The use of power flow controlling devices in the liberalized market

HVDC: an option for the future?

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Who am I?

Dirk Van Hertem

- Post-doc at the university of Leuven, Belgium
- Department of electrical engineering
- Research group Electa
- Power engineer, boss = Ronnie Belmans
- Treasurer of IEEE Benelux IAS/PELS/PES chapter
- Secrectary of IEEE Benelux section
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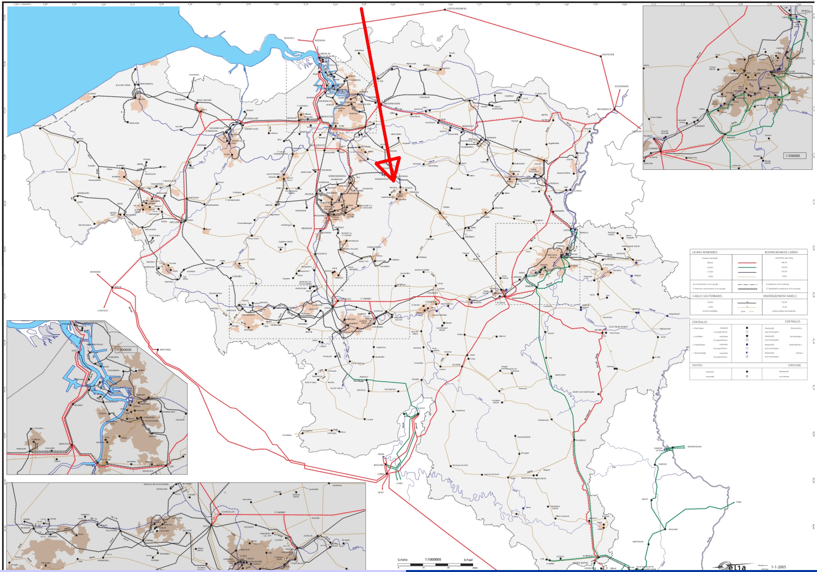

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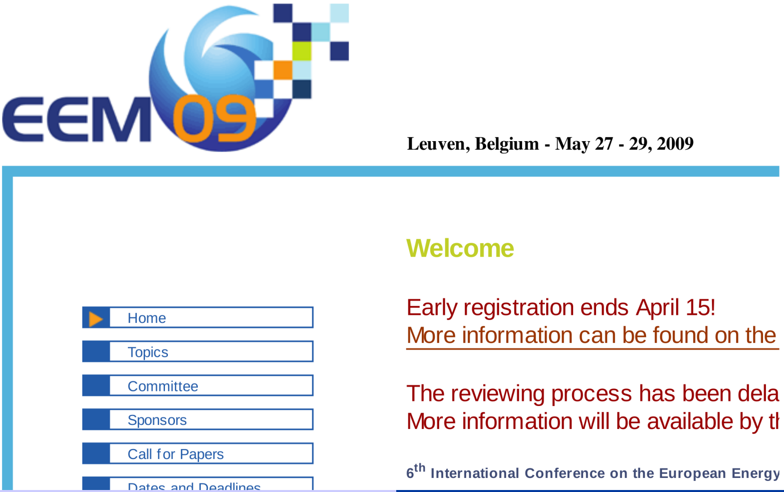


1. Power flow control
   - Introduction
   - Need for power flow control
   - PFC can be a solution
2. PFC in the meshed grid
   - Controlling PFC in an international context
   - Examples
   - Need for coordination
   - Regulations
3. HVDC
   - HVDC technology
   - Principles of HVDC
   - Future of VSC HVDC
4. Conclusions & Future work

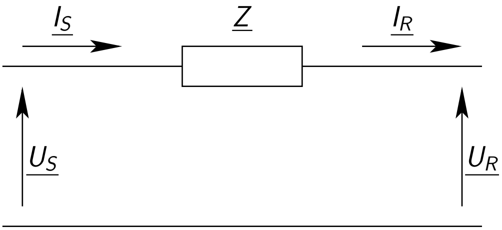
What is power flow control

Bending the laws of Kirchhoff

- In normal systems, power flows according to the laws of Kirchhoff
- Power flows in meshed networks depend on the injections of power in different nodes and the relative impedance of the lines
- Using power flow controlling devices, these flows can be influenced
- Overloaded lines can be relieved
- System can be adjusted to the situation: day-night, summer-winter

Power flow control

- Power flow equations for a simple transmission line:
  - Active power: $P_R = \frac{|\underline{U_S}| \cdot |\underline{U_R}|}{X} \cdot \sin(\delta)$
  - Reactive power: $Q_R = \frac{|\underline{U_S}| \cdot |\underline{U_R}|}{X} \cdot \cos(\delta) - \frac{|\underline{U_R}|^2}{X}$
- Receiving end power can be altered through voltage, impedance and angle



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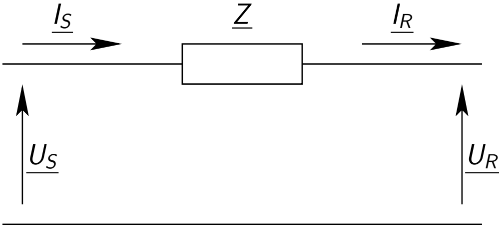

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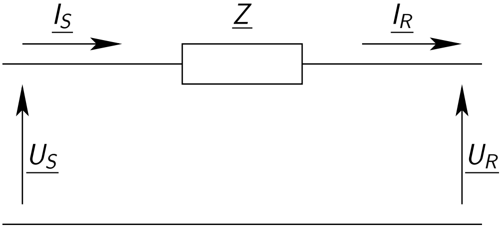

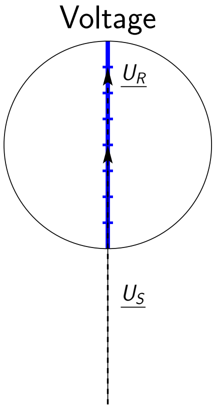

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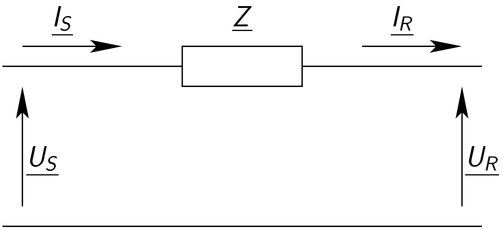
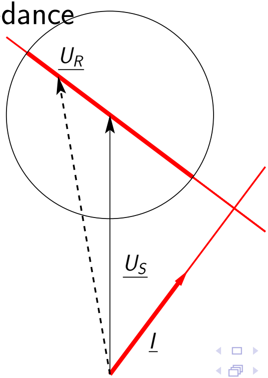


Impedance



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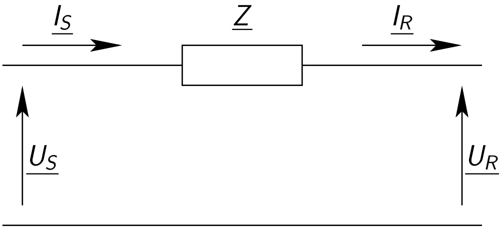
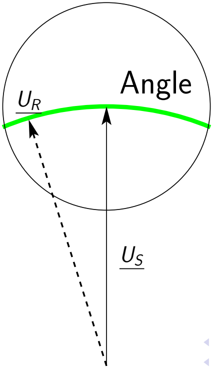
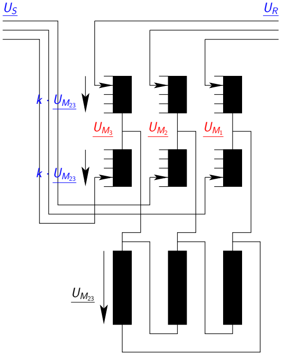
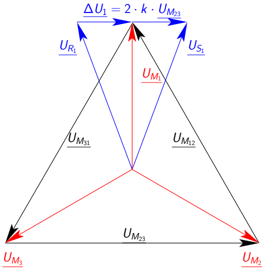




PFC devices

- PFC devices influence one (or more) parameters: U, δ or X
- Different technologies exist: mechanically switched, thyristor based and fast switches
- Some examples:
    - Phase shifting transformer
    - TSSC/TCSC





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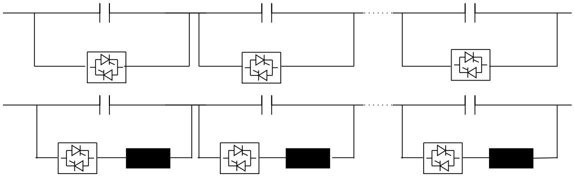
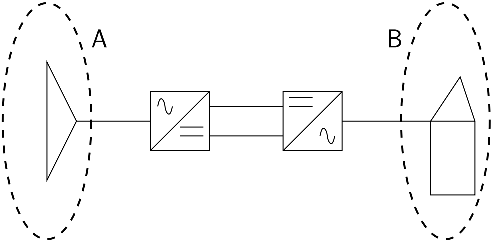


HVDC

HVDC is a special power flow controller

- Allows full, independent active power flow control
- VSC HVDC also provides independent reactive power flow control
- The ultimate power flow controller, yet not a true power flow controller



HVDC as a single link between two independent networks, no possibility for active power flow control

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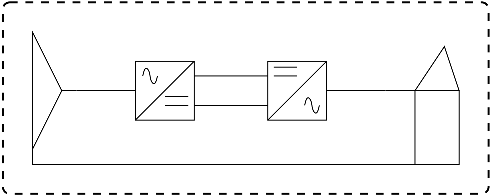

HVDC as part of the meshed AC power system, HVDC can be operated as a PFC, with a flow independent on the rest of the system

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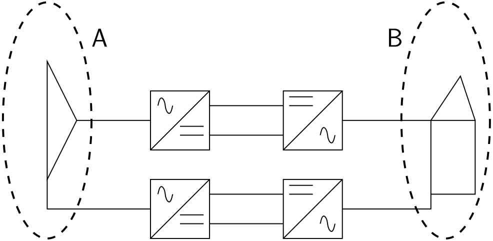


Two meshed networks are connected through HVDC. HVDC can be used as PFC when there is coordination

Power flow controlling devices: classification

AC Network controller

- Conventional (Switched)
  - R, L, C Transformer
- FACTS Devices (Fast, static)
  - Thyristor Valves
  - Voltage Source Convertor

	R, L, C Transformer	Thyristor Valves	Voltage Source Convertor
Shunt devices	Switched Shunt Compensation: L and C	Static VAr Controller (SVC) Thyristor Controlled Reactors (TCR),. . .	Static Synchronous Compensator (STATCOM)
Series devices	Switched Series Compensation: L and C	Thyristor Controlled and Thyristor Switched Series Compensator (TCSC and TSSC).	Static Synchronous Series Compensator (SSSC)
Combined Series & Shunt	Phase Shifting Transformer	Thyristor Controlled Phase Angle Regulators (TCPST) Classic HVDC	Unified Power Flow Controller (UPFC) VSC HVDC

Changes in the power system

New situation in the power system

1. Liberalization of the market
   - TSOs have less influence on active power injections ⇒ Money
   - Redispatching is more difficult/costly
   - Increased load and increased amount of international flows
   - Less stable pattern due to market: high volatility
   - Need for firm capacity for the market participants
2. Increased penetration of smaller, variable energy sources
3. Lacking investments in the transmission system
4. No single authority in Europe

⇒ Congestion occurs in the power system, often at interconnectors

⇒ Insufficient open market environment

⇒ Systems are operated with high uncertainty margins

Changes in the power system

New situation in the power system

1. Liberalization of the market
2. Increased penetration of smaller, variable energy sources
   - Renewables, CHP and new generator types emerged
   - Uncertain generation pattern and consequently uncertain flows
   - Balancing of wind is a problem for some countries
3. Lacking investments in the transmission system
4. No single authority in Europe

$\Rightarrow$ Congestion occurs in the power system, often at interconnectors

$\Rightarrow$ Insufficient open market environment

$\Rightarrow$ Systems are operated with high uncertainty margins

Changes in the power system

New situation in the power system

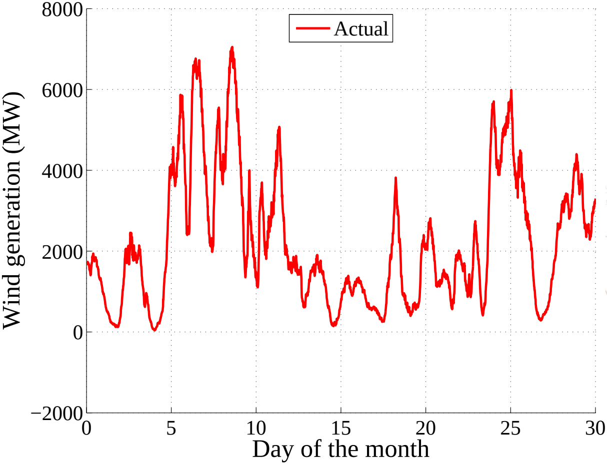
1. Liberalization of the market
2. Increased penetration of smaller, variable energy sources
3. Lacking investments in the transmission system
   - Difficult investment climate due to uncertain politics/regulations
   - Regulators consider mainly issues within their member state
   - Heavy opposition against any new investment (environmental, public, health,. . .)
4. No single authority in Europe

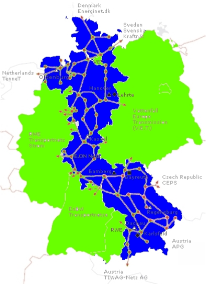
$\Rightarrow$ Congestion occurs in the power system, often at interconnectors

$\Rightarrow$ Insufficient open market environment

$\Rightarrow$ Systems are operated with high uncertainty margins

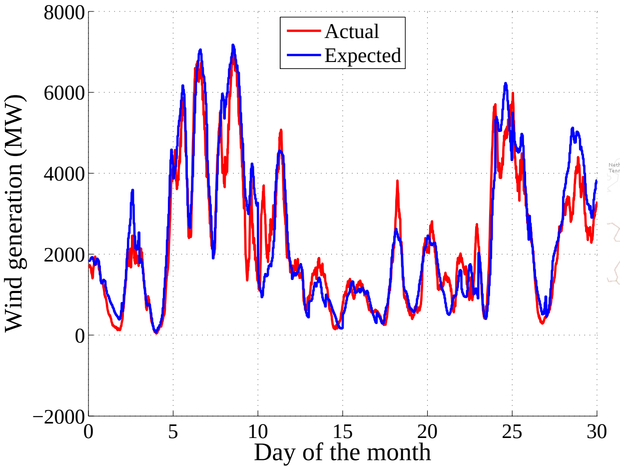
Unpredictability of wind power: international context

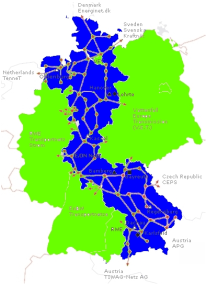




Real, estimated and mismatch wind generation in November 2007,
Day-ahead data for every 15 min

Unpredictability of wind power: international context





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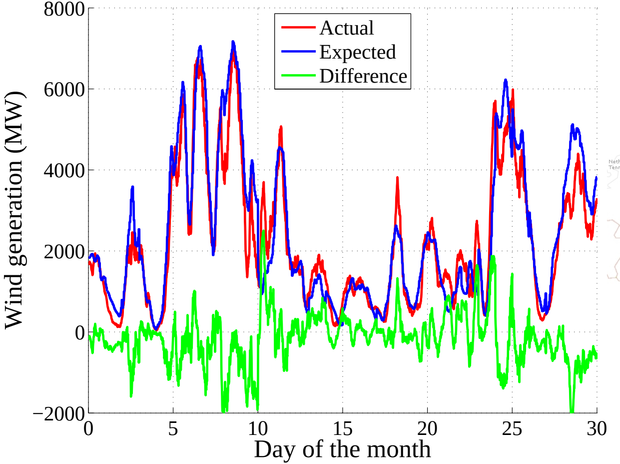

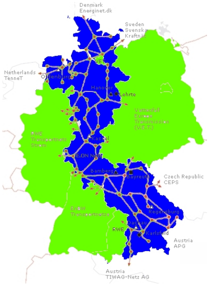

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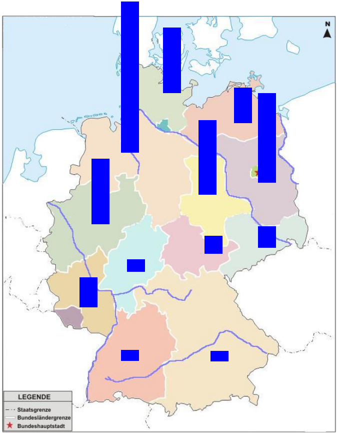
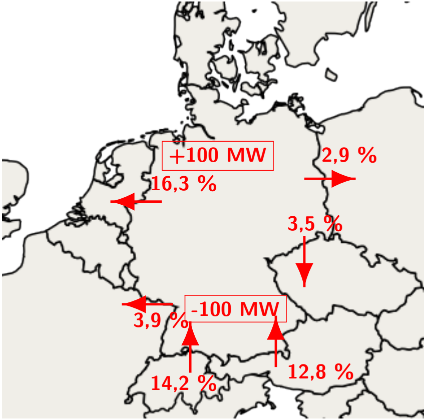
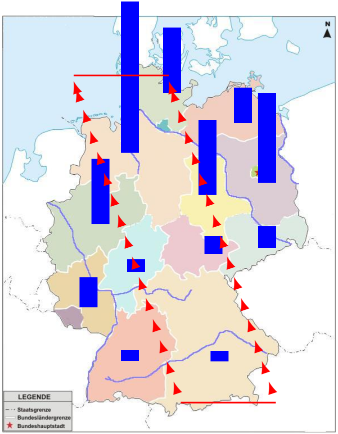
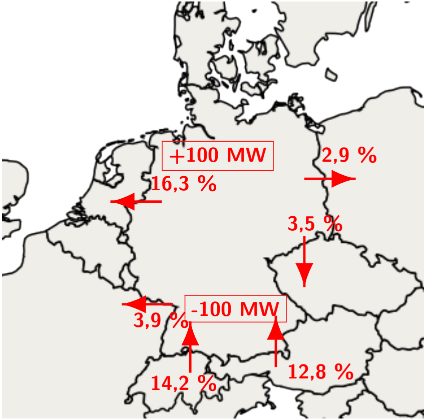




- Wind is predominantly located in the north. . . and is balanced in the south
- National problem can have international consequences

Unpredictability of wind power: international context





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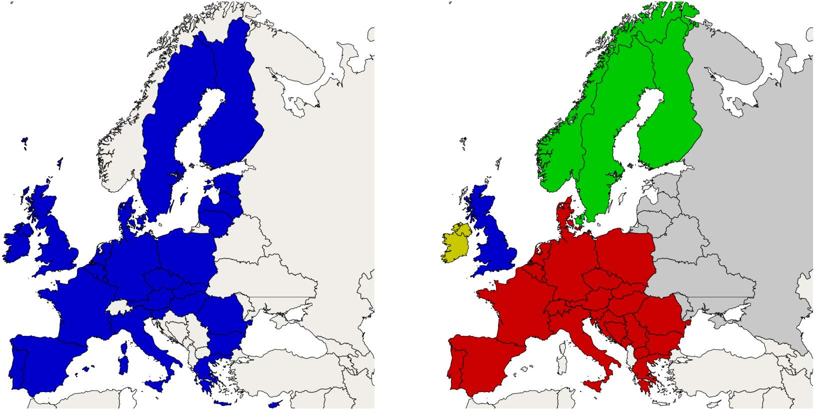
Difficult international setting

- There is no single European authority: an international patchwork
- Each has his own responsibilities and tasks
- No common authority and no common goal



European Union — Synchronous zones

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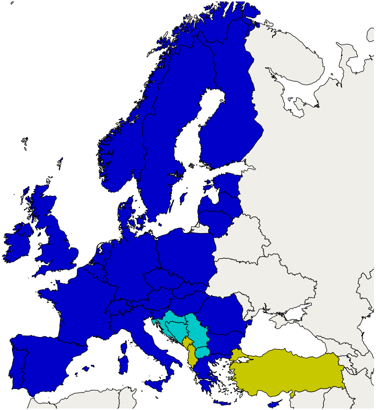

ETSO

TSOs

Reduced control capability of TSOs

Control before liberalization

- Redispatching: economic dispatch
- Topology changes
  - Changing lines
  - Capacitor switching
  - OLTC settings
- Special protection schemes

Control after liberalization

- Redispatching is expensive
- Topology changes and special protection schemes are still possible but limited application range

Goals

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3. Security
4. Economic operation of their system

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5. . . . and a little bit of market

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2. Optimal market use

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Goals

1. Security
2. Optimal market use
3. Economic operation of their system

Power flow controlling devices offer a possible solution

Local investment

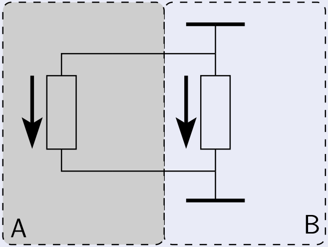
- TSOs can install them in their system, locally (easy permitting)
- TSOs can operate them
- Not that expensive

Optimize the current grid

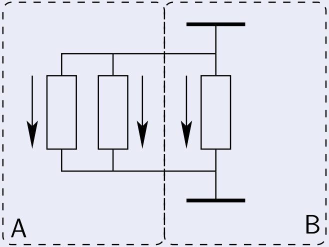
- Limit and control power flows
- Block loop flows
- Redistribute line loadings
- Minimize system losses
- Improve security
- Increase transmission capacity
- Make transmission capacity firm for the market

PFC can be an alternative to grid investments

Paradox of investing to relieve congestion



A is congested



Investing in A is ‘bad’ solution for A

PFC can be an alternative to grid investments

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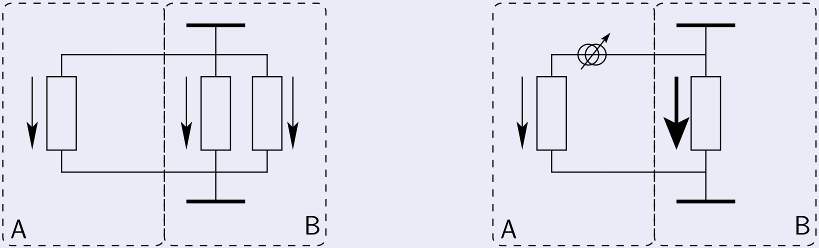


Investing in B would be best

PFC can help

Existing/planned power flow controllers in the Benelux

1. HVDC interconnector UK-FR
2. Meeden PSTs (2×)
3. Gronau PST
4. Monceau PST
5. Norned HVDC
6. Van Eyck PSTs
7. Zandvliet PST
8. BritNed (2011?)

(source: UCTE)

Control of PFC

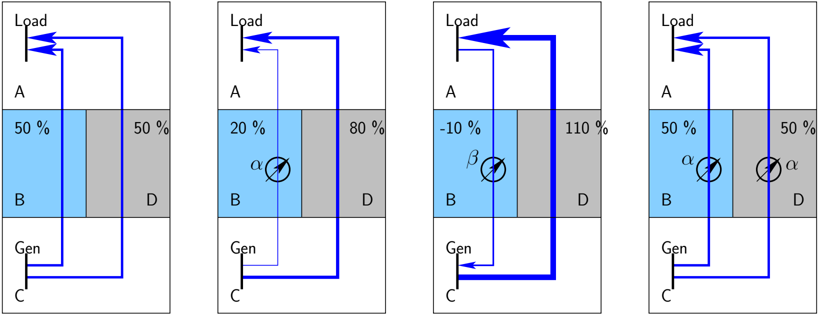
Locally controlled

- The investment is normally done by TSOs
- Therefore control is done by the TSO to fulfill his own objectives
- Payed for by the local market participants,
  so "revenues" should be returned to the local market as well
  - Optimal use of the transmission system
  - Minimum losses
  - Maximum security
  - Maximum transmission capacity

Effects are not local

- Devices are mostly placed on the border
- The effects of active power flow control can reach far into neighboring systems
- Some control actions are intended to influence "external" powers

Multiple zones, multiple PFC



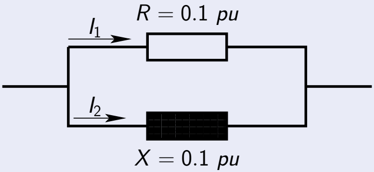
(A) (B) (C) (D)

Example of possible problems with power flow control in multiple zones

System losses with power flow control

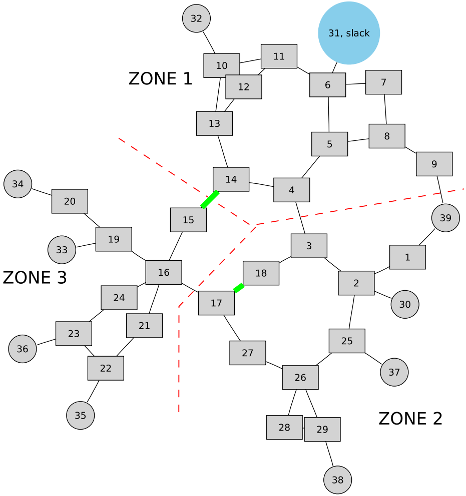
- Higher losses in one line $\neq$ higher system losses
- 0.1 *pu* R and 0.1 *pu* X in parallel

$\Rightarrow$ shift power to X



- A PFC can lower losses by pushing the current towards lines with lower resistance
- In case of a constant X/R ratio, the use of a PFC can only increase the overall losses in the system
- But also *lowering local losses* (while having higher system losses)
- Example IEEE39-bus system as test grid

Example: Three zone system, two PFC



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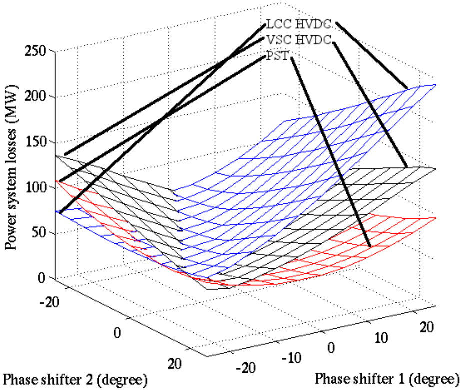
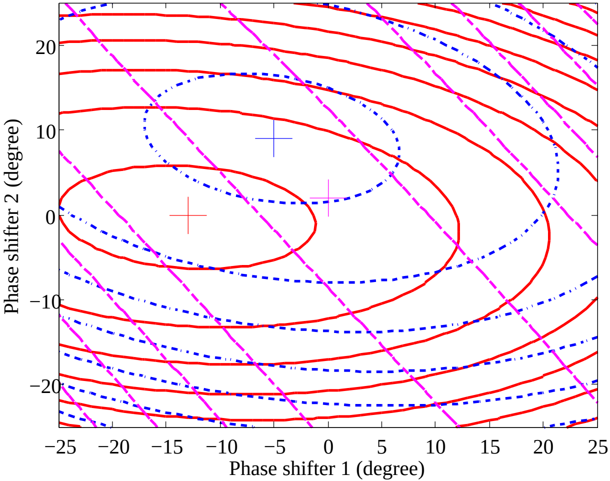


Figure: Overall system losses with two PFC devices installed.

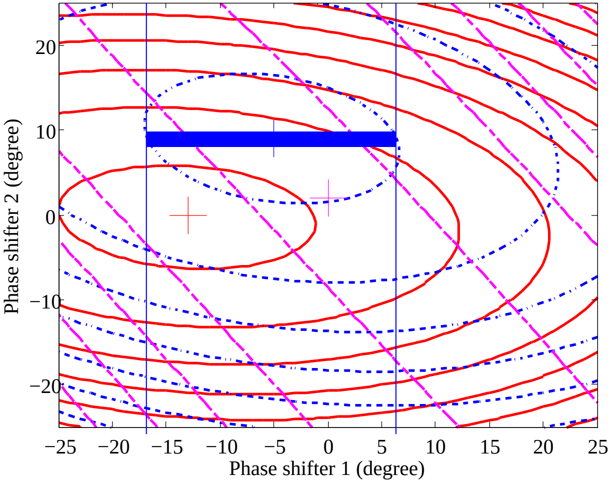
Losses within multiple zones, two PST



- Zone 1, Zone 2 and Zone 3: 3 optima

Losses in the 3 zones, dependent on the settings of the two PSTs.

Losses within multiple zones, two PST



- Zone 1, Zone 2 and Zone 3: 3 optima
- PST 1 is controlled by zone 2

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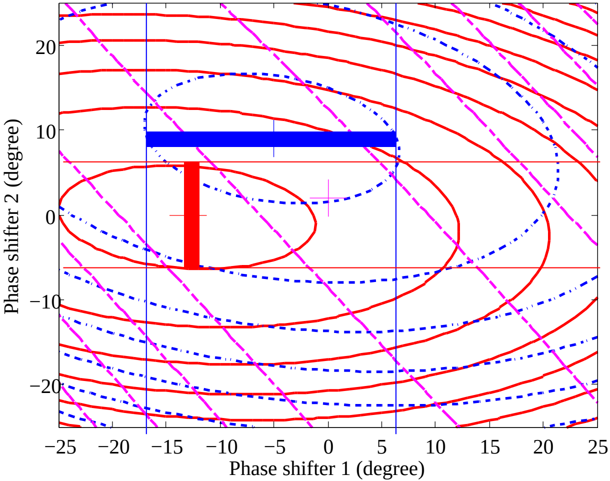
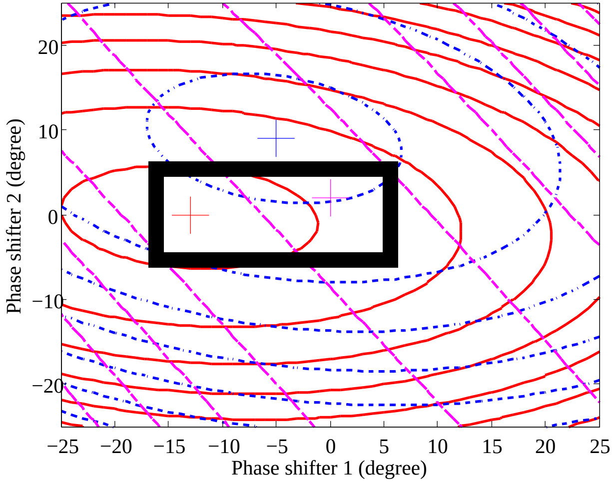


- Zone 1, Zone 2 and Zone 3: 3 optima
- PST 1 is controlled by zone 2
- PST 2 is controlled by zone 1 or 3 (interconnector) (example: 1)

Losses in the 3 zones, dependent on the settings of the two PSTs.

Losses within multiple zones, two PST



- Zone 1, Zone 2 and Zone 3: 3 optima
- PST 1 is controlled by zone 2
- PST 2 is controlled by zone 1 or 3 (interconnector) (example: 1)
- Initial control zone is “bad” for zone 2

Losses in the 3 zones, dependent on the settings of the two PSTs.

Losses within multiple zones, two PST

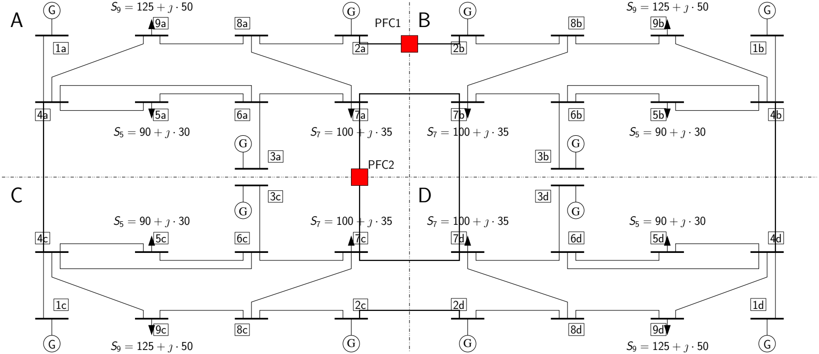
Suboptimal optimization

- 3 zones, 3 optimal phase shifter settings
- Phase shifters are not mutually controlled
- Good for one can be bad for another
- Nash-equilibrium?
- Best solution for the system is not achieved

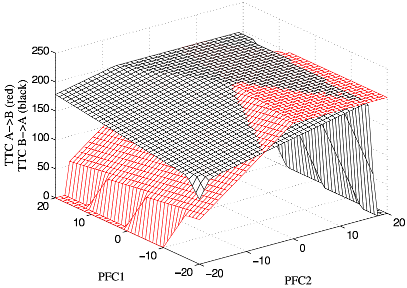
	Angle (PST1, PST2)			
Losses	$(-13°,0°)$	$(-5°,9°)$	$(0°,2°)$	$(-5°,6°)$
Zone 1	**11.4**	13.2	12.3	12.4
Zone 2	11.6	**8.72**	9.8	8.91
Zone 3	12.0	9.18	**9.17**	9.23
Total	35.0	31.1	31.3	**30.6**

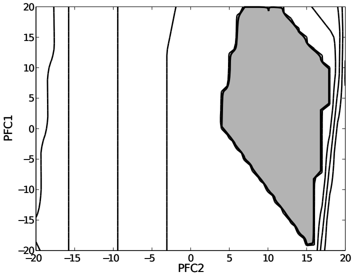
Transmission capacity

- PFCs are widely used to increase transmission capacity
- Newly defined example grid (all effects between zones are due to PFCs):



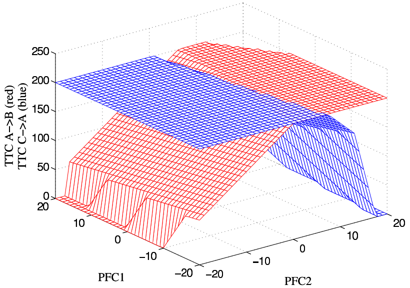
Effect of PFC

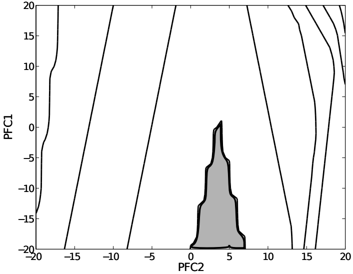




Transfer capacity between zones A and B dependent on PFC settings (import and export)

Effect of PFC





Transfer capacity from zone A to B and from C to A dependent on PFC settings

Need for coordination...

- Different objectives
  - Minimize local losses, not foreign
  - Maximize export capacity to "B", not import from "C"
- Objectives can be excluding
  - What is good for country "A", is not necessary good for "B"
  - And vice-versa
- Global objective is generally not reached when there are multiple objectives
  - TSOs are no competitors, but each has his own objective
  - Rather *unwillingly* obstructing other TSOs or grid users
- PFC control has financial repercussions
- Communication is key

Possible control regimes of PFC for the European system

- Local, single control objective
- Every party on its own
- Uncoordinated operation
- PFC coordination in a market environment
- Regional coordination
- Full coordination
  - New organization
  - Single ISO approach
  - Single TSO approach

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- Solving local problem

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- Full coordination
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- Local objective
- Do not take actions of neighbor into account
- Coordinate only for safety

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- Optimize, knowing neighboring systems
- Nash-equilibrium

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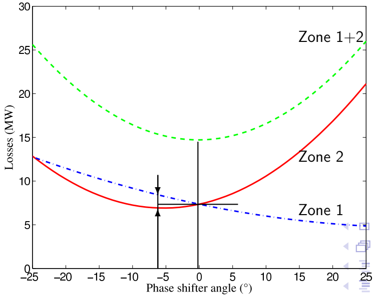
- PFC control is worth money
- Include in the market mechanism?



Possible control regimes of PFC for the European system

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- PFC influence is limited in distance
- Possibilities to implement in the current framework

Possible control regimes of PFC for the European system

- Local, single control objective
- Every party on its own
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- PFC coordination in a market environment
- Regional coordination
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  - New organization
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  - Single TSO approach

- Optimize social welfare
- Additional organization: difficult
- ISO: who will invest?
- TSO: national assets will have to merge

Possible control regimes of PFC for the European system

- Local, single control objective
- Every party on its own
- Uncoordinated operation
- PFC coordination in a market environment
- Regional coordination
- Full coordination
  - New organization
  - Single ISO approach
  - Single TSO approach ⇒ theoretically ideal solution

- Optimize social welfare
- Additional organization: difficult
- ISO: who will invest?
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Possible control regimes of PFC for the European system

- Local, single control objective
- Every party on its own
- Uncoordinated operation
- PFC coordination in a market environment
- Regional coordination
- Full coordination
  - New organization
  - Single ISO approach ⇒ investments are problematic
  - Single TSO approach

- Optimize social welfare
- Additional organization: difficult
- ISO: who will invest?
- TSO: national assets will have to merge

Possible control regimes of PFC for the European system

- Local, single control objective
- Every party on its own
- Uncoordinated operation
- PFC coordination in a market environment
- Regional coordination ⇒ most realistic first step
- Full coordination
  - New organization
  - Single ISO approach
  - Single TSO approach

- Optimize social welfare
- Additional organization: difficult
- ISO: who will invest?
- TSO: national assets will have to merge

Regulatory framework

Current framework

- PFCs are generally left out of the regulations
- UCTE operation handbook mentions PSTs as possible means of guaranteeing security
- No special required agreements exist to enforce PFC coordination

Regulatory framework

Proposed changes

- To the UCTE operation handbook:
  - **Policy 3, A, Standard 3.3:** PFC control settings: TSOs exchange all necessary information regarding PFC settings that are relevant for the international flows and resulting transmission capacities that are projected. These projected values are binding with a certain control margin, agreed upon with neighboring TSOs.
  - **Policy 4, Standard 2.1:** In case PFCs have a strong influence on the transmission capacity between control areas, an indication of transmission capacity must be provided well in advance in order to provide sufficient firm market capacity. Deviations from this network topology change outside the agreed margin, must be done in agreement with neighboring TSOs. In case congestion is anticipated due to a combination of PFC settings and market behavior, PFC devices can be used outside the agreed margin to alleviate congestion. This redispatching could come at a cost.

  $\Rightarrow$ Increased communication
- Future European regulation
  - PFCs and their effects should not be forgotten in forthcoming regulations
  - Aim for more coordination through effective regulations
    - Not only TSOs but also for regulators
- This is only a first step towards further integration, and insufficient on a long term

Part 2

HVDC

History of HVDC

Revival in the '50s

- Used for the transport of bulk power over long distances
- Sea connections
- Interconnection of non-synchronous networks
  - 50-60 Hz back-to-back: Japan, South-America
  - Asynchrounous networks: Fr–UK, Europe – Russia,. . .

Components

- Switching equipment first consisted of mercury arc valves. . .
- . . . the switchover to thyristors happened in the '70s. . .
- . . . IGBTs are the future? (first installation 1996)

HVDC properties

2 cables in stead of 3

No reactive losses

- No stability distance limitation
- No limit to cable length
- Lower electrical losses

No need for synchronism

- Connecting different frequencies
- Asynchronous grids (UCTE – UK)
- *Black start* capability?

Power flow (injection) can be fully controlled

Players

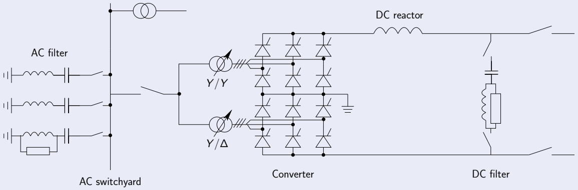
Only 3 big players

- ABB (e.g. Norned)
- Siemens (e.g. Basslink)
- Areva (e.g. Connection UK – Fr)

Two HVDC types

Classic HVDC/LCC HVDC

- Line commutated converter
- Thyristor based (used to be mercury valves)
- Reduce the harmonic impact
  - Converters: 6-pulse ⇒ 12-pulse (⇒ 24-pulse)
  - Harmonic filters
- Converters use reactive energy (absorb)



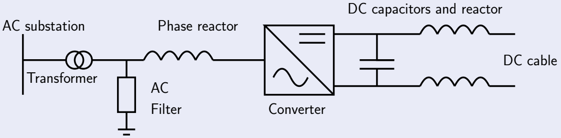
VSC HVDC

Two HVDC types

Classic HVDC/LCC HVDC

VSC HVDC

- Voltage Source Converter
- IGBT technology
- PWM signal (typically $1 - 2\ kHz$)
- Reactive energy can be delivered at both terminals
- Less harmonic filtering needed



VSC HVDC offers countless new possibilities

Advantages of VSC HVDC

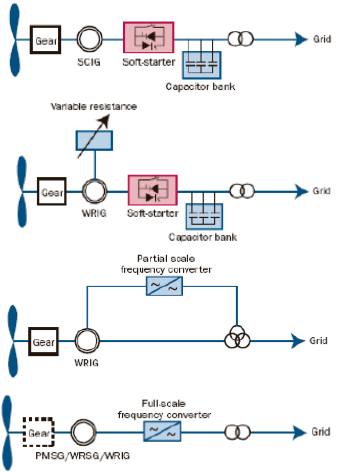
- Full converter controllable at both sides
  - P and Q can be controlled independently
  - Independent rotating field can be formed
- Very fast reactions possible
- Cheap cable connections are possible (XLPE)

Disadvantages

- Expensive converters
- Little experience
- High Losses
- Multi-terminal
- How to control the terminals?

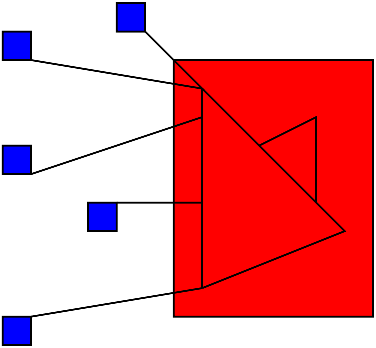
Connecting wind turbines (traditionally)

- Directly coupled to mains frequency
- The traditional approach allowed several technologies
  - Fixed speed induction generators (old technology)
  - Braking resistances
  - Doubly fed induction generators
  - Full converters



New technology allows new wind farm topologies

- Fully independent
- PQ controls are independent
- Grid frequency can be different
  - Lower: no gearbox
  - Higher: very small transformer
  - Not constant
- Offshore grids
  - Radial from the coast?
  - Multi-terminal



Radial connections

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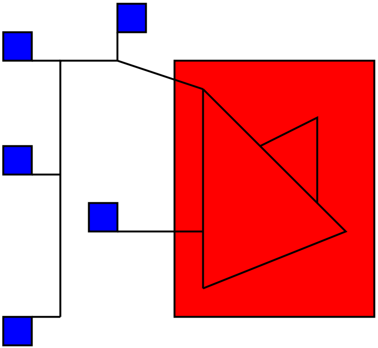

Multiple wind farms on one connection

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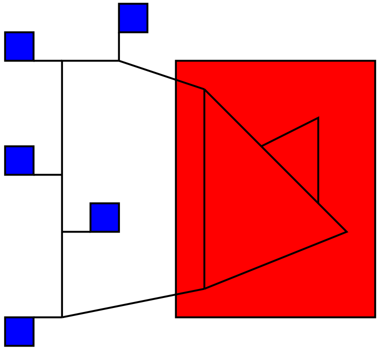

Offshore ring

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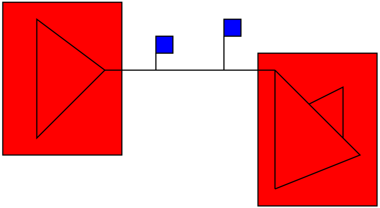
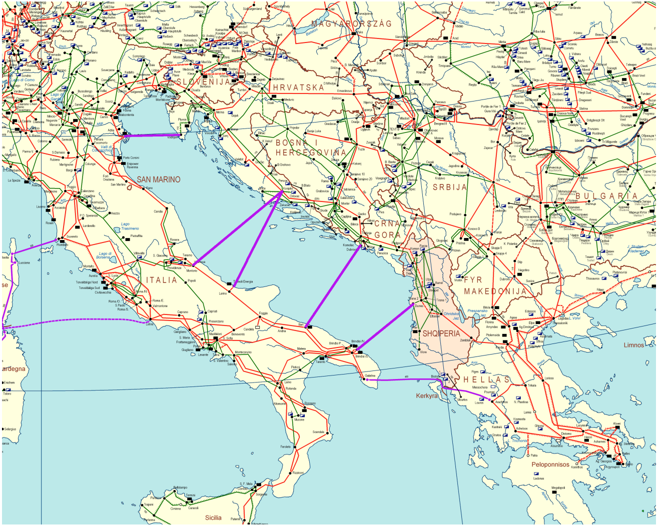


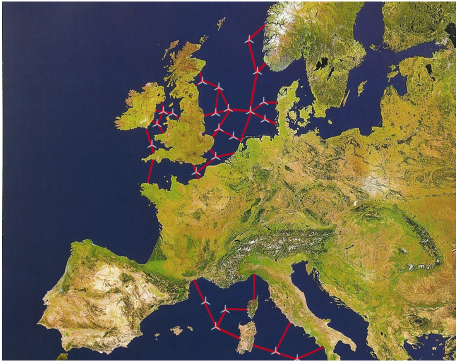
What with wind farms on interconnections?

Link between Croatia and Italy?



VSC HVDC as only alternative for hypergrids

- Supergrid = hot topic
- Connecting renewables



but...

- How will you connect wind?
- Which topology will you use?
- Multi-terminal does not (yet) exists?
- Protection?
- Power levels are currently too low for super grid
- How will the market work on this system?

There is a long way to go

VSC HVDC as only alternative for hypergrids

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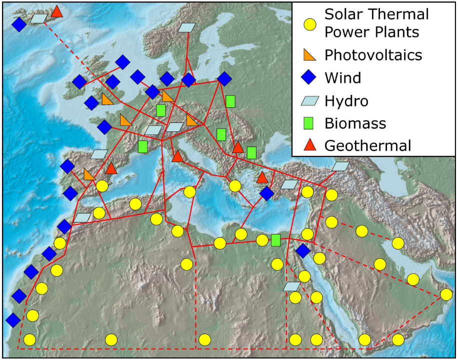
- Connecting renewables



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- Which topology will you use?
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There is a long way to go

Conclusions

- Liberalization changed the power system
  - Increased uncertainty concerning power flow patterns
  - Reduced control for the TSO
  - Investments were lacking after liberalization
- The current situation is not ideal nor a full implementation of the IEM
- PFCs can provide a solution to reduced control capabilities and lacking investments
  - This solution is not necessarily the best solution for the system
- Many different PFC technologies exist
  - Especially PST and HVDC are highlighted in the text
  - VSC HVDC is a new and promising technology

Conclusions

- PFCs influence the operation of the local transmission system
  - . . . also that of neighbors
- PFCs influence losses, transmission capacity, security,. . .
- At this moment, no true coordination is done
- First step: *communicate* (two amendments for UCTE OHB proposed)
- Second step: implemented in the regional initiatives framework
- Optimum would be full coordination, with a single European TSO?

PFC devices can improve the IEM, but they must be used in an internationally coordinated manner in order to achieve optimal system use
HVDC is back the future for the development of transmission systems

Future work

- Safety of the grid with PFC: working closer to the systems limits could lead to problems
  - additional safety precautions, adaptive control schemes and correct state estimation is needed
- VSC HVDC as a future element in the transmission system
  - VSC HVDC in a meshed system
  - Connecting renewables
  - Multi-terminal and eventually hypergrids

Questions

?