Grid Connection of Wind Farms

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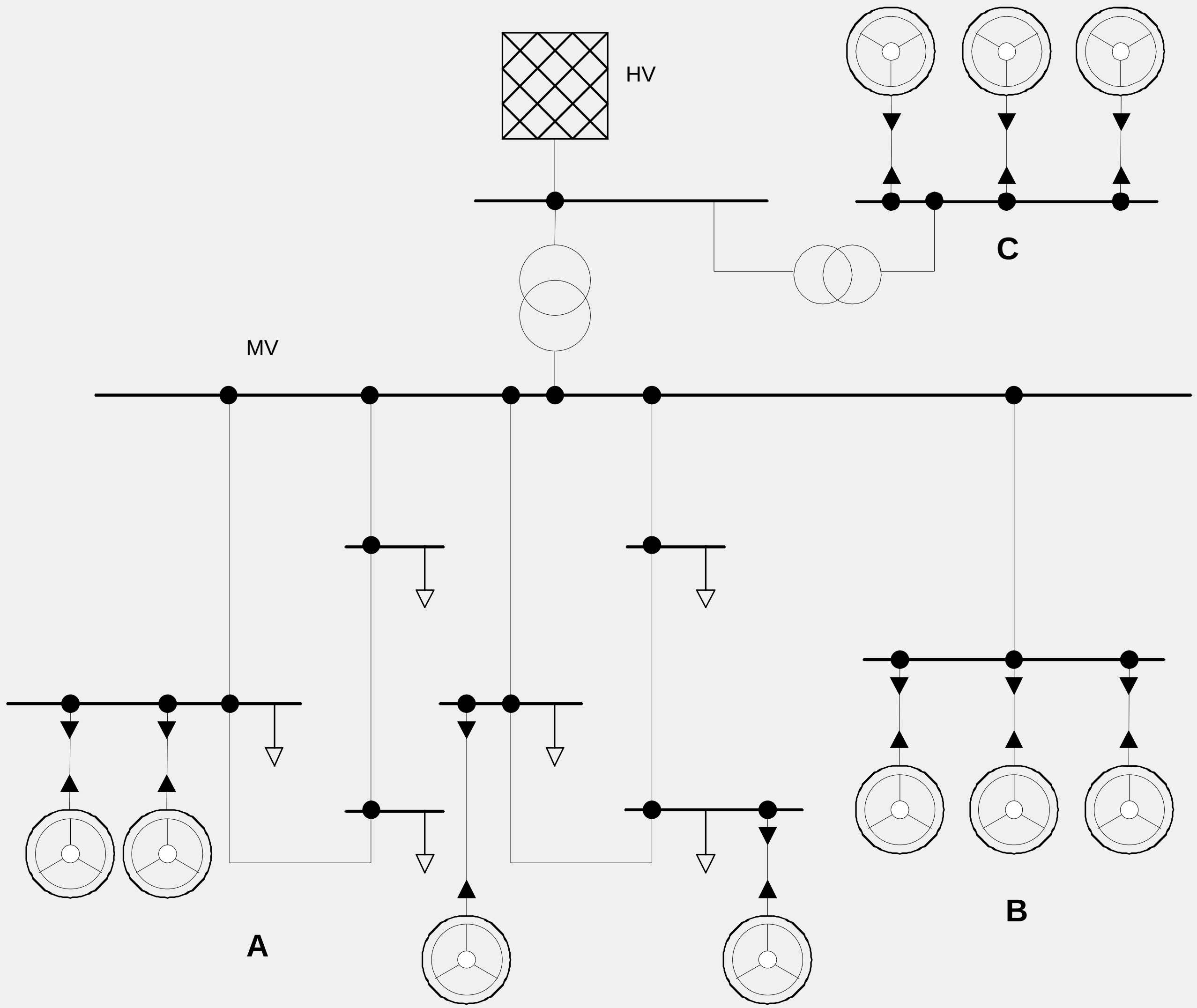
Grid Connection

- Impact on thermal loading of lines/transformers
- Impact on voltage during normal operation
- Short circuit currents
- Power Quality Aspects
  - Voltage dips because of WTG switching
  - Voltage dips because of transformer inrush
  - Continuous Flicker
  - Harmonics
- Behaviour during grid faults/Fault ride through requirements

Impact on Thermal Loading

Options for network connection



A Distributed/Embedded

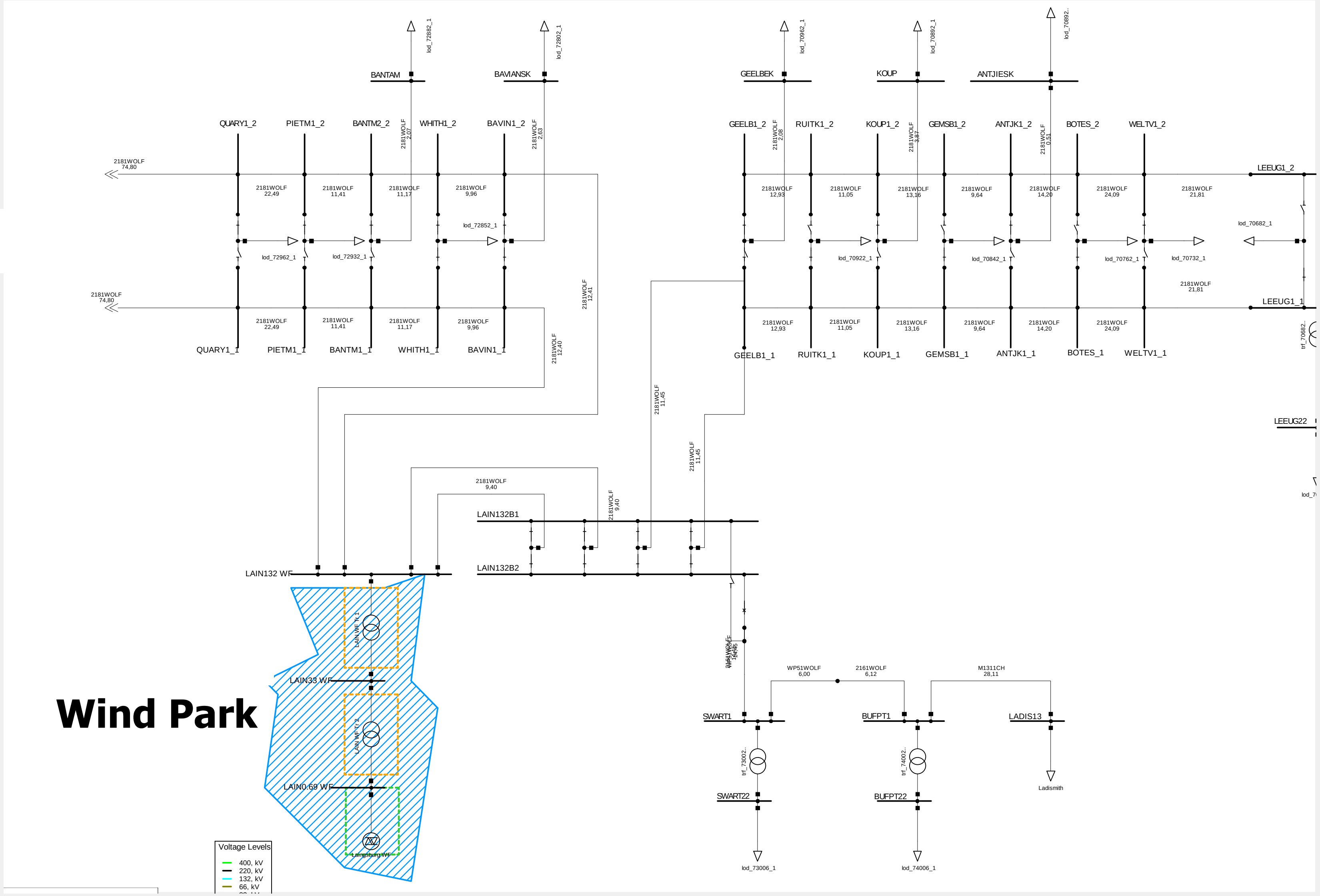
B MV Substation

C HV Substation

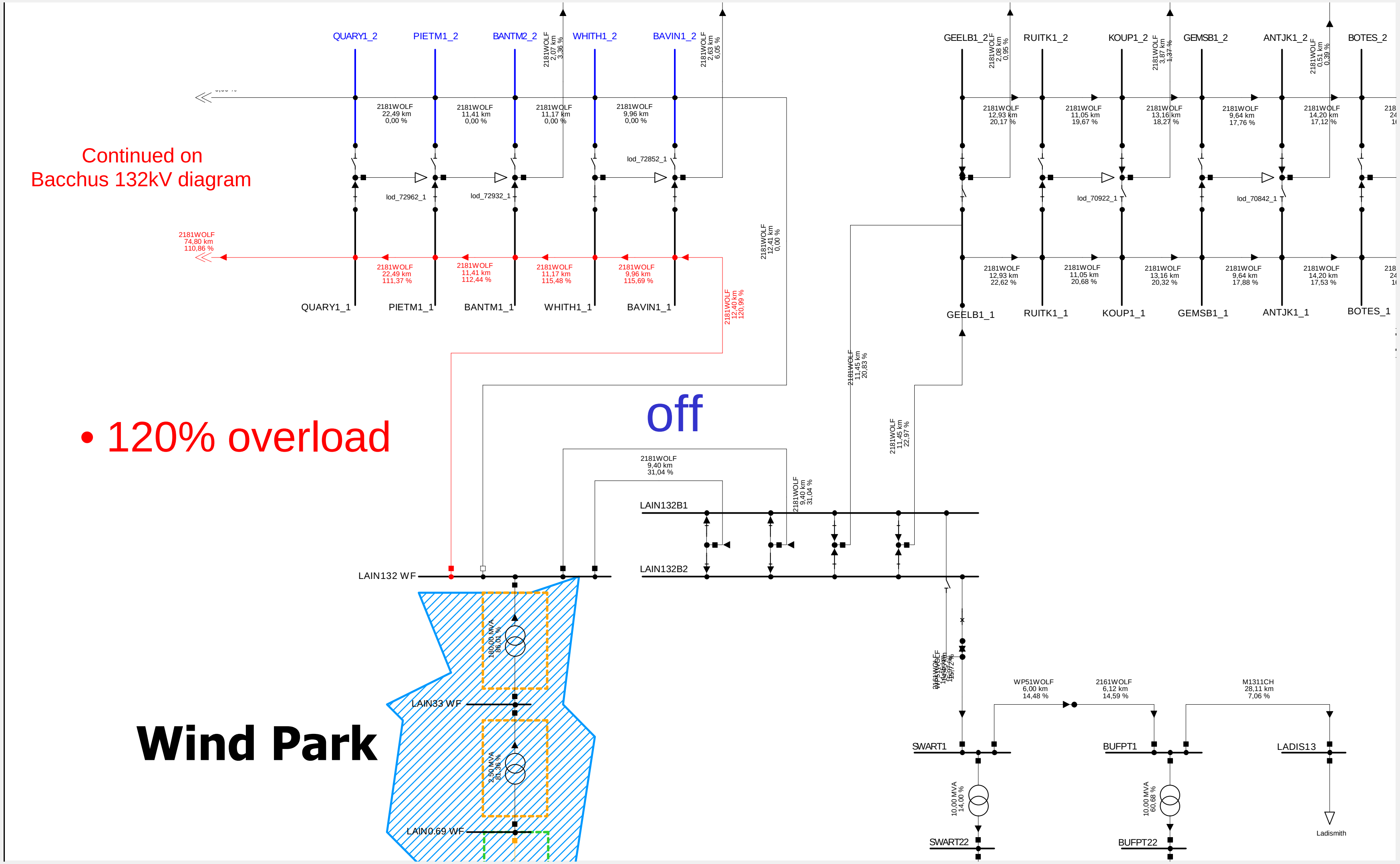
Impact on Thermal Loading of Lines/Transformers

- Additionally required transmission lines must be planned based on well defined scenarios, considering size and location of planned wind farms.
- Load flow studies required for combinations of:
  - Load level (High-/Low-load)
  - Wind speed level (High-/Medium-/Low wind)
- For avoiding investments in new transmission lines which are only required for a few hours per year, probabilities should be assigned to the studied cases.
- Assessment of potential of dynamic line rating recommended because of the good correlation of transmission line capacity and wind speed.

Impact on Thermal Limits – Example



Impact on Thermal Limits – Example

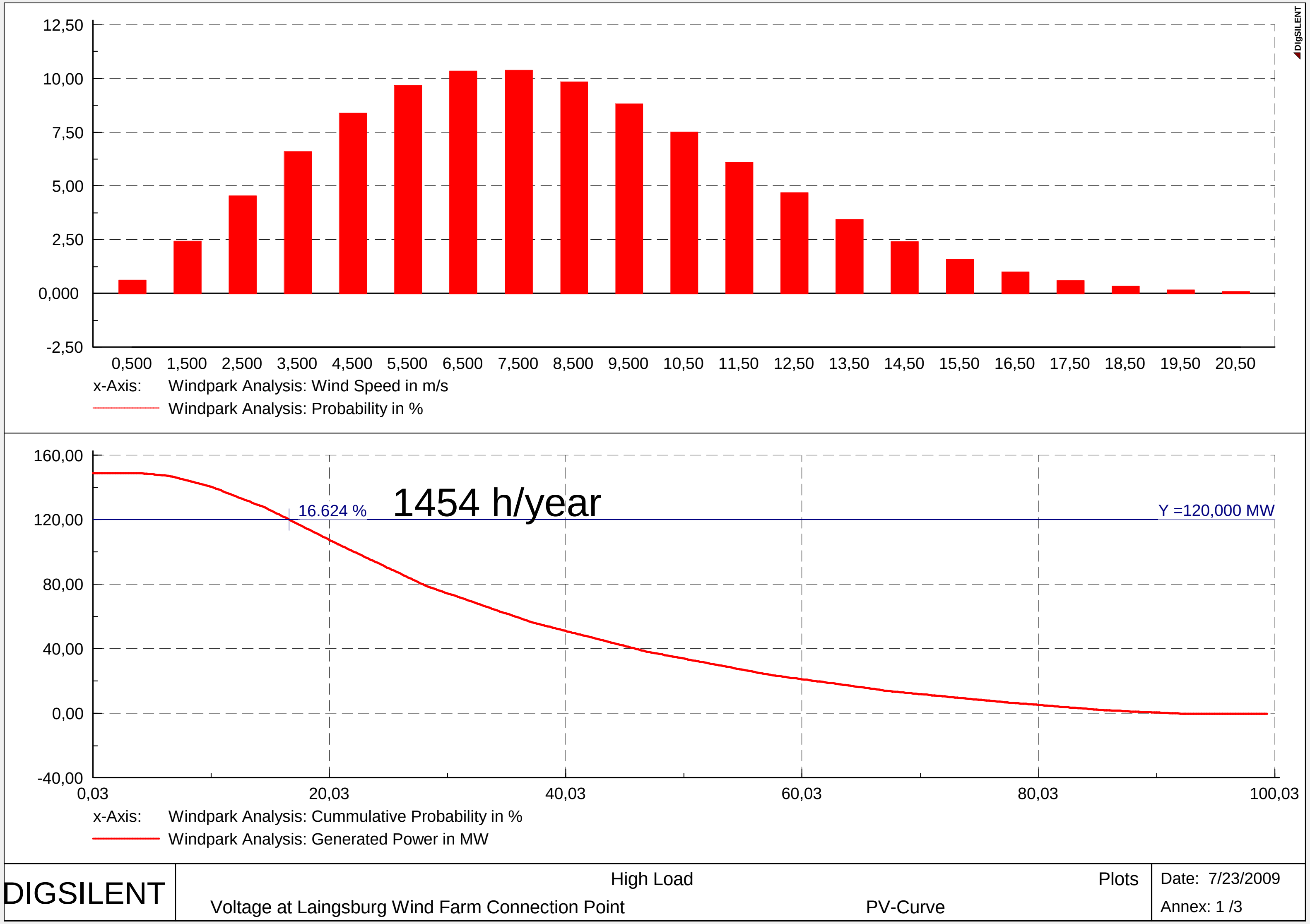


Impact on Thermal Limits - Example

General mitigation options if thermal limits are exceeded:

- Build a new line
- Limit wind farm output to 80% during all times (80% of rated output)
- Limit wind farm output in case of actual line failure (manual or automatic inter-trip).
- Consider dynamic line rating systems.

Violation of Thermal Limits – Cap Wind Farm Output



Violation of Thermal Limits – Cap Wind Farm Output

Not Delivered Energy depends on:

- Wind conditions (average wind speed)
- Site-specific aspects
- Power curve of turbines

Rough cost estimates (example):

- vw=7m/s:
  - Energy not delivered around 5% of potential energy
  - 150 MW wind-farm: 19 000MWh not delivered -> 23 750 000 R/year
- vw=8m/s:
  - Energy not delivered around 7,5% of potential energy
  - 150 MW wind-farm: 37 000 MWh not delivered -> 46 250 000 R/year
- Must be compared to annualized costs of required line upgrade

Violation of Thermal Limits – Cap Wind Farm Output under Contingency Situations

More cost effective solution:

- Limitation of wind farm output only in situations in which one circuit is available (planned outage, unplanned outage)
- In case of minor overloads (below emergency rating):
  - Manual action of system operator
- In case of major overloads (above emergency rating):
  - Automatic inter-trip scheme

Dynamic Line Rating - Potential

- Thermal loading of overhead lines depends on:
  - Ambient temperature
  - Wind speed -> correlation with wind generation

- Wind-generators:
  - cut-in wind-speed: 2.5...4m/s, rated: 12...16m/s
  - But: height, environment etc. must be considered too!

Ambient Temperature	**Line Rating expressed in MVA at 66 kV***		
	Wind Speed = 0.5 m/s	Wind Speed = 3.0 m/s	Wind Speed = 5.0 m/s
30 ºC	22.6	39.9	49.5
35 ºC	16.5	32.9	41.5

Impact on Voltage Variations

Voltage Variations

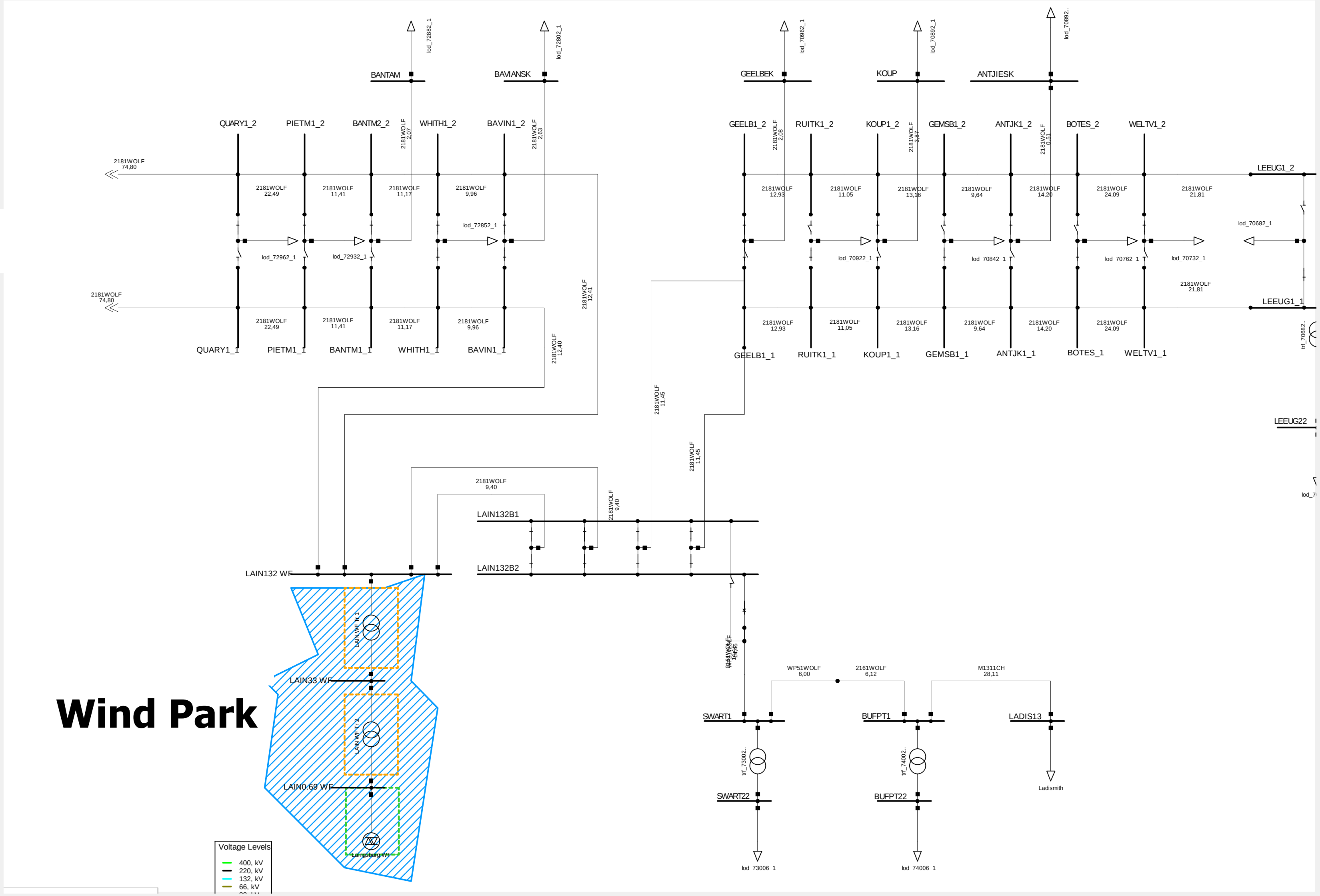
- Distribution Grids: Considerable voltage variations for varying MW because of low X/R ratios (large R)
- Transmission Grids: Substantially less voltage variations for varying MW becaus of high X/R ratios (low R). Contingency cases are more relevant.
- Mitigation Options:
  - Q(P)-Characteristic (open-loop voltage compensation)
  - Voltage control (voltage feed-back)

Voltage Variations - Procedure

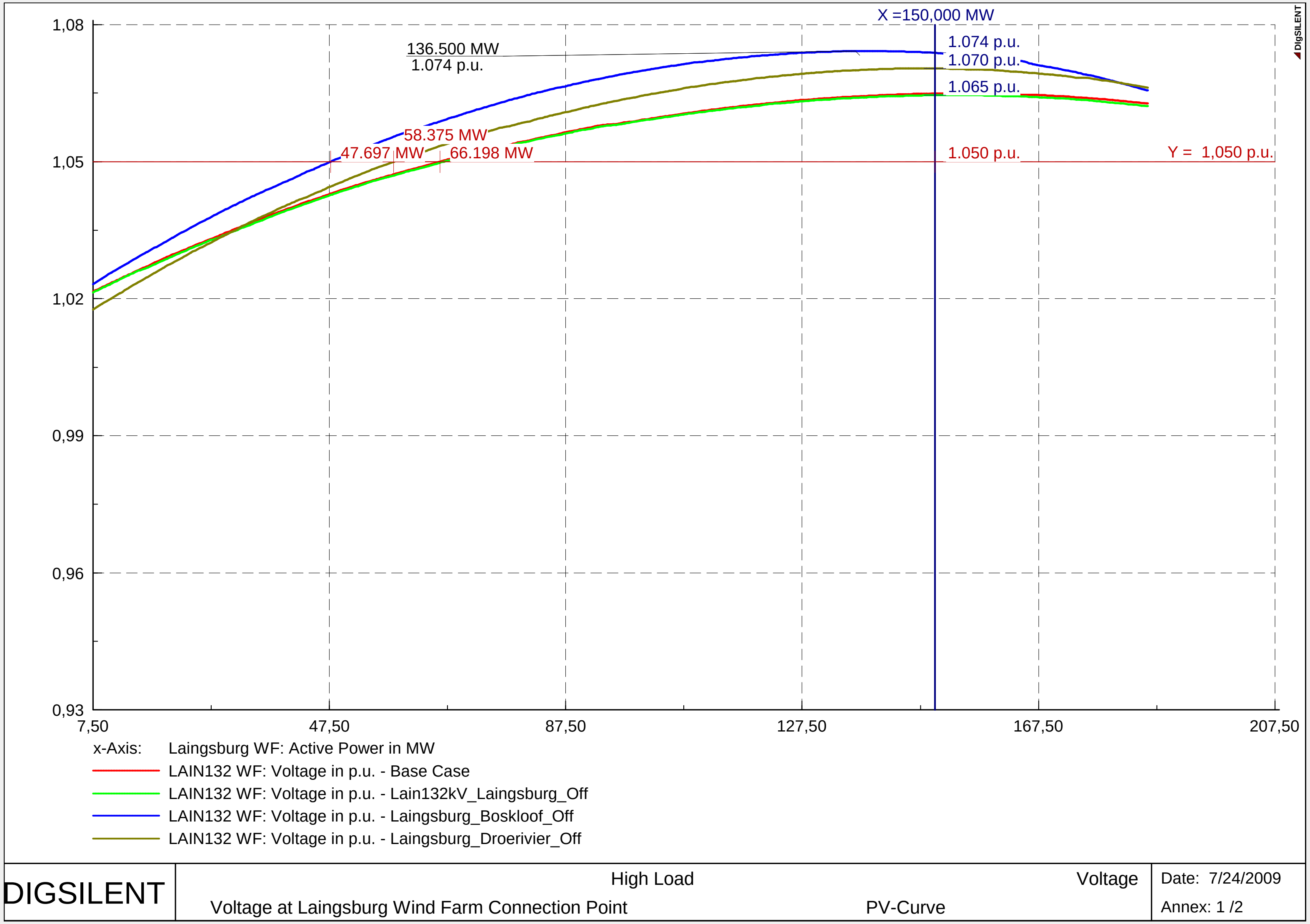
- Step 1 - System Operator: Identify required reactive power range at connection point
- Step 2 – Wind farm planner: Design the reactive power capability for complying with reactive capability requirements.

- Step 1 might be defined by a general Grid Code requirement -

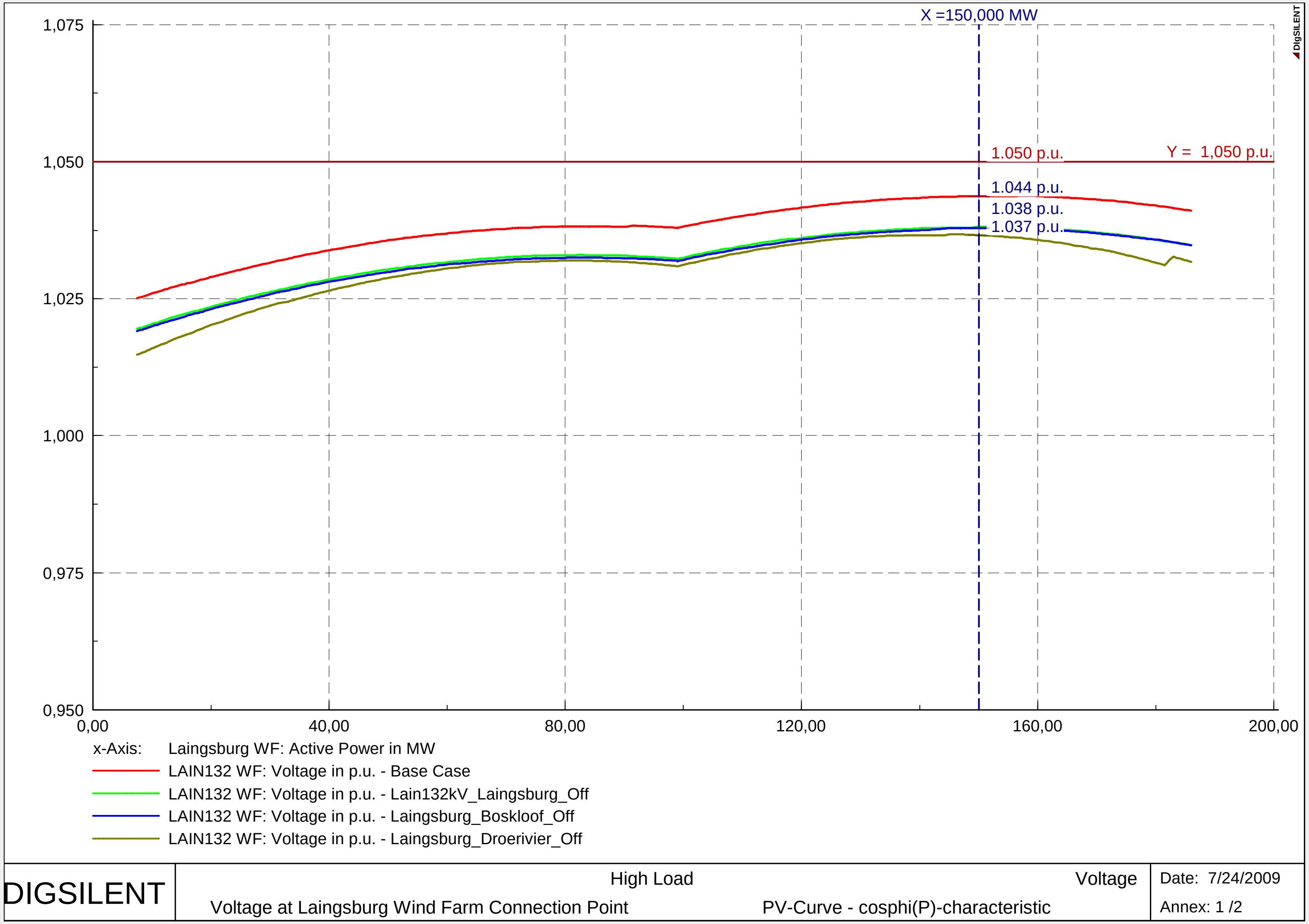
Example 1: Connection to Distribution/Subtransmission Grid



Voltage Variations/Step 1 – Example 1: cosphi constant (=1)



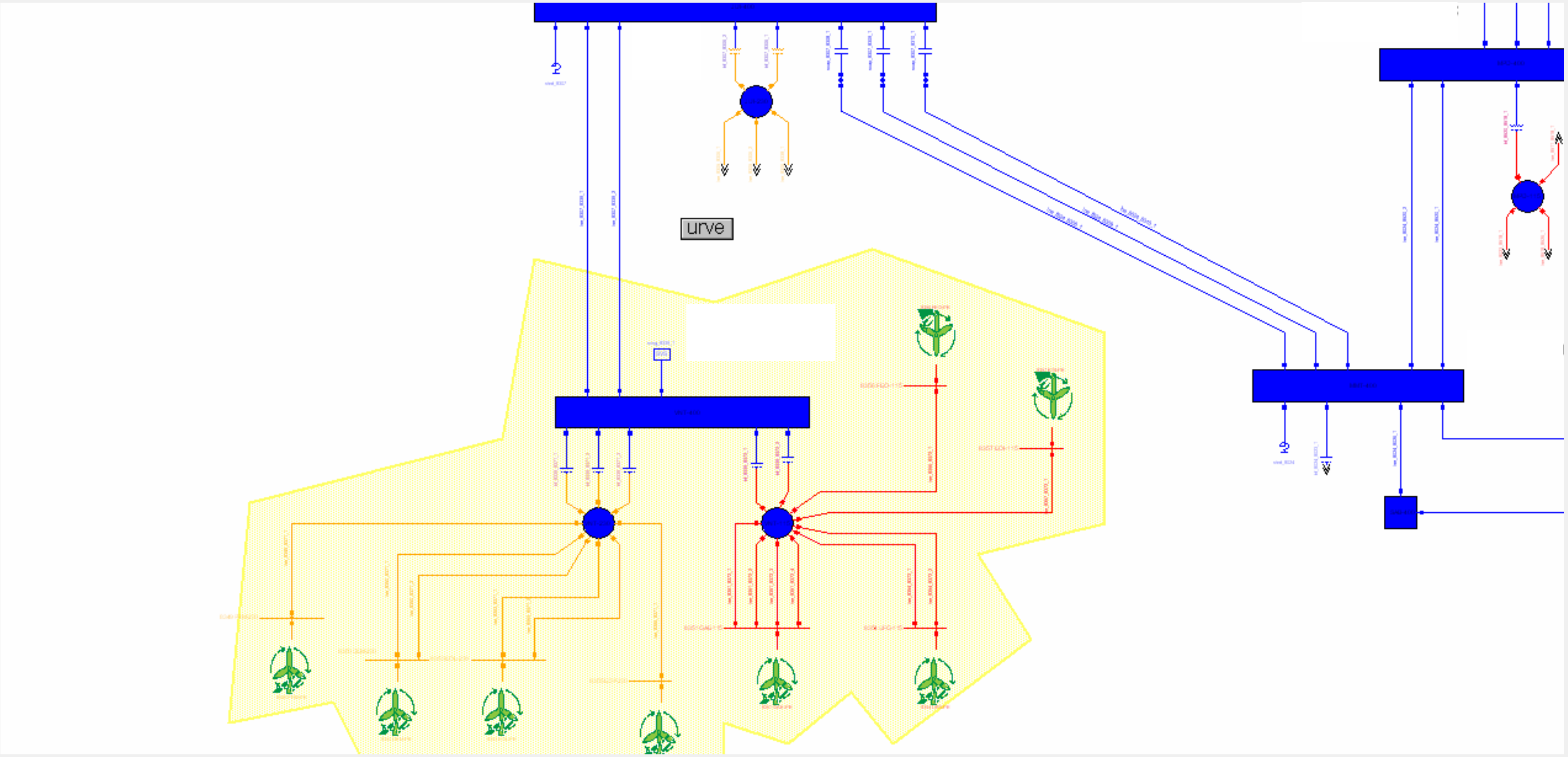
Voltage Variations/Step 1 – Example 1: cosphi(P)-characteristic



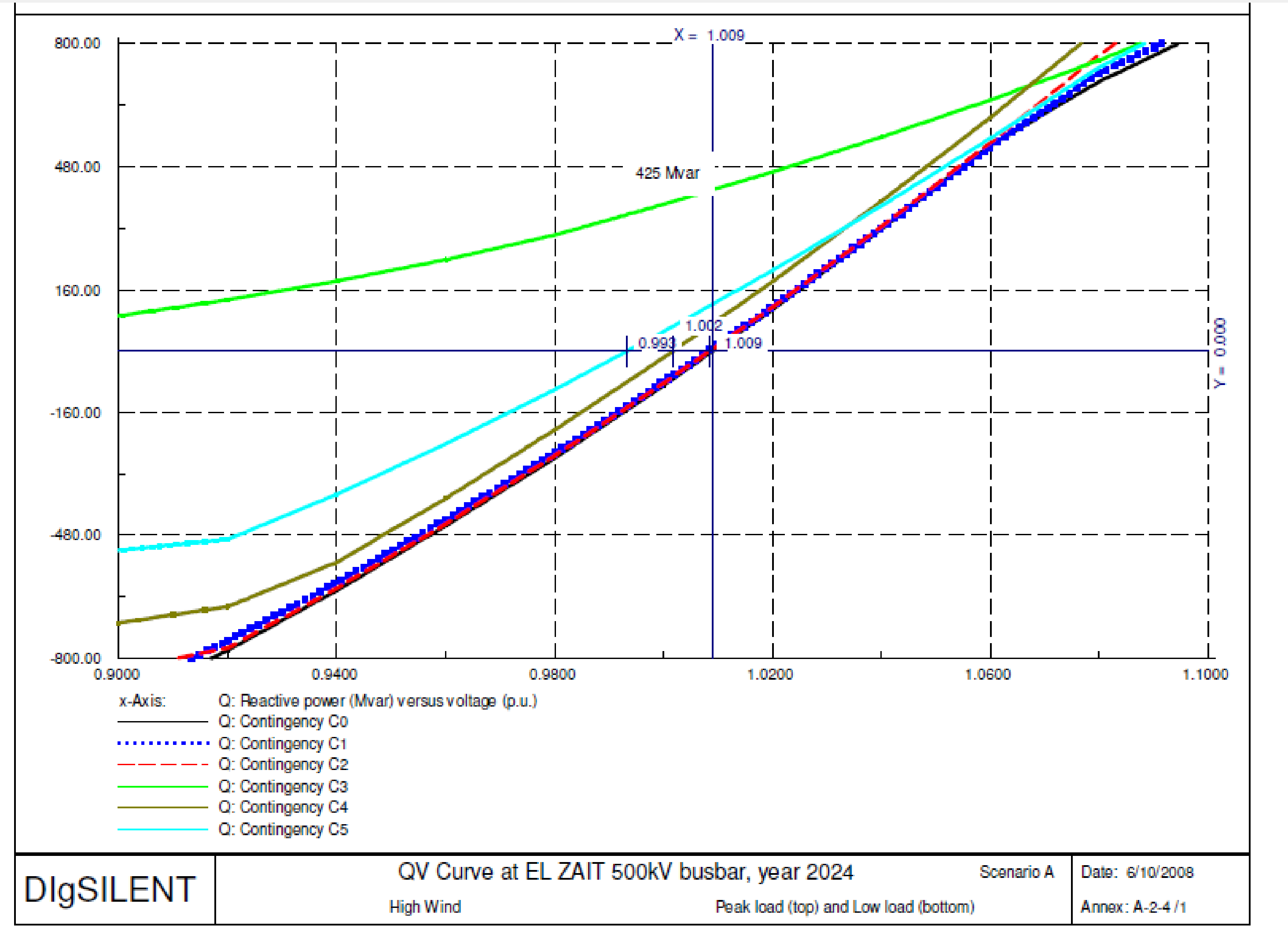
Voltage Variations- Example 1: Summary

- High voltages in case of cos(phi)=1
- Small voltage variations if cos(phi) adjusted to actually generated power (absorbing vars for compensating increasing voltage)
- Voltage control (with voltage feed-back) at wind farm connection point is possible but not required in this particular case because:
  - Only small voltage steps in case of contingencies
  - Only small voltage variations in case of different operational scenarios (high/low load)
  - No voltage stability issue

Example 2: Large Wind Farms at Transmission Level



Voltage vs. Reactive Power – Voltage Stability



Voltage Variations- Example 2: Summary

- Small Voltage Variations in function of active power variations (large X/R ratios)
- High Voltage Variations in case of critical contingencies
- Voltage control (with voltage feed-back) at wind farm connection point is required for maintaining voltage stability
- Required reactive power range can be determined by analyzing QV-curves

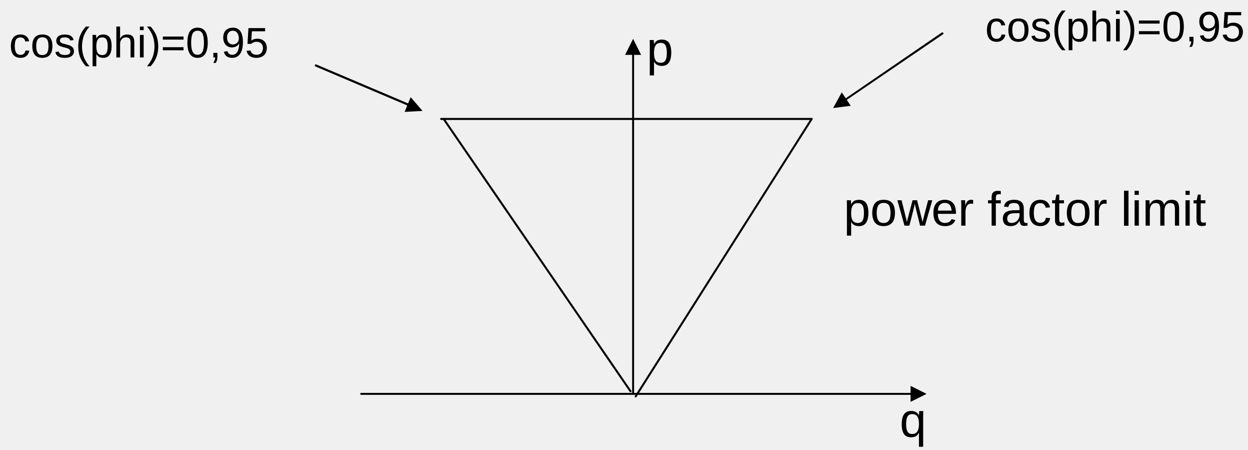
Voltage Variations/Step 2 – Wind Farm Design

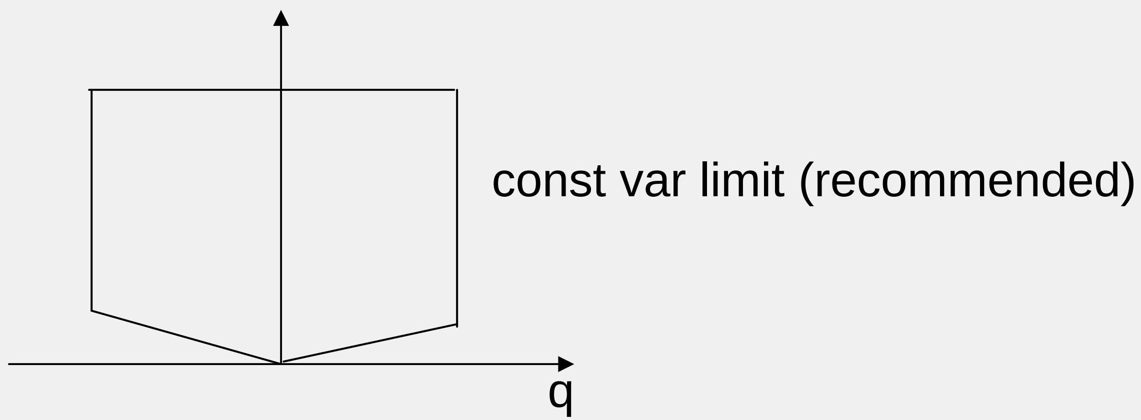
- Wind farm design must consider reactive power requirements.

- Reactive power capability at grid connection point is limited by:
  - Reactive power capability of wind turbine generators (WTGs)
  - Thermal ratings of cables in the wind farm collector system.
  - Voltage variations at the LV-nodes (voltage range of operation of WTGs)

- Requirement for additional reactive power compensation devices (STATCOM, switched shunts) must be taken based on:
  - Required reactive power capability
  - Required dynamic performance of voltage/reactive power control.

Reactive Power – Voltage Control





Voltage Variations - Wind Farm Design

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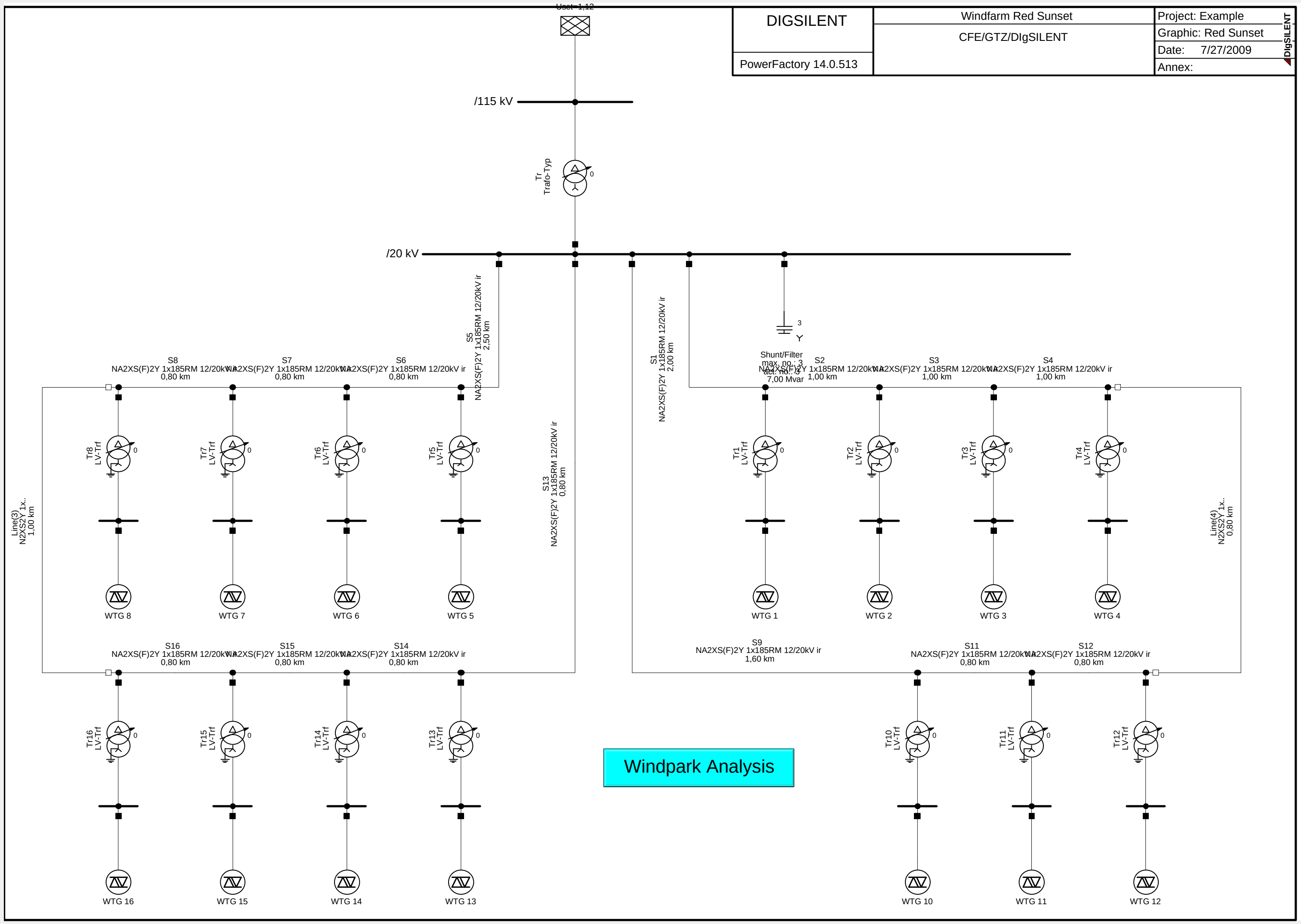
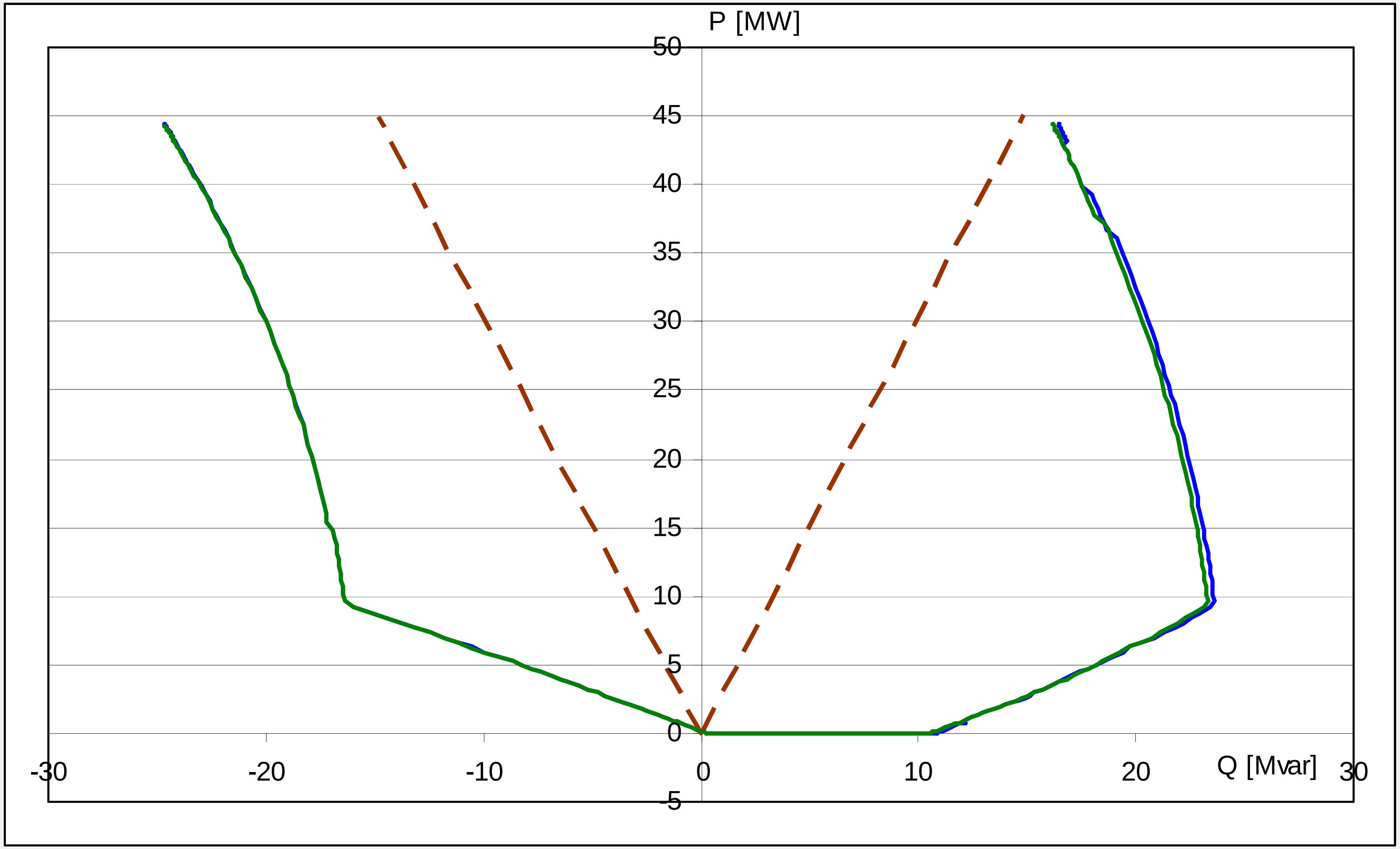
Voltage Variations – Wind Farm Planning Studies



Voltage Variations – Wind Farm Design Studies

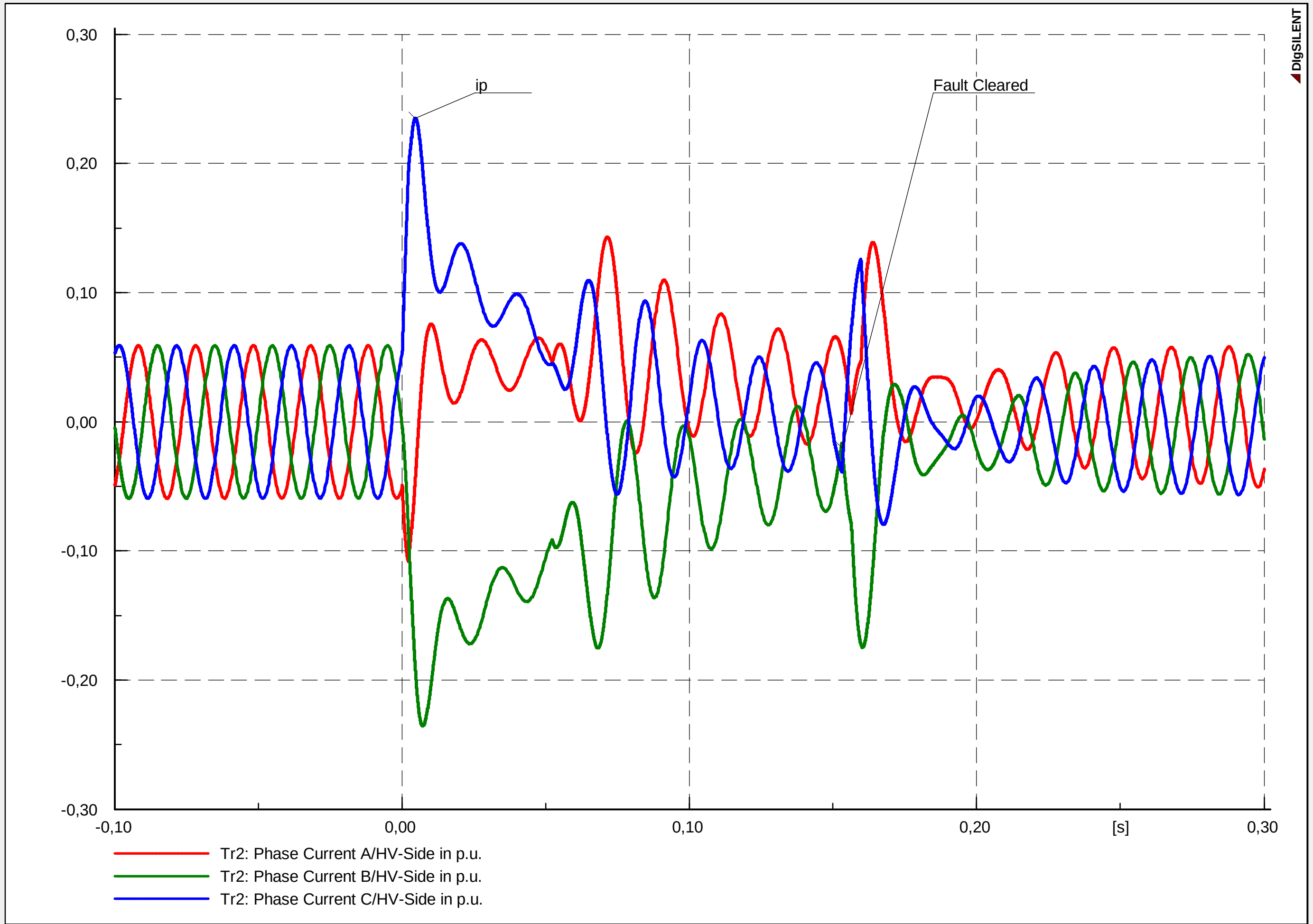


Short Circuit Contribution

Short Circuit Contribution of Wind Farms

- Calculation of max. short circuit currents:
  - Impact on short circuit ratings of existing components (substations, CB-ratings, cable-/line ratings, transformers etc.)
  - Impact on new components, inside the wind farm
- Calculation of min. short circuit currents:
  - Verification of protection settings

Short Circuit Contribution of Wind Farms



Fault Current of DFIG with Crow-bar protection

Short Circuit Contribution - Modelling

- DFIG and WTGs with fully rated converter are devices with controlled currents.
- DFIG is usually equipped with protection mechanisms (Crow-bar, Chopper), which make short circuit behavior highly non-linear.
- Difficult to model for steady state short circuit analysis, which is typically based on Thevenin-equivalents.
- No special consideration of WTGs given in IEC 60909.
- Proposed approach:
  - „Equivalent Synchronous generator“ approach: Characterizing WTG short circuit currents by subtransient and transient parameters.
  - Approach suitable for planning studies but not for highly accurate studies.

Power Quality

Power Quality

- Impact on Flicker
  - Continuous flicker
  - Flicker following switching actions (WTGs, Inrush)

- Impact on Harmonics
  - Harmonic injections
  - Impact on harmonic impedance

Continuous Flicker

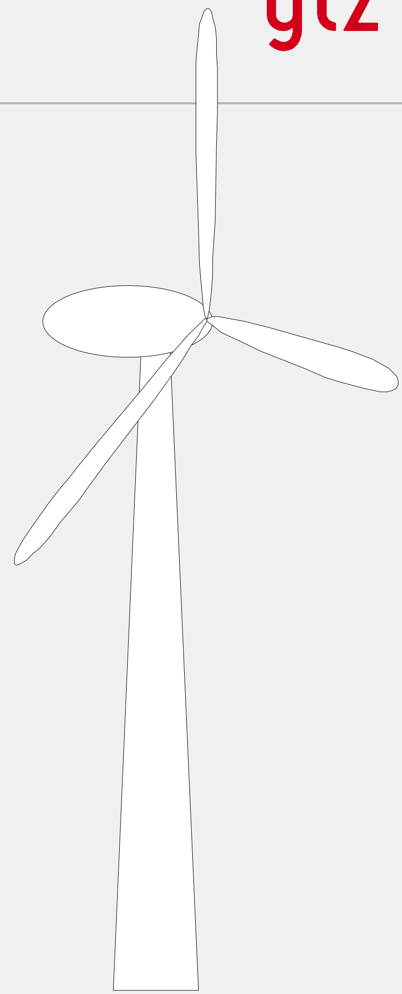
Caused by

- Turbulences
- “Rotational sampling”:
  turbulence variation across the rotor
- Tower Shadow
- Torsional oscillation

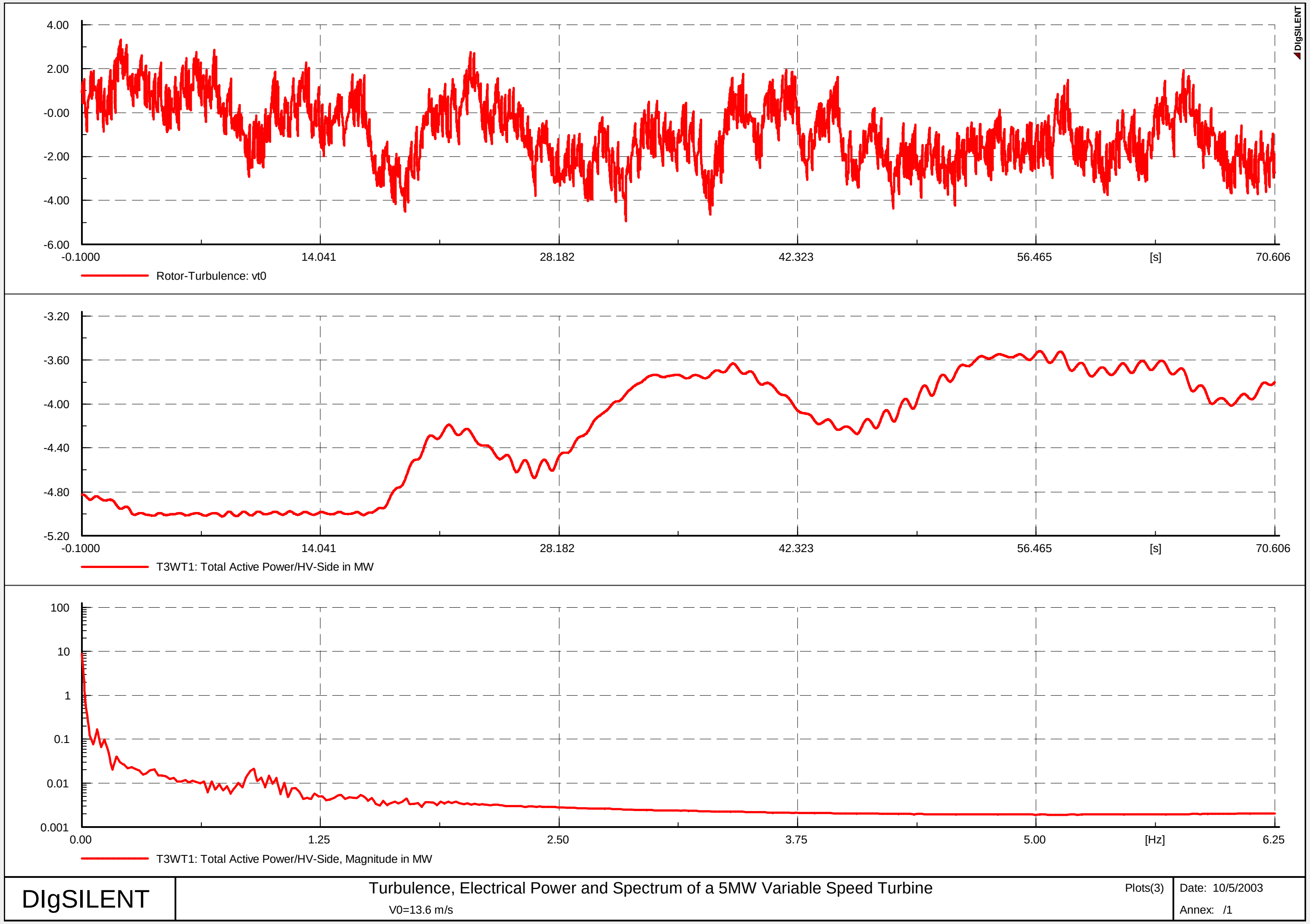
Applicable Standards:

- IEC 61000-3-6, IEC 61400-21

Mexican Grid Code: Pst<0,35
Plt<0,25



Continuous Flicker - Example

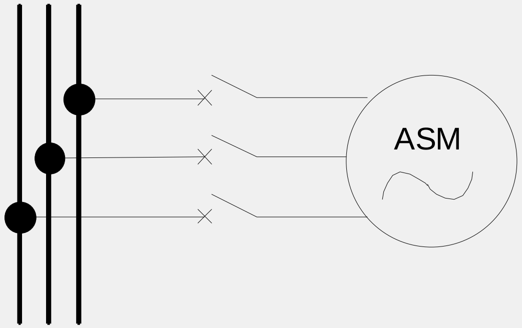


Flicker due to Switching Actions

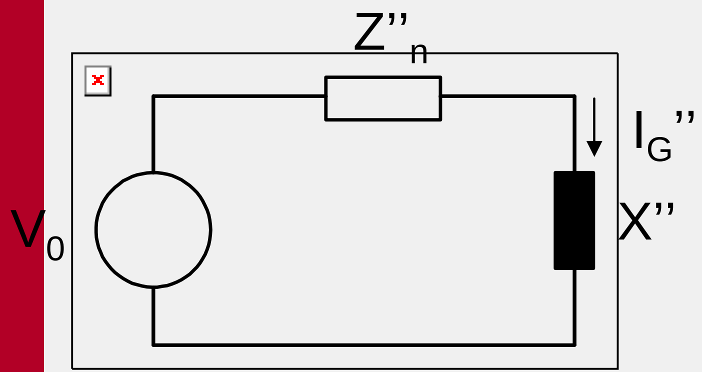
- WTGs automatically synchronize to the grid if $v_w > v_{cutin}$
- Variable speed WTGs: Very smooth synchronisation
- Fixed speed WTGs: Considerable voltage dip. Mitigation: soft cut-in
- Wind farm energization causes more considerable voltage dips:
  - Switching of WTG step-up transformers
  - Switching of main transformer
  - > only during wind farm energization, not repeting events.

Switching of Fixed Speed Induction Generator

Typical start-up procedure



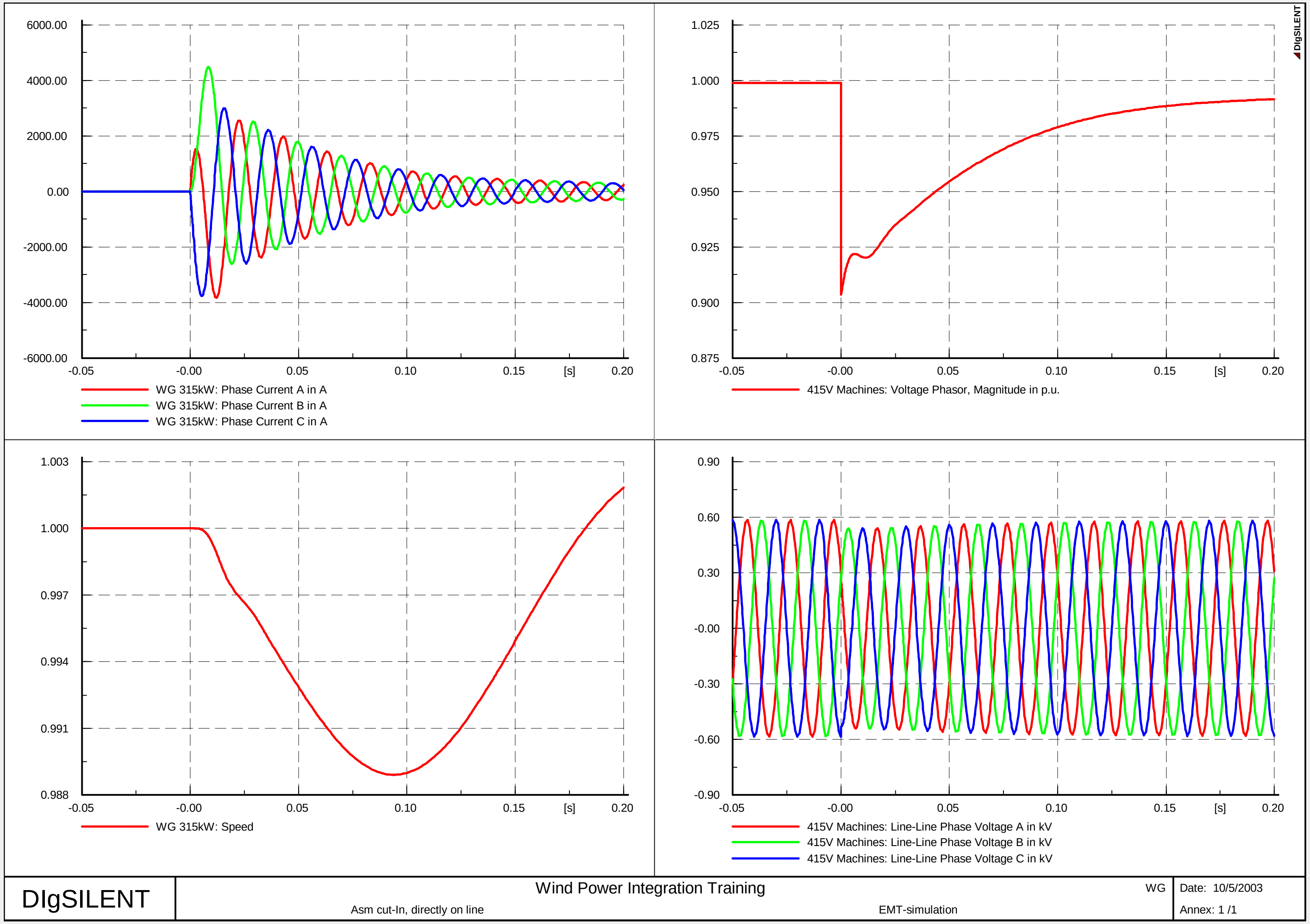
- Turbine pulls up the rotor to 0.9 ..1.1 $n_{nominal}$
- Breaker is closed



- Approximate Formula

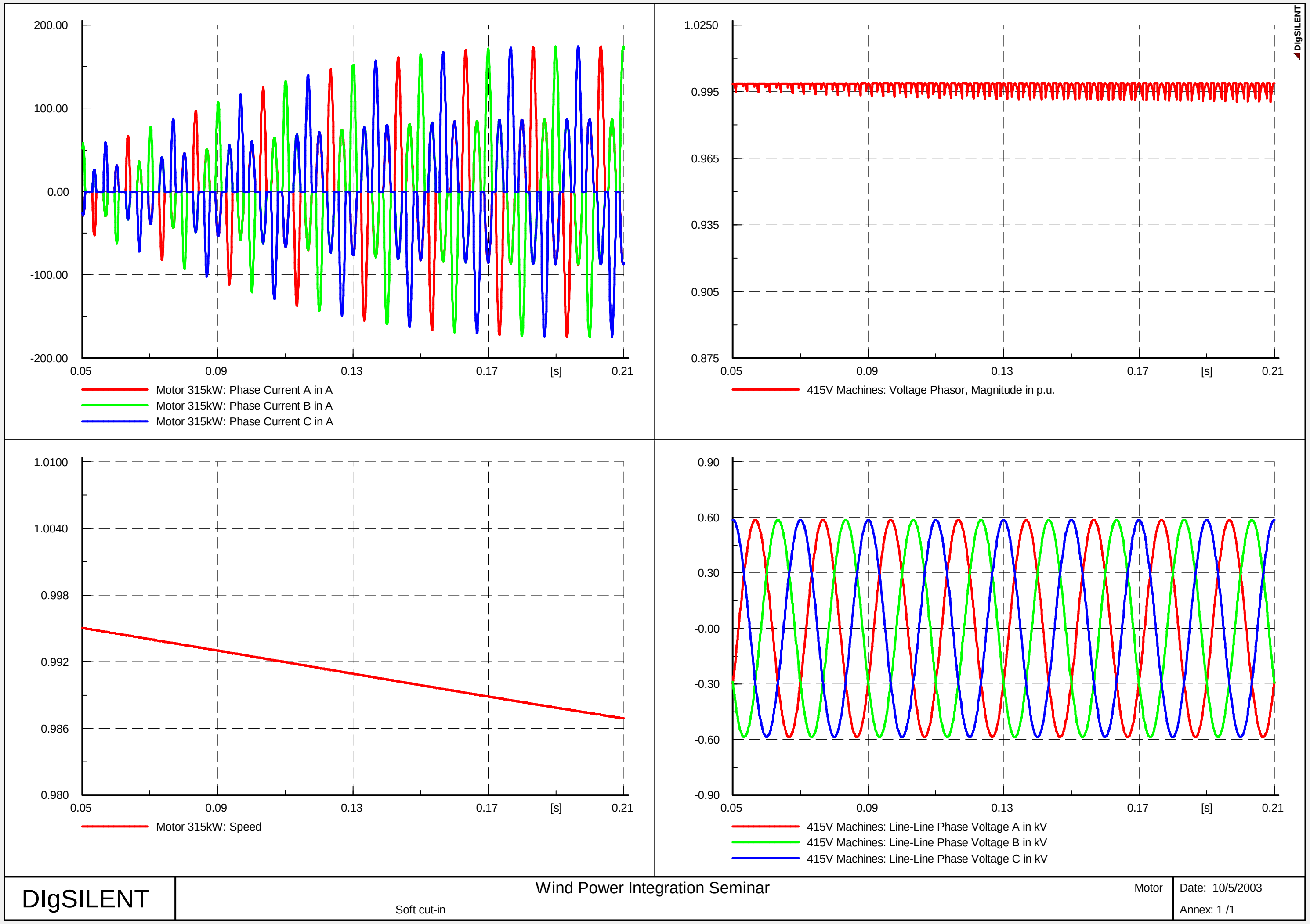
$$\Delta u = Z_n^{"} I_G^{"} = k_i \frac{S_{rG}}{S_n^{"}}$$

Switching

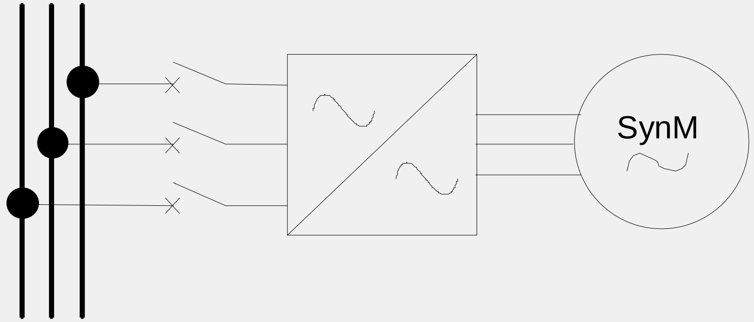


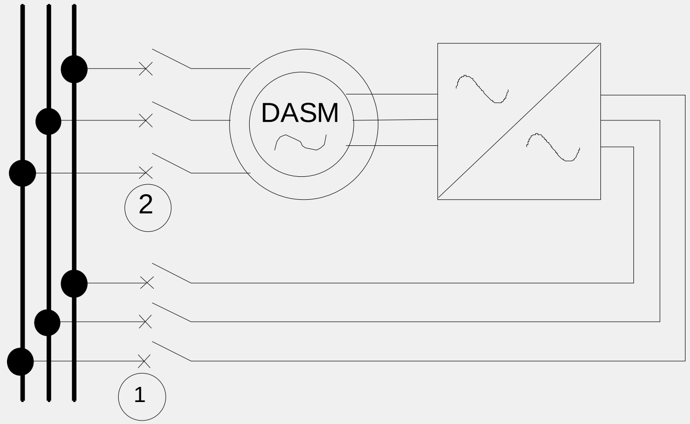
WG 315kW: Phase Current A in A
WG 315kW: Phase Current B in A
WG 315kW: Phase Current C in A
415V Machines: Voltage Phasor, Magnitude in p.u.
WG 315kW: Speed
415V Machines: Line-Line Phase Voltage A in kV
415V Machines: Line-Line Phase Voltage B in kV
415V Machines: Line-Line Phase Voltage C in kV
[s]
DIgSILENT
Wind Power Integration Training
Asm cut-In, directly on line
EMT-simulation
WG
Date: 10/5/2003
Annex: 1 /1

With Soft Cut-In

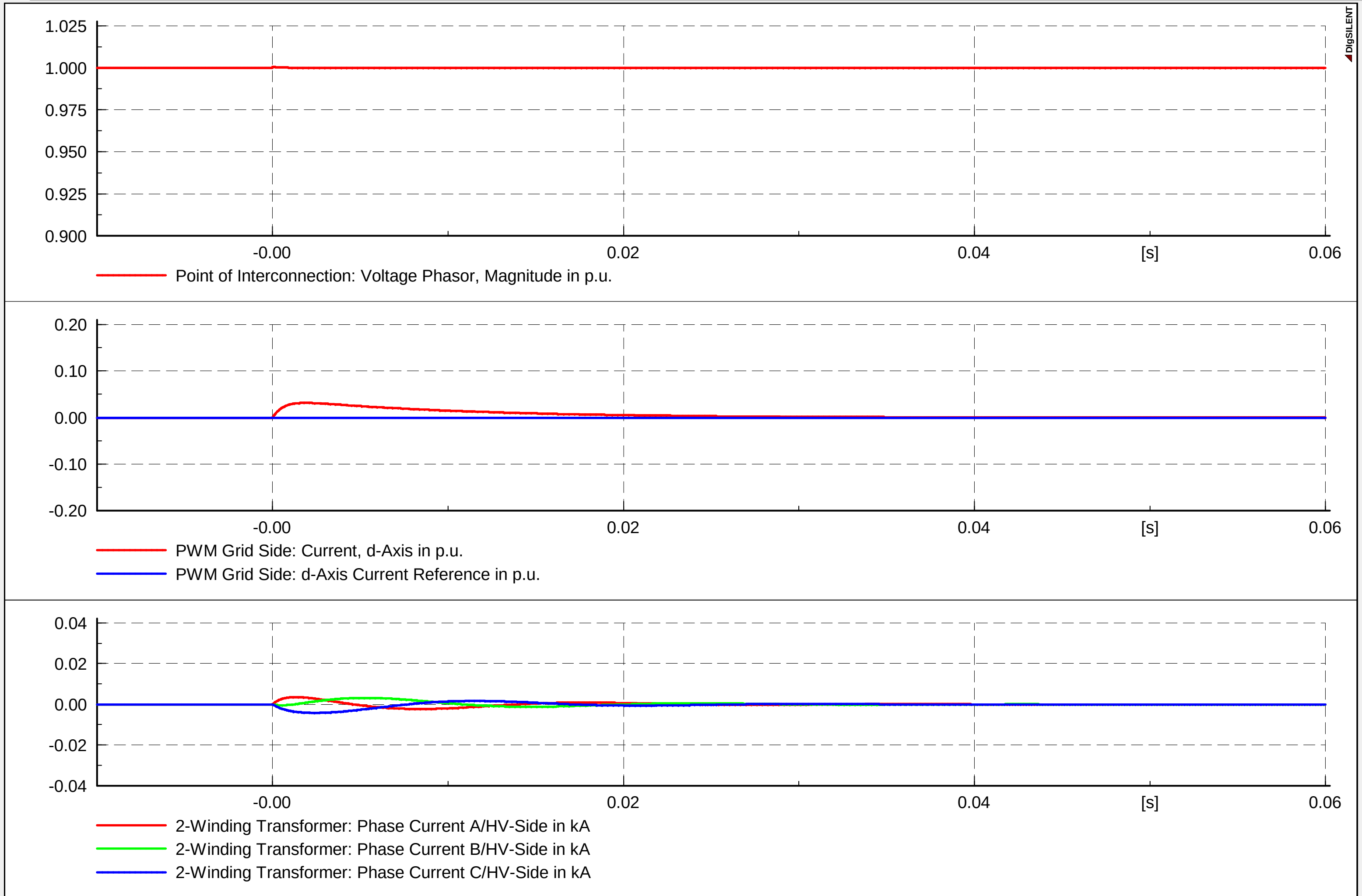


Switching of Variable Wind Generators



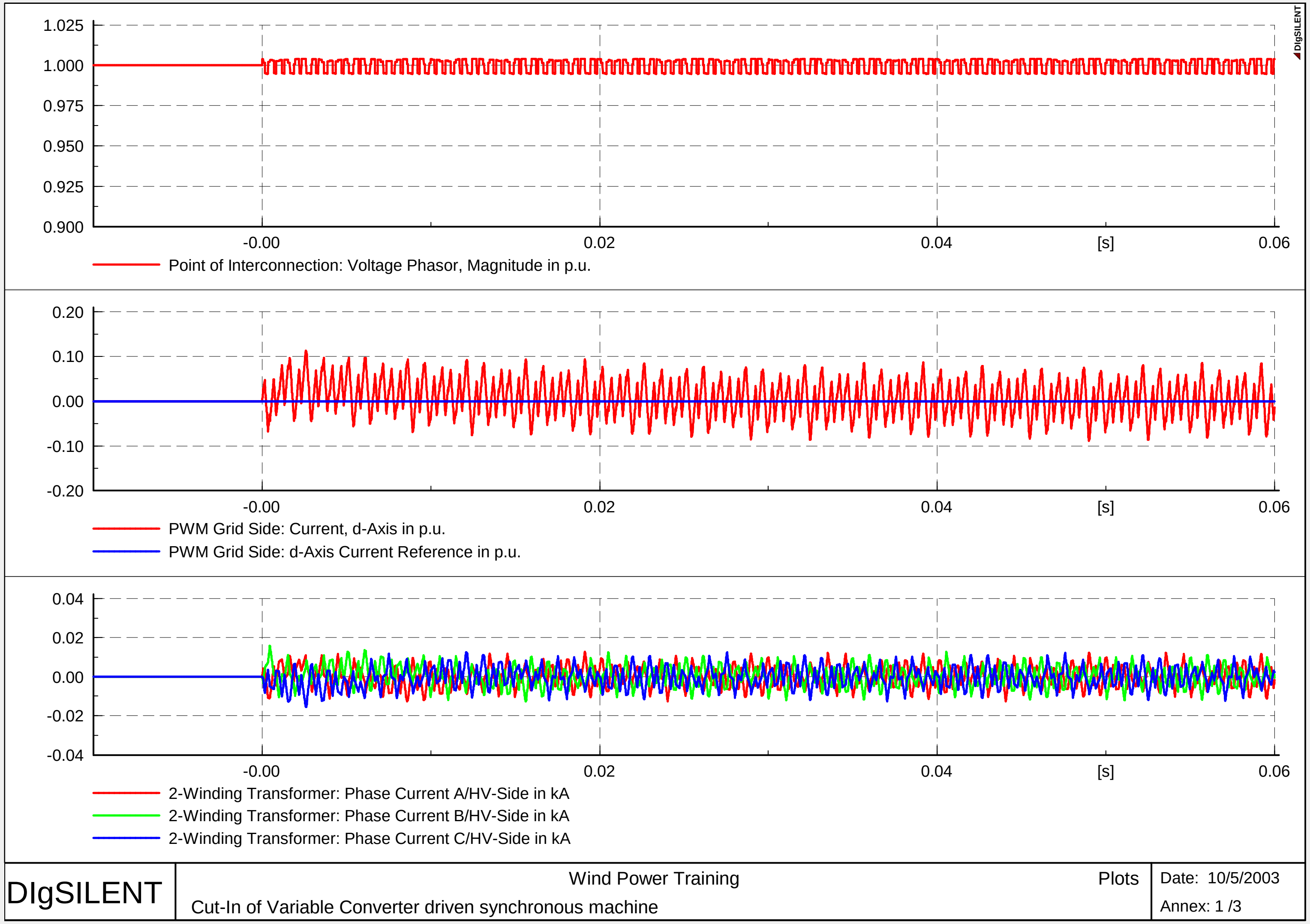


Connection of Variable Speed WTG



DIgSILENT	Wind Power Training Cut-In of Variable Converter driven synchronous machine	Plots	Date: 10/5/2003 Annex: 1 /3

Connection of Variable Speed WTG



Harmonic and Inter-Harmonic Injections

Harmonic injections caused by:

- Power electronics converters
  - modern PWM converters produce high order harmonics
- Saturation effects (Generator, Transformer)

Inter-Harmonic injections caused by:

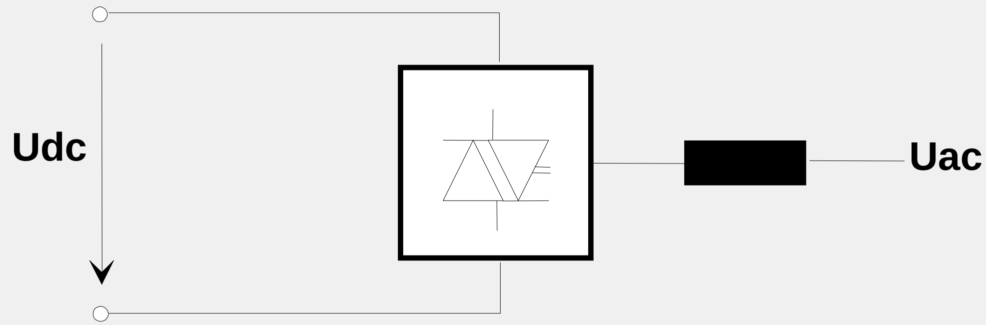
- PWM with switching frequency different from multiples of network frequency

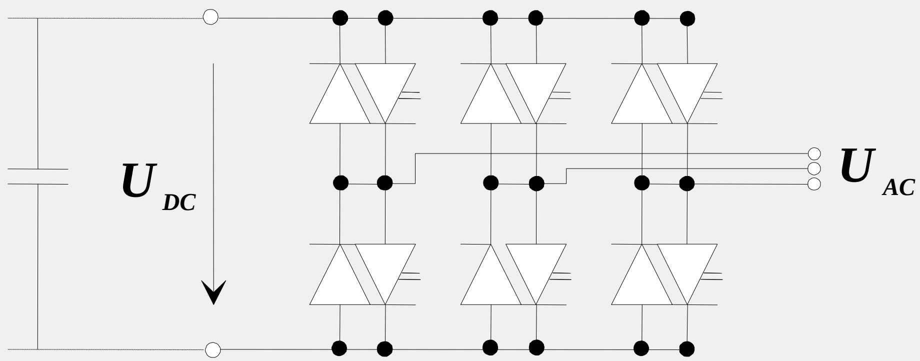
Effect

- Voltage distortion depending on network impedance
- Resonance problems

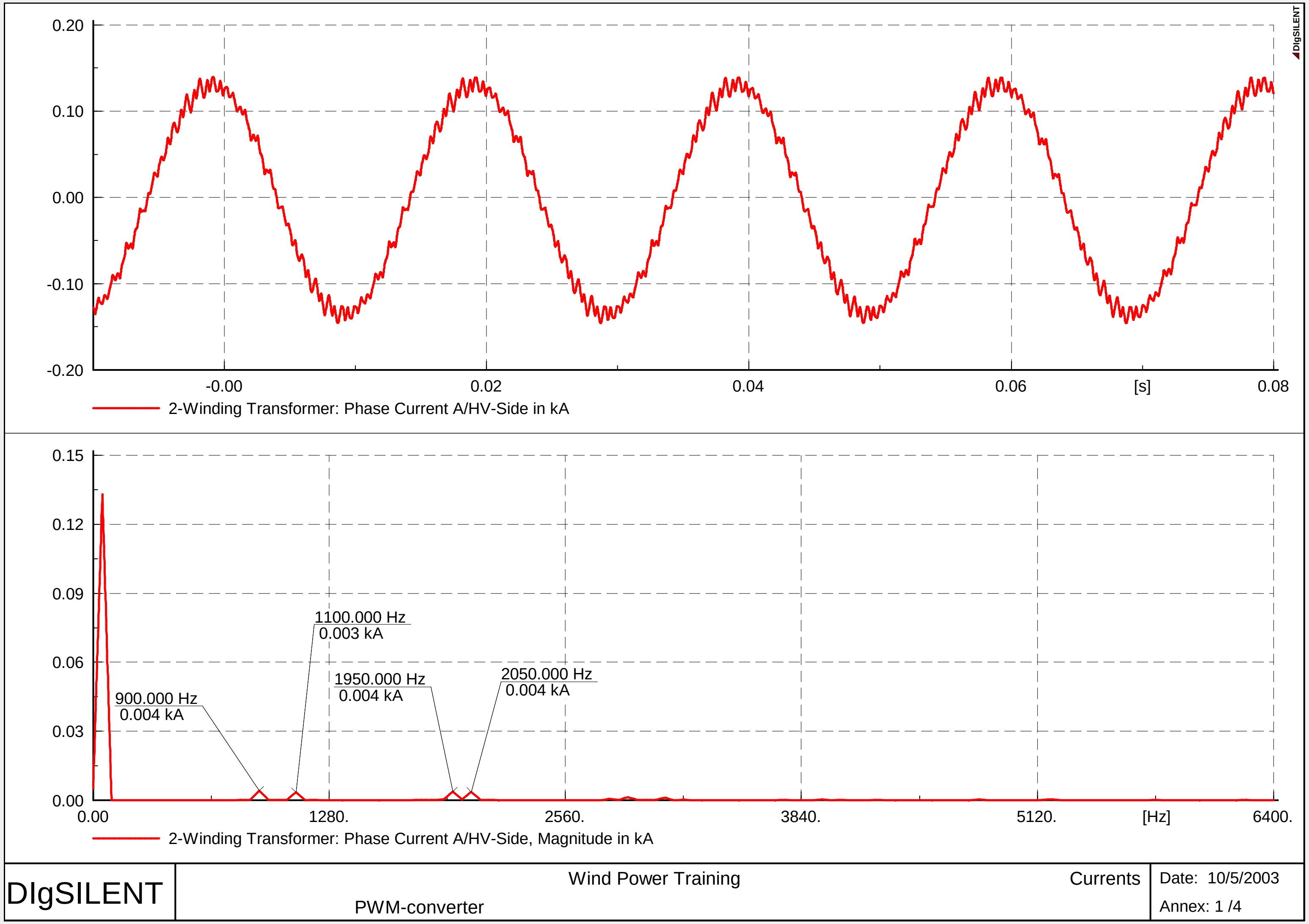
Standards: IEC 61000-3-7, IEC 61400-21

Self Commutated Converter





Self Commutated PWM Converter



Impact on Harmonic Impedance

- Voltage source converters:
  - define a path via the coupling reactance to earth for high frequency harmonics.
  - At low frequency harmonics: Controller transfer function needs to be considered too.
- Effect:
  - Shift of resonance frequencies (towards higher order).
  - Increased harmonic damping

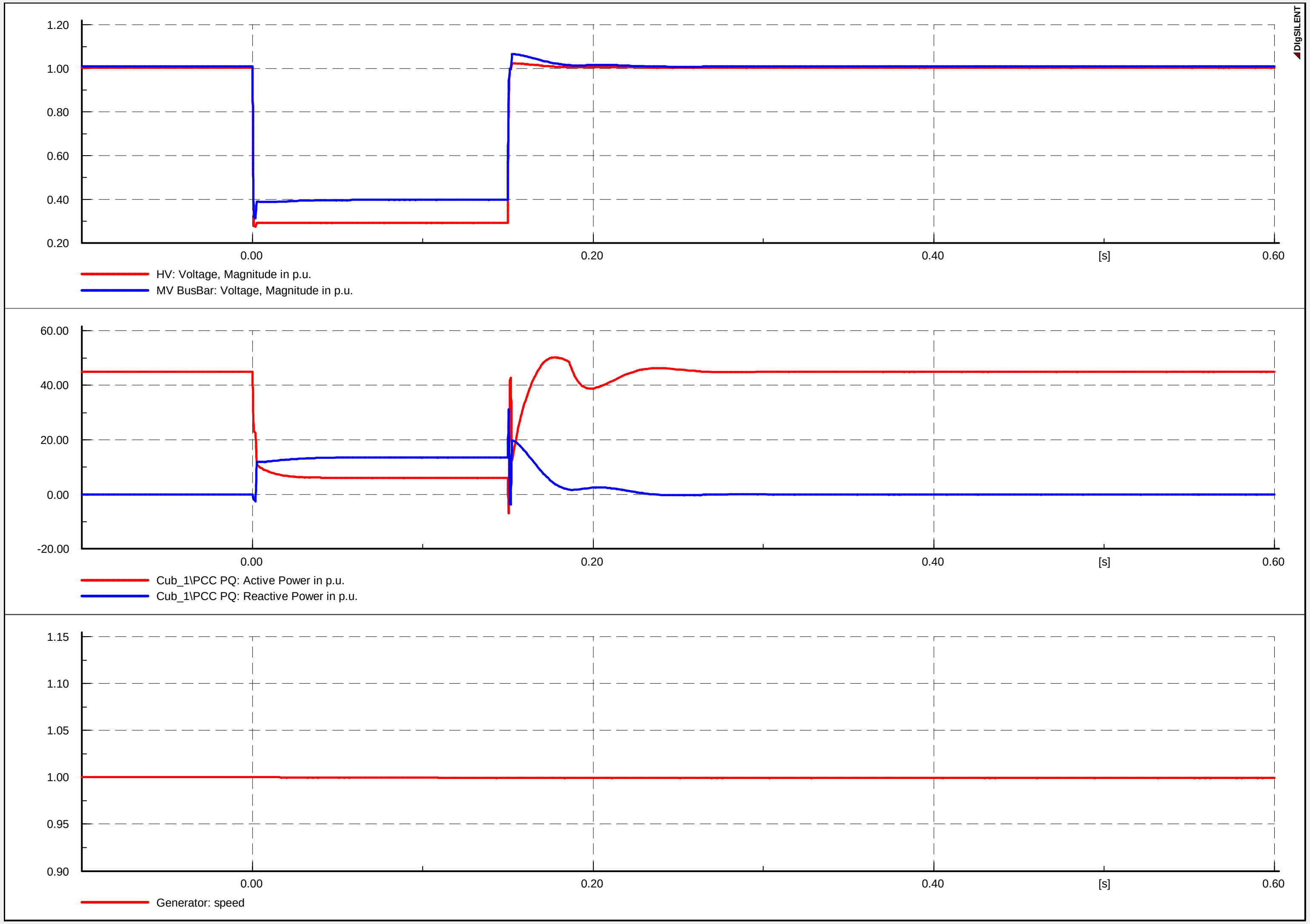
- Cable capacitance of wind farm-internal cables.
- Effect:
  - Shift of resonance frequencies (towards lower order)
  - Amplification of harmonic background distortion.

Impact on Flicker and Harmonics - Summary

- Analysis of Flicker and Harmonics using IEC 61400-21 data sheet of a typical variable-speed wind generator.
- Flicker generally low in case of large wind farms because Flicker-relevant turbulences within a wind farm are only weekly correlated
- Harmonics of modern wind turbines (with IGBT-converters) very low. Almost no harmonic current injections.
- WTGs can have a positive influence on harmonic impedance characteristics (improved damping, increased resonance frequencies)

Behaviour During Grid Faults – FRT Requirements

Example: Converter Driven Synchronous Genenrator



FRT Requirements: Summary

Basic FRT-Requirements:

- WTGs must not disconnect in case of voltage dips
- WTGs must deliver active power shortly after a voltage dip

Advanced FRT-Requirements:

- WTGs must inject reactive current during a fault (voltage support, protection excitation)
- WTGs must not absorb reactive power during voltage recovery

Thank You

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