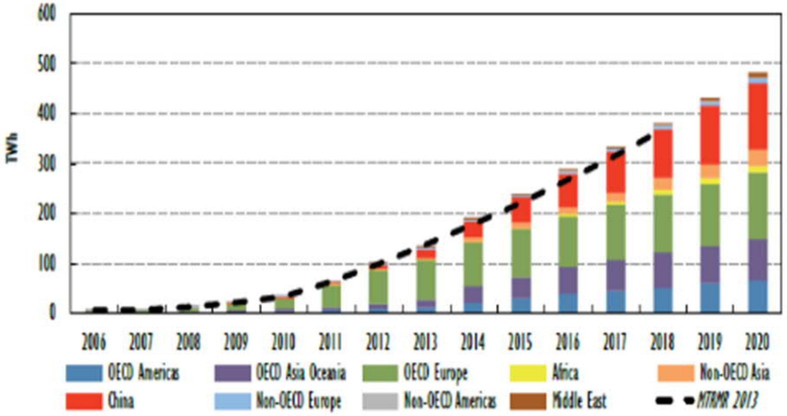
- Changing dynamics of power grid due to power electronics
- Grid impedance
- Synchronous reference frame (dq-domain)

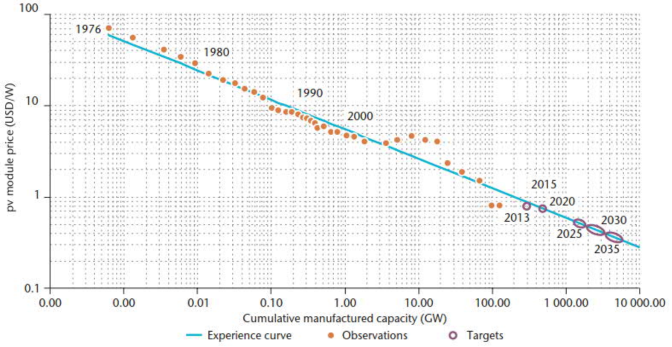
Power grid

- The amount of power electronics connected to power grid has been increasing
    - Inverter based power generation such as wind turbines and photovoltaic solar panels
- Power electronics are changing the dynamics of the power grid
    - Conventional power grid dynamics are determined by synchronous generators at transmission system level
    - Increasing amount of power electronics are affecting the resiliency of the networks to withstand faults and other events if not properly accounted for

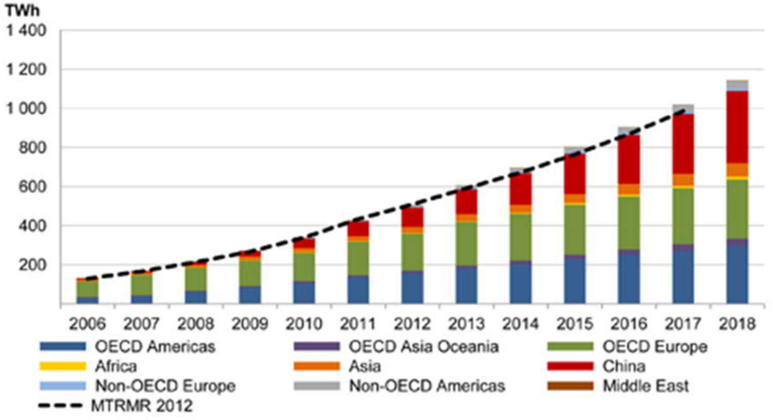
Increase in renewable power generation

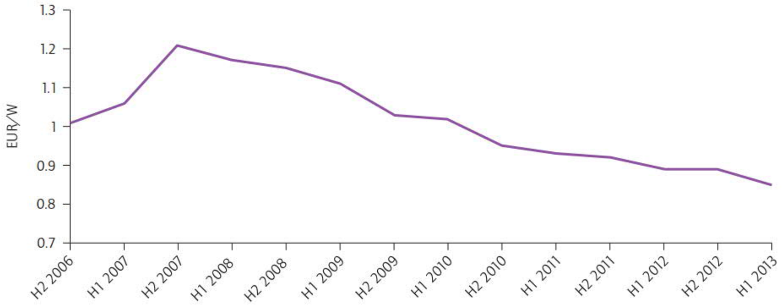
Solar power generation





Wind power generation





Power electronics in power system operation

- Synchronous generators are defined by their physics and controllers
  - Rotating mass, flux linkage etc
  - Requirements are defined by grid codes
  - Well known and standardized
- Power electronics are defined only by their control algorithms
  - Grid codes not well defined and updated regularly
- If the power electronics power generation penetration is low, the effect to operation minimal
  - Often modeled as negative loads for power system analysis
  - However, many areas have 50% of power generation is through power electronics

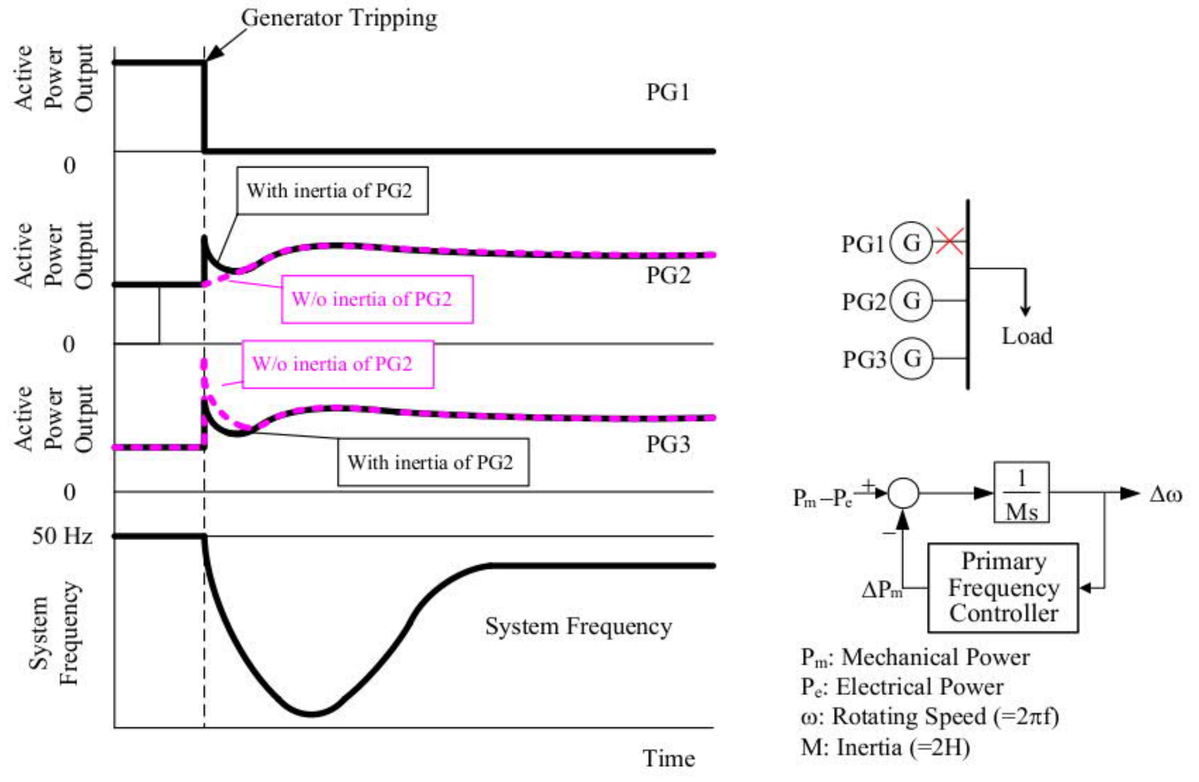
Power electronics in power system operation

- Difference between synchronous generators and inverter based generation
    - Synchronous generators are often large single units
    - Inverter based generation is often distributed wind- and solar energy generation
- Characteristics to synchronous generator are hard to emulate
    - System inertia
    - Short-circuit current
    - Grid forming capability (Black start)

Power grid inertia

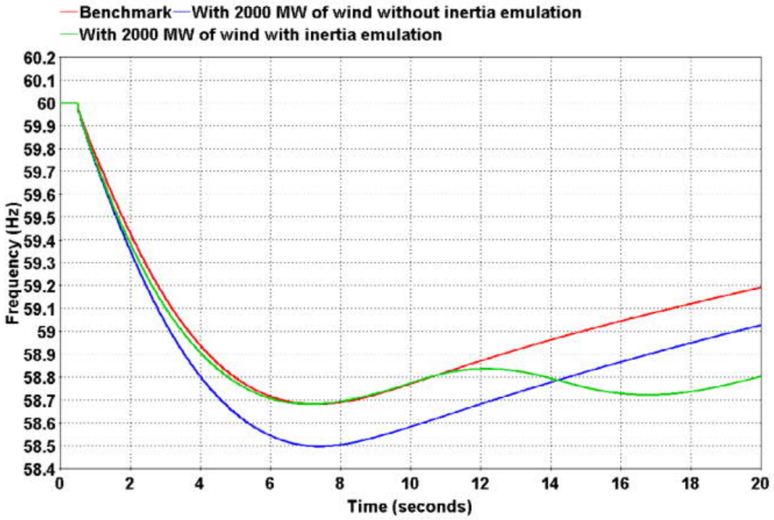
- Inverters do not have a rotating mass
  - Prime mover behind the inverter could have inertia, but its use must be achieved through inverter controls
- Inverters can emulated inertia
  - Increase or decrease in power output depending on Rate of Change of Frequency (ROCOF)
  - Increased inverter sizing due to higher currrent requirements
  - Energy source needed for the additional power requirement
    - Either operate below maximum power point or use a battery
  - Delay in response due to control delay
  - Cannot achieve instant response like a synchronouse generator due to this delay

Power generator response to a fault



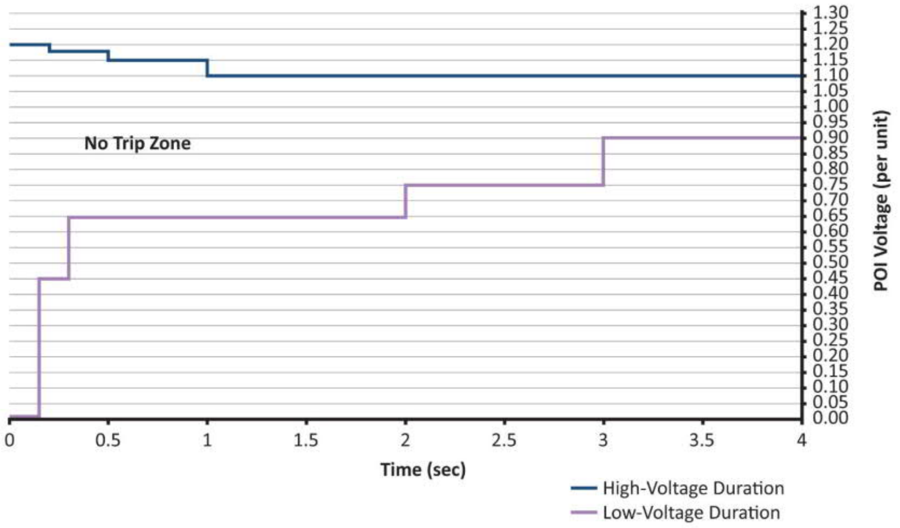
Power grid – Inertia emulation

- Wind farms are required to do frequency support in Quebec, Canada
  - Large percentage of wind power
  - Long transmission distances
- Wind turbines have small amount of inertia
  - Amplified by the inverter connection
  - Short duration of frequency support
  - Regeneration period after frequency support
- Lowest frequency during faults increased
  - Recovery lengthened



Fault Ride Through (FRT)

- Inverters are instructed to set current reference to zero or disconnect during faults
  - Changing as the percentage of power electronics is increasing
- Inverters aren’t capable of withstanding severe three-phase faults
  - PLL cannot detect the phase angle
- Modern grid codes are asking the inverters to have low voltage ride through capabilites



Fault current contribution

- Fault current supply is determined by the inverter control and not the physical characteristics as with synchronous generators
  - Often limited to slightly above 1 p.u. to not damage the inverter components
- Inverters cannot supply fault current
  - Unless significantly oversized
  - The voltage at the point of connection might drop to a low value and cause the phase angle of grid synchronization to be illdefined

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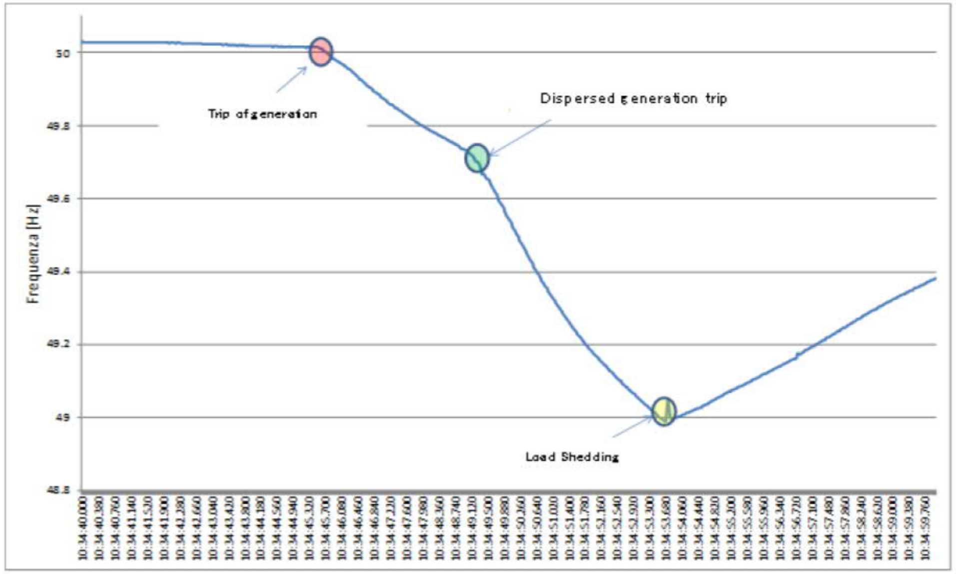
Fault Ride Through



- Lowering frequency caused an unintentional tripping of several inverters due to anti-islanding protection tripping

Reactive Power support

- Inverters are often operated with unity power factor over their entire active power output range
  - Most of the inverters do not have sufficient sizing for providing reactive power at full output
- During faults there is delay before an inverter can supply reactive power
- The inverters are designed to block negative sequence currents
  - Required for unsymmetrical fault currents

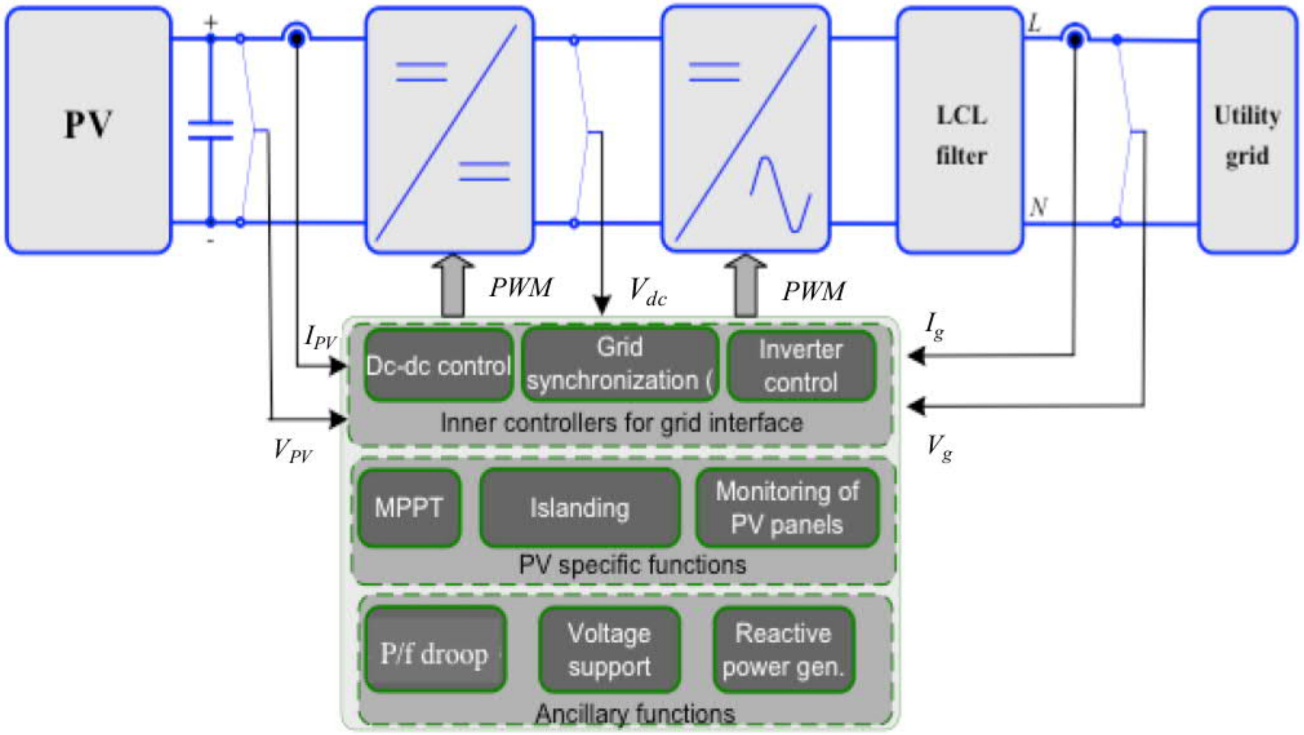
Harmonic emission

- Inverters produce non-sinusoidal currents that can be described as harmonic emission in frequency domain
- The harmonic emissions need to be assessed and controlled before connection is permitted
- IEC has standards of harmonic emissions but many countries have their own limits
- Depending on the type of the inverter the harmonic emissions can be significant

External protection

- Detect uncontrolled local islanding situations and disconnect generators to shut down this island (also know as ”Loss of Mains Protection”
- Reduce the power production to prevent over-voltage or over-frequency situation in the network connected to
- Assist the power system to reach a controlled state in case of voltage or frequency deviations beyond corresponding regulation values

Photovoltaic inverter



Behaviour to Large Voltage Deviations

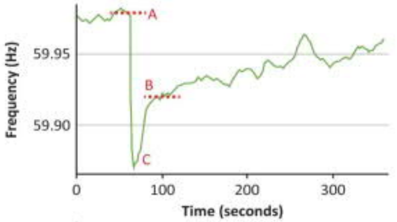
- Phenomena triggered by system faults such three-phase fault, single-line to ground faults and short circuit faults
- Inverters based power generation tends to reduce short-circuit current during faults
  - Voltage can drop to low levels and the recovery of the system after the fault can be hindered
- Total contribution of several inverters to the fault current may alter the fault current level enough to cause lack of coordination for overcurrent protection or hamper fault detection

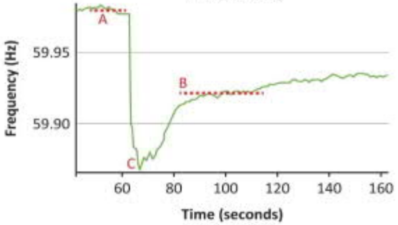
Transient stability

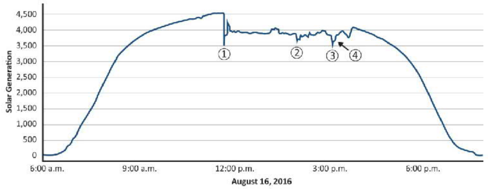
- The impedance of the power grid can be used to determine the stability of the grid connected devices
- The stability issues are caused by resonance between the power electronics and the power grid
- The resonances are caused by capacitive loads and elements in the power grid

Example – California August 2016

- Due to forest fires three 500 kV lines and two 287 kV power lines experienced multiple faults
  - Most significant resulted in loss of 1200 MW solar generation
- PV-plants were not directly affected, but the disconnect was a response to system fault
  - Most of the PV-inverters detected the distorted voltage wavefroms to be frequency below 57Hz
  - 2nd largest reason was due to system voltage reaching low voltage ride-through settings of the inverters

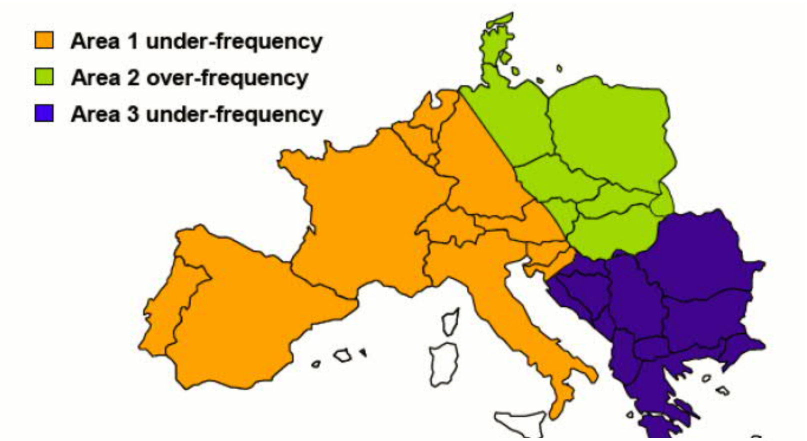


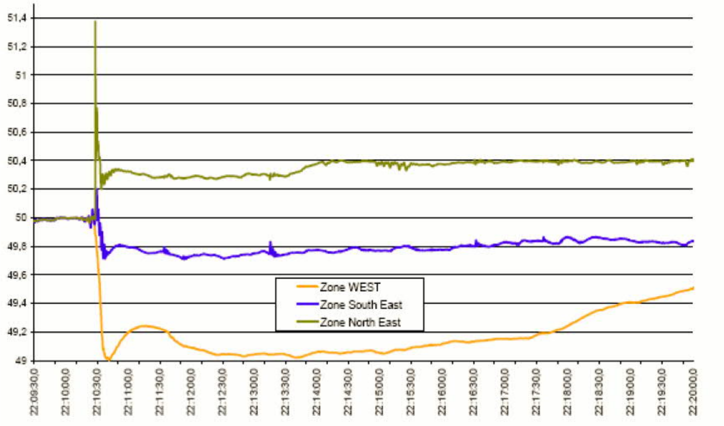




Example – European blackout 2006

- Major blackout, which cascaded through Europe
- Cause was a routing disconnect of a power line in Germany
  - High usage in other connections between east and west Germany
  - High wind power generation in the area
- The wind farms disconnected as the frequency dropped
- European power grid split into 3 different region





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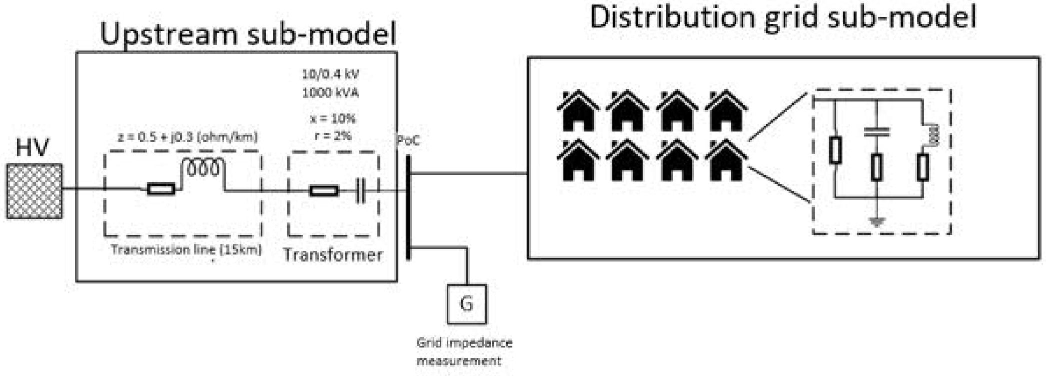
Power Grid Impedance

Impedance of the power grid

- Line+Transformer+Generator
- Typically inductive at fundamental frequency
  - Focus of traditional power system theory
  - Weak grid
- Resonance at harmonic frequencies
- Effect of loads; Variability with time
- Effect of neighboring power electronics

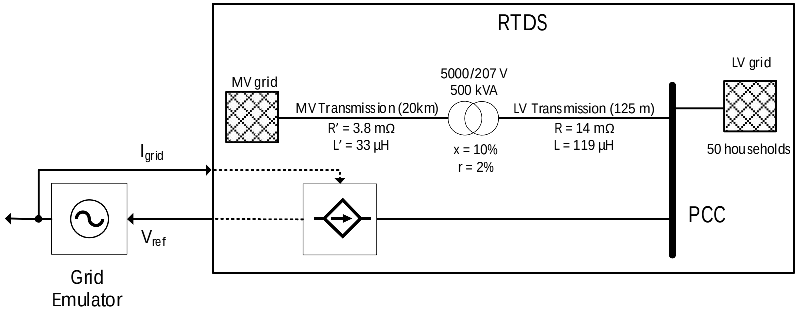
Impedance of the power grid

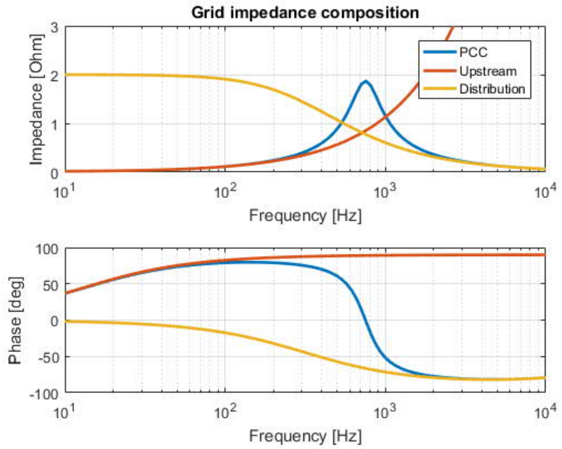
- The impedance of the power grid can be used to determine the stability of the grid-connected devices
- The stability issues are caused by resonance between the power electronics and the power grid
- Capacitive loads and elements in the power grid can cause resonant frequencies to grid impedance



Impedance of the power grid - Example

- The grid impedance is determined by the lowest impedance branch
  - Upstream grid when $f < f_{res}$
  - Distribution grid when $f > f_{res}$
  - Resonance at the frequency where the different branches have equal impedances
- Parallel resonance between the inductive upstream grid and capacitive load in downstream distribution system
  - 750 Hz in this scenario
  - Similar resonances have been measured from real systems





Power grid

- Interface between power grid and inverters are prone to instability
- For stability studies the point of common coupling (PCC) must be chosen from the point of measurements for inverter control
- Point of common coupling is the point where the inverter is considered to be connected to the power grid
  - Everything beyond that point is considered power grid
    - Power lines, transformers etc, grid-side filter components
  - Everything before that point is considered part of the inverter
    - Inverter, inverter-side filtering components

Short circuit ratio

- Metric that has been traditionally used to represent the voltage stiffness of a grid
  - High SCR indicates stiff voltages in the power system
  - Low SCR indicates low system strength and may require monitoring or additional studies
- Indicates the short circuit capability of the connected grid and it’s capability in voltage regulation
- In a low SCR network the any faults or switching of devices will cause significant changes in the grid voltage

Short circuit ratio

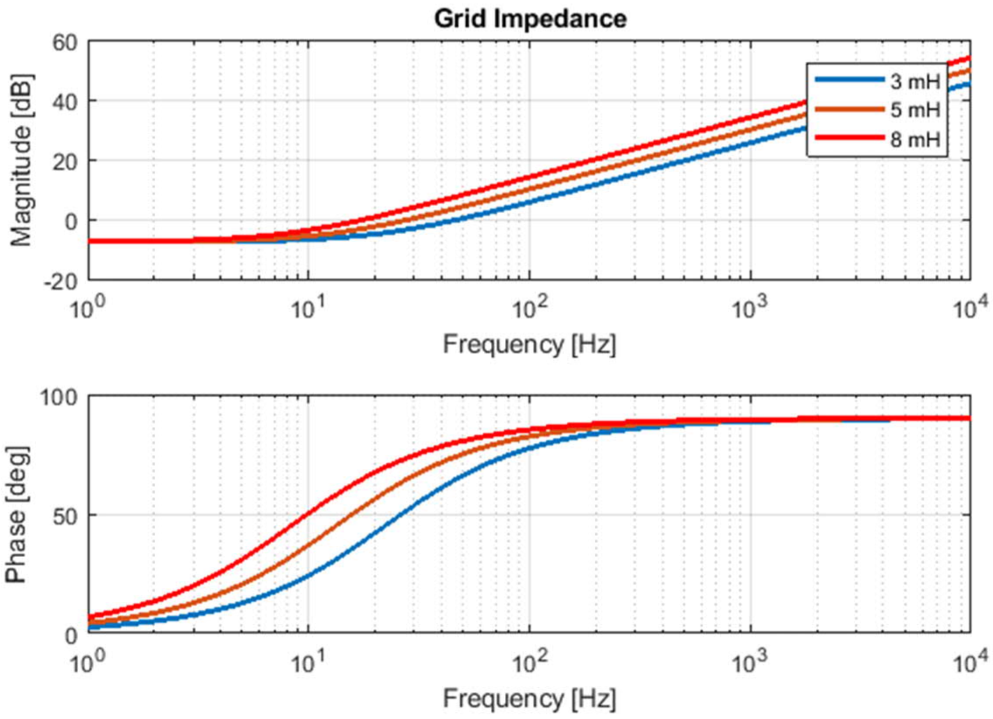
- Typical definition of weak / strong grid
  - SCR below 2 is considered very weak grid
  - SCR 2-3 is considered weak
  - SCR >3 is considered strong
- Increasing amount of power electronics decreases the SCR value of the power system
- Inverter PCC value calculated from the nominal values of the connection
  - $SCR = \frac{V_{PCC}^2}{S_n * 2\pi f_g L_g}, S_n = V_n * I_n$

Short circuit ratio

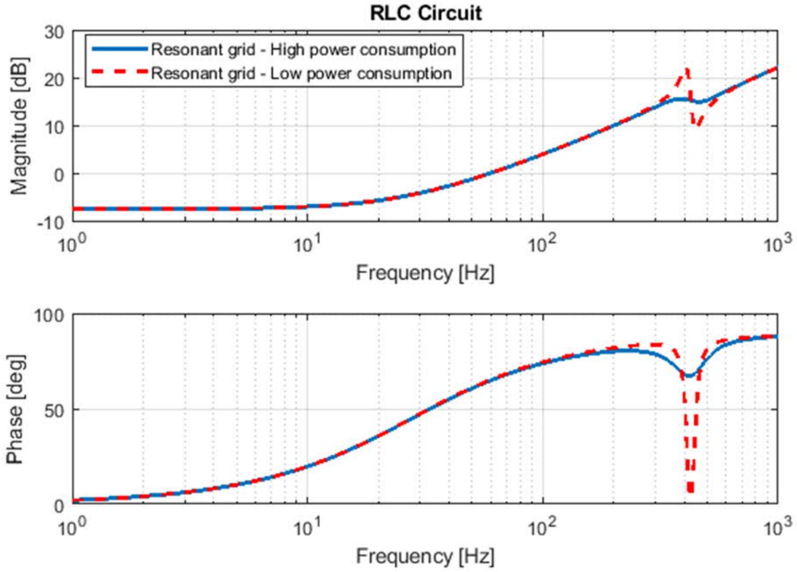
TU laboratory equipment Low voltage network, 120v, 60 Hz, 2,5 kW	
Grid inductance	SCR
2 mH	7.64
5 mH	3.06
8 mH	1.91

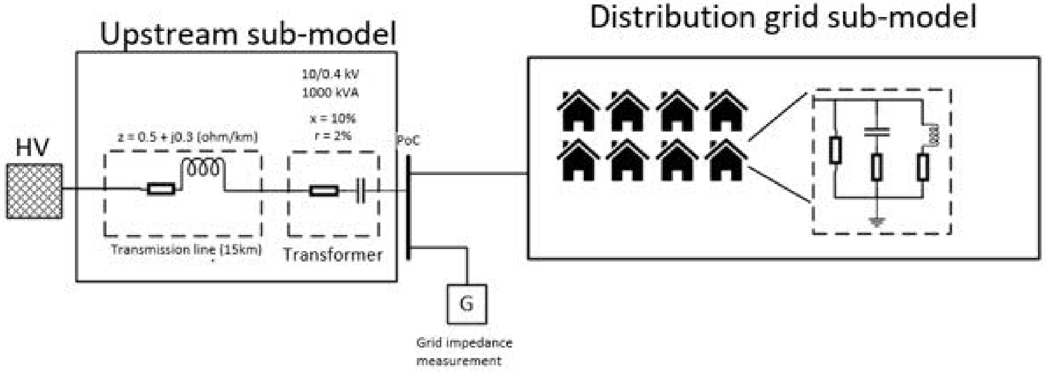
Example connection Wind turbine connection, 690v, 50 Hz, 2,5 MW	
Grid inductance	SCR
0.1 mH	6.06
0.2 mH	3.03
0.3 mH	2.02

Grid inductance

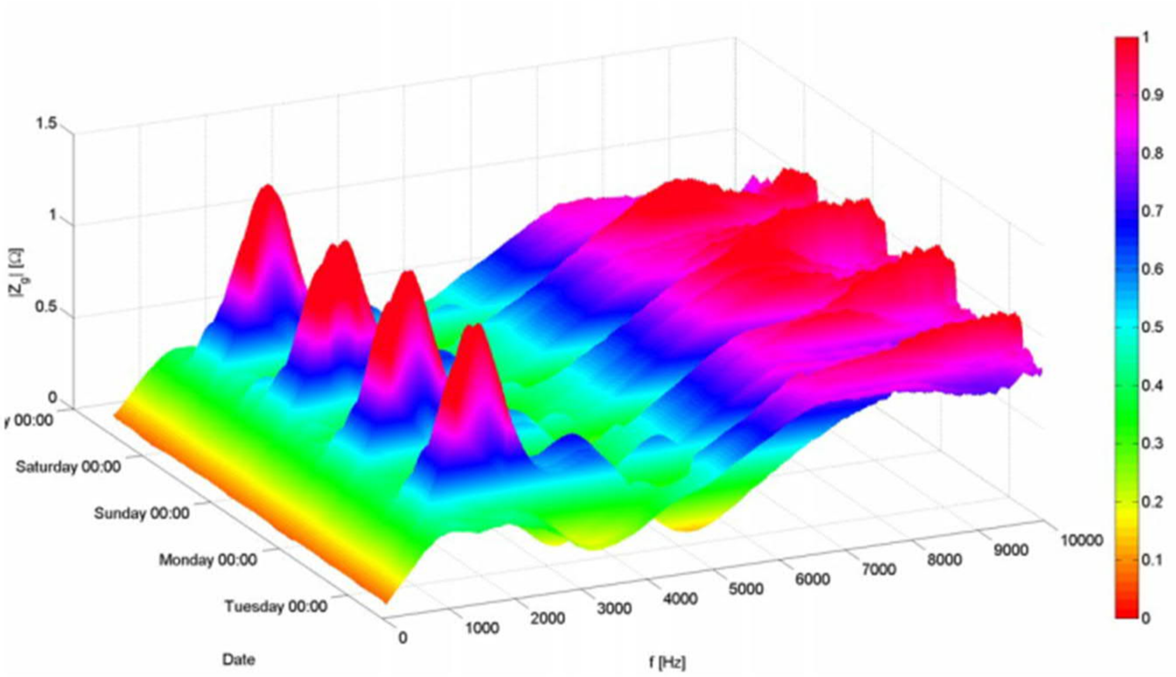


Grid Inductance – Resonant Frequency





Measured Grid Impedance

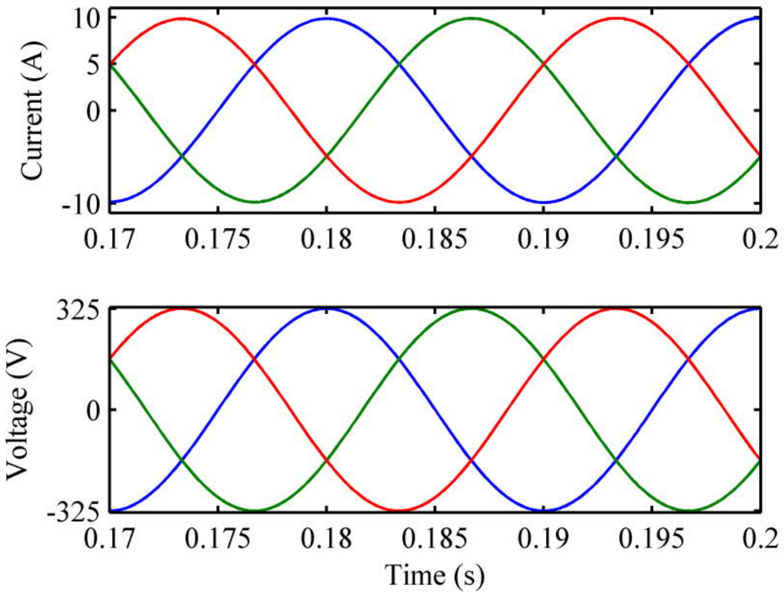


Grid-modeling

Synchronized reference frame

Modeling problem: Sinusoidal signals

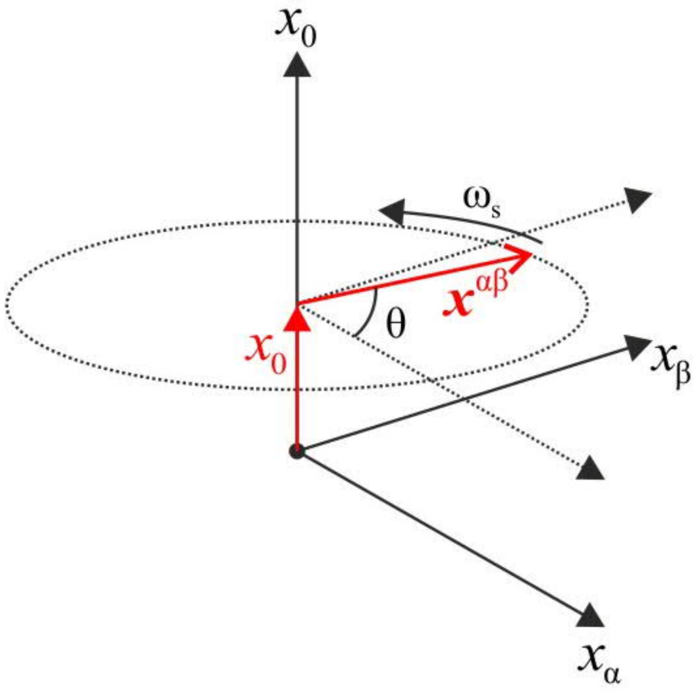
- Modeling problem for inverter dynamics
  - The system variables are sinusoidal
  - 3 interconnected phase
- The 3 sinusoidal waveforms (abc) can be transformed into 2 sinusoidal waveforms $(\alpha\beta)$
  - Clarkes Transformation
- The $\alpha\beta$-domain signals can be further transformed into 2 DC-signal (dq)
  - Parks Transformation



Modeling problem: Sinusoidal signals

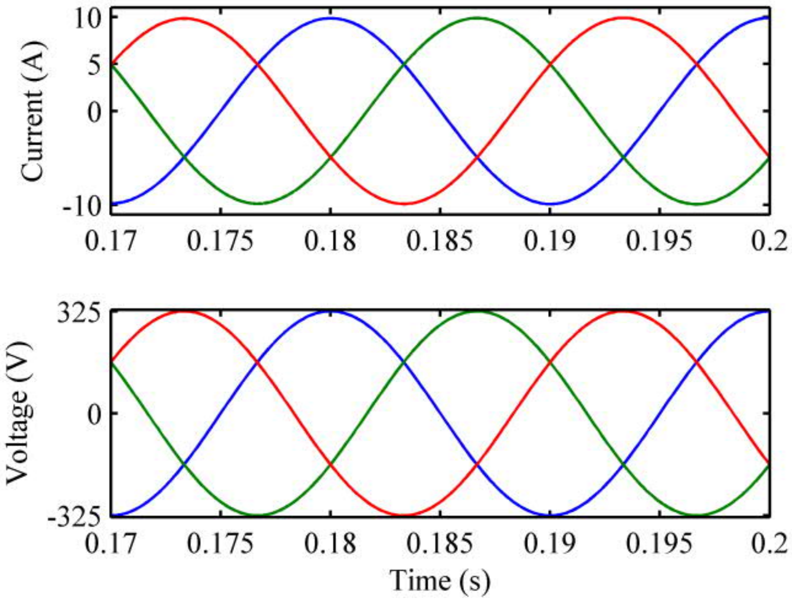
$$\begin{bmatrix} x_\alpha(t) \\ x_\beta(t) \\ x_0(t) \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \cdot \begin{bmatrix} x_a(t) \\ x_b(t) \\ x_c(t) \end{bmatrix}$$

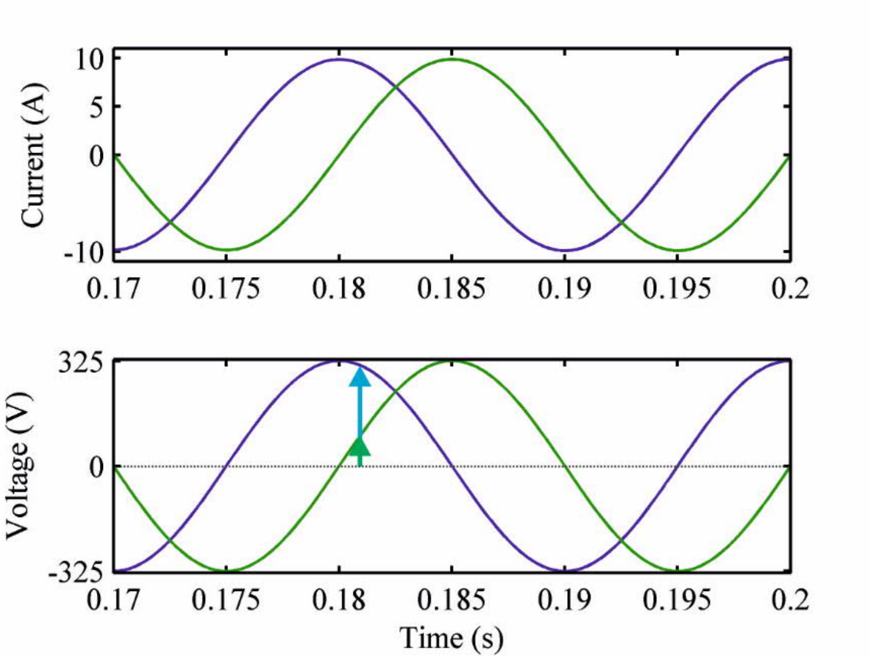
- Clarke’s matrix transforms a three-phase system ino a rotating space-vector
- Space-vector has three components (alpha, beta, zero)



Clarke’s Transformation

3~ AC system → Processing → 2~ AC system





Stationary reference frame

- Rotating vector is seen as a stationary vector in rotating reference frame

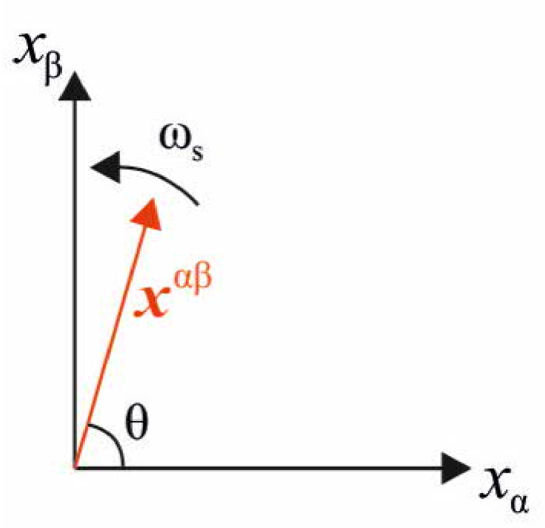


Figure 1: Rotating space-vector.

$$x^{\alpha\beta} = x_\alpha + jx_\beta$$

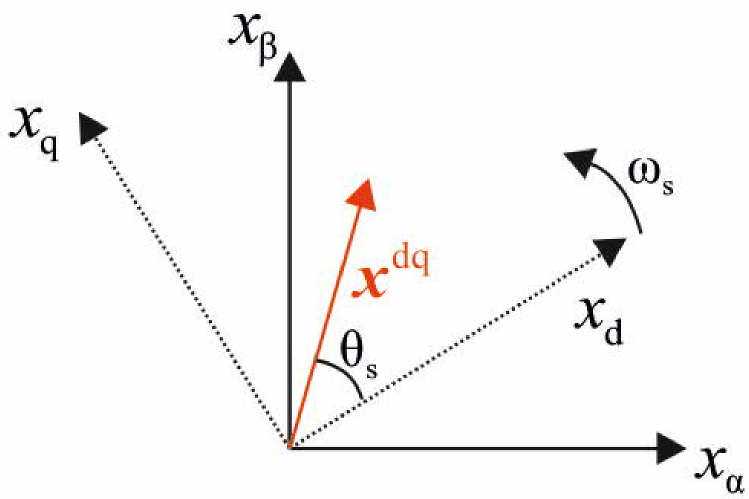
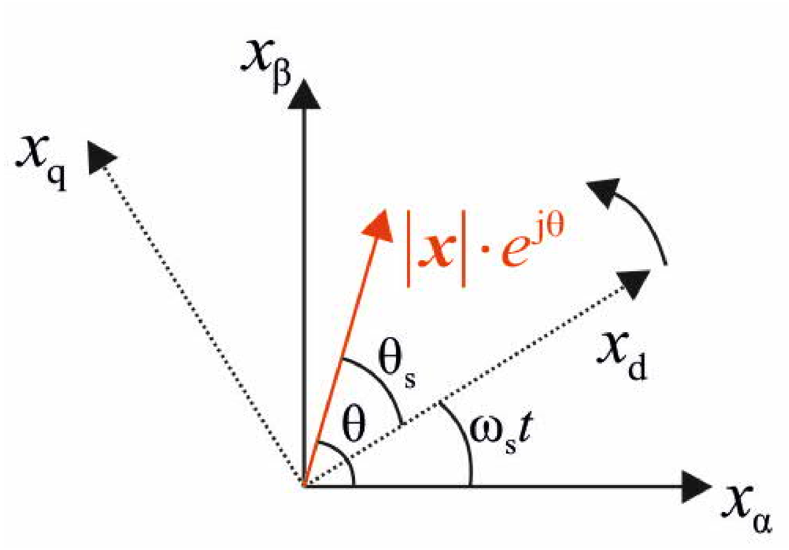


Figure 2: Synchronous reference frame.

$$x^{dq} = x_d + jx_q$$

Modeling problem: Sinusoidal signals

- Vector is rotated in the opposite direction at the fundamental frequency



$$x^{\alpha\beta} = |x| * e^{j\theta} \rightarrow x^{dq} = e^{-j\omega_s t}$$

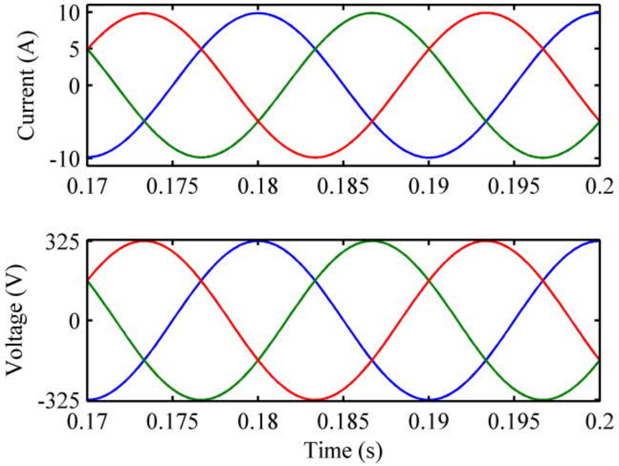
$$\begin{bmatrix} x_d \\ x_q \\ x_0 \end{bmatrix} = \begin{bmatrix} \cos(\omega_s t) & \sin(\omega_s t) & 0 \\ -\sin(\omega_s t) & \cos(\omega_s t) & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x_\alpha \\ x_\beta \\ x_0 \end{bmatrix}$$

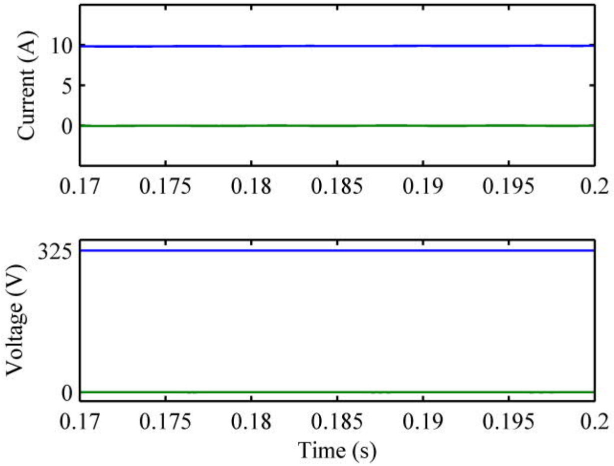
Park’s Transformation


AC system

Processing

DC system





Impedance in dq-domain

- Modeled as 2 systems with 2 outputs
- $Z_d = \frac{V_d}{I_d}$,
- $Z_q = \frac{V_q}{I_q}$
- Resonant peaks are seen as double peaks instead of one