Thomas Schmidt
ABB AG, Bad Honnef

Global Product Manager Phase Shifting Transformers der ABB

Thomas Schmidt leitet die Expertengruppe für Phasenschieber in Bad Honnef.

Das ABB Werk in Bad Honnef wurde 2000 zuständig für die Entwicklung und Vermarktung und Produktion von Phasenschiebertransformatoren innerhalb der ABB Gruppe. Herr Schmidt leitet seit dieser Zeit die Aktivitäten rund um dieses Produkt.

Thomas Schmidt war ab 1990 in verschiedenen Vertriebs- und Projektmanagement und Produktmanagement Funktionen tätig. Er hat einen Abschluss als Diplom Ingenieur der Elektrotechnik.

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Thomas Schmidt, ABB AG Power Products Division, September, 2015

Kepp the power flow under control
Phase-shifting Transformers

Power flow control with phase-shifting transformers

- Use of phase-shifting transformers
- Pay-back considerations
- How does a phase-shifting transformer work?
- Examples
- Challenges in PST designs

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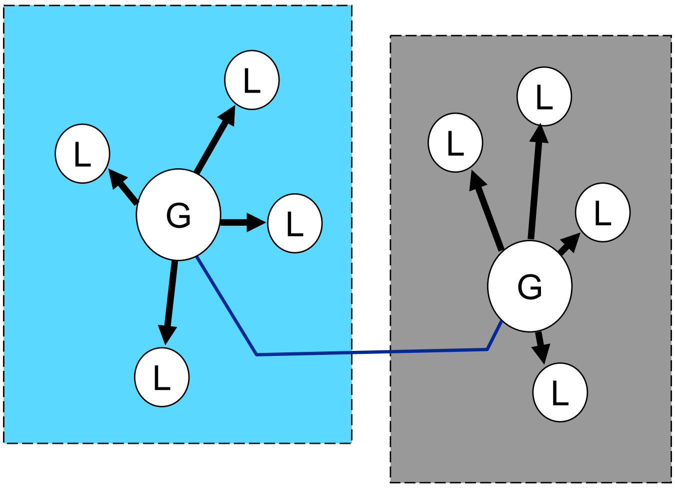
Control area:
Generation and loads balanced

Traditionally little exchange between control areas.

Each control area balances loads with its own generation

EHV systems (220 kV and 400 kV) were used as back-up only in the European grid.



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Control area:
Transmission on top of generation and loads

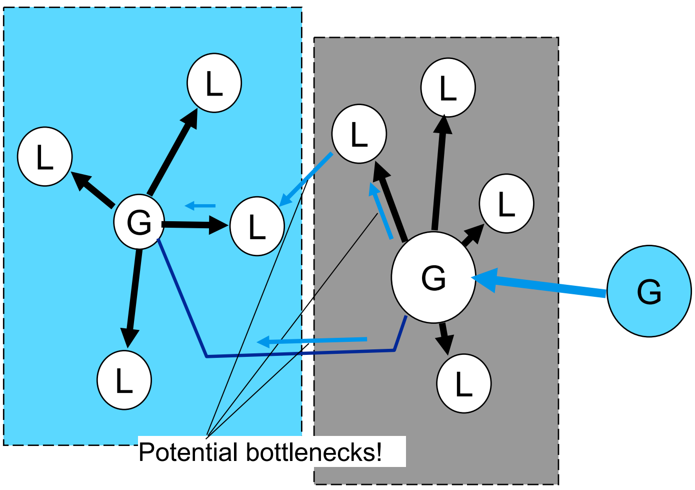
Changes in generation patterns.

New market participants.

Non-discriminating networg access politically enforced.

Utilization of transmission lines differs a lot from the time they were designed.
Utilization becomes quite volatile.

Bottlenecks need to be managed.



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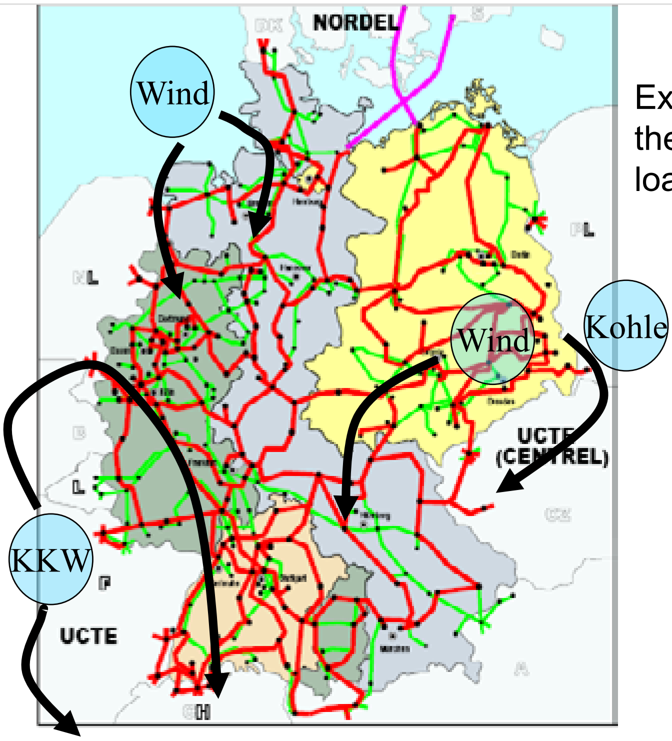

Examples for the change of load flows

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One of three 1400 MVA PSTs for ELIA during erection

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Sound house

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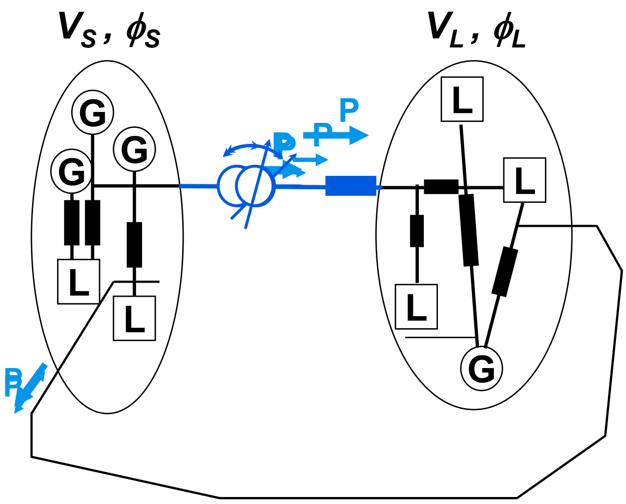
Power flow control with phase-shifting transformers
PSTs are power flow control devices

Two synchronous systems

Transmision angle difference ϕ_S - ϕ_L drives power flow across interfaces of control areas

Changing difference ϕ_S - ϕ_L by generation dispatch or load pattern will influence power flow through all links

Use of PST allows control of power flow, independent of "natural" transmision angle difference



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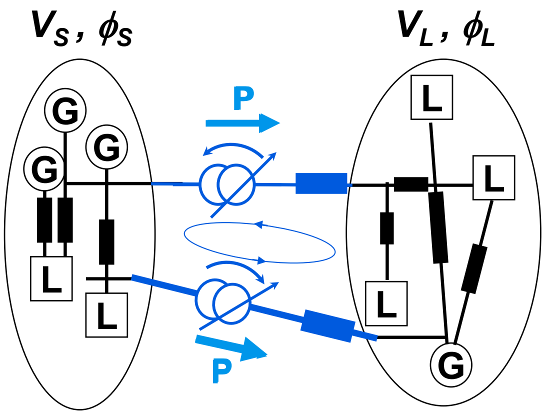
Power flow control with phase-shifting transformers
Optimization of load sharing and transmission capacity

Transmision lines with different impedances e.g. overhead / cable or 400 kV / 110 kV.

Transmision angle

difference ϕ_S - ϕ_L drives power flow with unbalanced load sharing of lines.
The low impedance line is overloaded, limiting the total transmission capacity of the corridor.

PST impose an additional circulating current, thus improving the balance of power flows.
The total transmission capacity increases.



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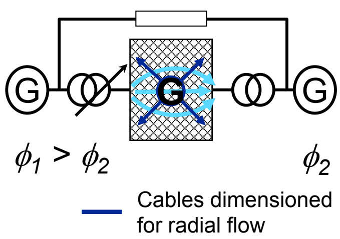
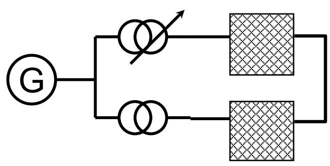
Power flow control with phase shifting transformers
Smaller scale applications



- Block parasitic power flow and overload due to transmission angle differences in feeding network(s)



- Distribution of power to different systems/ customers

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Pay-Back-Consideration

- Increase and control of transmission capacity, independent of the “natural” phase angle of the system, may relieve restraints on generation.
- 100 MW extra for 2000 h/a allowed to the grid can generate approximately 4 MEuro/a additional revenues (at ~ 20 Euro/MWh)

- The control of power flow is a pre-requisite for marketing transmission capacity
- 100 MW transmission capacity have a value of ~ 2 MEuro/year (at ~ 20 Euro/kW-year)
-
- **Pay back is possible within a period of 2 - 3 years !**

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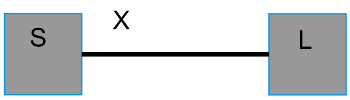
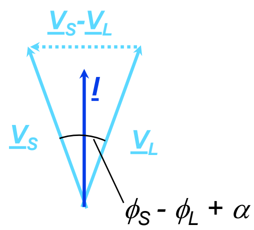
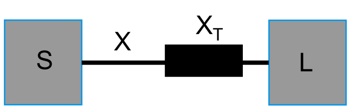
Power flow control with phase-shifting transformers
Phase shifting transformers are power flow controllers



$$P = \frac{V_S V_L}{X} \sin(\phi_S - \phi_L)$$



- The phase angle between two systems determines the power exchange



$$P = \frac{V_S V_L}{X + X_T} \sin(\phi_S - \phi_L + \alpha)$$

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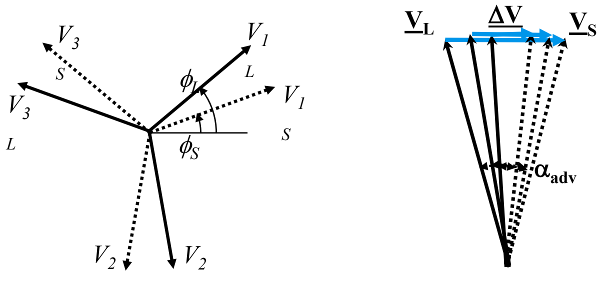
Principle of a phase shifting transformer



- The phase shifter rotates the phasor orientation between the source and load side.
- In pure phase shifting transformers a voltage in quadrature to the source voltage is injected into the line

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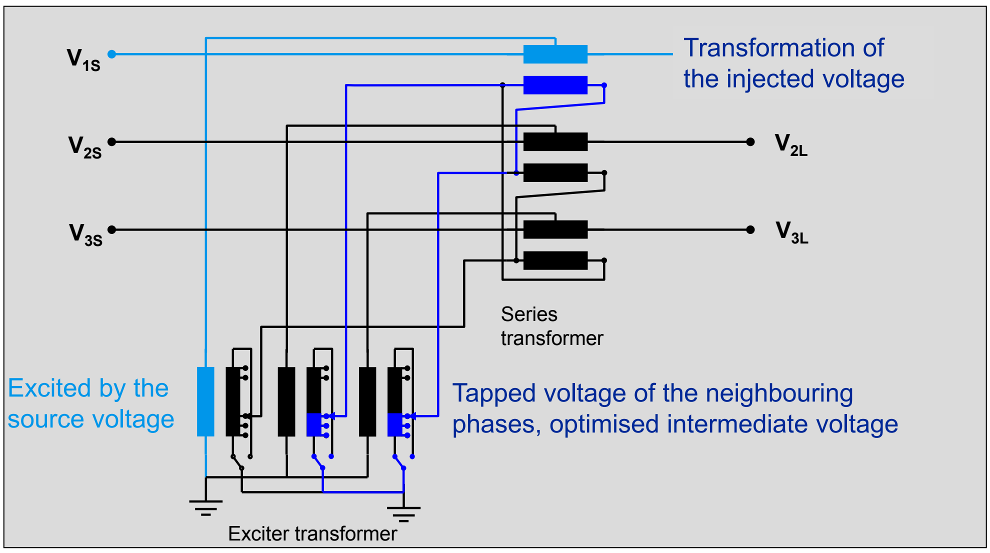
Principle of a phase-shifting transformer
Two core design



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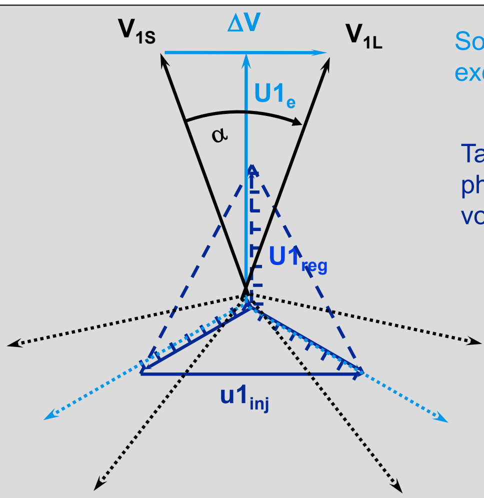
Principle of a phase-shifting transformer
Two core design



Source voltage U_e
excites the Exciter transformer

Tapped voltage of the neighbouring phases, optimised intermediate voltage to utilize the tap changer best

The resulting quadrature voltage u_{inj}
Will be transformed and will be injected between source and load (Voltage ΔV)

Rating of a phase shifting transformer

- **Typical specification**
- Rated throughput power 300 MVA
- Rated voltages
- Angle range 10°
- Insulation levels BIL / SIL / AC
- Impedance range

- The equivalent two winding rated power (physical size) is:
- 300 MVA x 2 sin $\Phi/2$ = 52 MVA for the main unit and
- 300 MVA x 2 sin $\Phi/2$ = 52 MVA for the series unit

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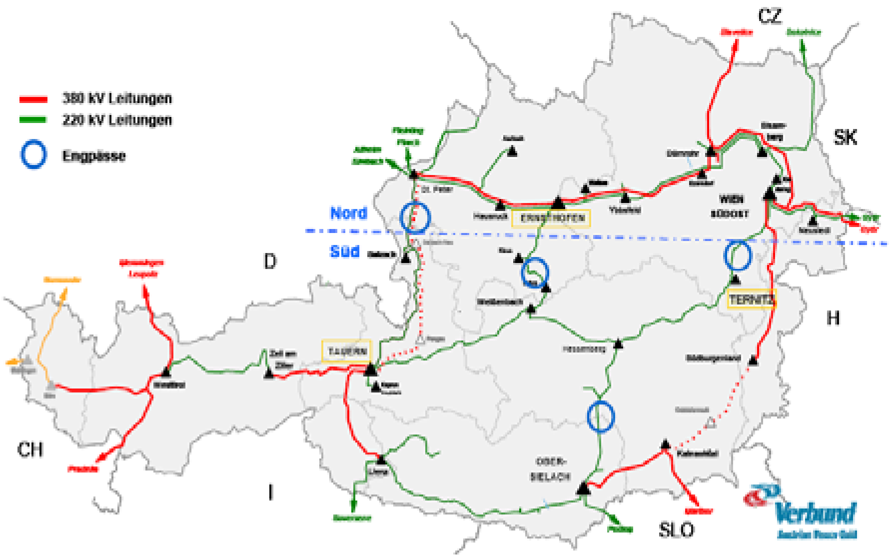
Example: APG Verbund, Austria



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Example: APG Verbund, Austria

Throughput Power	600 MVA
Physical Size	360 MVA (S) + 344 MVA (E)
Rated Voltages	232 kV / 232 kV
BIL / SIL	950 kV / 750 kV
Phase Angle Regulation	± 35° in ± 16 steps
Transport Dimensions	11.9 x 3.94 x 4.47 m
Transport Weight heaviest part	260000 kg
Total Weight	852000 kg
No-Load losses	0…105 kW + 98…88 kW
Load losses	870…875 kW + 0….806 kW
Impedance	14.5% + 0…4.75% rel. 600 MVA
Advance-Retard-switch in the series transformer, coarse/fine tap changer in the exciter transformer	

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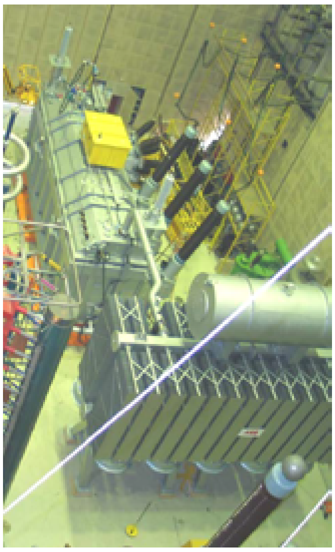
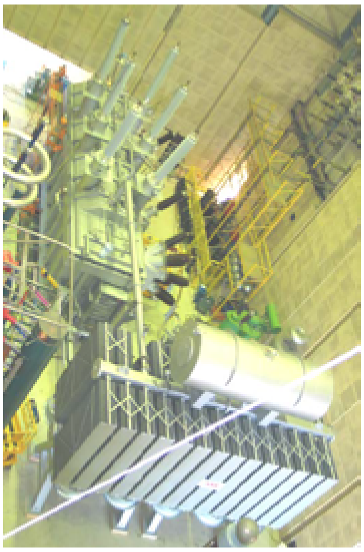
Temperature rise test
Exciter transformer and series transformer

600 MVA
232 / 232 kV
± 35°





Series transformer active part

600 MVA
232 / 232 kV
± 35°

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PST during dielectric testing

600 MVA
232 / 232 kV
± 35°
Cooling equipment not installed for dielectric tests

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Loading on barge in Bad Honnef

600 MVA
232 / 232 kV
± 35°

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Erection work in Kaprun, Austria

600 MVA
232 / 232 kV
± 35°

-17 db sound enclosure

600 MVA
232 / 232 kV
± 35°

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Challenges in PST design, manufacture and delivery
Design

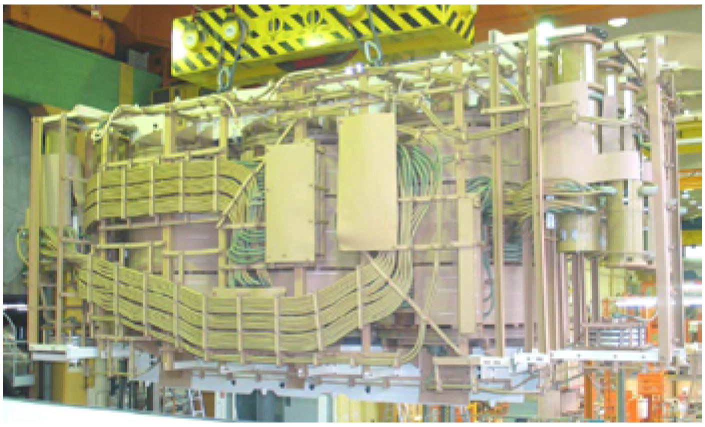
- PSTs are power transformers, with special internal connections, resulting in special loading conditions:
- Phase shift is felt as almost purely reactive loading for the magnetic circuit. Potentially strong load-dependent variations of induction in parts of the core(s).
- Regulating windings are for 100% of the transformer's rating, not just 10-20%. Dimensioning of the tap changers is critical.

Challenges in PST design, manufacture and delivery
Design

Active part of PST for TERNA Padriciano

370 MVA, 230 kV
+/- 31°

All internal connections on 230 kV potential



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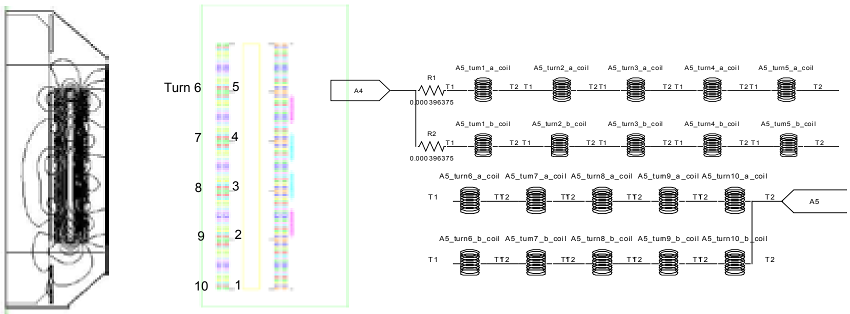
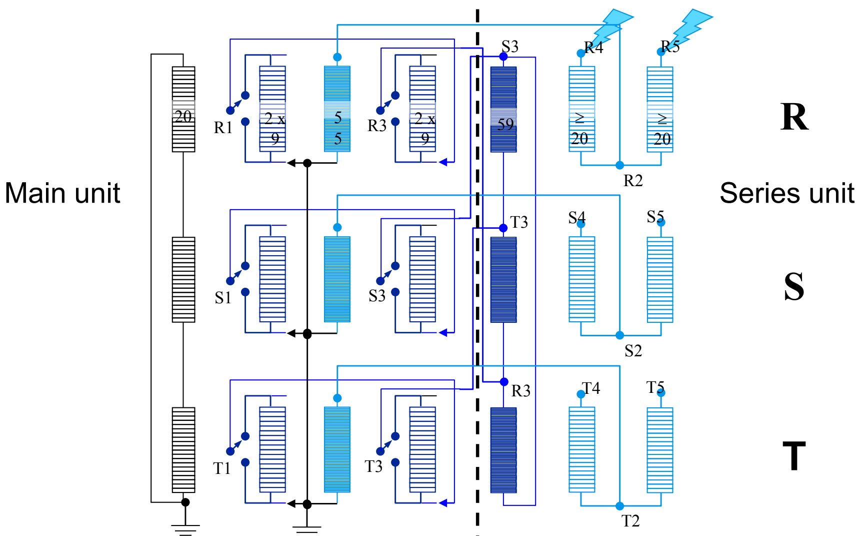
Challenges in PST design, manufacture and delivery
Current distribution



- High currents require use of large parallel conductors.
- Regulating windings with magnetic gaps expose these conductors to inhomogeneous B-field, inducing different voltages in parallel conductors
- Circulating currents may become critical.
- 2D and 3D coupled magnetic and circuit simulations.

High resolution transient modelling of voltages
RCL networks with hundreds of nodes for lightning impulse simulation



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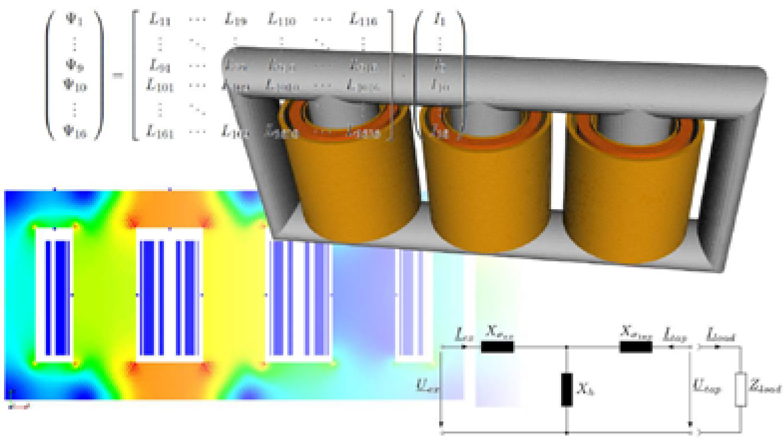
Challenges
Management of stray magnetic flux

- **RWTH IEM studies**



Challenges
Interpretation of customer requirements

- **Beispiel Excel tool Schiffer**

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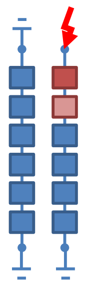
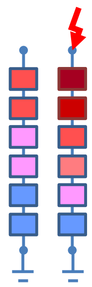
Recent developments
Switching impulse voltage distribution

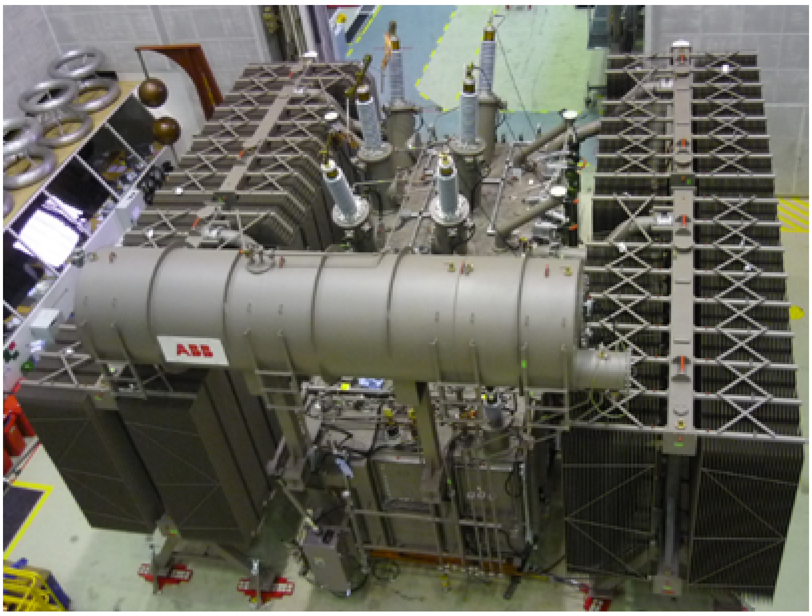
- Lightning impulse 1.2/50 µs
  - Necessary resolution: ~0.5 x c_{light} x 1.2 µs = 180 m, corresponding to < 100 turns, fraction of a winding.
  - Strong initial capacitive coupling, inductive coupling follows in tail of impulse.
  - Time delay between winding parts causes voltage gradients.



- Switching impulse 100/1000 µs
  - Necessary resolution: ~0.5 x c_{light} x 100 µs = 15000 m, corresponding to > complete winding
  - Inductive and magnetic coupling dominates
  - Usually only minor oscillations due to winding capacitances



300 MVA Phase-shifting transformer



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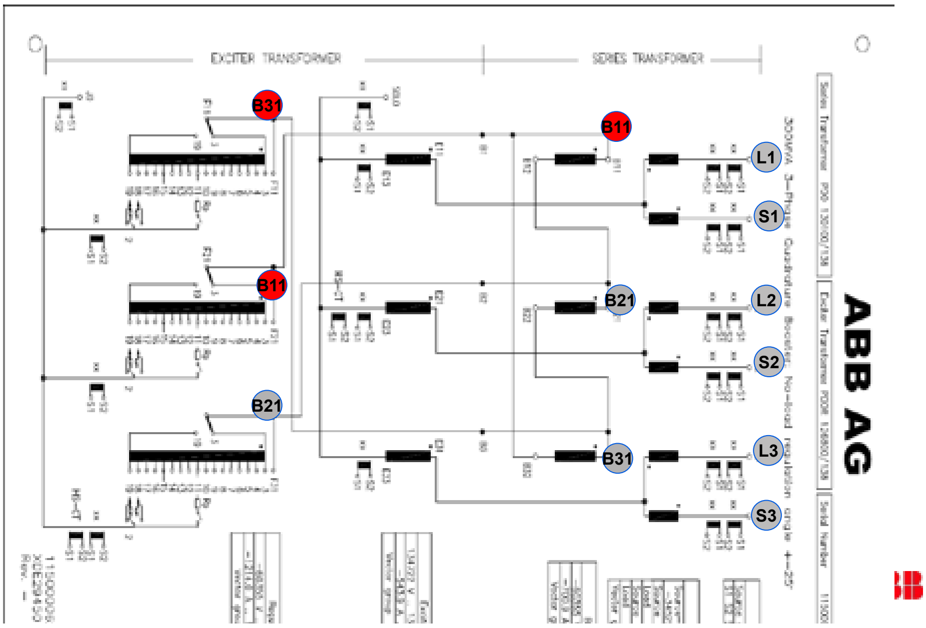
Connection diagram



Challenges
Switching impulse voltage distribution

- Unexpected oscillations during switching impulse.
- Main oscillation frequency much lower than simulated, required „unphysical“ tuning of capacitances.
- Detailed measurements of internal voltage distribution available

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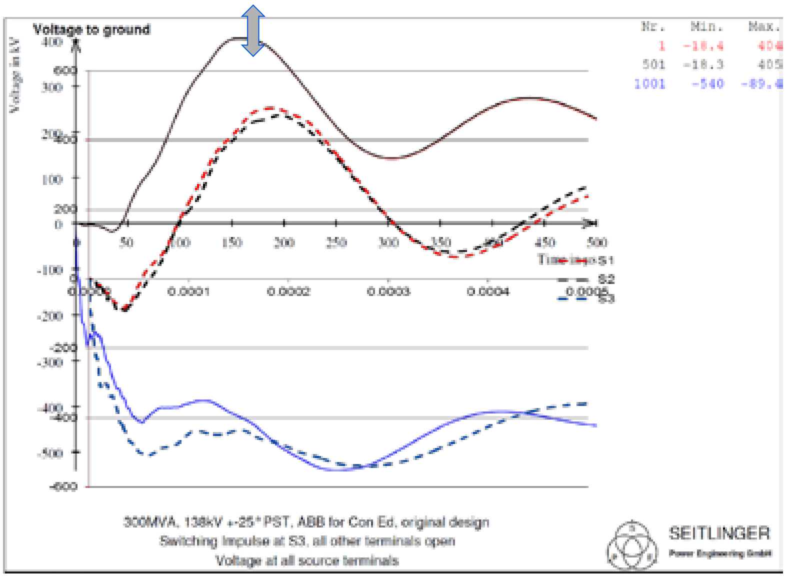
Voltages at S bushings

Comparison to RSO undisturbed, fast rise time



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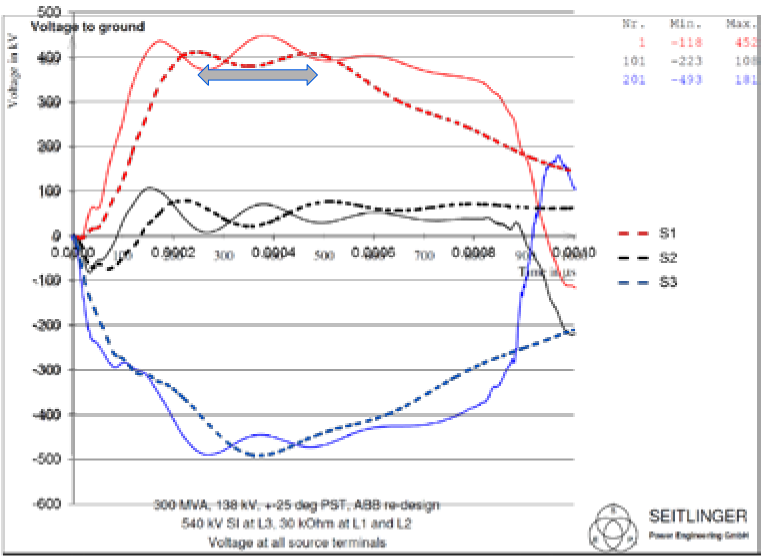
Voltages at S bushings

Comparison to RSO, file 5-4, SI on L3, max advance, slow rise time



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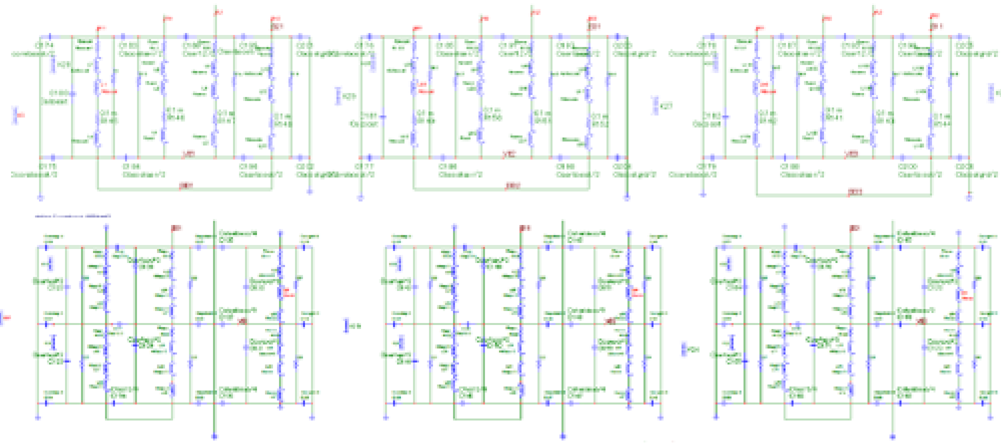
Modelling of transient voltages

Two coupled 3-phase active parts, with magnetic coupling, for switching impulse simulations



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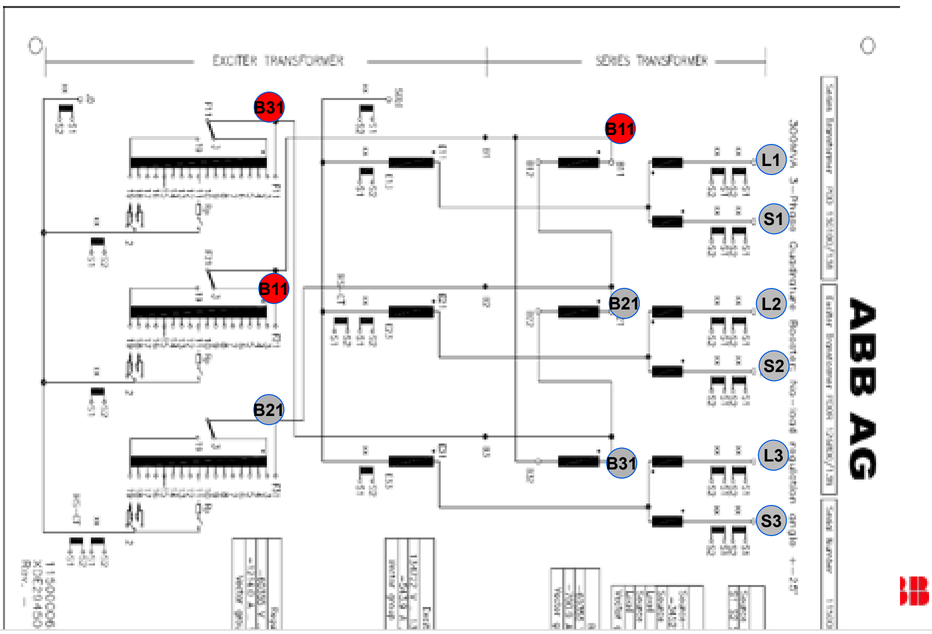
Connection diagram



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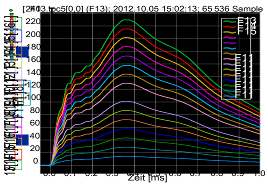
RSO measurement results
linear switching impulse voltage distribution within winding



Pictures from ConEd studies

Possible thesis work

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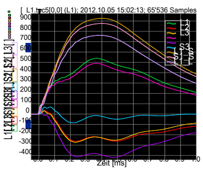
RSO measurement results
Switching impulse voltage distribution at bushings



Pictures from ConEd studies

Possible thesis work

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Example: TERNA Rondissone

1630 MVA
400 / 400 kV
+ 18°

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Conclusions

- **PSTs connect entire countries**
- **The power industry still needs real hardware**
- **People rely on it every day**

- **We need to utilize modern simulation software to visualize the dielectrical as well as magnetical and thermal or mechanical behavior**
- **This allows to drive more economical solutions**
- **But we should not forget to verify in reality what we simulate**
- **We need excellent scientists and engineers who understand the limits of such simulation**

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