A supergrid for Europe ... and also for the US?

Dirk Van Hertem
Dirk.VanHertem@esat.kuleuven.be

Department of electrical engineering
Division Electa
KU Leuven, Belgium

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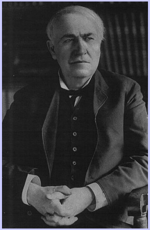
Objectives

- How does energy policy influence grid development?
- Why is HVDC suddenly so popular?
- What are the properties (technical and other) that drive the choice towards DC
- A first look at the grid developments (a.k.a. supergrid)

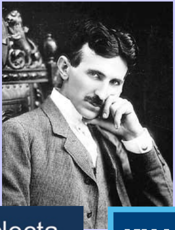
History: Struggle of the (scientific) titans

- At the dawn of electricity (1885 – 1890s): two struggling parties
  - Thomas Edison
  - Nicola Tesla (and Westinghouse)
- War of the currents: `http://www.youtube.com/watch?v=kn-nhXMhXQ4`
- Edison was heavily opposed to AC (Electrocution of condemned people was shortly called “Westinghousing”)
- AC won because of:
  - Easy to transfer up to higher voltages
  - Rotating field
  - Breaking DC currents

Thomas Edison



Nicolas Tesla



(source: thinkgeek)

Revival in the '50s

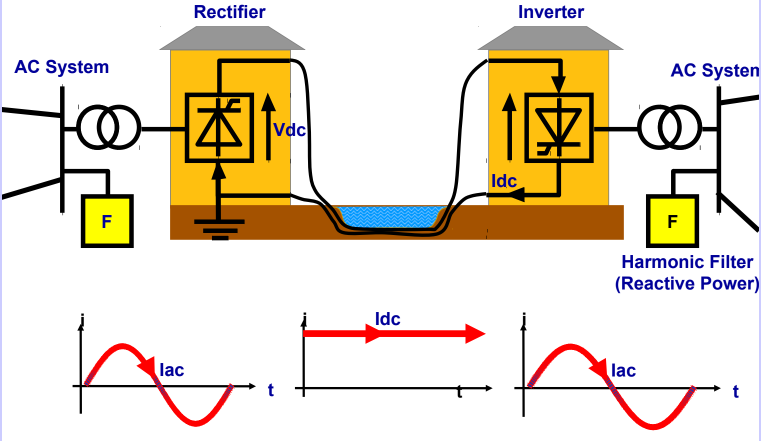
- Used for the transport of bulk power over long distances
- Used for undersea (cable) connections
- Used for the iterconnection of non-synchronous networks
  - 50-60 Hz back-to-back: Japan, South-America
  - Asynchrounous networks: Fr–UK, Scandinavia – Continental Europe, Europe – Russia,. . .

Second revival from the second half of the '90s

- New markets (e.g. China and India)
- Switching/acting component at first were mercury valves and later thyristors
- . . . transistor based components (IGBT) for HVDC started in the 90's
- Cable connections become more important

⇒ New applications such as offshore

From alternating current to direct current and back

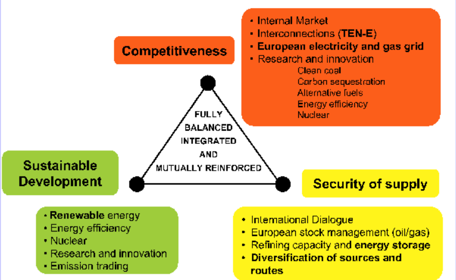


1. Introduction
2. The evolving power system
   - Before liberalization and the rise of renewables
   - More renewable energy generation
   - International market environment
3. Investments in the power system
4. HVDC
5. Comparing investment technologies
6. The supergrid to the rescue

- Before liberalization:
  - Mostly vertically integrated companies
  - All operational issues were within one company
  - Both generation and transmission investments were done in one company and coordinated
  - Synchronous system to increase security
  - Limited international trade, and mostly long-term contracts
- Before massive introduction of renewable energy sources and distributed generation:
  - Centrally planned generation
  - Centrally controlled
  - Focus on high availability
  - Bigger is better (economy of scale)

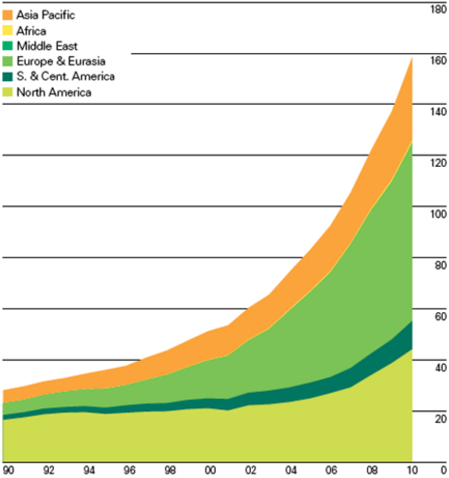
Policy that drives grid development

- EU energy policy triangle
- Environmental: EU has initiated 20/20/20 goals for 2020
  - 20 % of energy consumption by RES
  - 20 % GHG/CO_2 reduction
  - 20 % efficiency increase
- Security of supply and internal market require sufficient grid
- Post-2020 a continuation of the policy (27 % by 2030)
- Policy makers, environmental organizations, technology providers and energy companies strive for "more grid"
- 15 % interconnection capacity target by 2030



(source EU)

- Traditional power plants
  - Bigger is better, more economic
  - Size is limited by technology (GW power plants)
  - Generally investments and operation by centrally controlled, big companies
- Renewables, CHP and new generator types emerged
  - Generation units as small as 1 kW
  - Not centrally planned or controlled
  - Further increase to be expected in the future (Electrical cars?)
- Uncertain generation pattern. . .
  - $P_{wind} = f(v_{wind}^3)$, no light during the night and clouds,. . .
  - CHP output is usually dependent on heat process
- . . . and consequently uncertain flows
- Balancing of wind is a problem for some countries

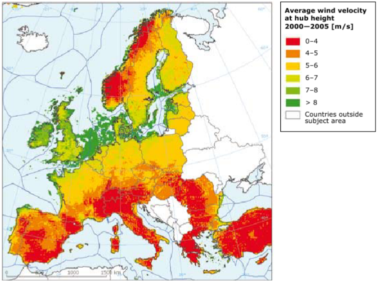


Growth in the supply of electricity from renewable sources in million tons of oil equivalent (BP Statistical Review)

- Electric energy is traded on the market in blocks of 1 or more hours
- Where different bids can come from different generators
- From anywhere in the system
- When a single company offers a block, this is not necessarily from the same generator
- Result: variable flows throughout the grid
- A higher reserve margin is needed

Many stakeholders are involved

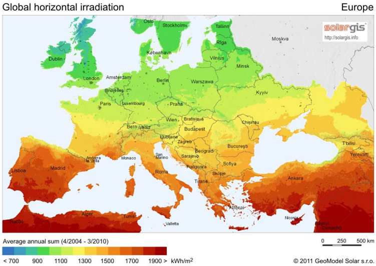
- TSO, Regulator, DSO, Generator company,. . .
- National, regional and local



Source: EEA, 2008.

Average wind profile in Europe (source: EEA)

- Large reserves of RES are available
- Easy to reach RES is already in use
- Currently ± 39 GW of wind and ± 39 GW of solar in Germany (± 20 % each)
- Rest of Europe is also rapidly increasing its renewable generation
- Offshore wind is expected to increase to 150 GW and onshore up to 250 GW (2030 targets for EWEA)
- Large resources in the North Sea region



Average solar radiation in Europe (source: SolarGIS)

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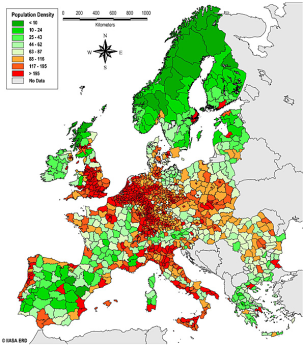
- Solar resources are mainly in the Mediterranean and even northern Africa



Population density in Europe (source: IIASA)

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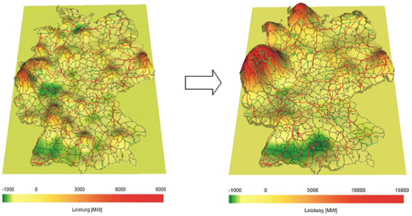
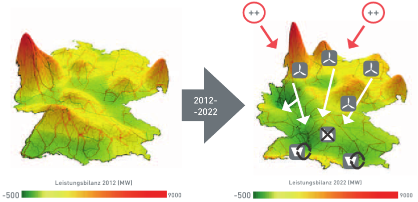
- Population is not located where the new generation is



(source RWE)



(source NEP)

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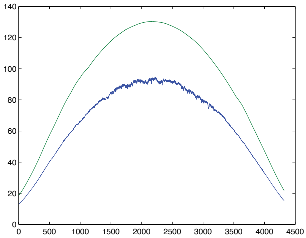
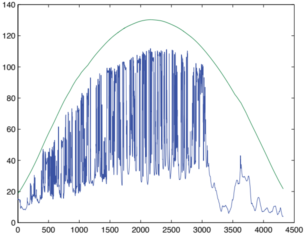
- Large resources in the North Sea region
- Solar resources are mainly in the Mediterranean and even northern Africa
- Population is not located where the new generation is
- Generation moves to the borders

- Time frame of variability is very important: ms → seconds → hours → daily → seasonal
- Variability requires flexible generators or demand which can ramp up and down
  - Variability of power generation might be smoothened over areas?
  - Looking at system-wide availability for balancing
  - Balancing from distant locations require
- Not all effects can be smoothened (e.g. local voltage profile)
- Some variability is very predictable
- Forecasting is essential



Clear day profile



Cloudy day profile

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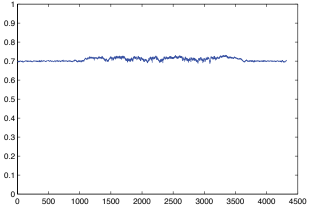
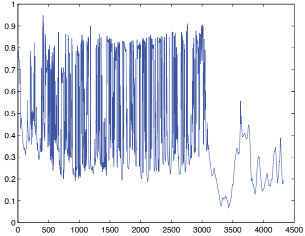
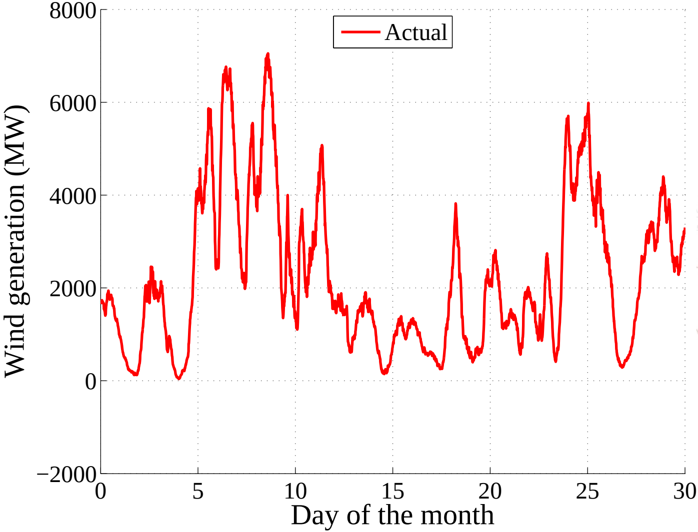
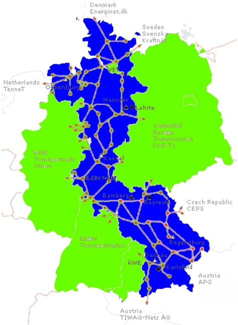


Clear day clear sky index

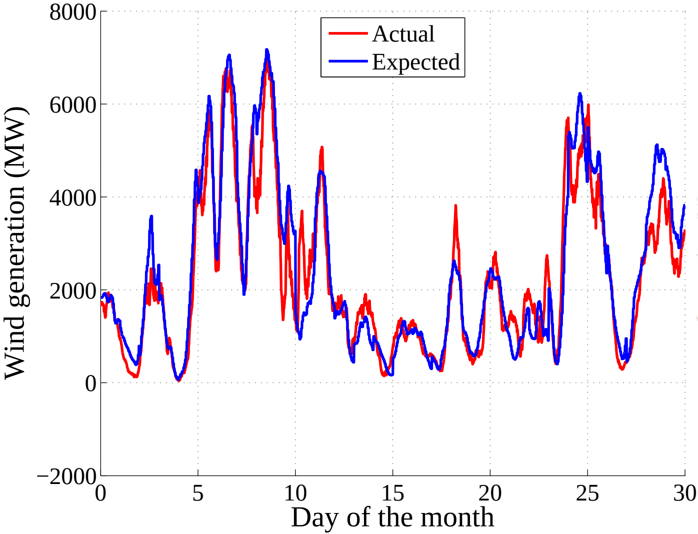


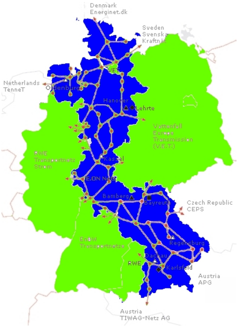
Cloudy day clear sky index





Real, estimated and mismatch wind generation in November 2007 in the E.On-Netz grid (Now transpower, part of TenneT), Day-ahead data for eve





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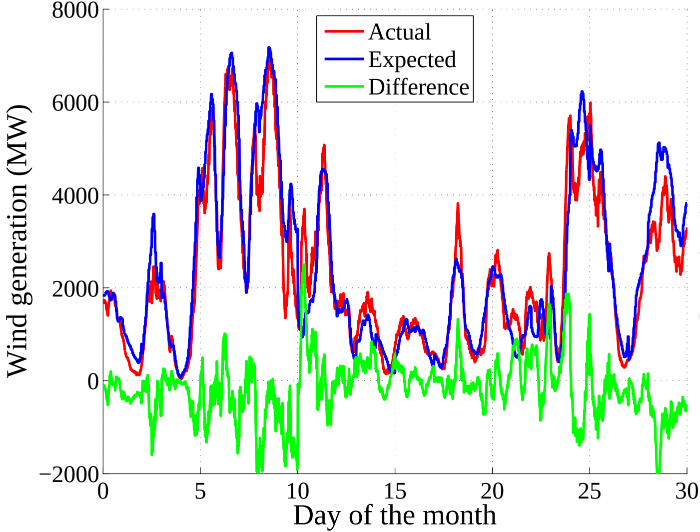

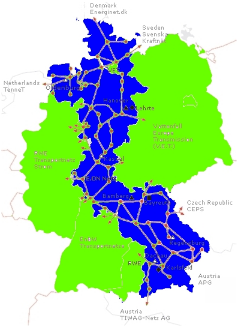

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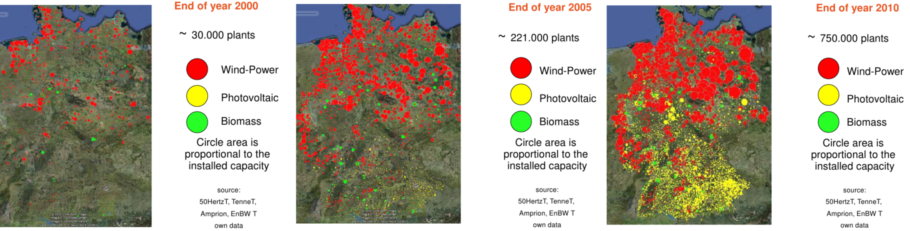
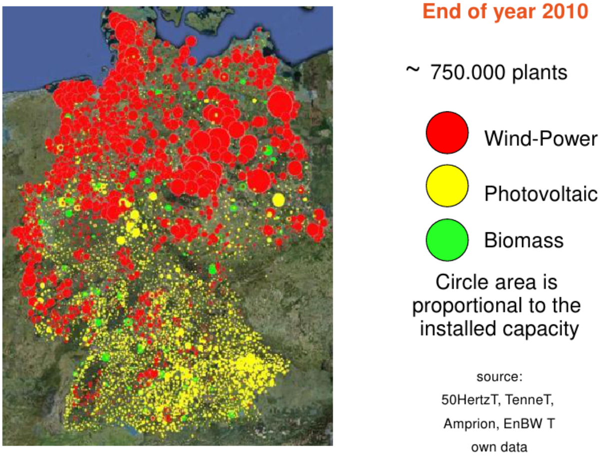
Location of RES in Germany (source 50 Hertz)

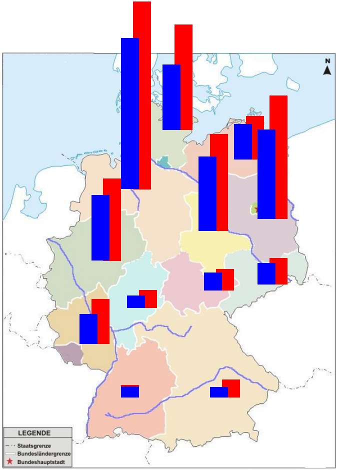


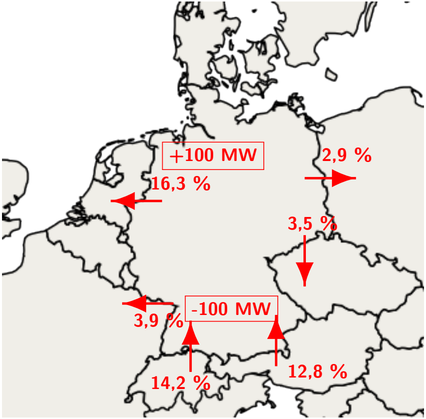
2000 2005 2010

Location of RES in Germany (source 50 Hertz)



Next step: offshore

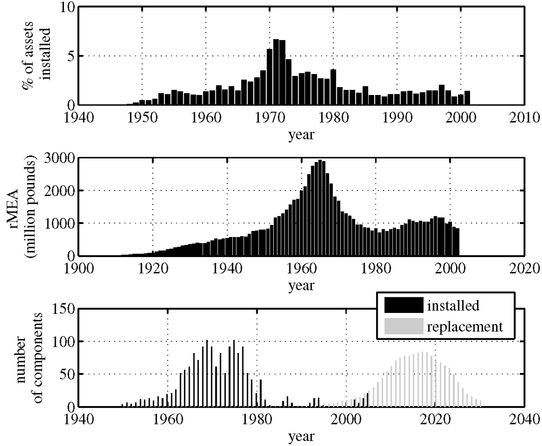




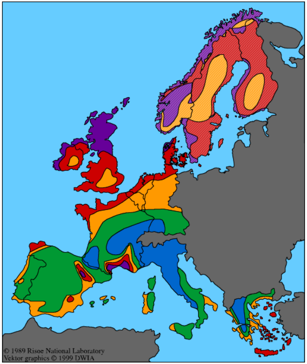
- Wind is predominantly located in the north. . . and is balanced in the south
- National problem can have international consequences
- (blue columns represent 2008 data, red columns 2011)

- Many problems are simple to "solve": increase capacity, build new lines
- In the vertically integrated system, investments were "easy"
  - Centrally controlled with government support
  - Security above everything else: overinvesting is ok
  - Centrally planned
- Now investments in transmission lines are subject to regulatory approval
  - Tariff reduction focused
  - National focused
- Policy and regulations (environmental, building permits,. . .) have become more stringent, complex and especially time consuming
- Uncertainty in policy and regulations cause difficult decision making
- Heavy public opposition (environmental, public, political, health,. . .)
  - NIMBY (not in my backyard), NIMTO (not in my term of office), BANANA (Built absolutely nothing anywhere near anything), CAVE (citizens against virtually everything),. . .

The grid was built about 40 years ago and assets are aging



sources: resp. RWE, PBPower/IBM and KEMA

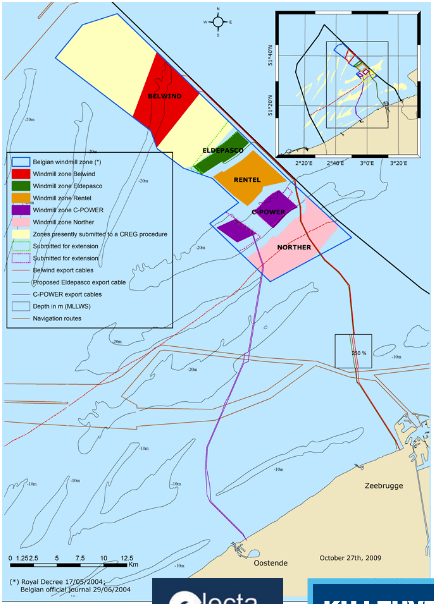


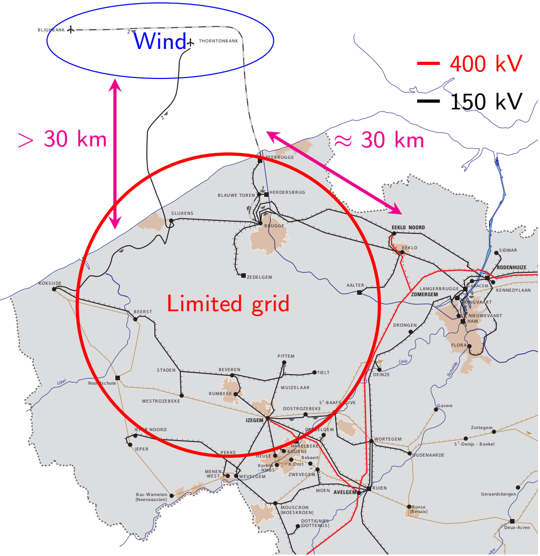
- TSOs use renewables often as “excuse” for new lines: fair or not?
- Any generation needs transmission
- Renewables needs more transmission:
- Renewables often located at remote locations
  - This is certainly the case for wind (NIMBY)
  - . . . and evident for offshore
- Second effect: Variability of wind makes that on average more grid is needed for the same load
  - Capacity factor of 1/3 or even lower
  - 100 MW wind installed is not 100 MW “traditional” generation

Concessions:

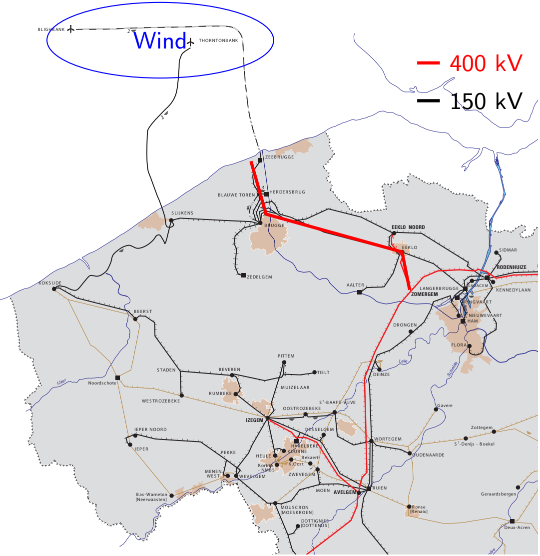
- C-power: 216-330 MW, 27 km
- Belwind: 165+165 MW, 42 km
- Eldepasco/Northwind: 219 MW, 38 KM
- Norther: 350-450 MW, 23 km

More coming/being processed





- Wind is located far from shore
- With limited grid in between
- Already loaded in inland direction



- Wind is located far from shore
- With limited grid in between
- Already loaded in inland direction
- Investments needed to accommodate all generation
- Upgrade proposed by Elia (Belgian TSO)
- Limited length of new lines needed (OHL), rest upgrade
- Long resistance ⇒ last hurdles
- Earliest realization 2013, real date 20??
- Construction of wind turbines faster?

Needed upgrades in the west of the US to achieve 20 % renewables/wind

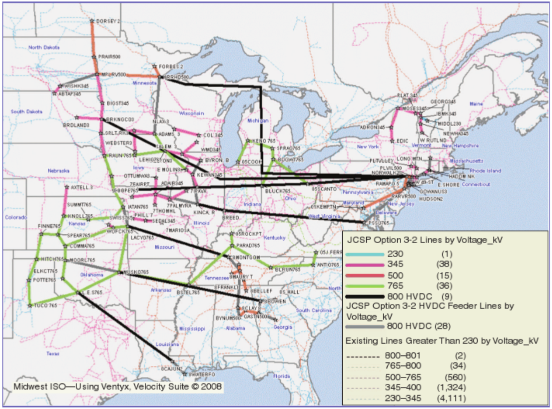


figure 5. Conceptual transmission overlay for the 20% wind-energy scenario (used with permission).

november/december 2009 IEEE power & energy magazine

. . . Similar investments needed in China (and India)

Sources: SGCC, CSG and TS.

AC and DC investments planned in China by 2015 (500 billion yuan investments)

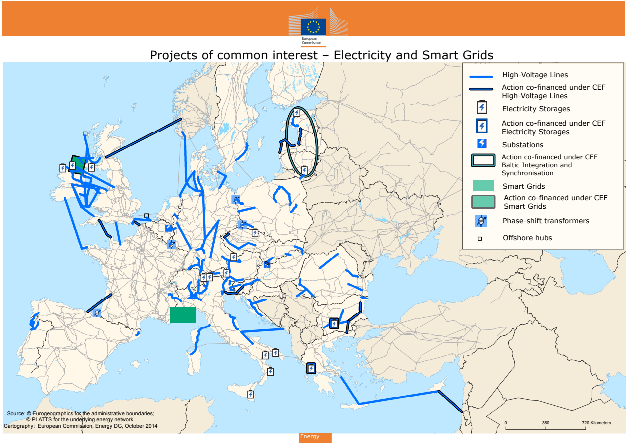


Figure: Priority interconnections in Europe (PCI)
http://ec.europa.eu/energy/infrastructure/pci/doc/2014_pcielec_smart_grid_cef.pdf)

	Obstacle	# Projects
1	Electromagnetic fields (EMF)	11
2	Environmental issues	9
3	Visual impact	7
4	Densely populated/Urban/Rural areas	7
5	Grid issues	9
6	Dependency on other project(s)	2
7	Authorization procedure and legal framework	12
8	Identification of cross-border points	3
9	Commercial Problem	3
10	Difficult terrain and weather	4
11	No perception of supra-national or European perspective	2

Table: Obstacles according to the priority interconnection plan of TEN-E

Different technologies can be used

- Additional AC overhead lines
- Upgrading/uprating the current system
- Underground AC cables
- Flexible power system operations
- High Voltage Direct Current (HVDC)

Different technologies can be used

For onshore reinforcements?

- Additional AC overhead lines
  - $\Rightarrow$ Permitting and long delays $\Rightarrow$ Difficult
- Upgrading/uprating the current system
  - $\Rightarrow$ Limited applicability, delay of structural investments
- Underground AC cables
  - $\Rightarrow$ Short maximum length (charging)
- Flexible power system operations
  - $\Rightarrow$ Limited applicability, delay of structural improvements
- High Voltage Direct Current (HVDC)
  - $\Rightarrow$ Getting quite some renewed attention

Different technologies can be used

For onshore reinforcements? For offshore reinforcements?

- Additional AC overhead lines
  - $\Rightarrow$ Permitting and long delays $\Rightarrow$ Difficult
  - $\Rightarrow$ No
- Upgrading/uprating the current system
  - $\Rightarrow$ Limited applicability, delay of structural investments
  - $\Rightarrow$ No
- Underground AC cables
  - $\Rightarrow$ Short maximum length (charging)
  - $\Rightarrow$ Yes, but for limited distances
- Flexible power system operations
  - $\Rightarrow$ Limited applicability, delay of structural improvements
  - $\Rightarrow$ No
- High Voltage Direct Current (HVDC)
  - $\Rightarrow$ Getting quite some renewed attention
  - $\Rightarrow$ YES, especially for longer distances

Main properties of HVDC

- Fewer cables are needed for equal power transmission
- No reactive losses
  - No stability distance limitation
  - No limit to cable length
  - Lower electrical losses
- No need for maintaining synchronism
  - Connecting different frequencies
  - Asynchronous grids (UCTE – UK)
  - *Black start* capability?
- Power flow (injection) can be fully controlled

3 main players

- ABB
- Siemens
- Alstom Grid

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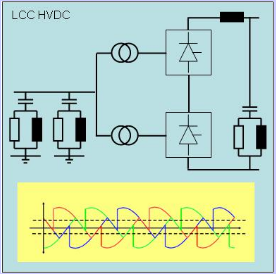
3 main players

- ABB
- Siemens
- Alstom Grid ⇒ Becomes GE
- Japanese manufacturers start to look outside of Japan
- Developments in China

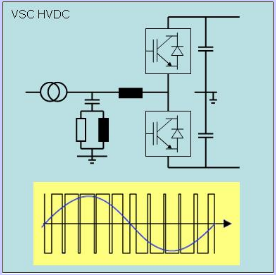
CSC/LCC technology

- Uses thyristors
- Large power ratings
- Large filter installation
- Strong AC grid required
- Oil based (Mass impregnated) cables
- Active power control
- Not viable for offshore applications

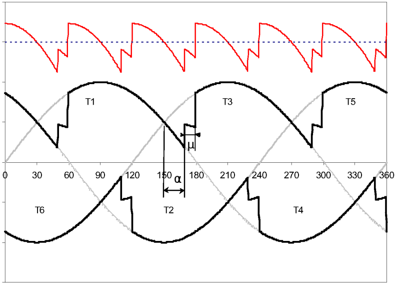


VSC technology

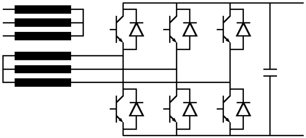
- Uses IGBT
- Medium power ratings
- Smaller footprint
- Can connect to any system
- XLPE (plastic) cables are possible
- Independent active and reactive power control
- Offshore applications are possible

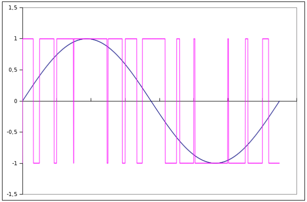


- LCC (Line Commutated Converter) or CSC (Current Source Converter) or Classic HVDC
- Thyristors are fired at a given angle
- Current always lags voltage (reactive power consumption)
- Extinguished by current passing through zero
- In normal operation, DC current is kept constant, voltage is altered
- Power reversal done by reversing the voltage polarity

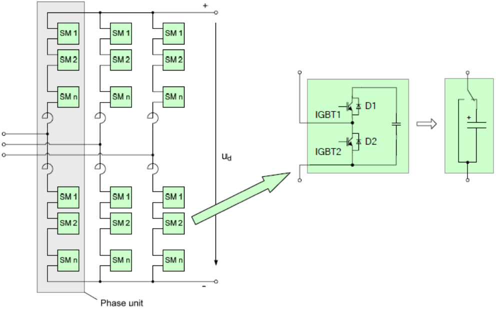


- Voltage source converter
- Basic block: 6-pulse IGBT converter (large frequency converter)
- PWM controlled (2-level converter)
- In normal operations, DC voltage is kept constant, currents are reversed
- Power reversal by reversing the currents





- Old converters were too lossy (high $\frac{dU}{dt}$)
- Multi-level converters were introduced
- 3 manufacturers, 3 implementations...



Siemens implementation: Modular Multilevel Converter (MMC, M2C)

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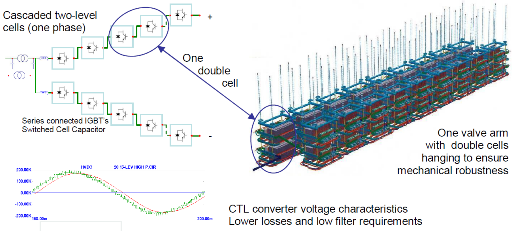

ABB implementation: Cascaded 2-level

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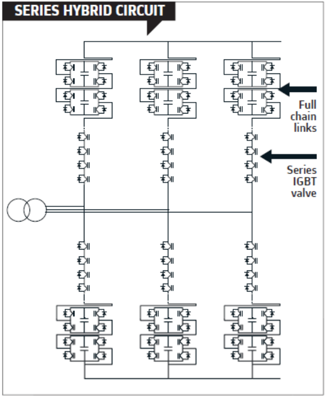
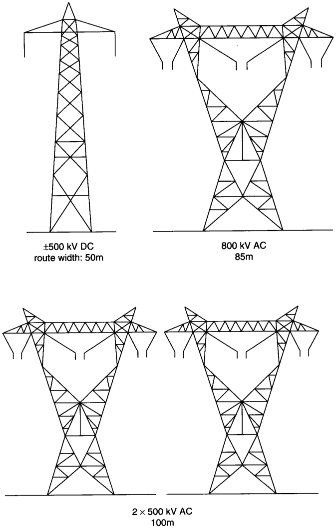


Hybrid MaxSine solution of Alstom Grid

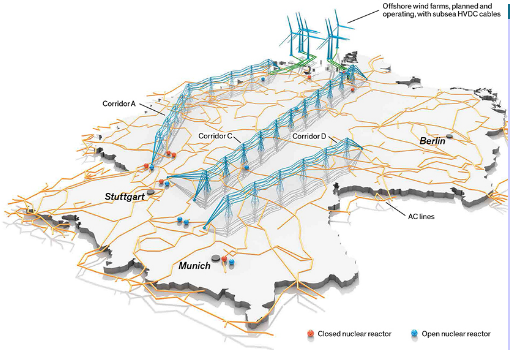
More expensive than overhead but...

- Less visual pollution
- No varying electric or magnetic fields (people are afraid of this)
- More acceptable to the public ⇒ faster planning approval
- No flashovers due to pollution
- More reliable than overhead
- Preferred solution in Europe



(source Arrillaga)

- If OHL is applicable, AC right of way is much higher
- Typical tower structures and rights-of-way for alternative transmission systems of 2 000 MW capacity.
- Right-of-Way of a cable: few meter
- Possible investment option: upgrading existing AC lines to HVDC systems



(source: IEEE spectrum)

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LCC HVDC

- Cheaper
- Larger powers
- Lower losses
- Longer experience
- Proven reliability
- Significant danger for harmonic resonance
- Absorb reactive power ($50 - 60$ % of P)
- Overhead and cable
- DC current polarity does not change
- Possible commutation failure

VSC HVDC

- P and Q/U control
- Independent rotating field
- Harmonic filter requirements are low
- Smaller footprint (especially important offshore)
- Power oscillation damping (also with voltage)
- Black start capability
- AC breaker needed for fault operation in DC cable
- DC voltage polarity does not change
- Multi-terminal operation is quite straightforward

Connection to Offshore loads and generators

- Independent AC voltage control allows to manage weak (offshore) grids
- Independent rotating field
- Small footprint and weight
- Cheaper solution for large(r) distances
  - $\pm 60\ km$ for $400\ kV$
  - $\pm 80\ km$ for $220\ kV$
- or for high power ratings
- Decoupling of AC and wind network
- Offshore dynamics can be fully controlled
  - Fault handling
  - Power quality (flicker and others)
- $f_{offshore}$ is controllable: Variable speed wind farm network for efficiency
- Stable operation of the AC grid

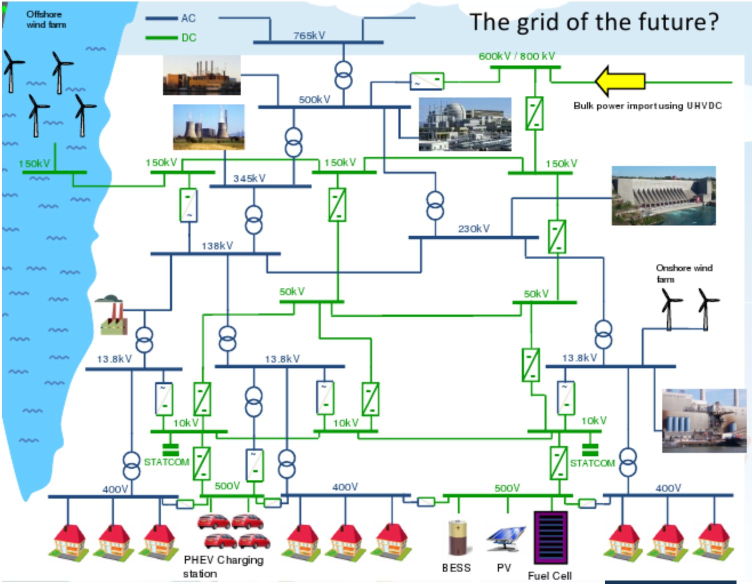
Nothing is perfect

- Losses are relatively high
- Protection in the AC network is not trivial
  - VSC HVDC can only deliver rated power (switching of with AC faults)
  - Conventional overcurrent protection may not work
  - Low current $\Rightarrow$ longer fault detection is permitted
  - No extra inertia $\Rightarrow$ Frequency tripping adjustments?
- Dynamic model not freely/fully available
- New component which is not well known with the operators (no experience)
- Ratings are limited
- Connection of a large number of converters (wind farm) to a main converter can lead to issues

DC for more than bulk power

- With renewables (especially offshore wind), VSC HVDC already used for intermediate power ratings
- DC application is not limited to the transmission level
- At the lowest levels, DC is already used
  - Most power electronic supplies
  - Most storage devices (or UPS)
  - Some energy sources
- On a local level, DC might take over AC power supplies (especially in special cases such as data centers etc)
- Special applications for city infeed?
- Two parallel systems (AC and DC) might co-exist
- Electric car charging infrastructure might provide the necessary leverage
- Development of the DC-DC converter is essential

Vision of a multi-level DC grid: DC-DC converters needed!



(Source: Alstom grid)

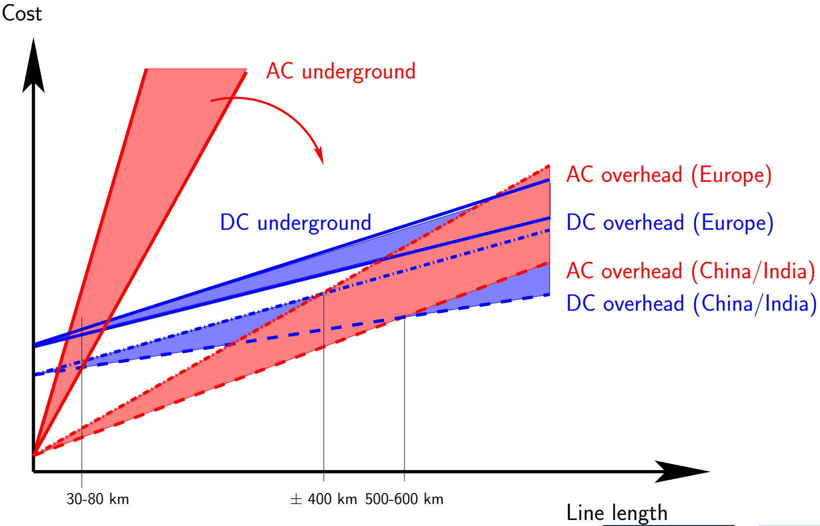
LCC HVDC

- Standstill losses: $\pm 0{,}1\ \%$ of nominal power, per converter station
- Load losses: $\pm 0{,}7\ \%$ of power flow, per converter station
- Cable/line losses: $R_{DC} \cdot I^2$

VSC HVDC

- Standstill losses: $\pm 0{,}18\ \%$ of nominal power, per converter station
- Load losses: $\pm 0.8\ \%$ of power flow, per converter station
- Cable losses: $R \cdot I^2$
- Voltages are still lower (limited to $\pm 320\ kV$), higher currents and higher line losses
- AC voltage control enables loss minimization (minimize Q)

Comparing options for GW transport



Technical comparison

Table: Comparison of classical AC transmission (OHL, uprating and cable), power transmission using FACTS or PST for power flow control (PFC) and HVDC, both VSC and classical (LCC)

	AC OHL	uprating	AC cable	AC PFC	LCC HVDC	VSC HVDC
length limitations	few	few	yes	no	no	no
trans. cap. increase	high	medium	medium	medium	high	medium
power control: active	no	no	no	yes	yes	yes
power control: reactive	no	no	no	dependent	no	yes
grid interconnections	synchr.	synchr.	synchr.	synchr.	any	any
losses	low	low+	low+	low	medium	medium+
power oscillation damping	no	no	no	possible	limited	yes
power reversal	fast	fast	fast	fast	slow	fast
Installation cost	low	low	high	medium	medium	high

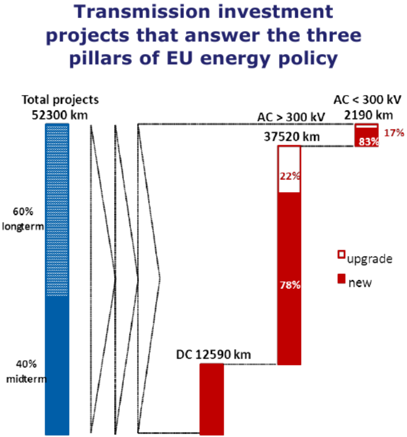
This is what is in the corporate advertisements

Looking at the PIP obstacles

		AC OHL	Uprating	AC cable	PFC	HVDC
EMF	peak-value	+	+/-	-	+	++
	corridor	-	+/-	+	+	++
Environment, Visual impact, Densely populated areas		--	+/-	+	++	+
Grid issues		-	-	--	+/++ (vsc)	+/++ (vsc)
Additional capacity		++	-	+	-	++/+ (vsc)
Length		+	+	-	NA	++

- Note: Aggregated list of obstacles as given by table on PIP projects
- Conclusion: OHL is often considered as the preferred option, but other options must be considered
- Using underground solutions, possibly through HVDC, has several advantages

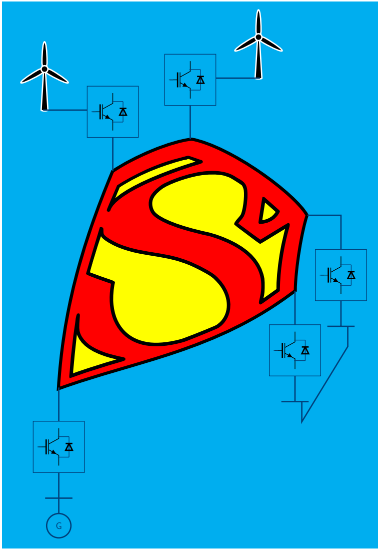
- **Security of Supply**
- **Integration of RES**
- **The completion of the IEM**



ENTSO-E vision on future investment needs in Europe
(source ENTSO-E/Elia)

Energy needs to be transmitted over larger distances

Conclusion: we need a fundamental upgrade of the grid!



HVDC seems to be the preferred option

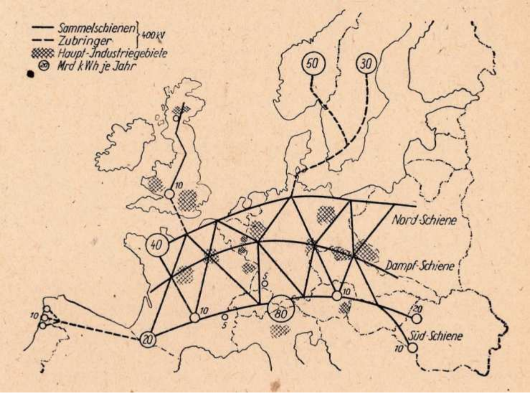
But how is it going to look like?

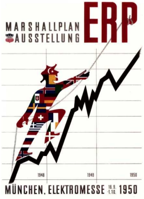
What is a supergrid?

- A popular definition: a supergrid is an overlay grid connecting different generation and load centers over larger distances
- It serves as a backbone, connecting different regions and sources
- Adds reliability and security of supply to the system
- A grid offers redundancy
- Sometimes also called “hypergrid”

New?

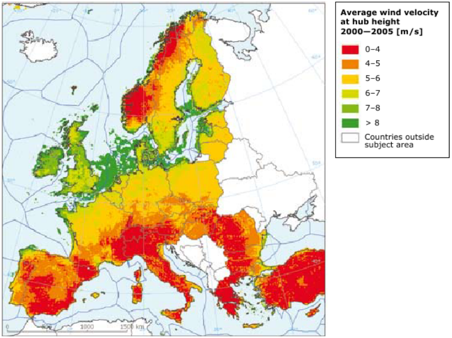
- Recurring issue
- Electric transmission started from 1 generator to several local loads
- Grids became interconnected, at increasingly higher voltages
- The 400 kV grid became the supergrid of the 50’s





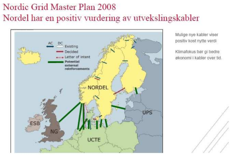
Early idea of a supergrid (after WW2)
Implemented as a $400\ kV$ AC grid

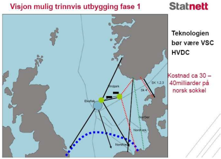
- There is plenty of renewable energy available
- Solar from the Sahara, wind from the North Sea and hydro from Norway
- The energy needs to reach the consumer

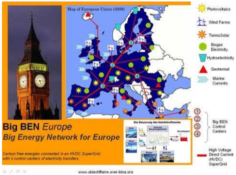


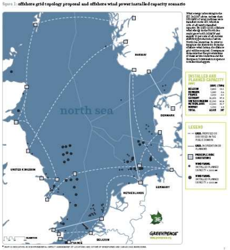
Source: EEA, 2008.

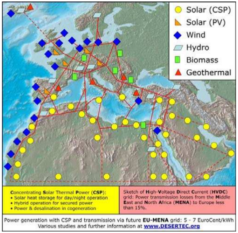
- $\pm 1\ km$ between mills ($1/km^2$)
- take 10 MW/mill (future)
- UCTE: 600 GW generation
- Capacity factor $1/3$
- Required surface to replace UCTE generation: $\frac{600 \cdot 10^3 \times 3}{1 \times 10} = 180 \cdot 10^3 km^2$
- square of $430\ km \times 430\ km$
- or $100\ km$ wide, $1800\ km$ long coastal track (Germany has about $2300\ km$ coastline)

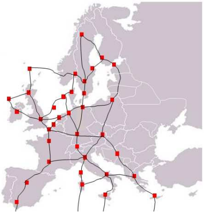


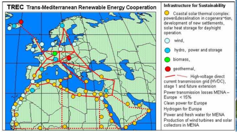




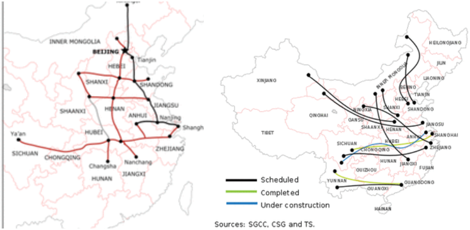






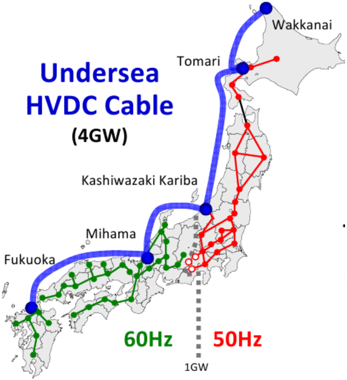


electa
KU LEUVEN

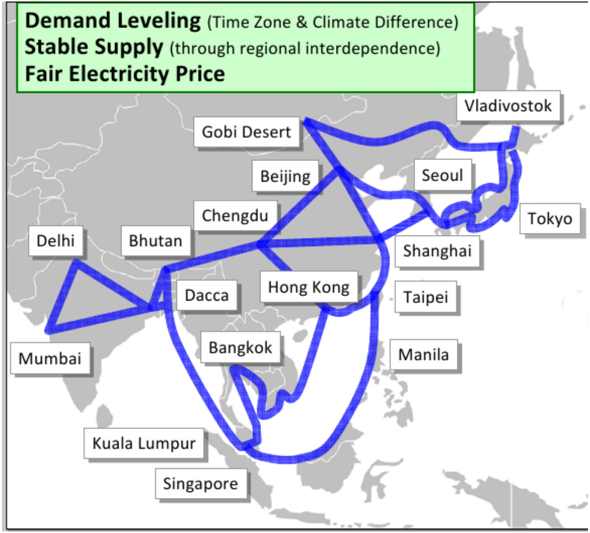


- Atlantic Wind Interconnector (USA)
- `http://atlanticwindconnection.com`

- AC and DC investments planned in China by 2015 (500 billion yuan investments)



source: Paradigm Shift in Energy, Japan Renewable Energy Foundation;
`http://jref.or.jp/images/pdf/20110912_presentation_e.pdf`



source: Paradigm Shift in Energy, Japan Renewable Energy Foundation;
`http://jref.or.jp/images/pdf/20110912_presentati`

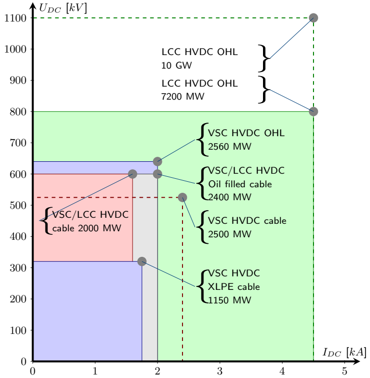
In order to accommodate all generation and loads

- Fundamental increase in transmission capacity
  - 1-2 GVA per circuit and 400 kV is not sufficient
- Transmission over longer distances
  - Efficiency is important
- Connection to different offshore resources and synchronous zones
- Reliability of the overall system should be maintained (or even increased)
  - N-1-like concepts should apply to the new system as well
- The new overlay grid must be compatible with the current system
  - Including operation, markets,. . .
- . . . and the system should be cost effective in comparison to alternatives

- An alternative to an overlay or backbone grid is stretching the use of the current infrastructure
- Making optimal use of existing right-of-way
- Using known technology
  - New AC lines where possible
  - Point-to-point HVDC
  - Flexible grid use (e.g. phase shifting transformers, Dynamic line rating,. . .)
  - Flexible generation
  - Re-conductoring (Converting AC to DC, high current conductors,. . .)
  - Smart grids. . .
- No fundamental upgrade (small changes)
- But at much lower immediate cost than a full upgrade
- An new supergrid must compete with traditional concepts

- Although AC is can be an option, focus in Europe is on HVDC
- Cables are limited (both AC and DC)
  - Yet, offshore requires cables
  - Rating (in MVA and kV)
  - Section length (1 km on land)
  - High power AC cables offshore are difficult (too cumbersome?)
- Majority lives $< 500\ km$ from shore
- For interconnections (between asynchronous zones), HVDC is a must

HVDC system capabilities



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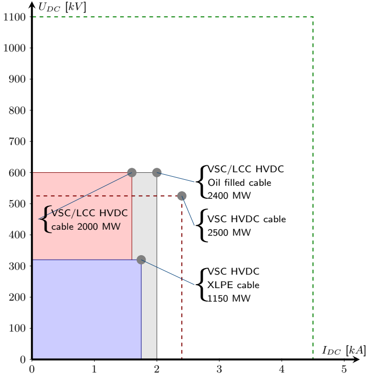
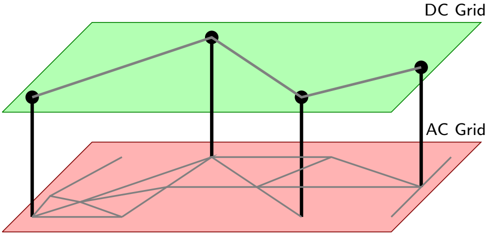
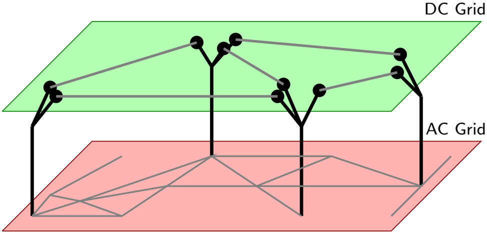
HVDC cable system capabilities





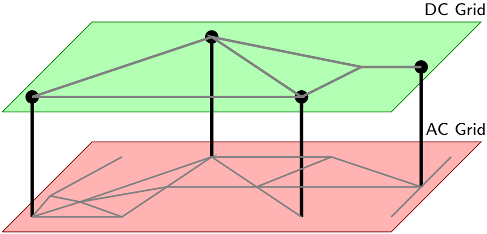
Option 1

- Multi-terminal without redundancy
- DC and AC system form each others redundancy
- Injections and thus DC flows are controlled



Option 2

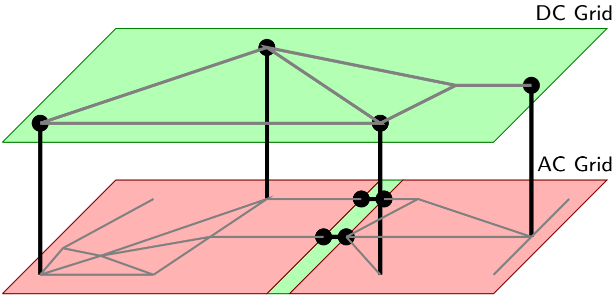
- Grid of point-to-point DC lines
- Converter at both ends
- Some lines in the AC grid are replaced by DC lines
- Full control
- AC connections and therefore AC protection devices
- Many expensive and lossy converters

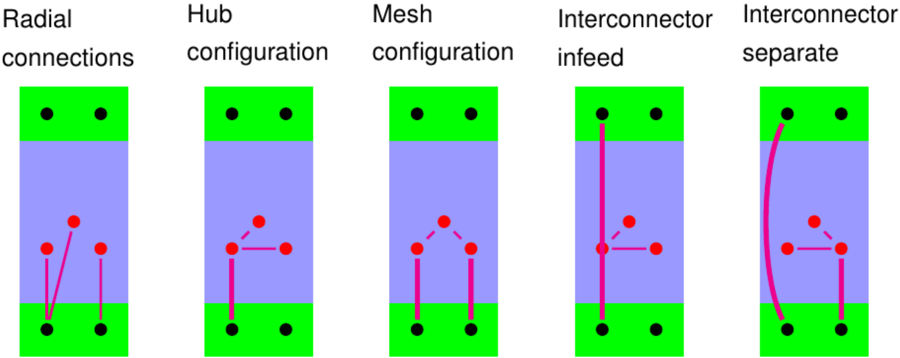


Option 3

- Meshed DC grid
- Redundant lines
- Only converters at interface between AC and DC grid
- Reduced losses
- DC flows can not be directly controlled
- Cigré workgroup B4-52 considers only this a real DC grid

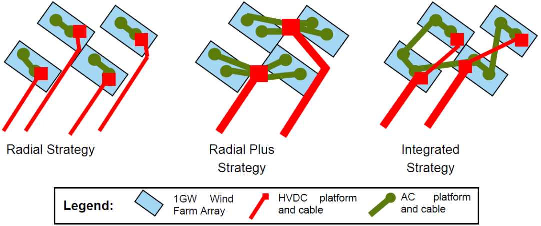
- In synchronous AC systems, events propagate throughout the system
- By subdividing current synchronous zones in different smaller zones, this can be reduced
- Part of the synchronizing power would be lost as well
- Might be an option for currently loosely or non-synchronized systems (USA?)





- At this moment, no real meshes and no connections to existing interconnectors or joined developments
    - Krieger's Flak. . .
- No "real" offshore grid

- An overlay grid is not built overnight
- All investment decisions taken effect future investments
- Transmission investments are linked to generation investments
- Overrating to accommodate future generation?
- Each project has given lead times

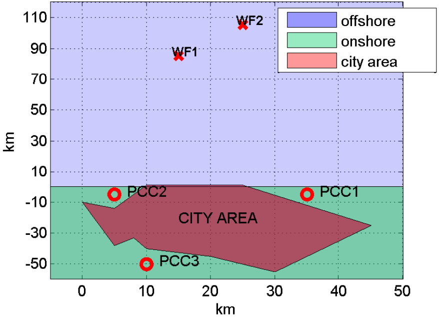


Different planning approaches for connection offshore wind (National Grid UK)

- Two wind farms (550 MW)
- WF_2 is installed 5 years after WF_1
- Several PCC available (different capacities)
- Forbidden zones exist

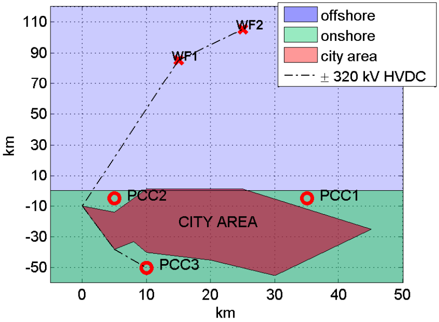
Assumptions for transmission system optimization

$Capacity\ PCC_{1,2}$	200 MW
$Capacity\ PCC_3$	1200 MW
$Voltage\ level\ PCC_{1,2,3}$	400 kV
$Voltage\ level\ WF_{1,2}$	30 kV
$Lifetime$	25 ae
$Energy\ price$	50 €$/MWh$
$Interest\ rate$	5 %



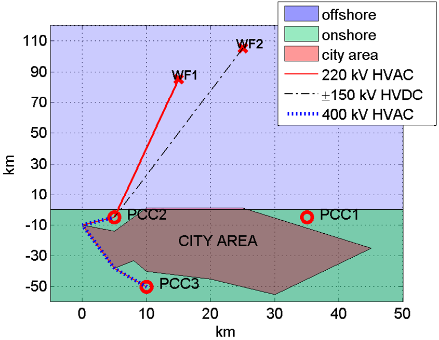
Wind farms and points of common coupling of study case

- Two wind farms (550 MW)
- WF_2 is installed 5 years after WF_1
- Several PCC available (different capacities)
- Forbidden zones exist
- Integrated: Optimal investment costs $669{,}4$ M€
- 160 km grid of which 109.4 offshore

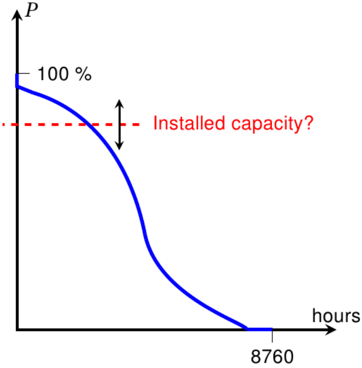


Optimal transmission layout for integrated approach

- Two wind farms (550 MW)
- WF_2 is installed 5 years after WF_1
- Several PCC available (different capacities)
- Forbidden zones exist
- Integrated: Optimal investment costs $669{,}4$ M€
- 160 km grid of which 109.4 offshore
- Non-integrated: 708.3 M€
- Circuit length more than double
- Break-even depends on investment delay, interest rate...

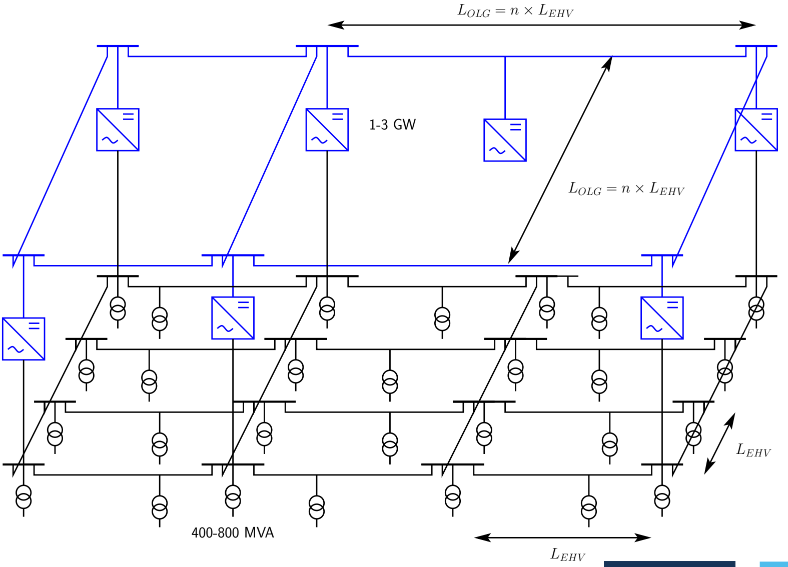


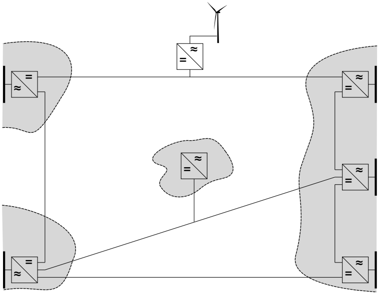
Optimal connection of WF_1 and WF_2 with non-integrated approach



- Is it interesting to invest up to rated capacity?
- How much redundancy is desirable?
- Decrease investment cost
- Depends on the energy yield (full load hours)
- And the expected value of the energy
    - At maximum wind power, what is the energy price?
- Loss of power
    - e.g. oil rig: extra power produced by diesel generators or load reduction during partial outage
    - e.g. wind farm: wind farm curtailment
- In case of a meshed grid, how much must be invested?

- The transmission system is meshed because of economics and reliability concerns
  - The new system should be meshed as well
- A new overlay grid should be an order of magnitude larger/bigger
  - 4-8-10 GVA per circuit and 500-800 kV
- Converter stations will connect layers as transformers do now
- A HVDC overlay grid will have fully controllable injections
- Not all DC nodes will be connected to a synchronous zone
- Few nodes per country
  - Some countries only one? Security?


$L_{OLG} = n \times L_{EHV}$
1-3 GW
$L_{OLG} = n \times L_{EHV}$
L_{EHV}
400-800 MVA
L_{EHV}



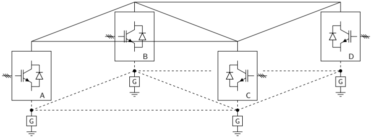
DC grid topology: Criteria?

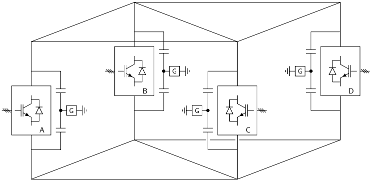
- Extensibility
- Reliability
- Cost
- Flexibility
- ...

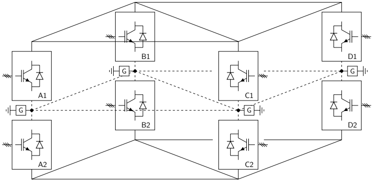
Bipolar? Monopolar? Symmetric?
Asymmetric? Combination?

Solid grounding? High impedance? Inductive?
One ground or more?

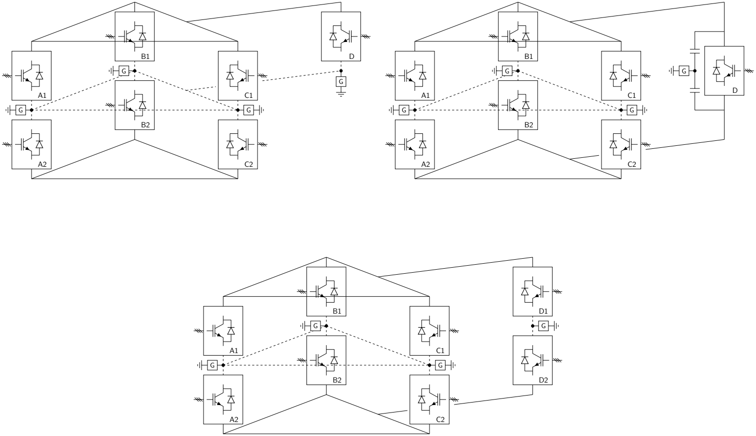
Fully asymetric monopolar, symmetric monopolar or bipolar DC grid

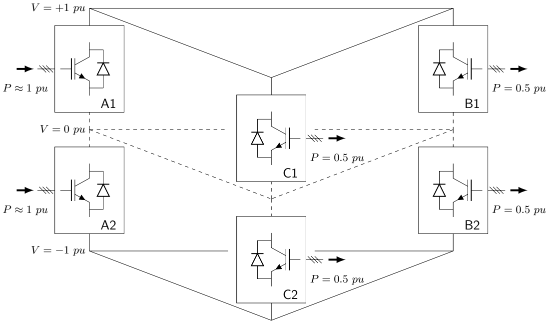






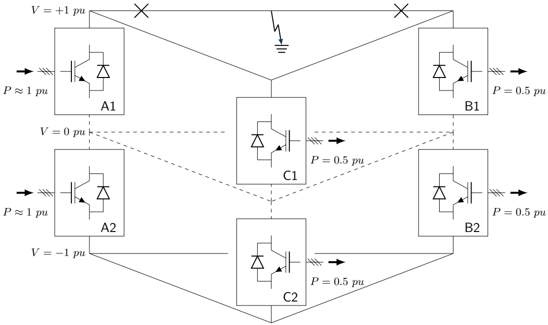
DC grid: combination of different topologies





Three terminal bipolar DC network

- Converters modeled as voltage sources, cables represented by a resistance
- Converters at terminal A act as voltage regulators
- Normal operation: no current through metallic return



Three terminal bipolar DC network

- Converters modeled as voltage sources, cables represented by a resistance
- Converters at terminal A act as voltage regulators
- Normal operation: no current through metallic return
- Post-fault operation after line outage between A1 and B1?
- Need to redefine power/voltage control, power flow scheduling. . .

- System underneath needs fundamental upgrades as well
  - Currently, few nodes are able to absorb or withdraw several GW
- The changing flow directions will require a new grid setup
  - Offshore wind resources will result in a grid which is oriented from the shore to inland regions
- Fewer connections (in comparison to 400 kV) to lower levels result in higher impacts in case of outages
- Events on the DC system will propagate to the AC system and vice versa
- The controllable power injections will change the underlying grid
- Multiple synchronous zones must be considered
  - $\#$ connections to zones such as Ireland ($< 10\ GW$ installed capacity), Scandinavia ($\approx$ 61 GW)

- Similar to the AC system, standards are needed
- Standard voltages
  - Once chosen, it is difficult to change
  - What with the integration existing/upcoming lines?
- Different manufacturers must be able to connect to the same DC system (no vendor lock-in)
- The control systems of different manufacturers/owners must operate together and without detriment to the AC system
- Grid codes will be required

Supergrid protection boundaries

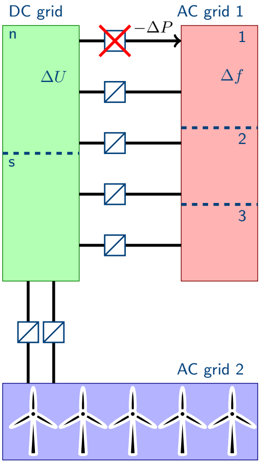
- Fault causes rapidly changing currents in all lines
- Selectivity: Only the affected element must be switched
- IGBTs cannot withstand high overloads
- Fast enough (DC: no inductance $X_{\mathcal{L}}$ to limit the current)
- Only in case of DC fault and not during load change or AC fault

Consequences

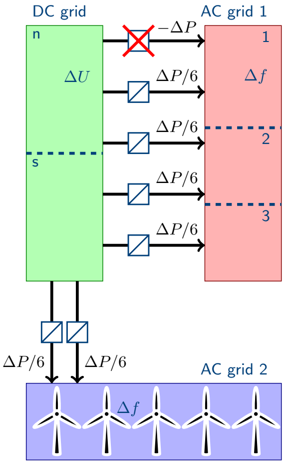
- Fault location (branch) detection within a few milliseconds
- Too fast for communication between measurement devices
- Independent detection systems
- Opening at both sides of the faulted line
- No opening of other branches?
- Backup in case this fails
- New superfast DC breakers are needed ($\approx 5\ ms$)

- What needs to be communicated?
  - ⇒ Depends on the control system
- Time-stamps (as with PMU) might be needed
- Fast control most likely needs to be done without communication
- The system must be able to run “a while” without communication (N-1)
- Coordinated power oscillation damping needs high amounts of data transfer (possibly at specific moments)
- Protection could require very quick communication (with low bandwidth): fast and reliable enough?

- At any time, the power balance must be zero: $\left(\sum_i P_{AC\to DC}\right) - P_{loss} = 0$
- Injections can be fully controlled (DC) but compensation for losses is needed
- Slack bus or distributed slack bus?
  - Consensus is building around distributed slack
  - but not all nodes will participate (equally)
- Power flows are according to the laws of Kirchhoff
- Redispatching of DC injections might be needed to change DC flows and avoid congestion
- The DC system flows are determined by the DC voltages (or DC voltage differences) at the converter side
- DC voltage (differences) in the DC system is comparable to the frequency (difference) in an AC system
- The DC system controls need to be integrated in the market: Day-2, Day-ahead and intraday scheduling and operations

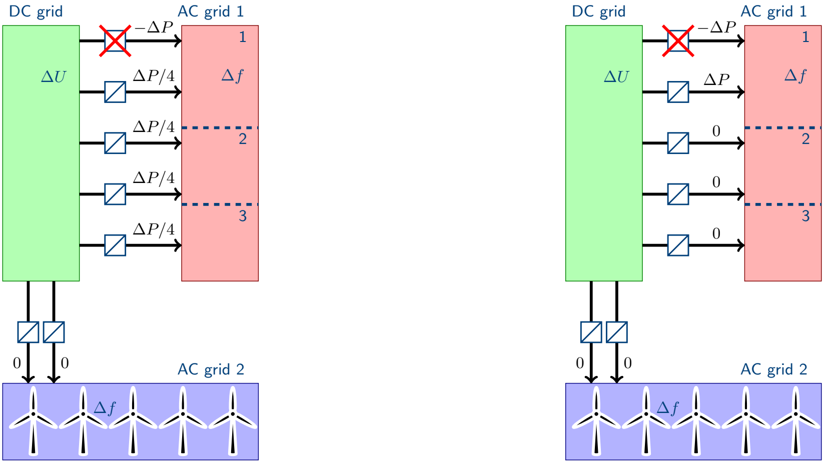


(a) Outage of a converter station connecting the HVDC grid with AC grid 1, zone 1



(b) Equal droop reaction causes all converters connected to the HVDC grid to contribute

Figure: Solving unbalances through power injection adjustment (simplified, assuming the wind farms to contribute equally to disturbances)



(a) The schedule with AC grid 2 is corrected, resulting in only a contribution from AC grid 1

(b) Control zone 1 of AC grid 1 takes the full unbalance over from the other systems

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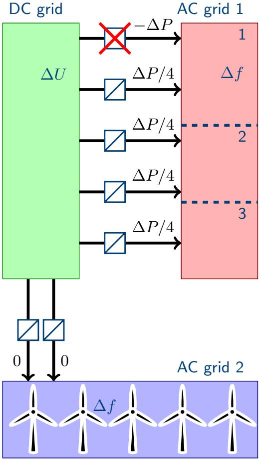

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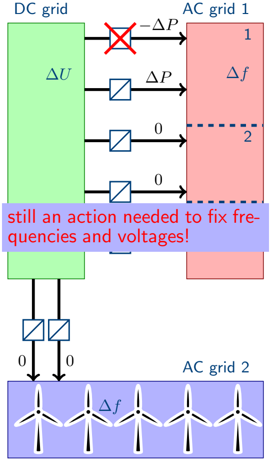

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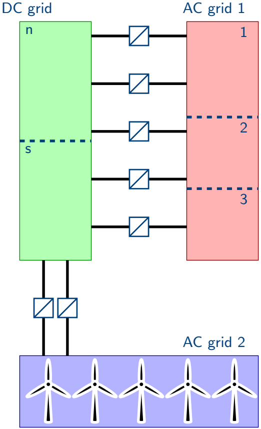
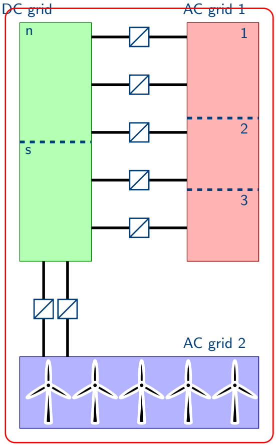


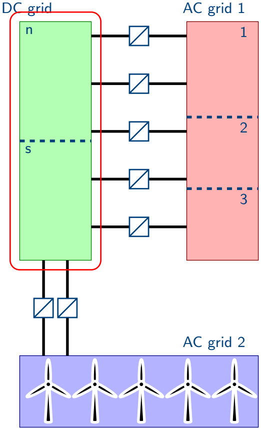
Area which is operated by the same entity:



Area which is operated by the same entity:

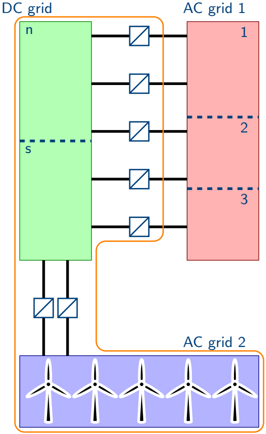
1. One single zone of operation

A DC grid as part of a larger system: where is the border



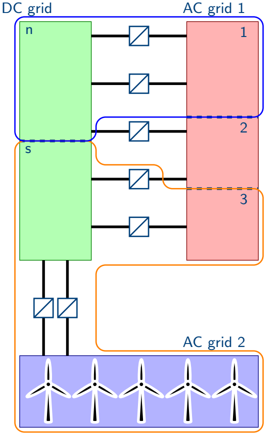
Area which is operated by the same entity:

1. One single zone of operation
2. DC separate from the AC system



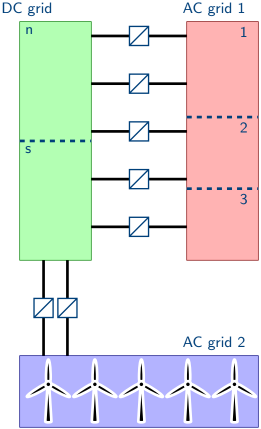
Area which is operated by the same entity:

1. One single zone of operation
2. DC separate from the AC system
3. Offshore separate



Area which is operated by the same entity:

1. One single zone of operation
2. DC separate from the AC system
3. Offshore separate
4. Based on country borders



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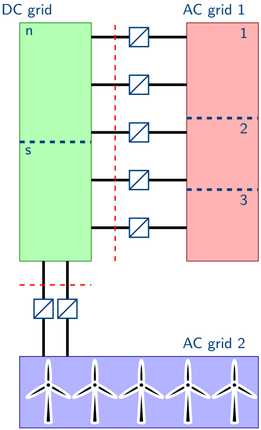
⇒ Different possible definitions.

⇒ Different implementations

⇒ Different consequenses towards cost-benefit



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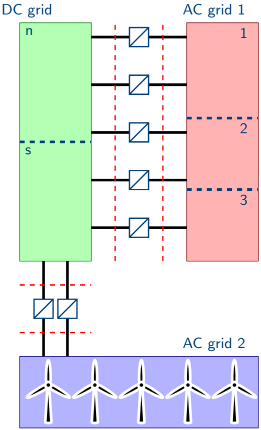
Where to draw the border between AC and DC:

1. At the DC busbar/PCC
2. At the AC busbar/PCC
3. Halfway the converter

the border determines the interactions and who controls?



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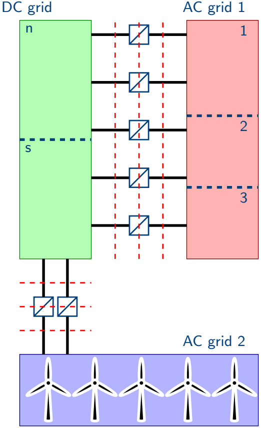

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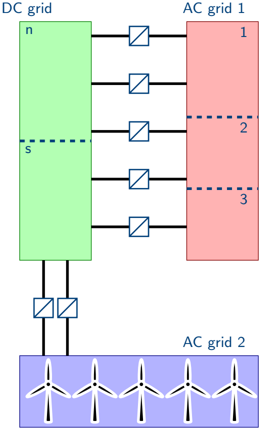
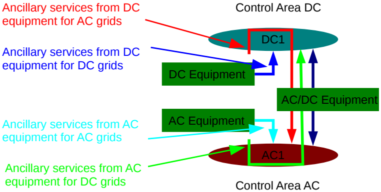


- AC system is operated "N-1"
  - where N is per AC zone
- hybrid AC/DC system?
  - N-1 on AC + DC system
  - N-1 on AC and DC system separately
  - DC system operated as N-1? or can we use the DC (AC) system as a backup for the AC (DC) system?
  - How can we use power flow control using converter controls (currative actions)?
  - Generation curtailment as standard action?
- Dynamic support via the DC system
  - Virtual inertia
  - Power Oscillation Damping
  - Support during alert and emergency state

- Ancillary services are all services required by the TSO or DSO to enable them to maintain the integrity and stability of the transmission or distribution system as well as the power quality. (Eurelectric)
- Exchanged between stakeholders, possibly from other systems
- Can be defined as:
  - AC equipment for AC grids ⇒ "standard"
  - DC equipment for AC grids ⇒ ± ENTSO-E grid code
  - AC equipment for DC grids ⇒ undefined
  - DC equipment for DC grids ⇒ undefined
- Minimum set of ancillary services for DC grids:
  - Energy Balance and reserves
  - DC transmission capacity reserve and power flow control
  - DC loss compensation
  - Energizing of DC subsystems, DC black start and restoration



Basic economics

$$NPV(t) = \sum_{i=0}^{t} \frac{Revenue(i) - Expenses(i)}{(1+r)^i}$$

- With $NPV(t)$ the net present value of the investment after t years
- $Expenses(i)$ in each individual year: investments, permitting, maintenance, operations,. . .
- $Revenue(i)$ in each individual year: tariffs, congestion fees, capacity charges,. . .
- r the discount rate taken into account

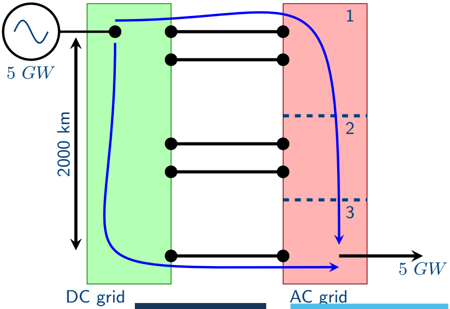
In practice

- Each individual stakeholder makes his own evaluation
- Revenues should cover for made expenses
- Discount rate: risk sensitive (regulated entity or not, ex-ante or ex-post determination of revenues, delays,. . .)
- For each individual project

- Current system consists of AC grids owned and operated by TSOs, with regulator supervision
- Offshore: under debate
- Different regulating frameworks exist
- Framework of the overlay grid is yet unsure
- The framework determines:
  - Ownership
  - Investment policy
  - Tariffs (remuneration)
  - But also technical operations
  - Investment risk
- The technically most optimal solution might not be the most appropriate ones

Managing the system

- What is the objective during operations
- Who controls
- Who invests?



- Regulation differs over borders
- Regulations defines who will pay, who will receive revenues
- A harmonized and stable policy is required before any investment occurs
- Who is going to invest? (e.g. for offshore connections to wind farms)
- What is the incentive to do preparatory investments?
- Investments are also a matter of risk
  - Decrease risk due to technical reasons
    - Failures, maintenance, single points of failure, etc.
  - Decrease risk due to economical reasons
    - Develop the right market scenarios
  - Take into account regulatory risk
    - Stable policy?
  - Adequate regulation can significantly reduce investor risk
- There is plenty of money, but investments are in competition with other investments

Income: 4 clear economic benefits

1. Access to remote energy sources
2. Higher penetration of renewable energy sources by improved balancing
3. Improved grid security
4. Reduced congestion in the system

Costs: expensive installation

- HVDC terminals and cables are expensive
- There are other resources besides renewables (generation mix)
- Radial HVDC links to shore are possible as well (is meshed cheaper?)
- AC system upgrades might be sufficient for many years

Pay-back time

- Is it interesting from an economic point of view to install a supergrid?

- It is unlikely that the supergrid will be built in one effort
- Some parts might already exist!
- New lines are being built, e.g. to connect offshore wind farms
  - should they be built with a supergrid in mind?
- First radial, later meshing?
  - is there a financial incentive to do so?
  - what do we need to do now to accomodate that?
  - also with different owners?
- Will there be one supergrid, or more?
- Offshore might be easiest, but will probably not be enough
- Offshore supergrid will require fundamental changes in the onshore grid

Transmission system investments: the broader picture

- Regulated business
  - It is not up to the system operator to determine what he wants to pay for!
  - The regulator approves
- Unregulated assets:
  - Return on investment more important than investment cost
- Transmission costs are relatively low compared to other costs (specifically generation)
- Example (source, Europacable):
  - in the UK, total transmission costs is about 4 % of the total electricity bill
  - the costs for transmission (as part of the energy bill) are overestimated by the public
  - There is a majority that is willing to pay more for undergrounding
- Policy makers are willing to pay for (invest in):
  - Green image
  - Local economy (HVDC and offshore wind is largely a European product)
- Investors are willing to put money on the table:
  - Low risk investments (infrastructure with government backing)
  - Good return on investment

- The EU system is undergoing a lot of changes
- Especially renewables require considerable additional transmission assets
- Not only to connect offshore wind, but also for market and services
- HVDC grids are seen as the ideal solution for future offshore grids
- VSC HVDC can be used to connect offshore wind and different asynchronous zones
- Remaining challenges:
  - Technology is not yet fixed: voltages, protection, layout,. . .
  - Economics are not always clear: what is the return on investment
  - A sound, consistent and stable regulatory framework is needed to make good use of the potential of offshore grids
- The European Supergrid will likely be a VSC HVDC cable system

?

Dirk Van Hertem
Dirk.VanHertem@esat.kuleuven.be

Key takeaways:

- DC transmission is the preferred technology for the supergrid
- It is an open research field