Power System Services of PV-systems: Requirements, testing and application in Germany

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Power System Services of PV-systems: Requirements, testing and application in Germany

- Introduction
- Power System Services of PV-systems
  - Grid code requirements
  - Test procedures for PV-systems
- Application of power system services
  - Voltage control by reactive power
  - Voltage control by active network components
- Conclusions

1. Introduction
Generating capacities in Germany

- Generation capacity in Germany
  - 137.5 GW (in 2009) in total
  - 46 GW of RES
- Wind
  - Increase since 1994
  - 25 GW in 2009
- PV
  - Increase since 2004
  - 17.3 GW in 2010
  - 52 GW in 2020[1]

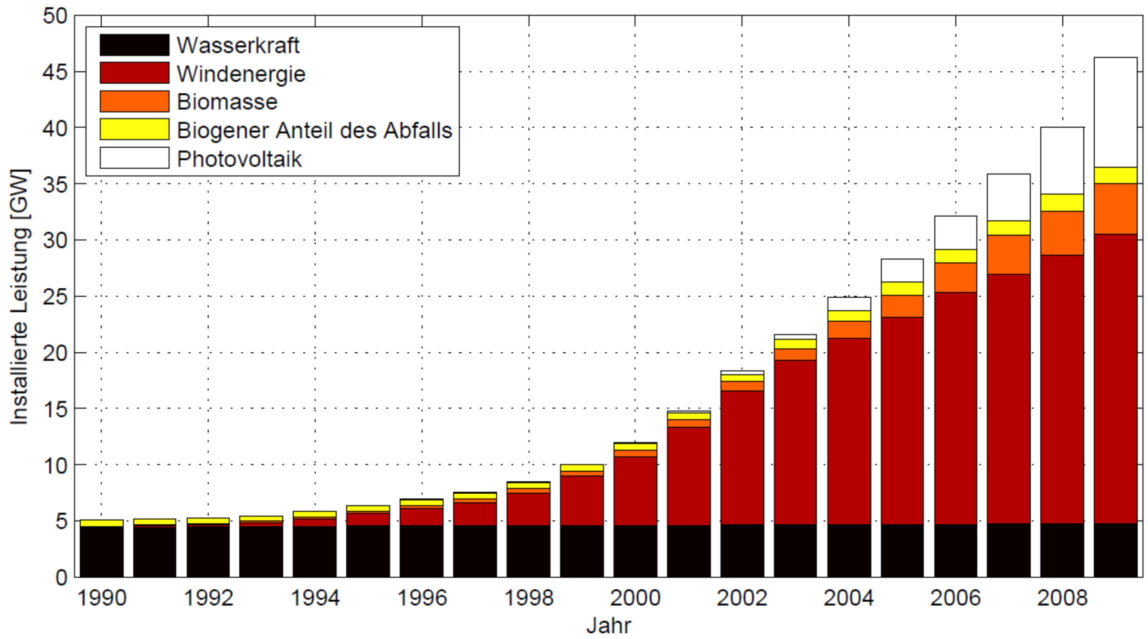

Diagram: Fraunhofer IWES, Data: Erneuerbare Energien in Zahlen, BMU, 2010

[1]: National development plan for renewable energies

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1. Introduction
Interconnection of PV-systems

- Interconnection of PV-systems mainly to LV due to power ratings
- Interconnected of PV-systems to HV or MV
  - ≈18%[1] (end of 2008)
- Jan. 2009 to Sept. 2010
  - 9335 MW_p new installed PV-power
  - Share of PV-systems with rated power > 100kWp: 3278 MWp
- Grid integration of PV on distribution system level

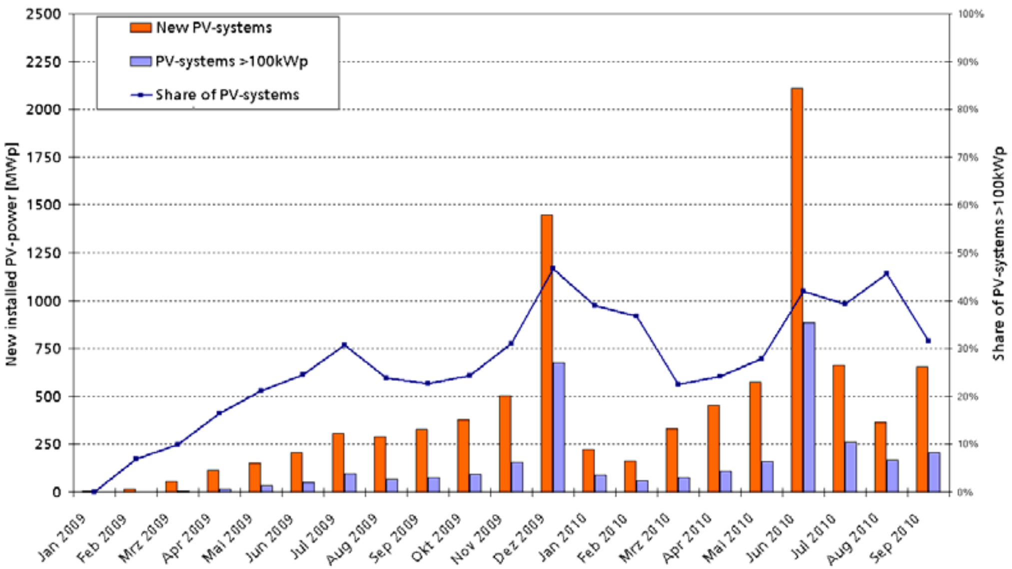

Diagram: Fraunhofer IWES; Data: Information of new installed PV-systems of BNetzA

[1]EEG Statistikbericht 2008; BNetzA

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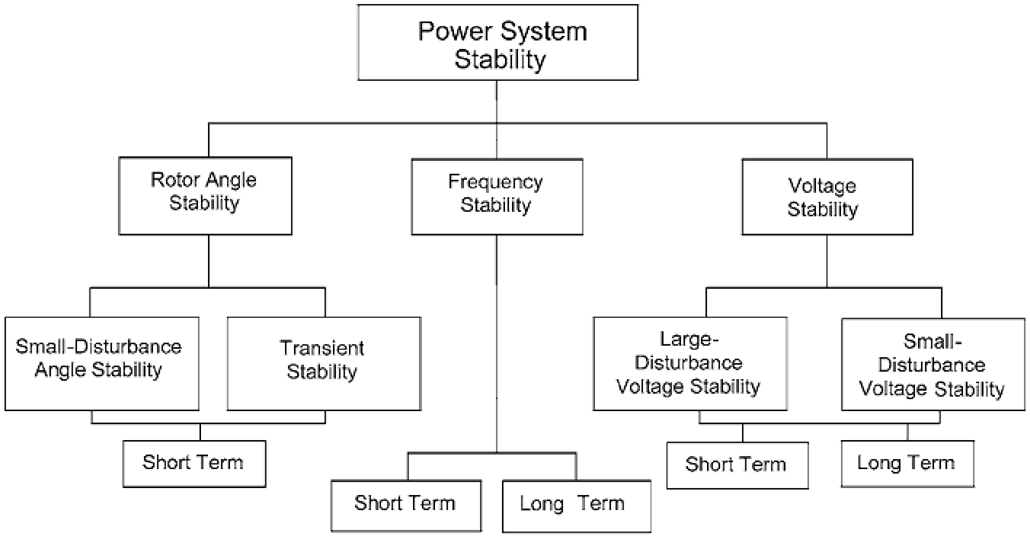
1. Introduction
Grid integration constraints

- Power System Stability
  - Rotor angle stability
  - Frequency stability
  - Voltage stability
- Network Constraints
  - Capacity of lines, cables, transformers
  - Power quality
    - Steady-state voltage limits
    - Harmonics
    - Flicker
    - …



Source: Definition and Classification of Power System Stability, IEEE/CIGRE Joint Task Force on Stability Terms and Definitions, IEEE Transactions on Power Systems, Prabha Kundur et. al.

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1. Introduction
Grid integration challenges and approaches

- Transmission network (HV/EHV)
  - Challenges
    - Power generation not located to load centers
    - Integration of offshore wind parks
  - Approaches
    - Grid reinforcement
    - Power System Services of DER units
    - Central storages
    - FACTS

- Distribution network (MV/LV)
  - Challenges
    - Bidirectional power flows
    - Voltage control
  - Approaches
    - Power System Services of DER units
    - Active network components
    - Manageability of loads
    - Local storages
    - Grid reinforcement

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2. Power System Services of PV-systems
Grid code requirements – Overview

- Pre-condition for connection
  - Fulfilling of technical minimum standards concerning electrical behaviour (§6 EEG)
  - Link to grid codes
  - Approval of Conformity by certificates (§64 EEG)
- Grid codes in Germany
  - Describe behaviour of DER units in order to meet system needs
    - High voltage / Extra high voltage
      - Transmission Code 2007
    - Medium voltage
      - BDEW MV-guideline
    - Low voltage
      - E VDE-AR-N 4105 (Draft version)


Technische Richtlinie
Erzeugungsanlagen am
Mittelspannungsnetz

Richtlinie für Anschluss und Parallelbetrieb von
Erzeugungsanlagen am Mittelspannungsnetz

Ausgabe Juni 2008

bdew
Energie. Wasser. Leben.

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2. Power System Services of PV-systems
Grid code requirements – Overview

- Distribution code „DER plants connected MV distribution grid“
  - Technical requirements for DER plants (steady state / transient)
  - Basic procedure for approval of conformity
- Link to Technical Guidelines of FGW for verification of requested electrical behaviour
  - FGW TR3: Testing procedures
    - Link to IEC 61400-21
    - Adaptation of test procedures for PV
  - FGW TR4: Modelling
  - FGW TR8: Certification

Technische Richtlinien
für Erzeugungseinheiten

Teil 3:

Bestimmung der
Elektrischen Eigenschaften von
Erzeugungseinheiten am
Mittel-, Hoch- und Höchstspannungnetz

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2. Power System Services of PV-systems
Grid code requirements – Overview

- Static requirements
  - Limitation of power-quality characteristic parameters
    - Harmonics, interharmonics and higher frequency components
    - Flicker
    - Switching operation
  - Active power control
    - Active power reduction by network operator
    - Active power reduction at over-frequency
  - Reactive power control

- Dynamic requirements
  - Fault-ride-through (FRT) capability with no disconnection of DER plants during the voltage dip
  - No change of active power generation after faults
  - Feed-in of reactive power during the fault for voltage stabilization
  - Limitation of short-circuit current

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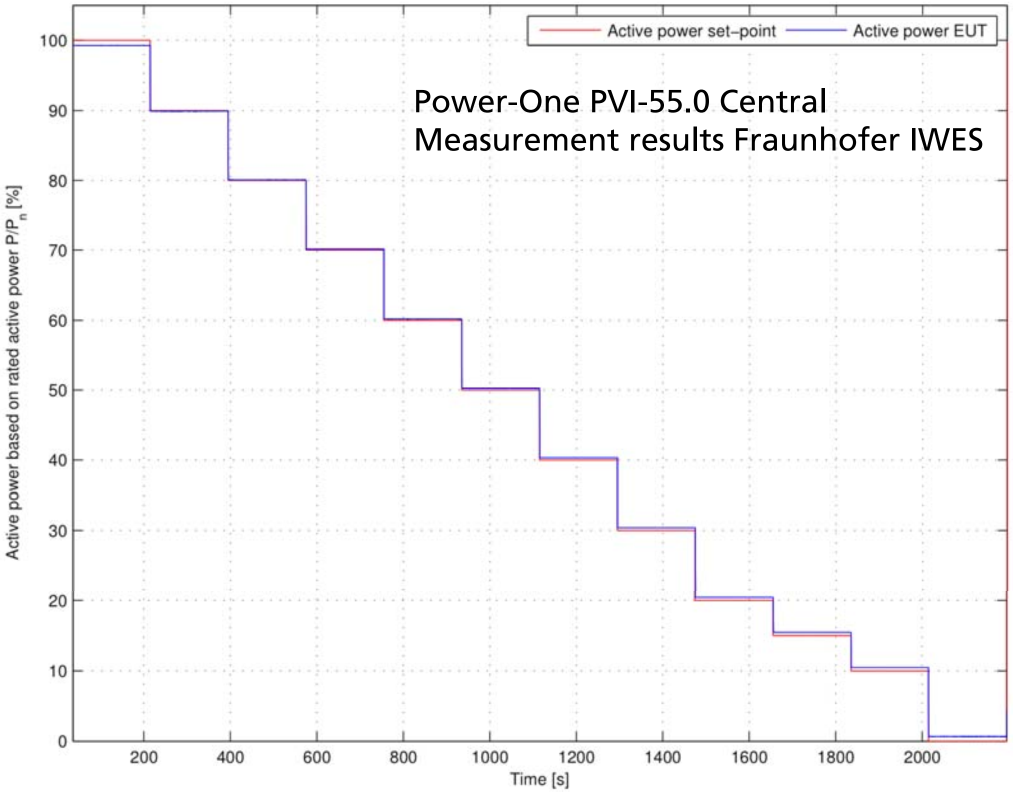
2. Power System Services of PV-systems
Grid code requirements – Active power control

- Grid safety management
  - In case of danger for grid operation / overloading of network equipment
- Network operator is allowed to reduce active power remotely
- Unit / plant must technically be able to reduce active power in steps of ≤ 10% P_n
- Common power reduction levels are 100%, 60%, 30% and 0%
- Response time of 1 minute at most



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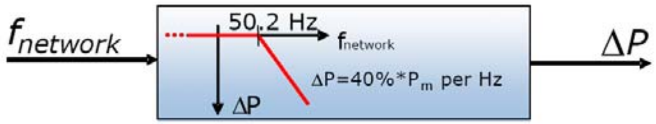
2. Power System Services of PV-systems
Grid code requirements – Active power control

- Automatic active power reduction depending on grid frequency
- Grid support in case of power surplus
- Avoiding grid instabilities due to immediate disconnection of large generation capacities
- Under normal grid conditions no impact on energy yield
- For inverter no additional hardware required



$$\Delta P = 20\,P_m \frac{50.2\,Hz - f_{network}}{50\,Hz} \quad \text{at } 50.2\text{ Hz} < f_{network} < 51.5\text{ Hz}$$

P_m instantaneously available power

ΔP power reduction

$f_{network}$ network frequency

within the range of	$47.5\text{ Hz} < f_{network} \leq 50.2\text{ Hz}$		no limitation
at	$f_{network} \leq 47.5\text{ Hz}$ and $f_{network} \geq 51.5\text{ Hz}$		disconnection from the grid

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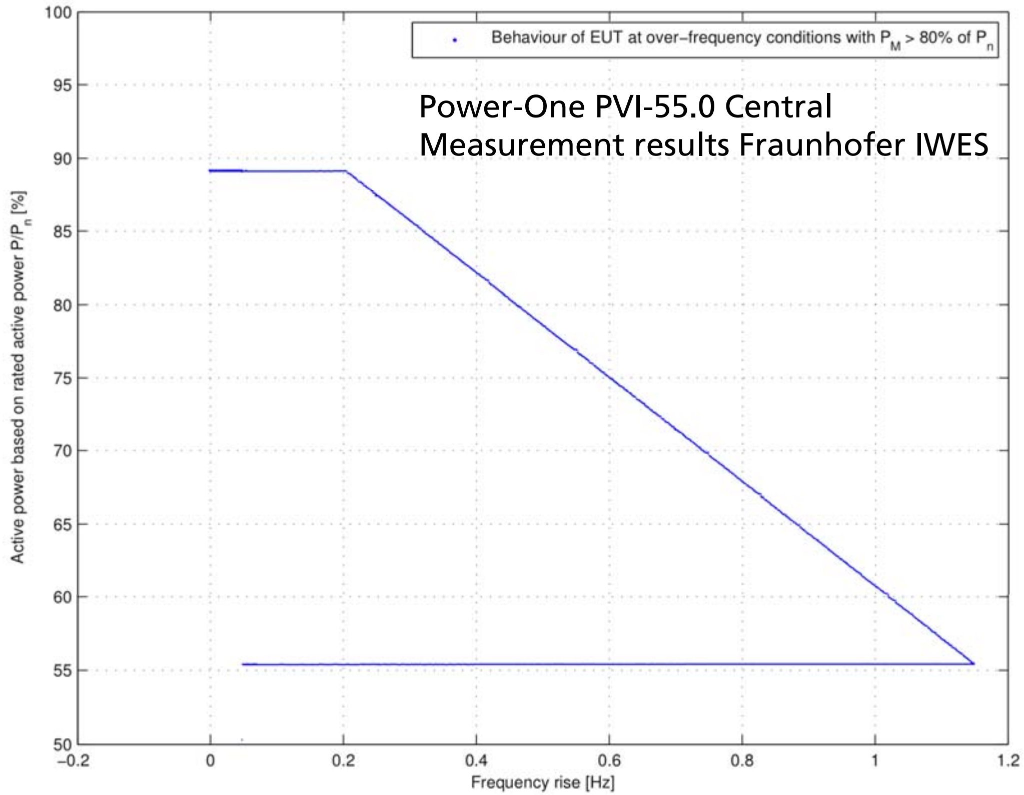
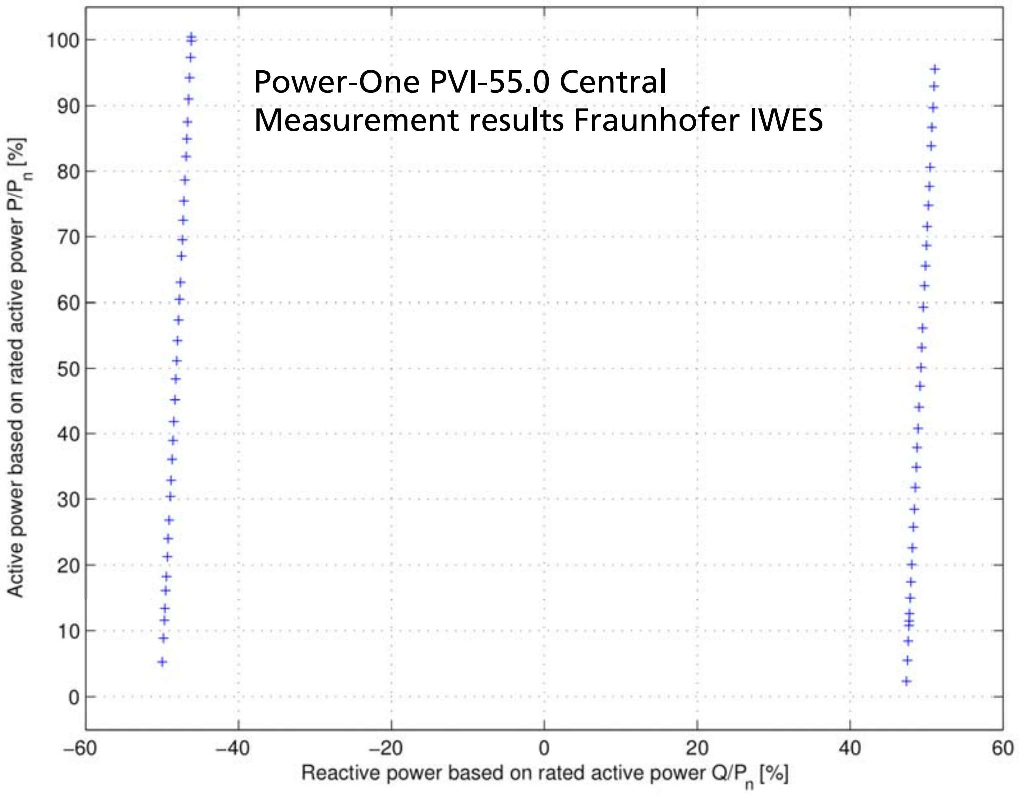
2. Power System Services of PV-systems
Grid code requirements – Active power control

- Measurement results of a Power-One PVI-55.0 Central inverter at Fraunhofer IWES
- Start of reduction at $f_{Grid} >$ 50.20 Hz
- Instantaneously available power at 50.20Hz is used for active power reduction calculations
- Amount of active power reduction is determined by droop with of 40% per Hz
- Internal „hysteresis": Rerise of active power if $f_{grid} \leq$ 50.05 Hz



2. Power System Services of PV-systems
Grid code requirements – Reactive power capability

- Maintenance of grid voltage
- Generating unit must be able to provide reactive power during normal operation
- Required power factor cos φ at network connection point of plant:
  - $0.95_{underexcited}$ to $0.95_{overexcited}$
- Impact on inverter design
  - Apparent power has to be increased



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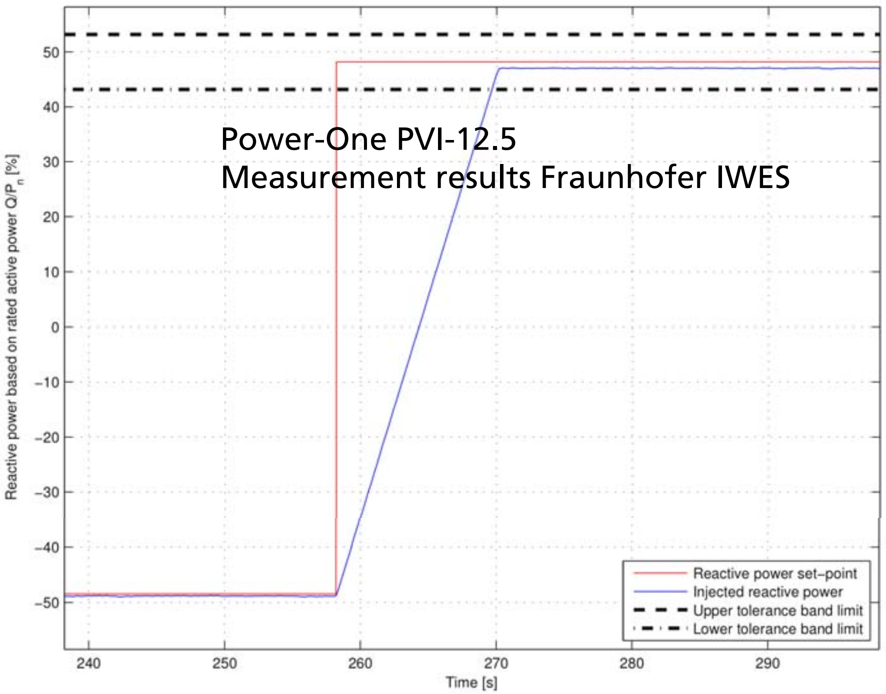
2. Power System Services of PV-systems
Grid code requirements – Reactive power capability

- Reactive power set-point provision
  - Fixed set-point for Q or power factor cos φ
  - Variable set-point for Q or power factor cos φ provided remotely by network operator
  - Characteristic curve
    - cos φ (P) droop
    - Q(U) droop
- Response times
  - Variable set-points: few minutes
  - Characteristic curves
    - 10s to 1 mim



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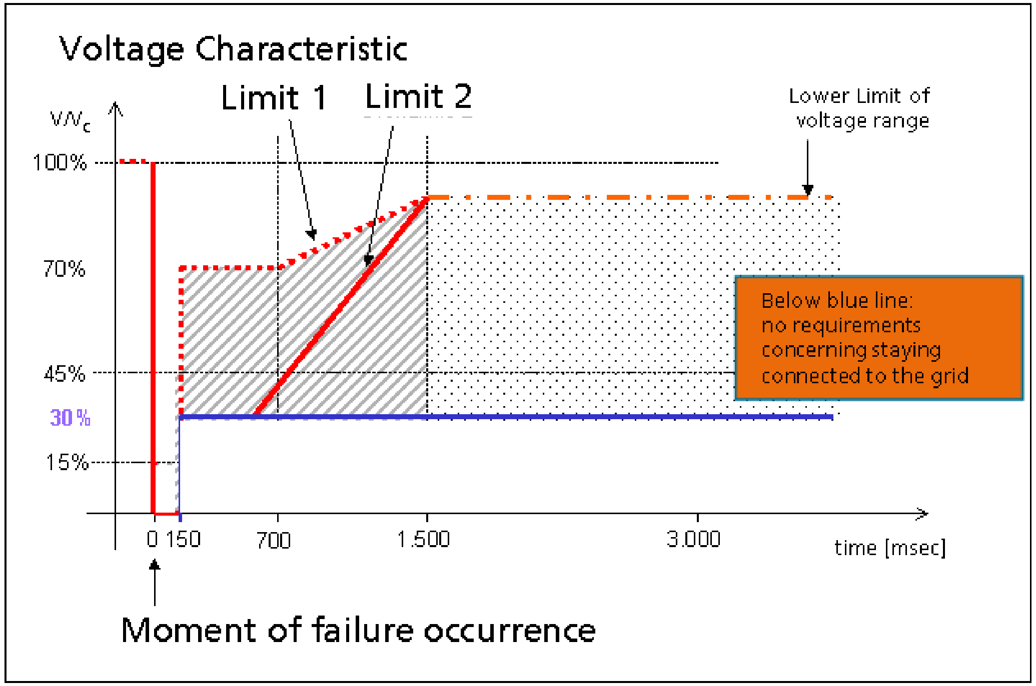
2. Power System Services of PV-systems
Grid code requirements – Fault-Ride-Through (FRT)

- Generating units must stay connected during grid faults
- Different FRT-curves
  - Type 1: Direct coupled synchronous generators
  - Type 2: all other generating units
- Requested behaviour of generating unit depends on mainly two factors:
  - Depth of voltage dip
  - Duration of voltage dip
- Behaviour of unit:
  - Stay connected during fault
  - Short time disconnection with resynchronisation within 2s at most
  - Reactive current injection + short time disconnection
  - No requirements



Source: Erzeugungsanlagen am Mittelspannungsnetz. BDEW, Release June 2008

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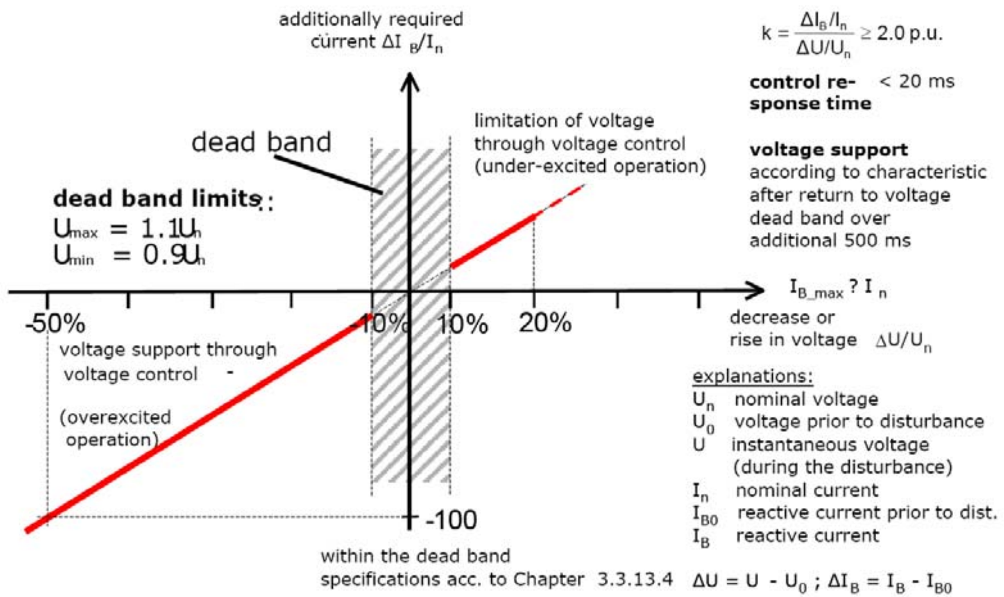
2. Power System Services of PV-systems
Grid code requirements – Fault-Ride-Through (FRT)

- Reactive current injection of unit according to Transmission Code 2007
- Amount of reactive power is determined by k-factor
  - $k = \Delta I_b/I_n \,/\, \Delta U/U_n$
    - Depth of grid fault
    - Reactive current before fault
    - Voltage before fault
- Response time ≤ 20 ms
- Max. reactive current: $I_b \leq 1.0$ In
- Max. duration of reactive current injection: time of fault clearing + 500ms
- In terms of unsymmetrical faults a release of overvoltage protection has to be avoided



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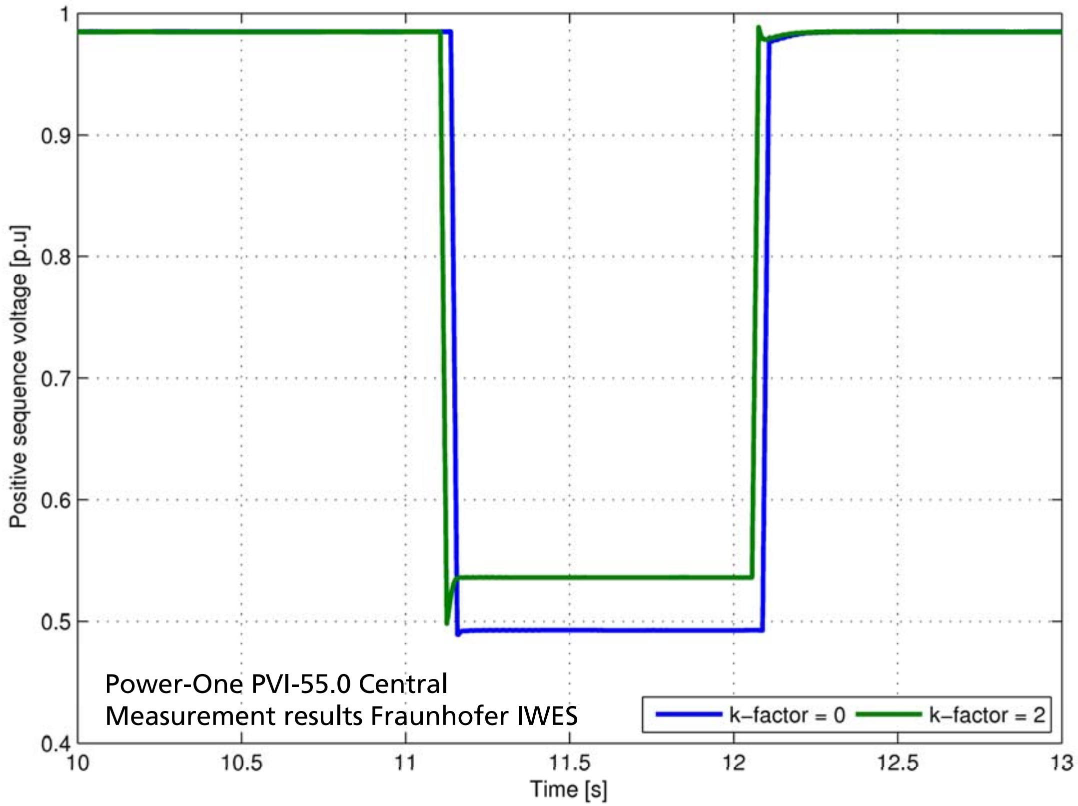
2. Power System Services of PV-systems
Grid code requirements – Fault-Ride-Through (FRT)

- Influence of reactive current on grid voltage during fault
- For both cases the same voltage dip is used
  - k-factor 0: no reactive current
  - k-factor 2: due to reactive current voltage is raised



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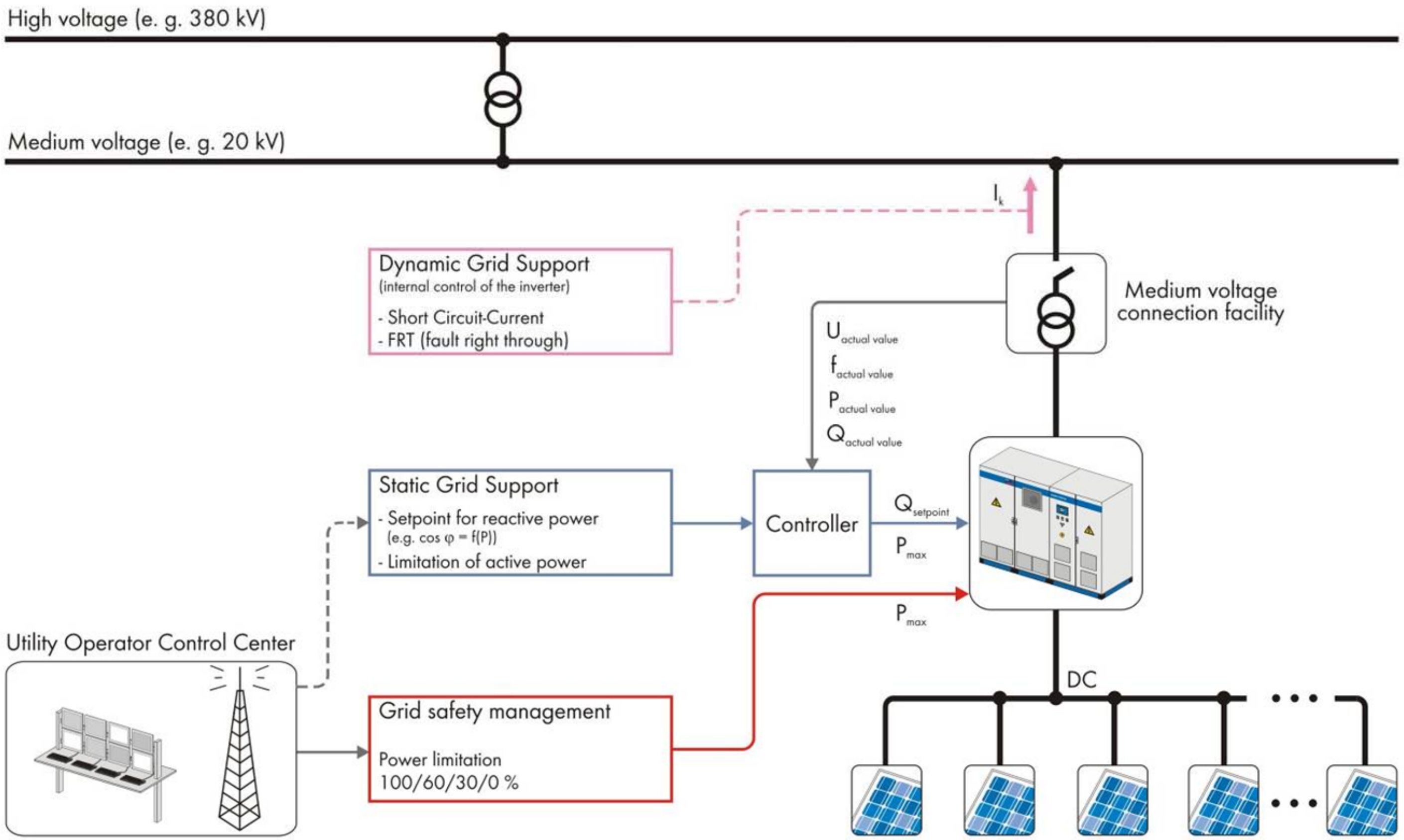
2. Power System Services of PV-systems
Grid code requirements – Implementation



Source: SMA Solar Technology AG

2. Power System Services of PV-systems
Test procedures for PV-systems – Testing environments

- AC-network simulator with additional impedance network
  - 90 kVA
  - Linear amplifiers
  - 4-quadrant operation
- PV-simulator 30kW
- Special testing equipment for PV-systems with higher power ratings

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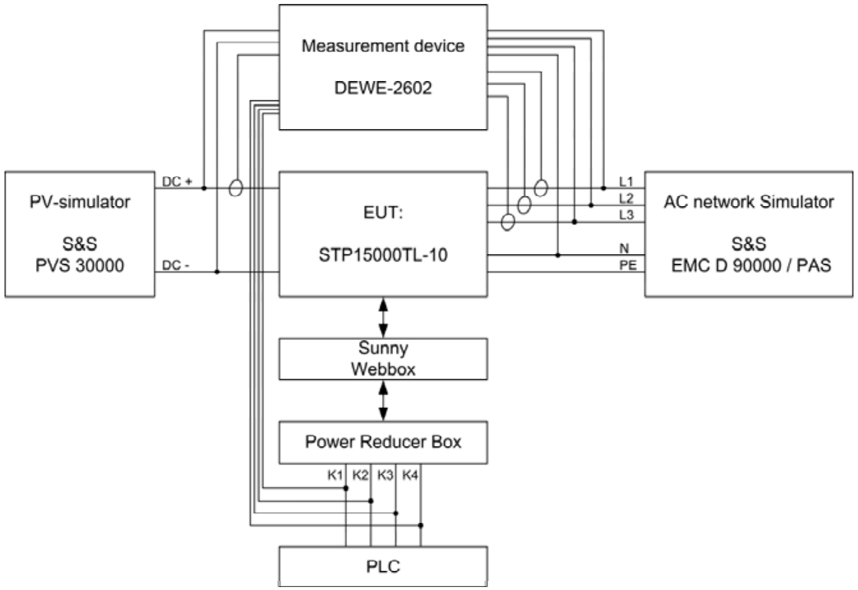
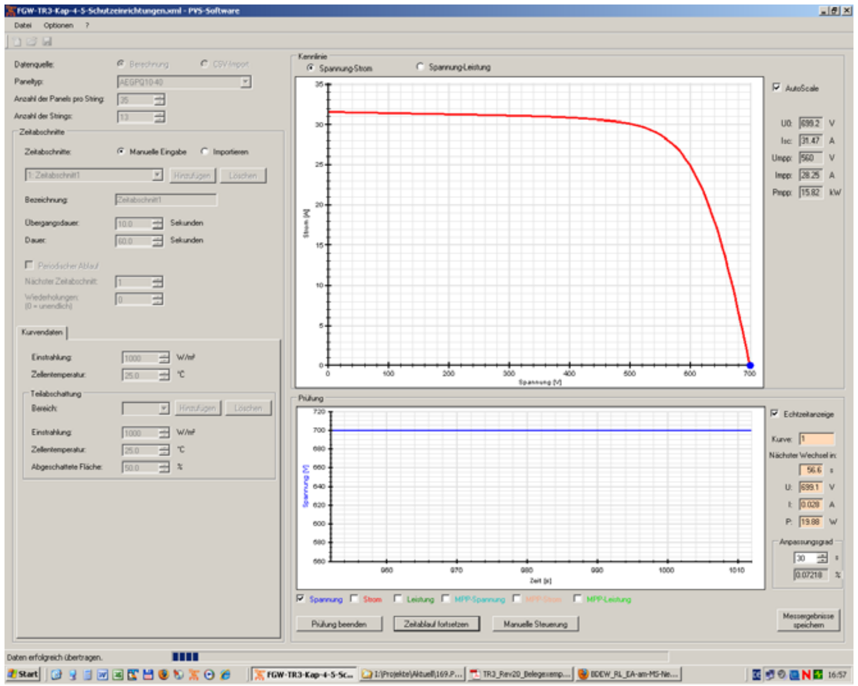
2. Power System Services of PV-systems

Test procedures for PV-systems – Testing environments





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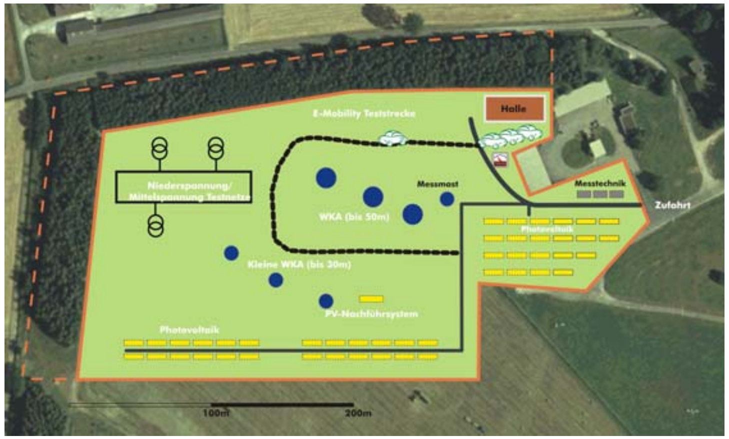
2. Power System Services of PV-systems
Test procedures for PV-systems – Testing environments

- SysTec
  - Experimental hall with 600m^2
  - Testing environment for high power converters and network components
  - Testing environment for grid integration of E-Mobility



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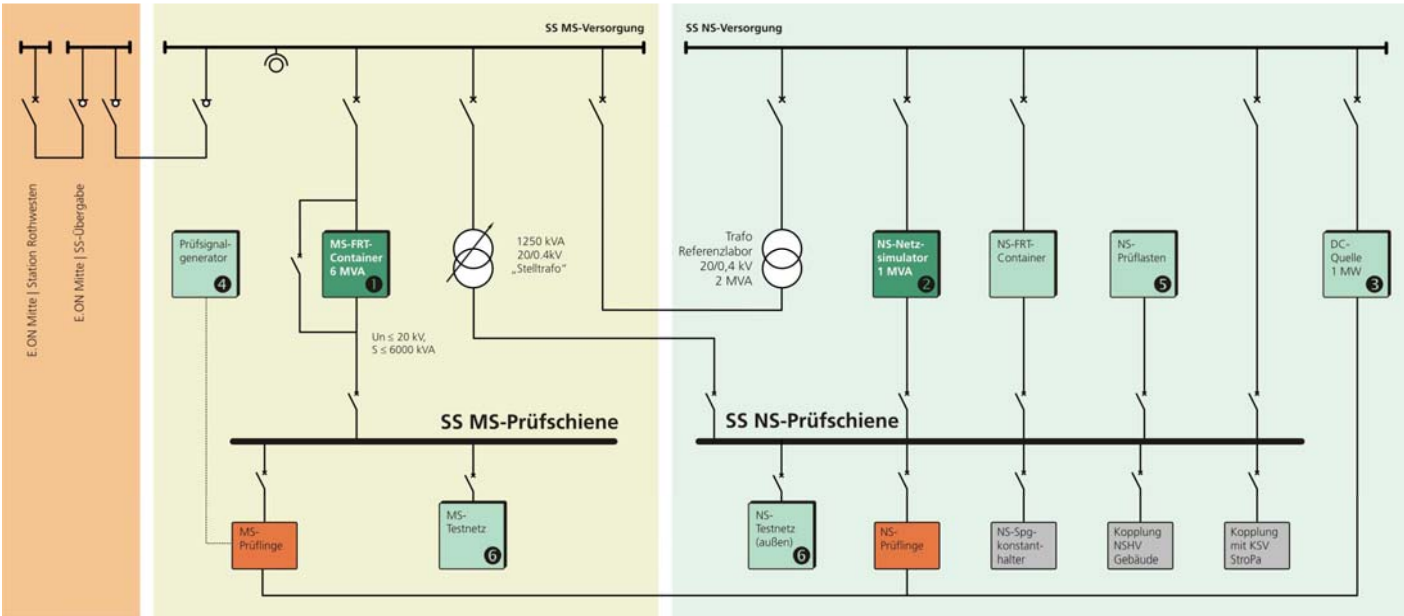
2. Power System Services of PV-systems
Test procedures for PV-systems – Testing environments

- 6 MVA FRT-container (MV)
- 1 MVA AC-network simulator (LV)
- 1 MW DC-source
- Signal generator
- Loads (resistive, inductive, capacitive)
- LV and MV test networks



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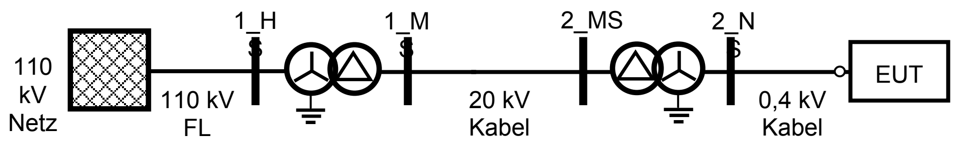
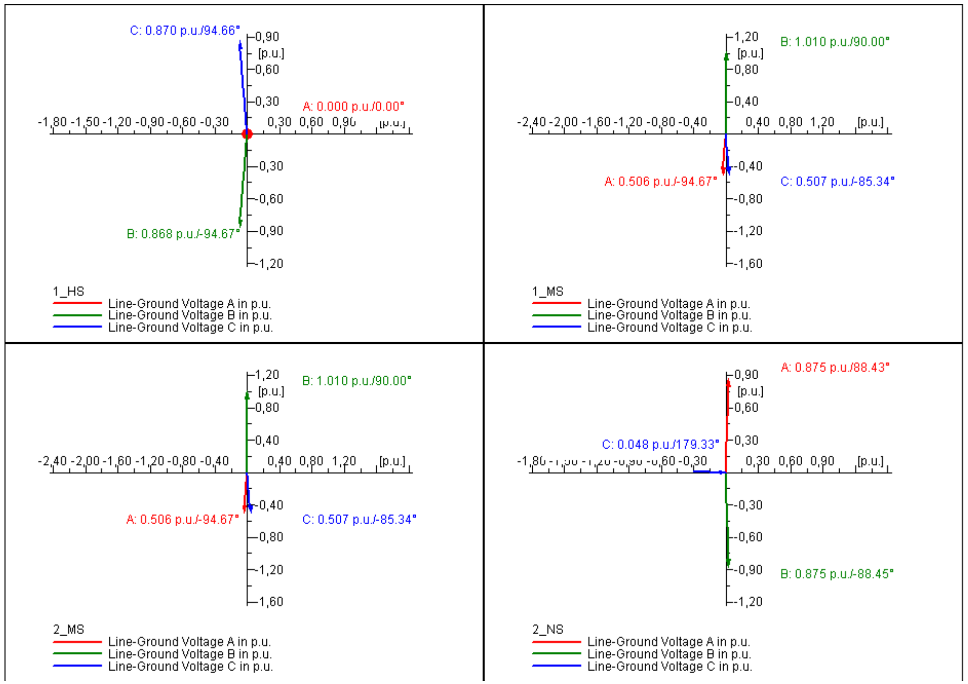
2. Power System Services of PV-systems

Test procedures for PV-systems – Testing procedures

- Test of behaviour of DER units during grid faults normally done with FRT-containers
- FRT containers designed for high power ratings (100 kW < P < 6 MVA)
- Not applicable for string inverters (P < 20kW)
- NS-FRT tests with network simulator
  - Calculation of voltage phasors at LV network for faults (3phase and 2 phase) in HV and MV networks
  - Real reproduction of voltage curves with low ohmic programmable AC-network sources
  - Real emulation of network impedance by adjustable R-L-network





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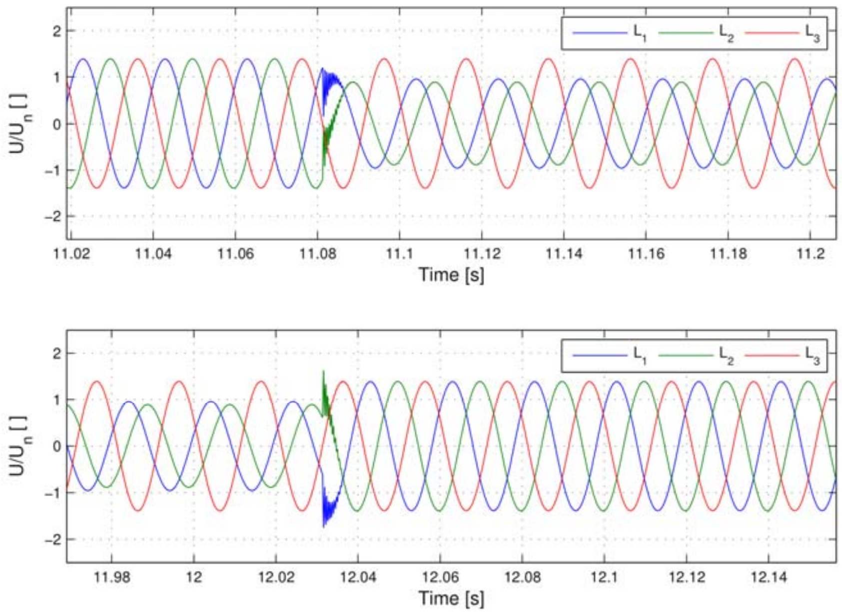
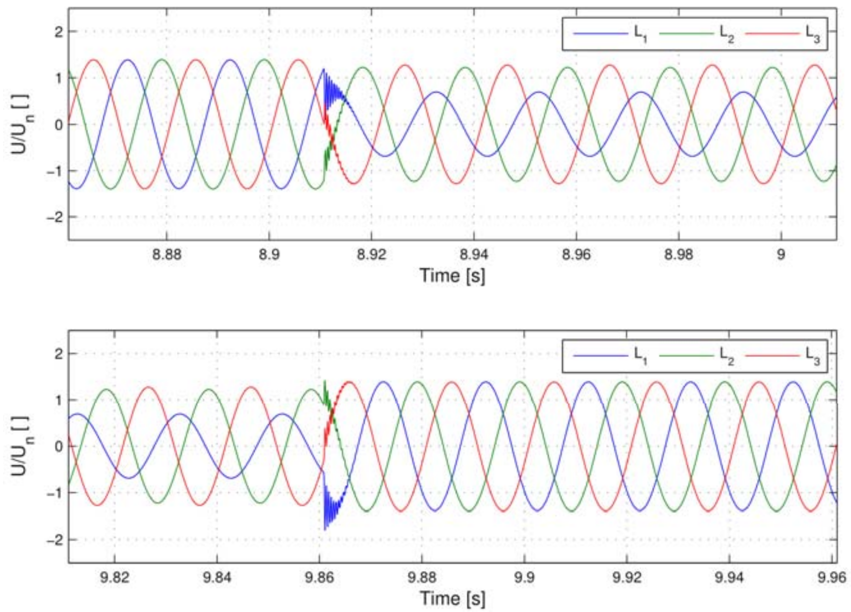
2. Power System Services of PV-systems
Test procedures for PV-systems – Testing procedures

- Unbalanced 2 phase fault
- MV/LV transformer: Dd



- Unbalanced 2 phase fault
- MV/LV transformer: Dy



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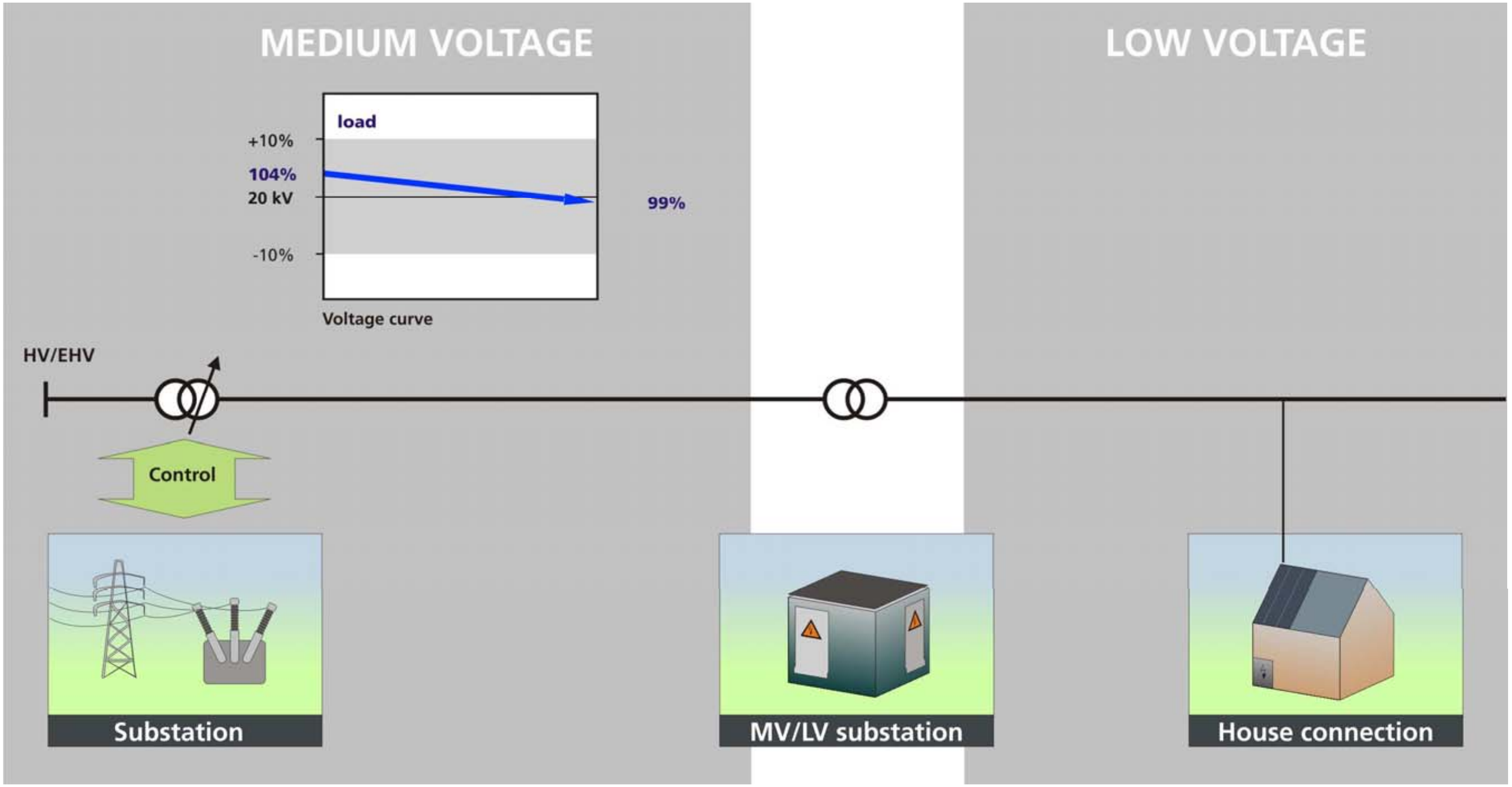
3. Application of power system services
Voltage Control



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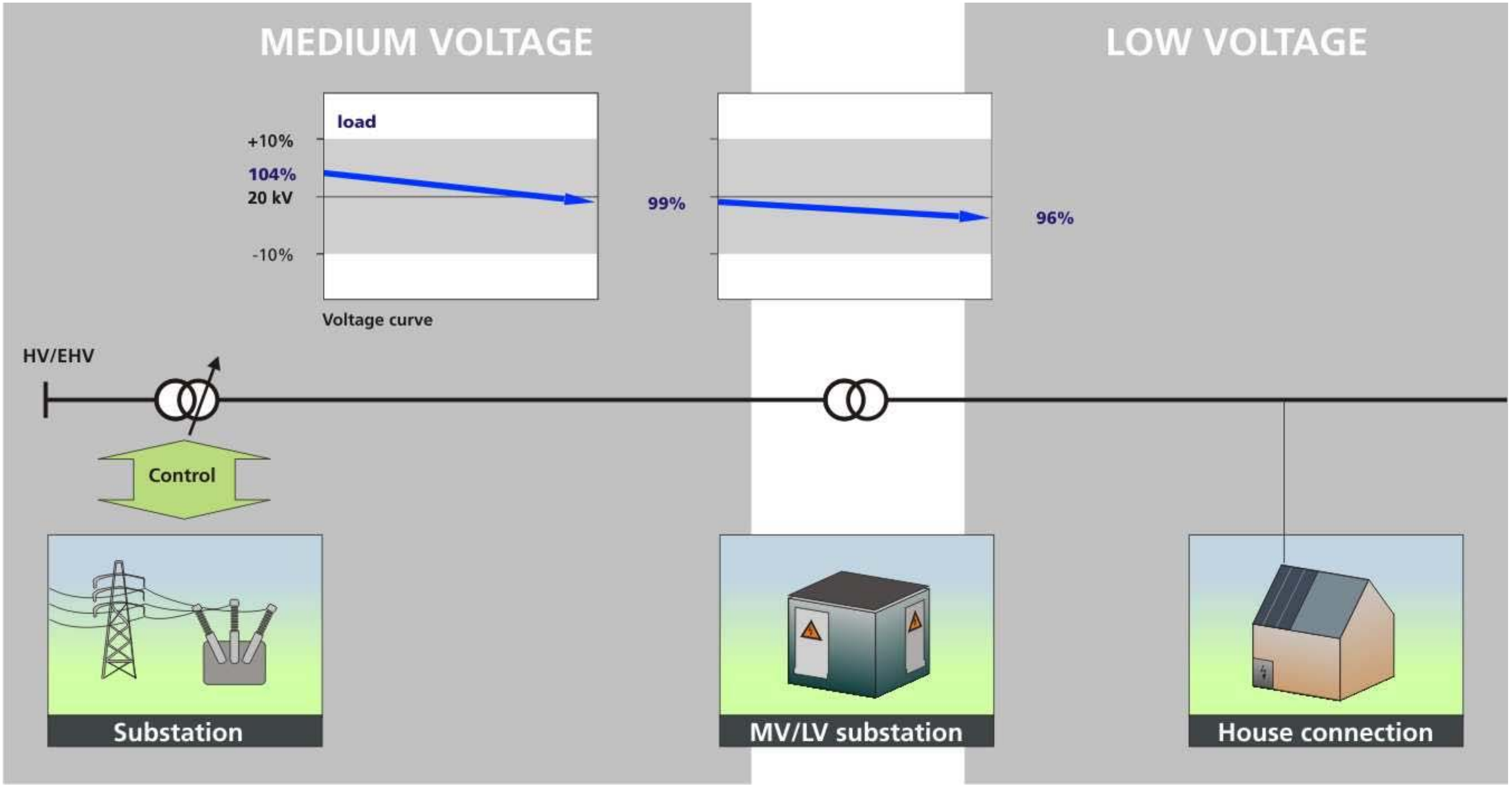

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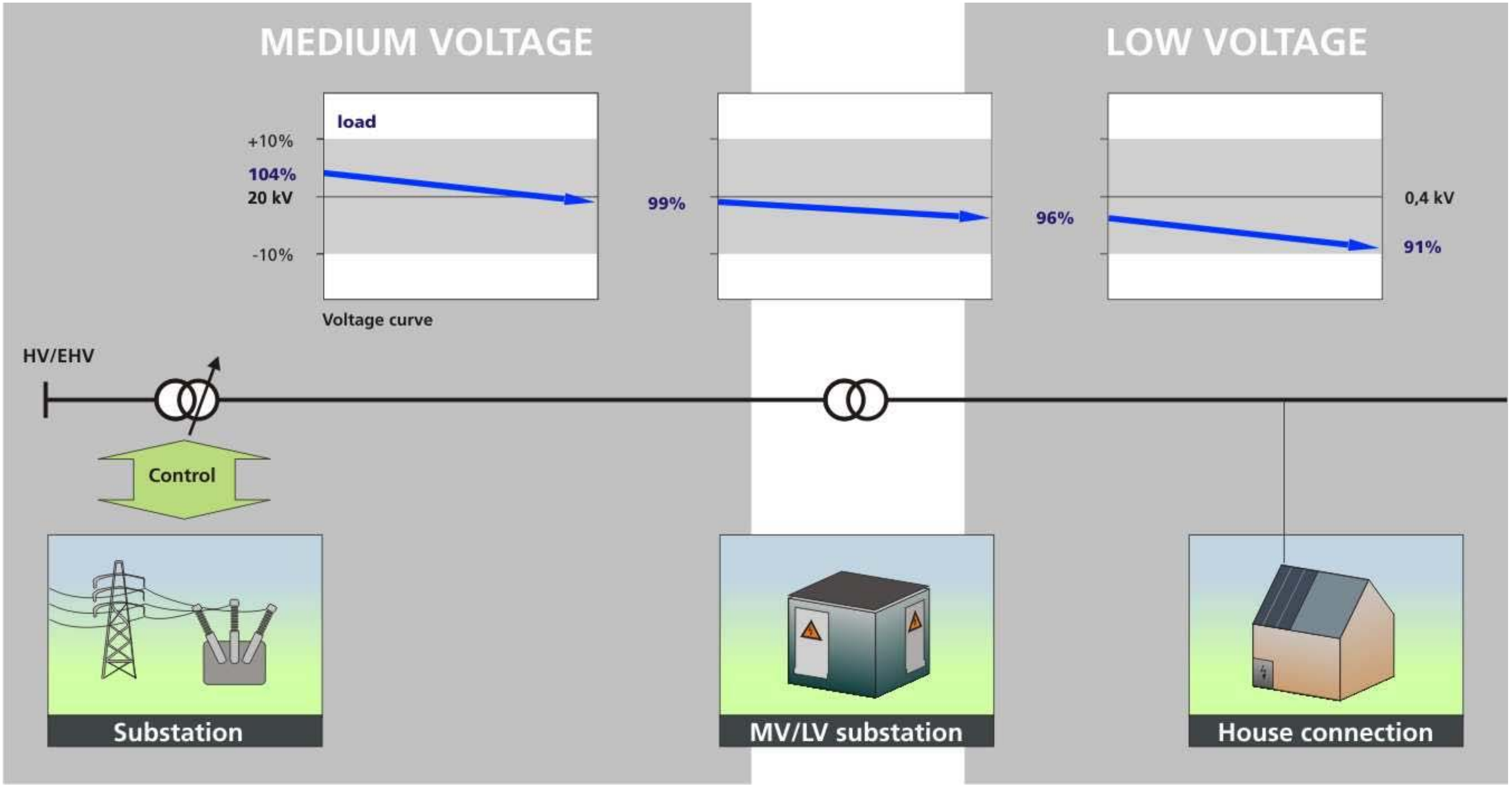

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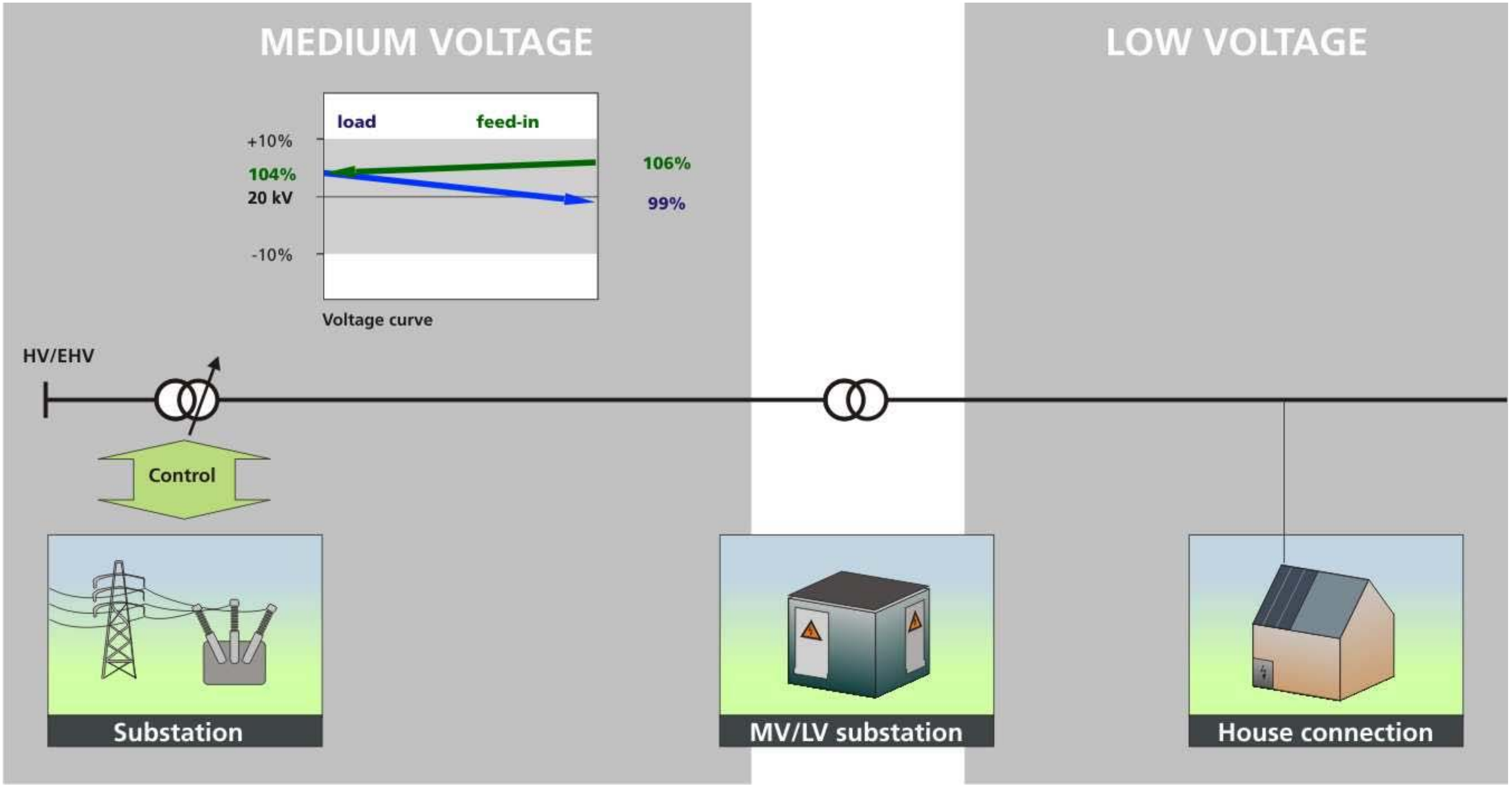

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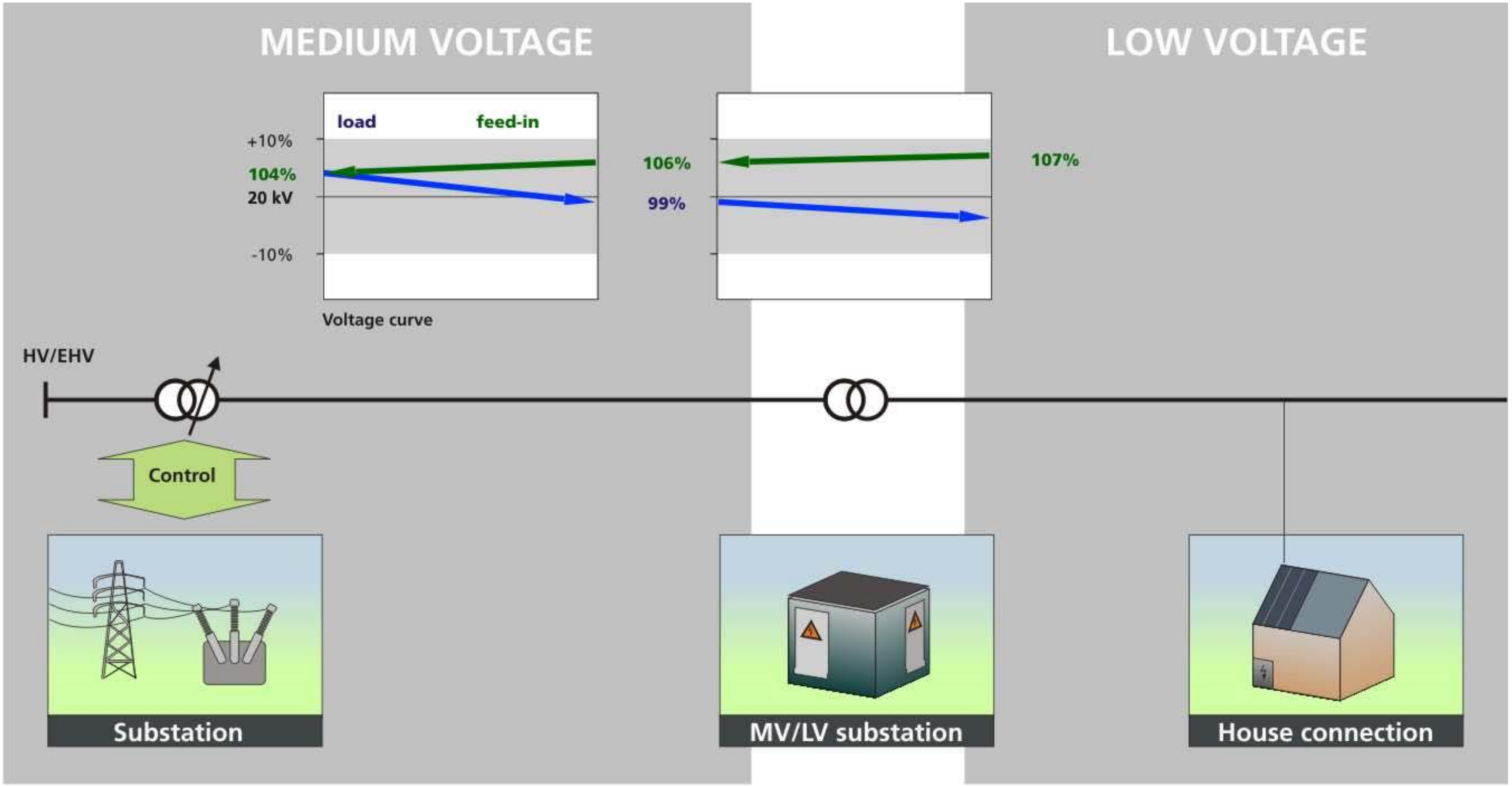

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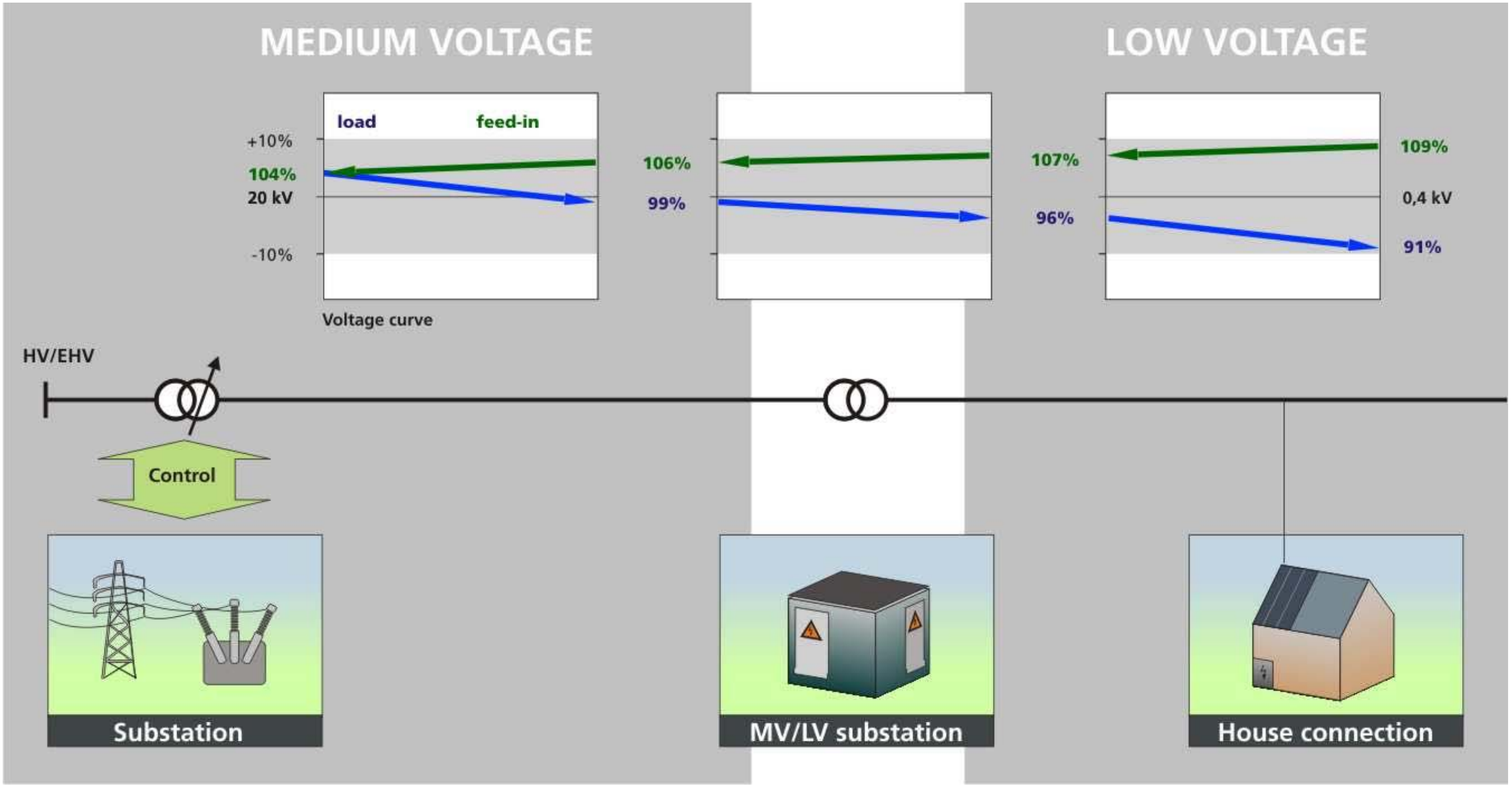

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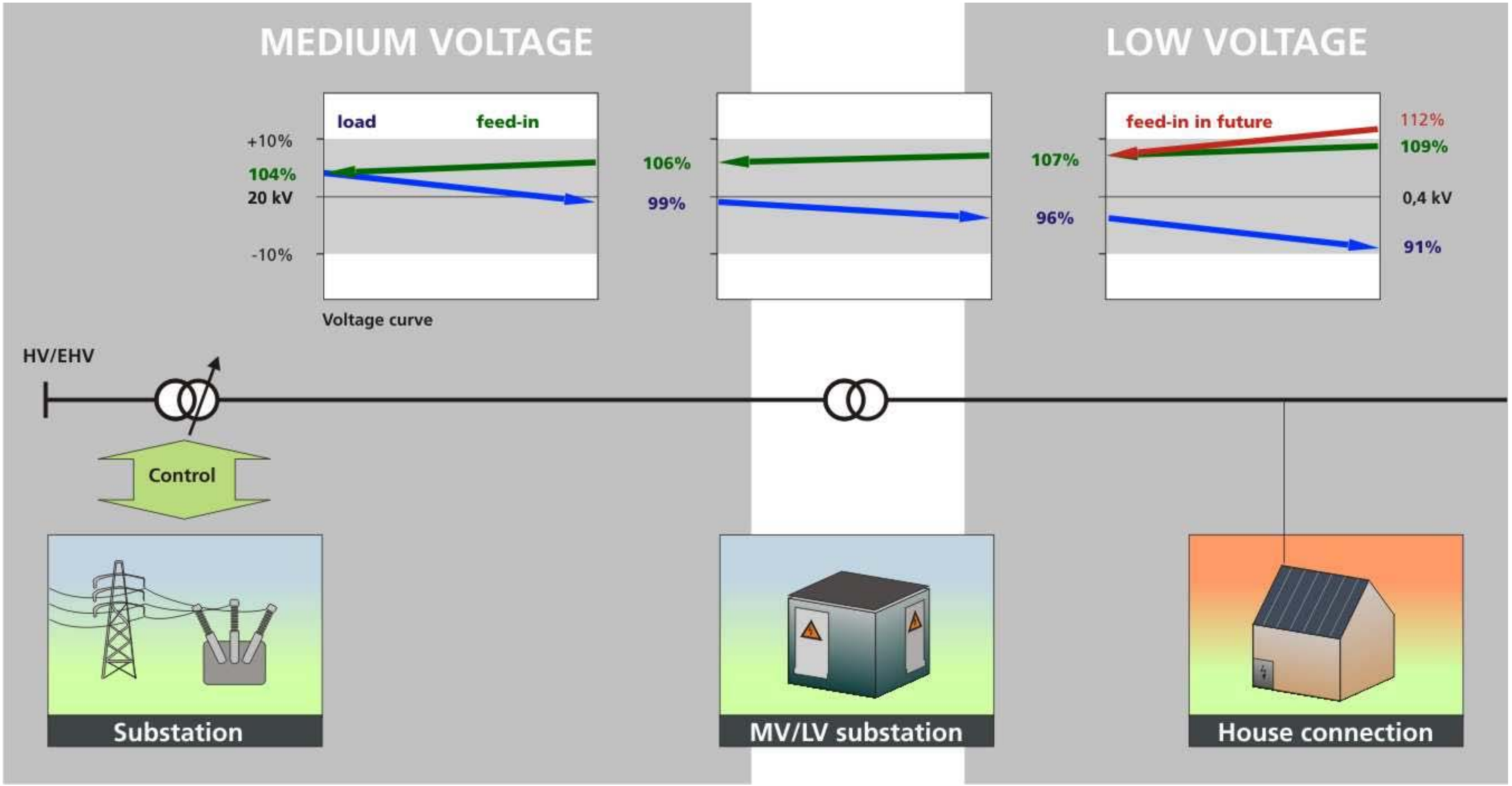

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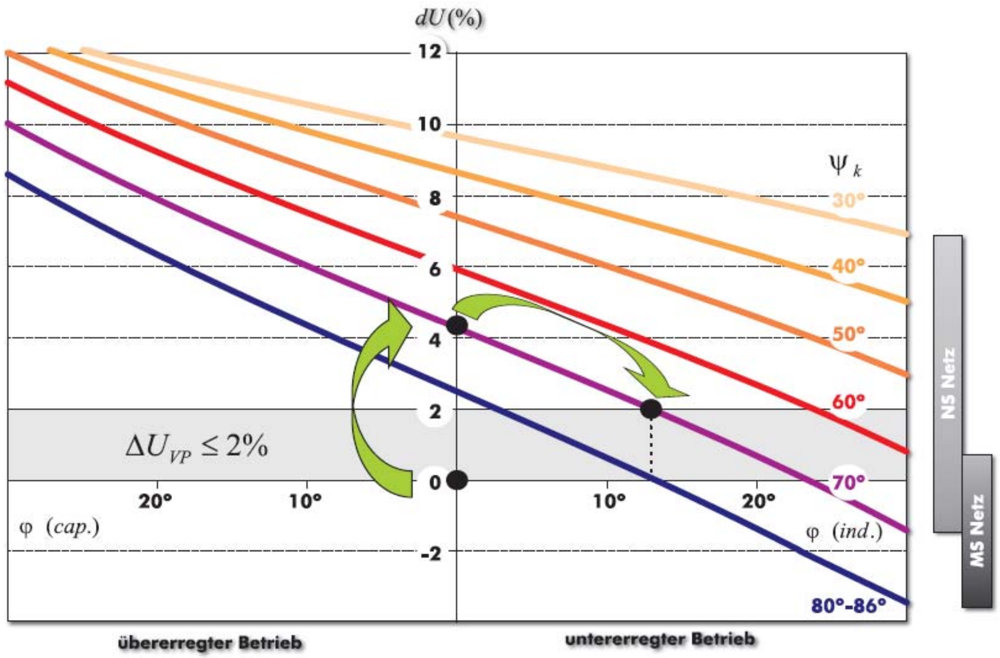
3. Application of power system services
Voltage Control – Reactive power

- Selective voltage change by power factor control of DER unit
  - ψ_k: network impedance angle
  - S_{SC}: Short circuit power
  - $S_{A,max}$: nominal power of DER unit

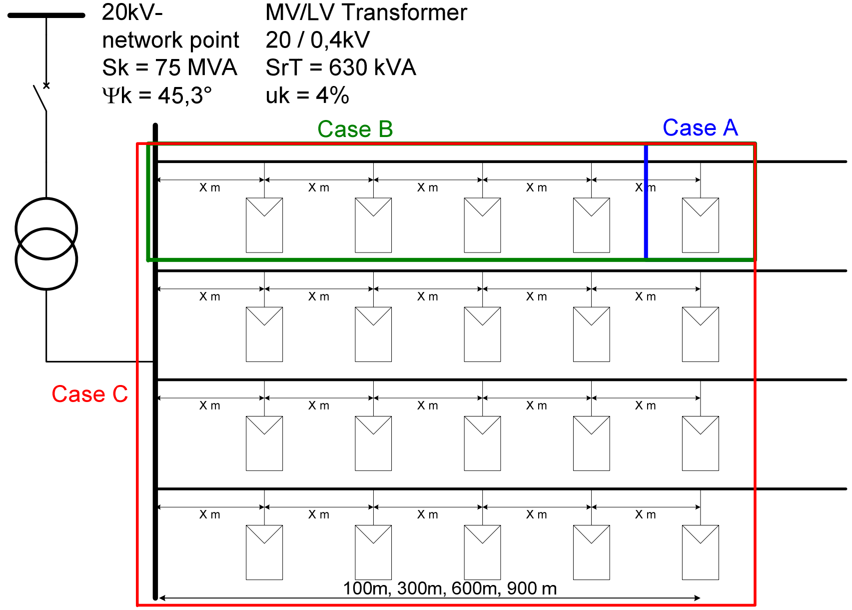
$$\Delta u_{aV} = \frac{S_{A,\max} \cdot \cos(\Psi_{kV} + \varphi)}{S_{SC}}$$



Source: B. Valov, Volle Nutzung der Netzkapazität und Spannungsstabilisierung durch neues Auslegungskonzept für PV-Kraftwerke, 24. Symposium Photovoltaische Solarenergie, Bad Staffelstein, 2009

3. Application of power system services
Voltage Control – Case studies

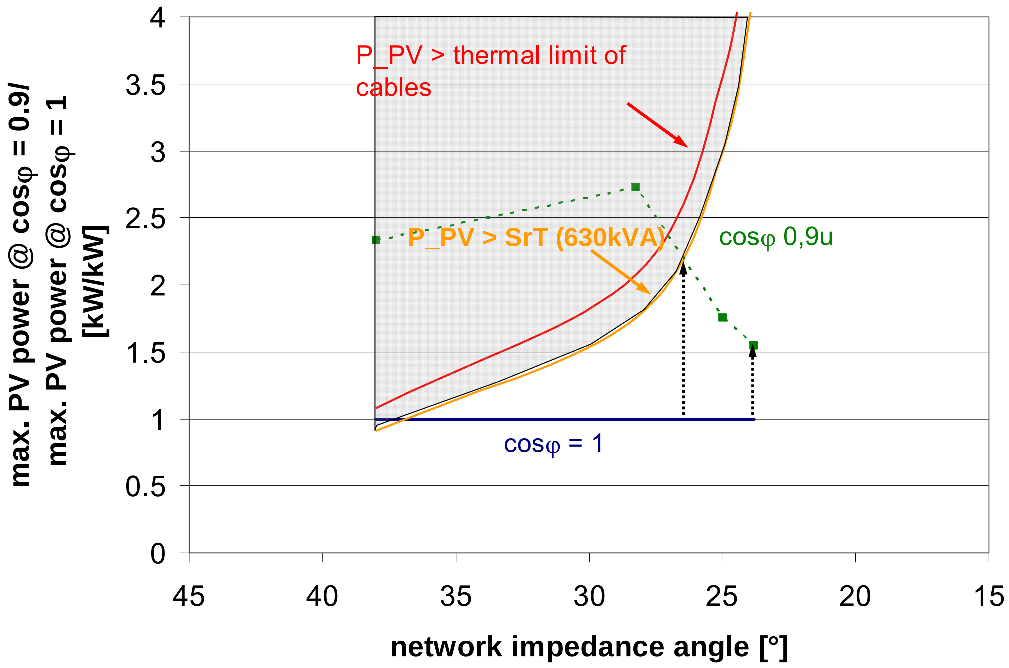
- Generic network case studies
  - Case A: Single feeder network, single PV-system
  - Case B: Single feeder network, five PV-systems
  - Case C: Four feeders, each with 5 PV-systems
  - Different feeders length are considered (100m, 300, 600, 900m)



3. Application of power system services

Voltage Control – Potential of reactive power

- Case C: 4 feeder, 5 PV-systems per feeder, cos φ=0.9, max. voltage rise 3%
- Relative increase of connectable PV systems due to reactive power voltage control varies between 1.5 and more than 2.
- At larger network impedance angles (resp. short feeder) the thermal limits of the network transformer or the cables may be reached.
- Example (S_k = 1,2 MVA, Ψ_k = 25° , 4x5 PV-systems)
  - cos φ = 1.0: 216 kW in total
  - cos φ = 0.9: 378 kW in total (factor of 1.75)



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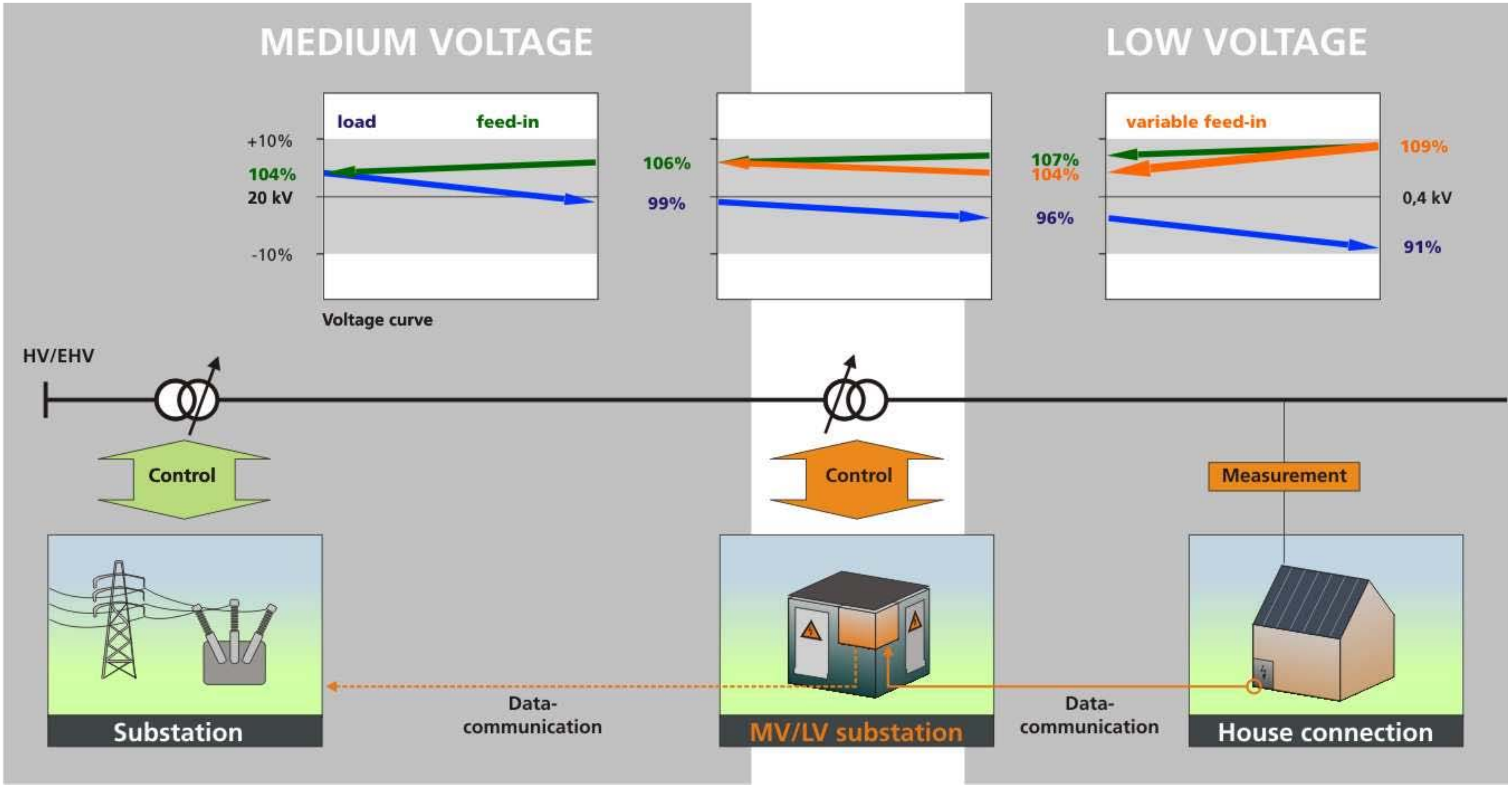
3. Application of power system services

Voltage Control – Active network components



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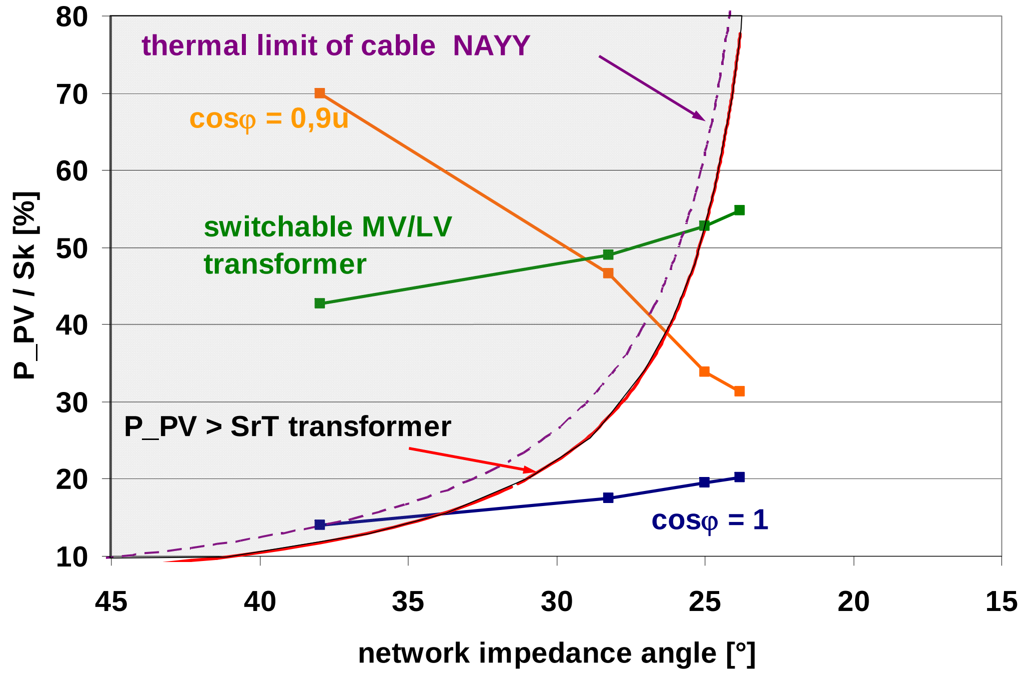
3. Application of power system services
Voltage Control – Active network components

- Extended Use of the available voltage band
  - Case C: 4 feeder, 5 PV-systems per feeder
- Switchable MV/LV transformers provide an alternative way to control the voltage in LV networks.
  - transformer with steps 2x ± 2.5%
  - allowed voltage rise increases from 3% to 8%
  - max. connection power increase by a factor of 2.7
- In particular useful for longer feeders
- Example (Sk = 1,2 MVA, Ψk = 25° , 4x5 PV-systems)
  - cos φ = 1.0: 216 kW in total
  - cos φ = 0.9: 378 kW in total
  - Smart transformer: 538 kW in total



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4. Conclusions

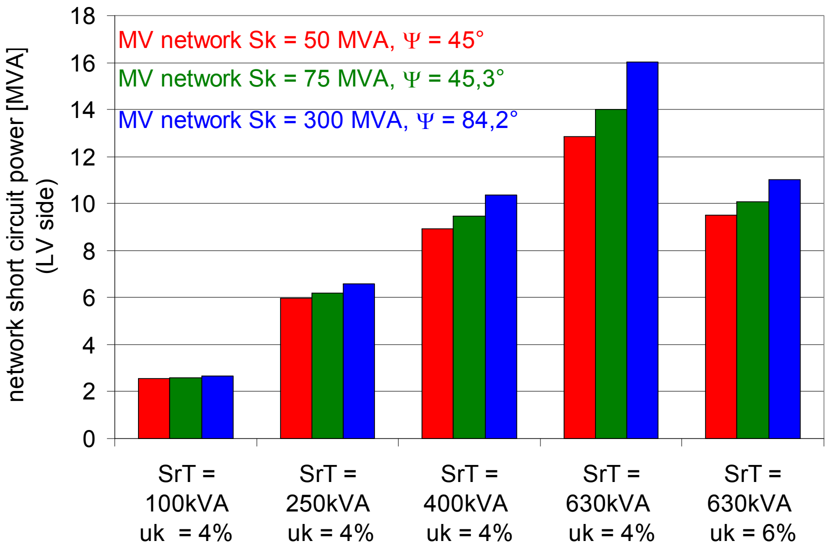
- Share of renewable energy sources increases
- Power system services
  - are required to keep network stability
  - are required to overcome network constraints for further increase of renewable generation
- PV-systems are well suited to provide power system services
  - Grid Codes describe technical requirements for DER units
  - Intensive testing of conformity with guideline is required
- Application of power system services of PV-systems
  - Voltage control is a major objective in distribution networks
    - By using reactive power voltage control the maximum permissible PV power may be increased by a factor 1.5 up to more than 2 (for the analyzed generic networks)
    - Controllable MV/LV transformer allows to connect 2.7 more PV power to the network compared to the normal case (suited for long feeders)

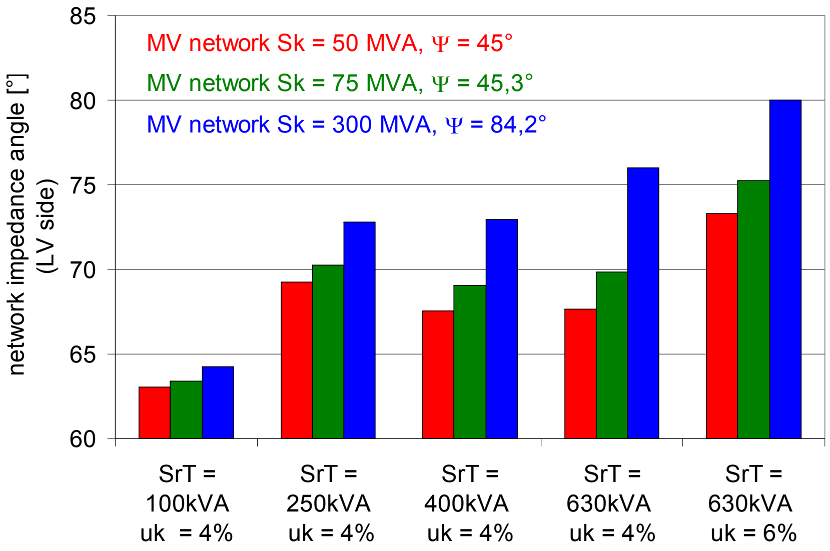
Backup

3. Application of power system services

Voltage Control – Effect of network parameters

- S_k and Ψ_k at the LV bus-bar of the MV/LV substation
  - Short circuit power and network impedance angle at the LV bus-bar of the MV/LV substation are mainly determined by the transformer
  - In particular the short circuit power (S_k) can be well estimated from apparent power (S_{rT}) and short circuit voltage (u_k) of the MV/LV transformer.





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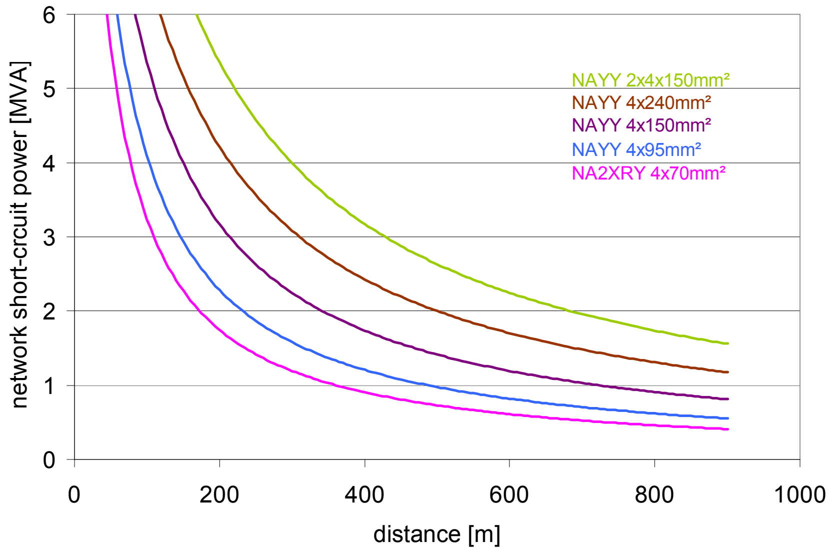
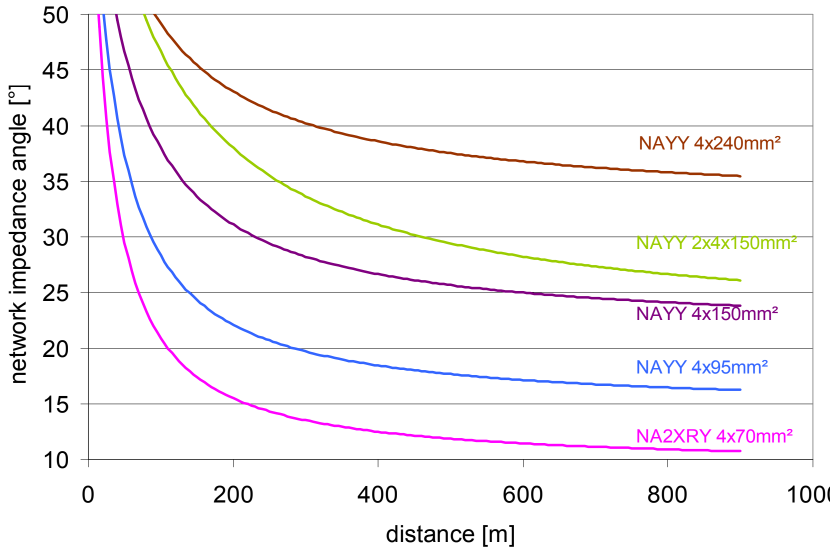
3. Application of power system services

Voltage Control – Effect of network parameters

- Effect of different cable types
  - S_k and Ψ_k decrease with increasing distance to the substation
  - The cable type determines how fast S_k and Ψ_k decrease
  - At long distances the effect of the cable type dominates
  - Example: 600m distance, NAYY 4x150mm² → S_k = 1,2 MVA; Ψ_k = 25°





Fraunhofer IWES

3. Application of power system services

Voltage Control – Maximum permissible connection power

- Power factor cos φ=1, max. voltage rise 3%)
  - S_k and Ψ_K at the end of the feeder are sufficient to describe maximum permissible PV power
  - The serial placement of PV systems leads to a higher amount of connectable power because of the lower voltage rise of the PV systems connected to stronger network points
  - Case C (parallel feeders) results in similar curves, but per feeder PV power is lower, because of the voltage rise in the substations LV-busbar