



Coordination of HVDC interconnections

Spyros Chatzivasileiadis

Best Paths Project www.bestpaths-project.eu

multiDC Project www.multi-dc.eu





Best Paths

- Beyond state-of-the-art technologies for power AC corridors and multi-terminal HVDC systems
- 39 partners from all over Europe
- 63 million EUR
- 4 years
- End: 30 September 2018









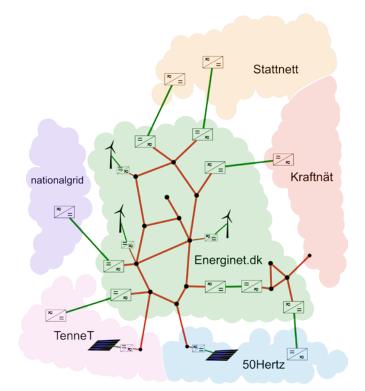


multiDC

Innovative Methods for Optimal Operation of Multiple HVDC Connections and Grids

- Innovation Fund Denmark Grand Solutions
- Partners:
 - Two neighboring TSOs:
 Energinet, Svenska kraftnät
 - Three universities:DTU, KTH, Univ. of Liege
 - One major manufacturer: ABB
 - Advisory Board: RTE, Nordic RSCI
- 4.2 million USD
- **4 years**; Start May 1, 2017











Three main drivers

- 100% renewables
 - Varying inertia systems
 - Uncertainty
- 100% inverter-connected devices
 - How is stability and operation affected?
 - How to model them?
- HVDC Grids









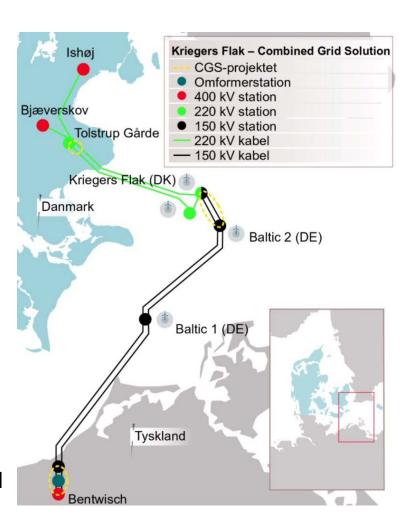






Kriegers Flak

- Denmark Germany: AC+HVDC
- First interconnection in the world that integrates off-shore wind farms along its path
- 400 MW Back-to-Back HVDC
- Wind Farm Kriegers Flak (DK): 600 MW
- Wind Farm Baltic (DE): 336 MW
- HVDC Master Controller to:
 - Control voltage
 - Avoid overloadings
 - Ensure market outcome by mitigating wind forecast errors









North Sea Wind Power Hub

- Construction of island(s) in the middle of the North Sea
- Integration of up to 150 GW of offshore wind farms
- HVDC interconnections to Denmark, Germany, the Netherlands, UK, Great Britain, Norway, Belgium
- Coupling the energy markets
- Agreement between Denmark, Germany, and the Netherlands already signed (2017)



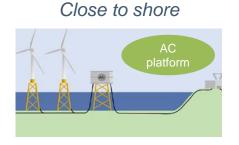




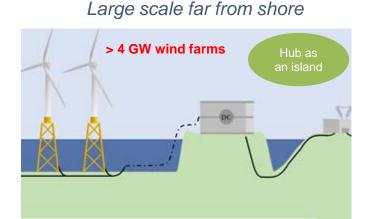


Grid Connection Options for Offshore Wind

Far from shore















- Far-shore becomes near-shore
- Distribution point for different countries
- 2030 and beyond

- Modular approach
- Each island: up to 30 GW
 Vision: 150 GW in North Sea
- First step: 12 GW









How will the wind farms be connected to the island?

How will the island be connected to the mainland?

These are still open questions

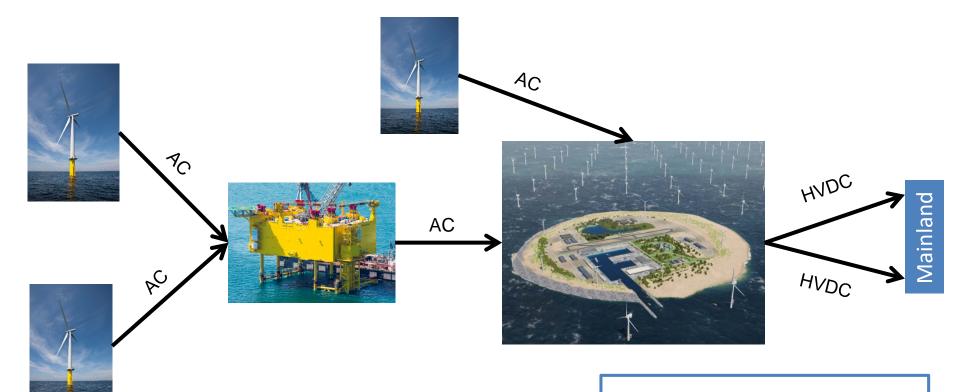






A connection possibility





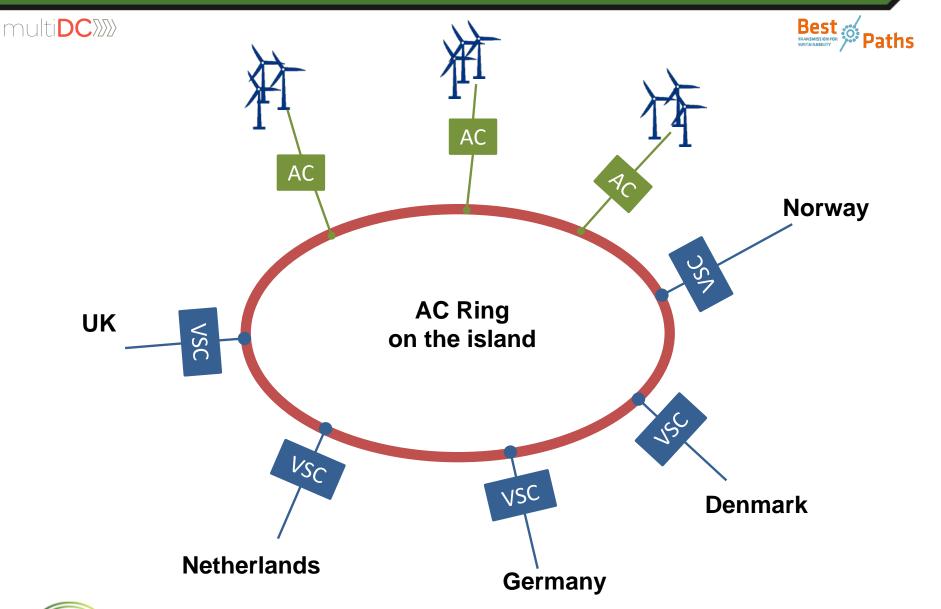
AC: Low-frequency AC

HVDC: Point-to-point HVDC

Information from Peter Larsen and Fitim Kryezi, Energinet and from www.northseawindpowerhub.eu
Figures courtesy of Ørsted A/S, Siemens, and Northseawindpowerhub









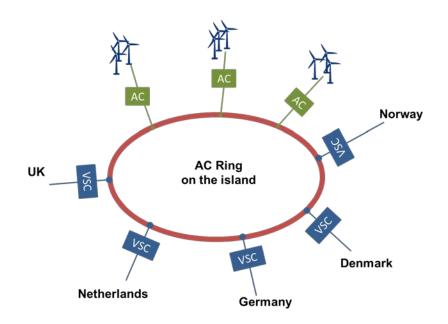




Power & Energy Society

Challenges and Opportunities Challenges and Opportunities

- Zero-inertia AC Ring
 - Fast transients
- Coordination of the control of the VSC converters
 - Grid-forming shared among the converters?
 - Dealing with failures (N-1)
- Sharing wind power among the countries
 - Ownership of wind farms
 - Do we need to adapt the market structures?

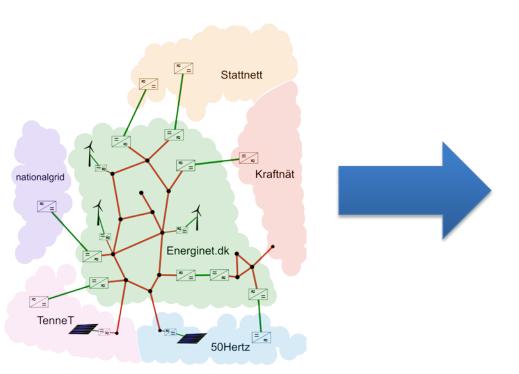








Addressing current challenges while preparing for the North Sea Wind Power Hub













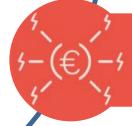
The three pillars



Robust frequency control of varying inertia systems



Coordinated control of AC/DC systems



Market integration of meshed HVDC connections

Implementation at PowerlabDK



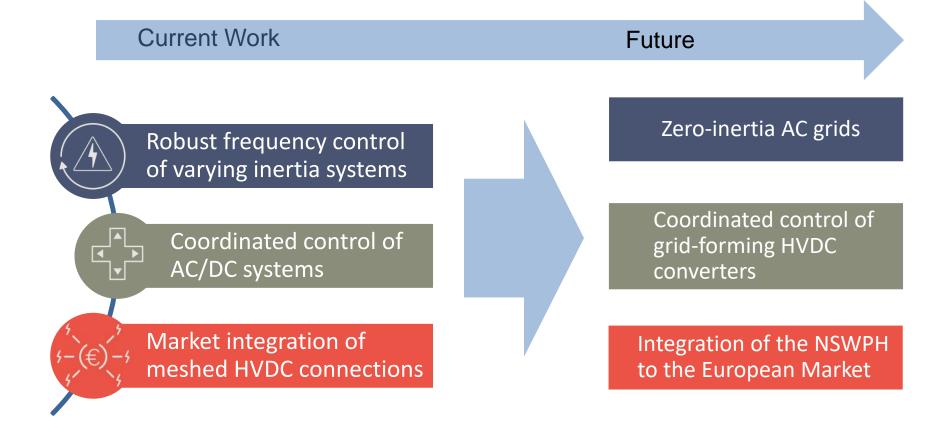








From Current Challenges to the North Sea Wind Power Hub (NSWPH)











Robust Frequency Control for Varying Inertia Systems

- m_i and d_i vary depending on the RES infeed
 - more RES infeed → less conventional generation → lower inertia
 - less RES infeed → more conventional generation → higher inertia

$$m_i \dot{\omega}_i = -d_i \omega_i + p_{mech,i} - p_{el,i}$$

- Decreasing inertia should improve the damping ratio
 - d_i/m_i describes how fast a frequency deviation is brought back to equilibrium
- Decreasing inertia should increase ROCOF
 - Disturbances are scaled by 1/m_i
 - With low inertia the rotor speed becomes more vulnerable to shocks



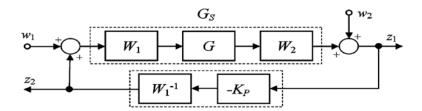


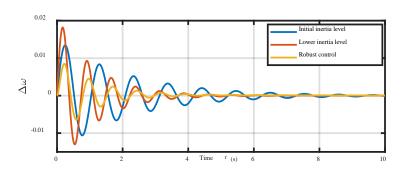




Robust Frequency Control for Varying Inertia Systems

- H_∞ optimal control
 - Minimizes the maximum singular value of the closed-loop system
- Robust frequency control
 - Attenuate the gain at higher frequencies, resulting to lower ROCOF and lower maximum frequency deviation
 - Adds some slight damping to electromechanical oscillations





Misyris, Chatzivasileiadis, Weckesser, Robust Frequency Control for Varying Inertia Power Systems, accepted at ISGT Europe 2018, link to paper



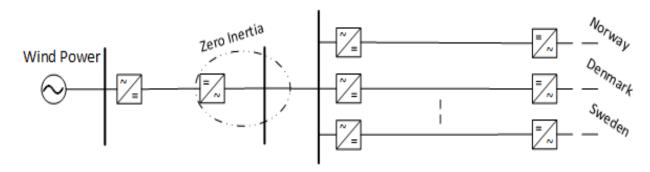






Robust Frequency Control for Varying Inertia Systems – Future Steps

North Sea Wind Power Hub as a test case



- From low-inertia to zero-inertia
 - Zero inertia → Coupling between active and reactive control in the absence of a stiff frequency and voltage



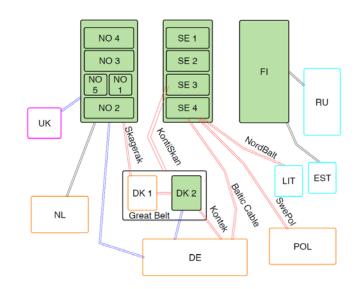




Coordinated control of Multi-Area AC/DC systems



- Focus on Emergency Power Control (EPC)
 mechanisms and sharing of reserves
 between asynchronous systems
- Currently, EPC in Nordics works as follows:
 - If f < threshold then transfer = xx MW</p>
- Goal: move from stepwise-triggers to droop-frequency control
 - Transmitted power is continuous and linearly dependent on the frequency deviation



HVDC link	Step	Freq. trigger [Hz]	Capacity [MW]	Ramp rate $[MW/s]$	Time delay [s]
KontiSkan 1+2	1	49,8	150	20	0,3
	2	49,6	150	50	0,1
	3	49,5	150	200	0,05
Baltic Cable	1	49,55	150	100	0,5
	2	49,2	300	100	$0,\!5$
SwePol	1	49,4	150	100	0,5
	2	49.1	300	100	0.5





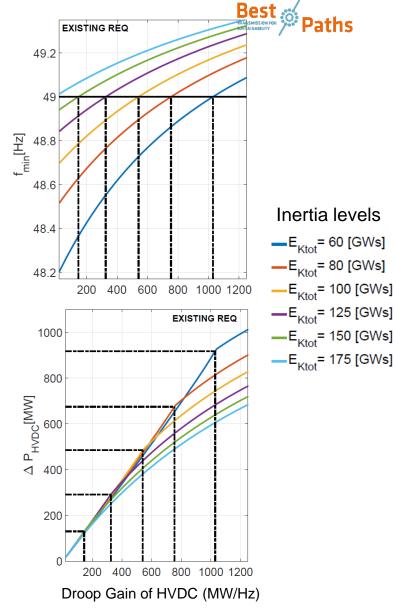
multi**DC**>>>>

EPC: Trigger (existing) vs Droop (proposed)

- Trigger: power continues to get transferred even if ROCOF becomes positive
 - This power does not help reduce the frequency nadir
- Droop: for any inertia level, the required power is less than in the "trigger" EPC

	No EPC	All links in EPC	Total	Unused
[GWs]	$f_{min,no}$ [Hz]	f_{min} [Hz]	[MW]	[%]
80	48,50	48,93	2378	59
100	48,68	49,05	2138	61
125	48,83	49,16	1538	48
150	48,93	49,23	1238	36
175	49,00	49,27	1238	37

Obradovic, Ghandhari, Eriksson, Assessment and Design of Frequency Containment Reserves with HVDC interconnections, accepted at NAPS 2018, <u>link to paper</u>



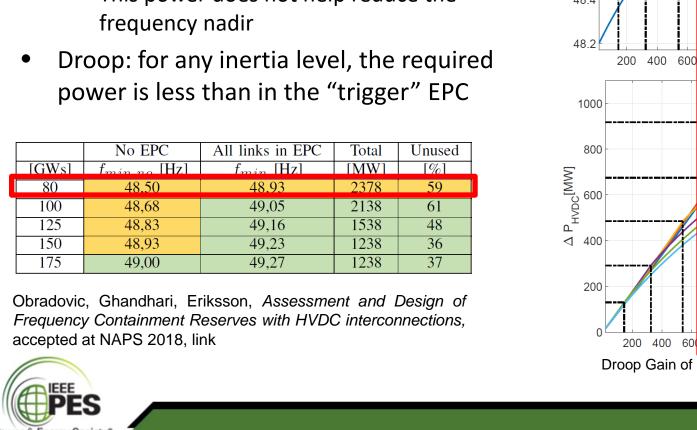


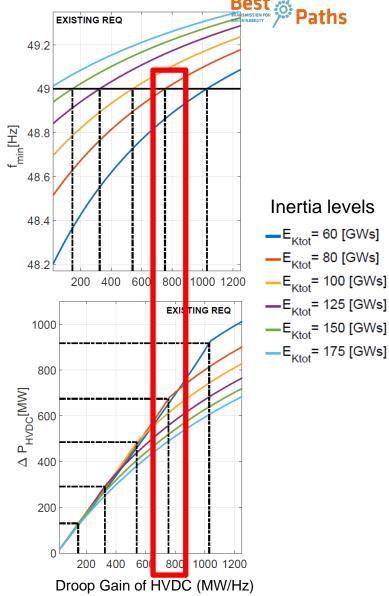


multi**DC**

EPC: Trigger (existing) vs Droop (proposed)

- Trigger: power continues to get transferred even if ROCOF becomes positive
 - This power does not help reduce the frequency nadir



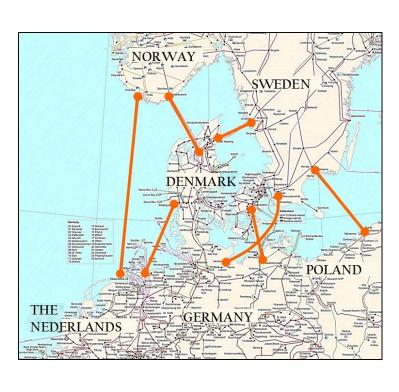




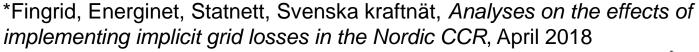




Market Integration of HVDC



- HVDC interconnectors are usually longer than AC interconnections
- HVDC losses are not negligible
- If price difference between areas is small, TSOs cannot recover the cost of HVDC losses
 - Cost of the losses higher than potential revenue
- Introduction of an HVDC loss factor in market clearing*







multi**DC**

Best Paths TRANSMISSION FOR PATHS

An example: Kontiskan

NORD POOL						
	MWh/h		EUR/MWh			
05-07-2018	SE3 > DK1	DK1 > SE3	SE3	DK1		
00 - 01	0,0	4,1	50,34	49,13		
01 - 02	23,1	0,0	48,55	45,48		
02 - 03	103,9	0,0	47,54	44,31		
03 - 04	0,0	49,0	47,14	47,14		
04 - 05	71,9	0,0	47,34	47,34		
05 - 06	41,3	0,0	49,35	47,57		
06 - 07	80,7	0,0	53,17	51,89		
07 - 08	60,5	0,0	56,43	57,71		
08 - 09	109,0	0,0	61,21	61,21		
09 - 10	137,1	0,0	60,94	60,94		
10 - 11	364,0	0,0	62,41	62,41		
11 - 12	190,6	0,0	64,07	64,07		
12 - 13	0,0	19,4	63,88	63,88		
13 - 14	0,0	0,0	63,57	52,25		
14 - 15	0,0	0,0	59,04	52,06		
15 - 16	34,7	0,0	57,56	51,84		
16 - 17	90,8	0,0	53,97	52,02		
17 - 18	139,8	0,0	52,97	52,97		
18 - 19	161,2	0,0	54,83	54,83		
19 - 20	237,0	0,0	55,41	55,41		
20 - 21	154,6	0,0	55,10	55,10		
21 - 22	21,7	0,0	53,79	53,79		
22 - 23	3,5	0,0	52,05	52,05		
23 - 00	0,0	34,7	50,21	50,21		

DC LINK BETWEEN DENMARK AND SWEDEN



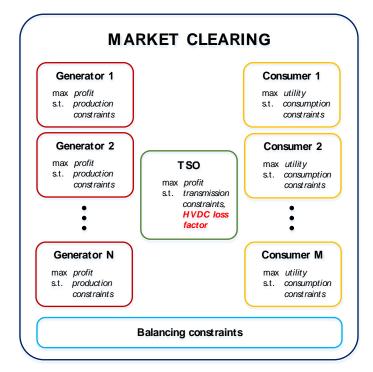
- 2018: price difference Sweden-Denmark has been zero for >2400 hours (54%)
- 2017: more than 5300 hours (61%)
- Total cost of losses during those
 5300 hours was approx. 0.9 M€ for
 a single HVDC line



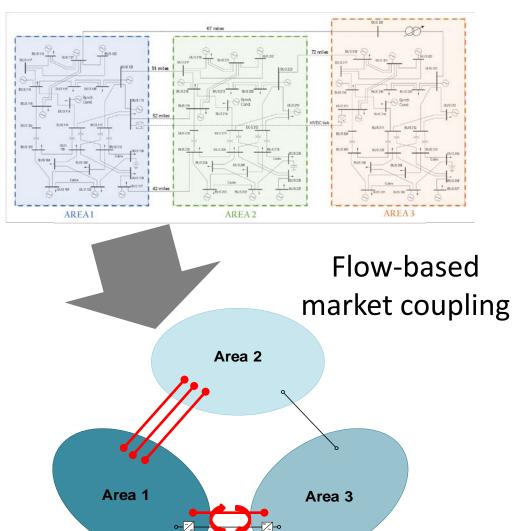


multi**DC**

 Mixed complementarity problem for the market clearing



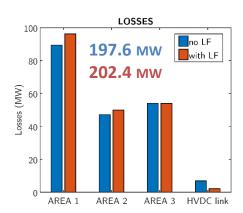
3-area IEEE RTS 72-bus SYSTEM







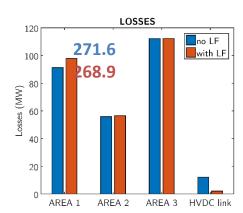
nulti<mark>DC Normal Operation</mark>



The penalization of the HVDC line results in an increase of losses in the AC system

ECONOMIC LOSS 206.9 \$/h

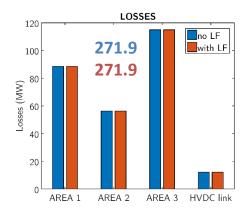
LOOP FLOWS



With the introduction of the LF loop flows are avoided

ECONOMIC BENEFIT 114.1 \$/h





Losses are covered by the price difference due to congestion

ECONOMIC BENEFIT 0 \$/h

- Introducing an HVDC loss factor in the market clearing algorithm can have a positive or negative effect depending on the system under investigation
- Future work: Investigating different solutions to account for losses in nonradial HVDC systems









PowerlabDK at DTU

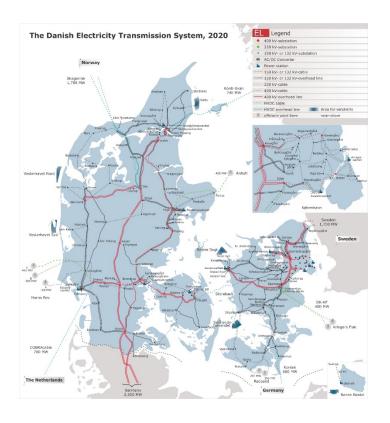
- Power Hardware in the Loop Simulations:
 - Robust control for varying inertia
 - Control of grid-forming HVDC in a zero-inertia AC grid
 - Coordinated control of HVDC for sharing reserves in the Nordic region



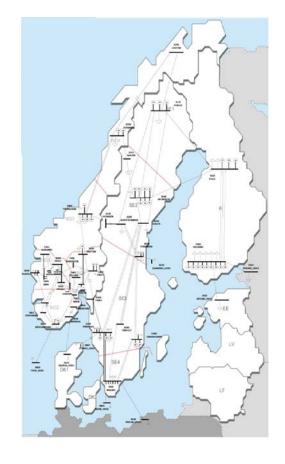


Development of a dynamic AC/HVDC Nordic model













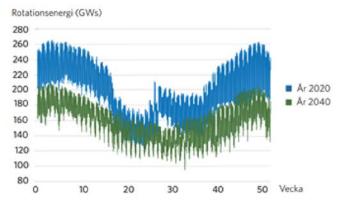
Development of a dynamic AC/HVDC Nordic model



- Danish system: already implemented in RTDS
- Nordic-44 system (Swedish equivalent, including Norway & Finland)
 - Adjusted system kinetic energy
 - Adjusted reactive power

Power & Energy Socie

- Integration of wind power (20 GW of wind by 2030)
- Working on an open-source VSC-HVDC converter model



Estimated kinetic energy in Nordic countries in 2020 and 2040

Prior work on the Nordic Test System Development in

Thierry van Cutsem, Advancements in Power System Analysis Test Cases: Voltage Stability (18PESGM2383)

Tue, Aug 7, 1:00pm-3:00pm, Room OC-D133+D134







Conclusions

- Holistic approach to the emerging problems of multiple HVDC interconnections and grids
 - Robust control for varying inertia and zero-inertia systems
 - Emergency power control coordination of multi-area AC/DC grids
 - Market Integration of HVDC
- Developing solutions applicable to the North Sea Wind Power Hub
- Real implementation at PowerlabDK





















Thank you!

spchatz@elektro.dtu.dk www.chatziva.com

www.bestpaths-project.eu

www.multi-dc.eu



















