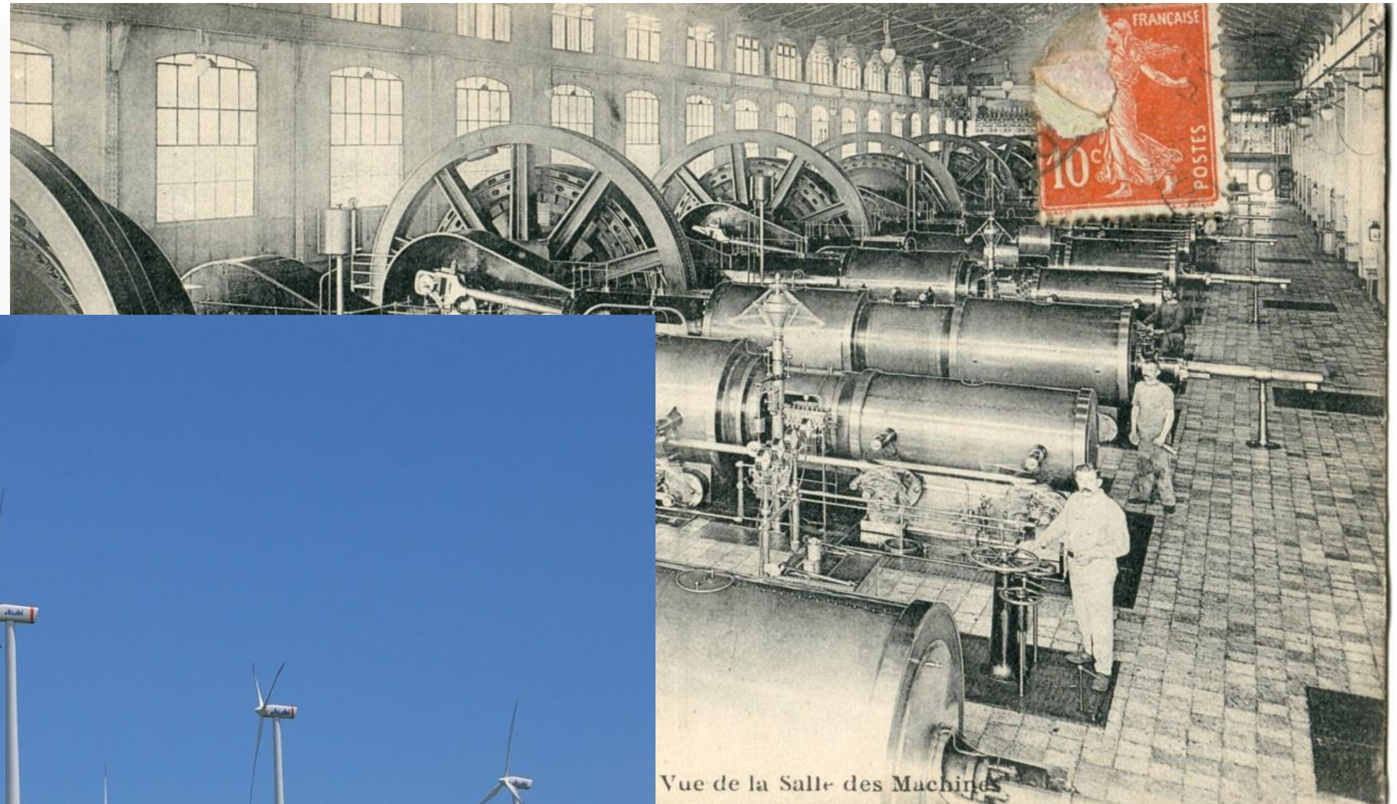
WINPOWER Project (Feb. 2011 – Feb. 2015) - 11 partners

ANR-10-SEGI-016

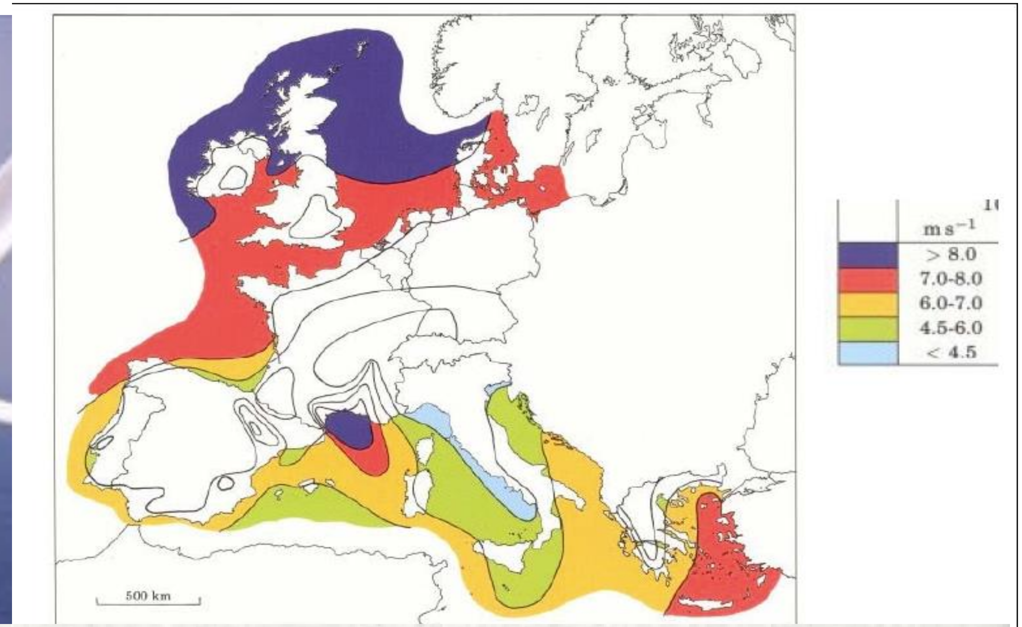
***Coordinator*: Gilney Damm**
EECI / Evry Val d'Essonne University

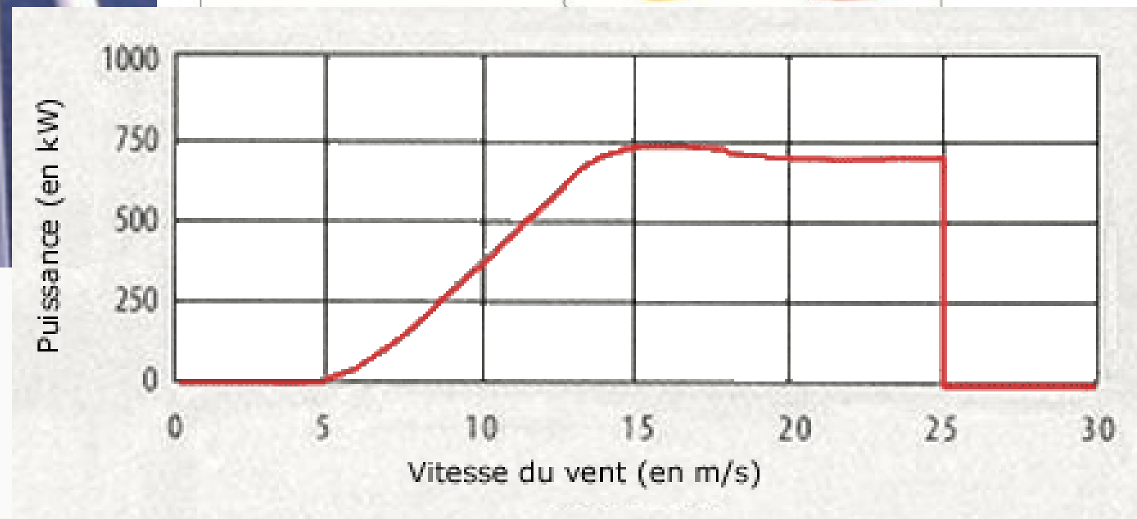
Motivation

Power networks are changing…



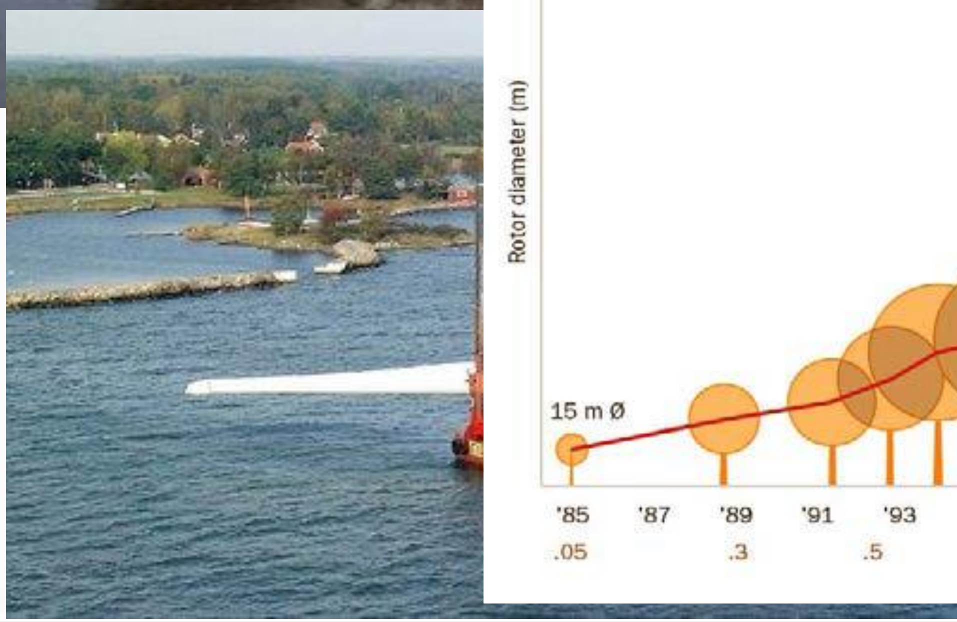
Off-shore Wind power generation

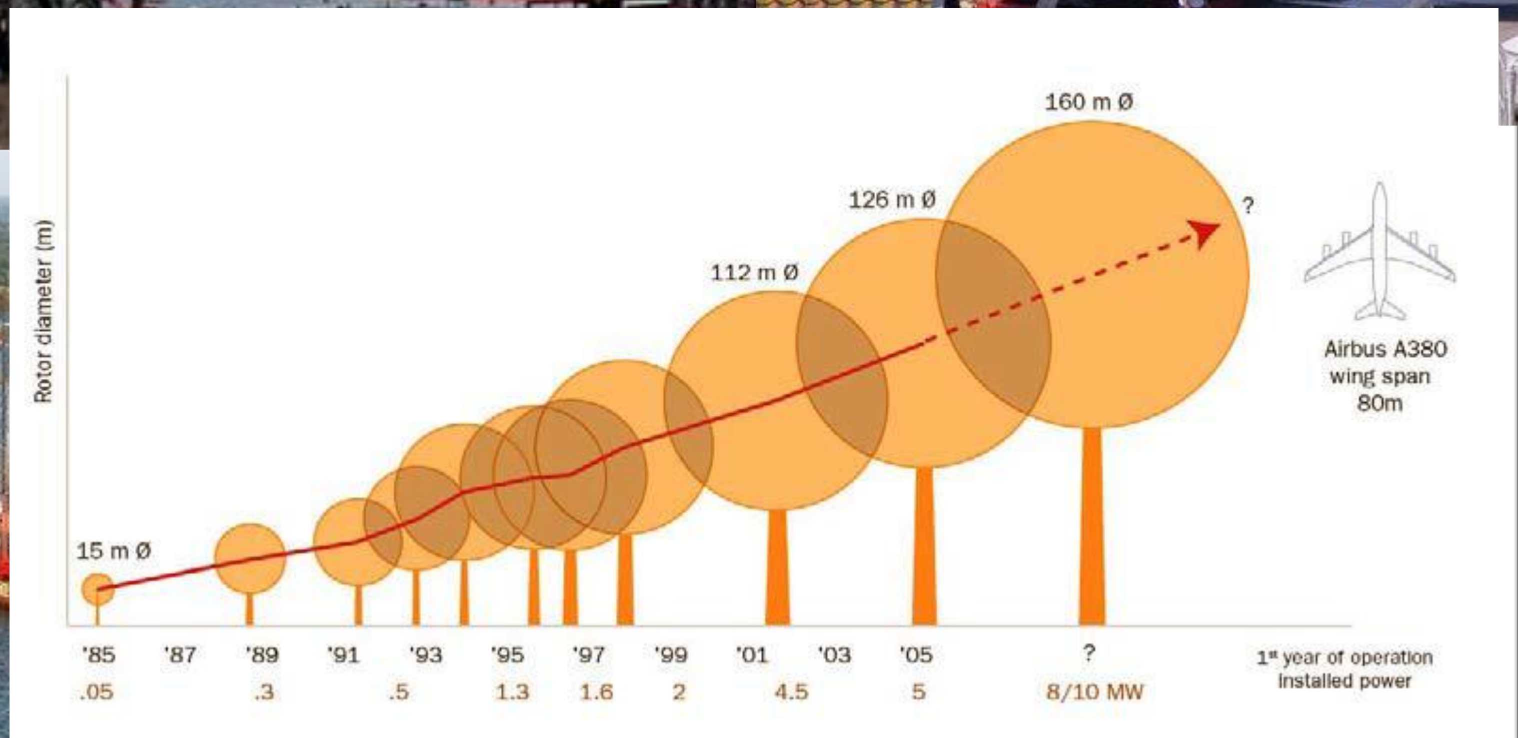




Stronger, steadier and more predictable

Ever growing Off-shore Wind Farms



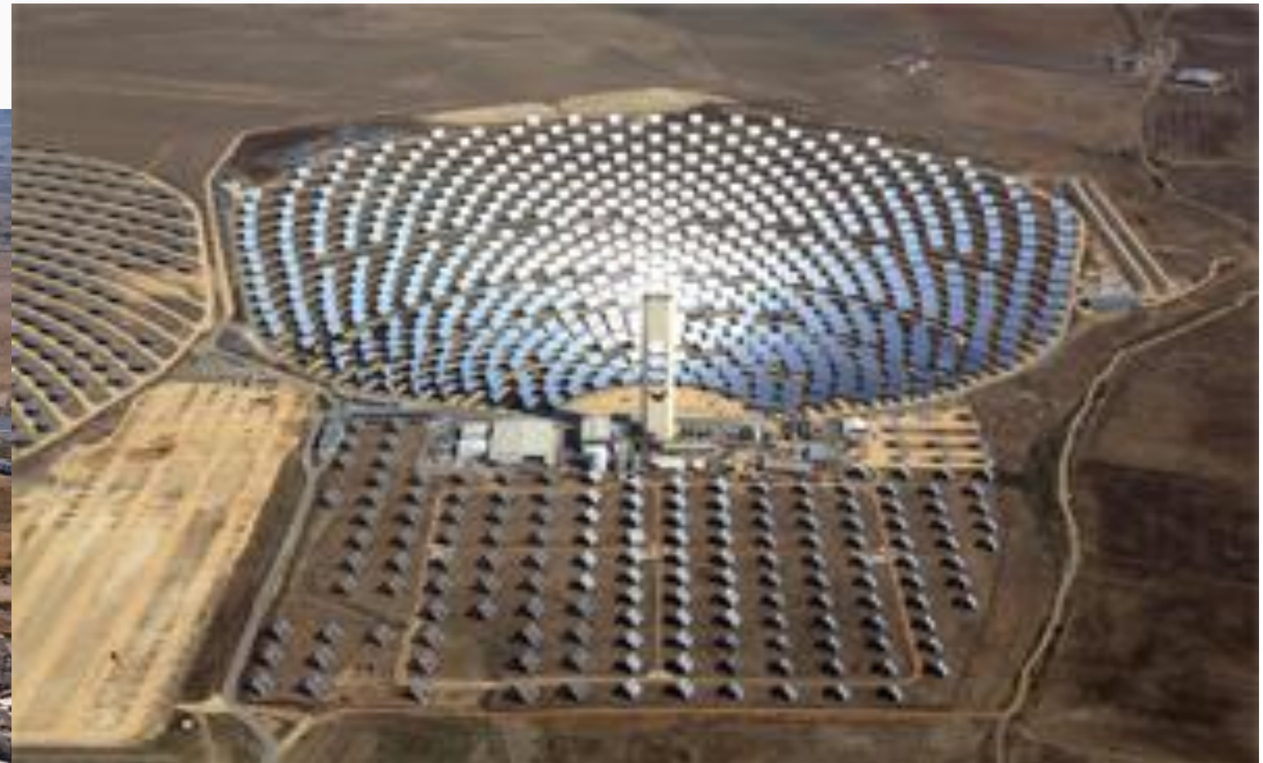


Marine current / Tidal Power

EDF - Paimpol Brehat (Brittany - France)

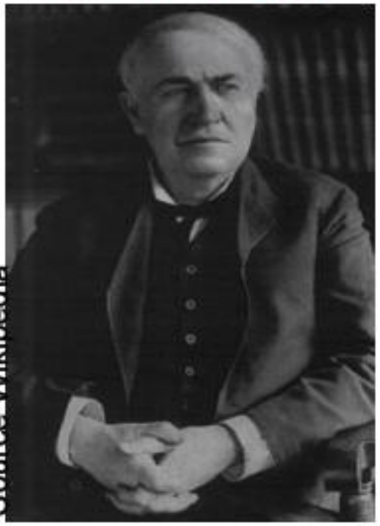
Siemens SeaGen - Strangford Lough
in Northern Ireland

Solar Power – Solar Thermodinamic



Large scale integration of renewables – particularly off-shore

Thomas Alva Edison
(1847–1931)



Source Wikipedia

The War of Currents

Nikola Tesla
(1856–1943)

Source Wikipedia

Edison and Tesla Fight Over How To Power the World

DC or AC ?

George Westinghouse
(1846–1914)

Source Wikipedia

UNITED STATES PATENT OFFICE.

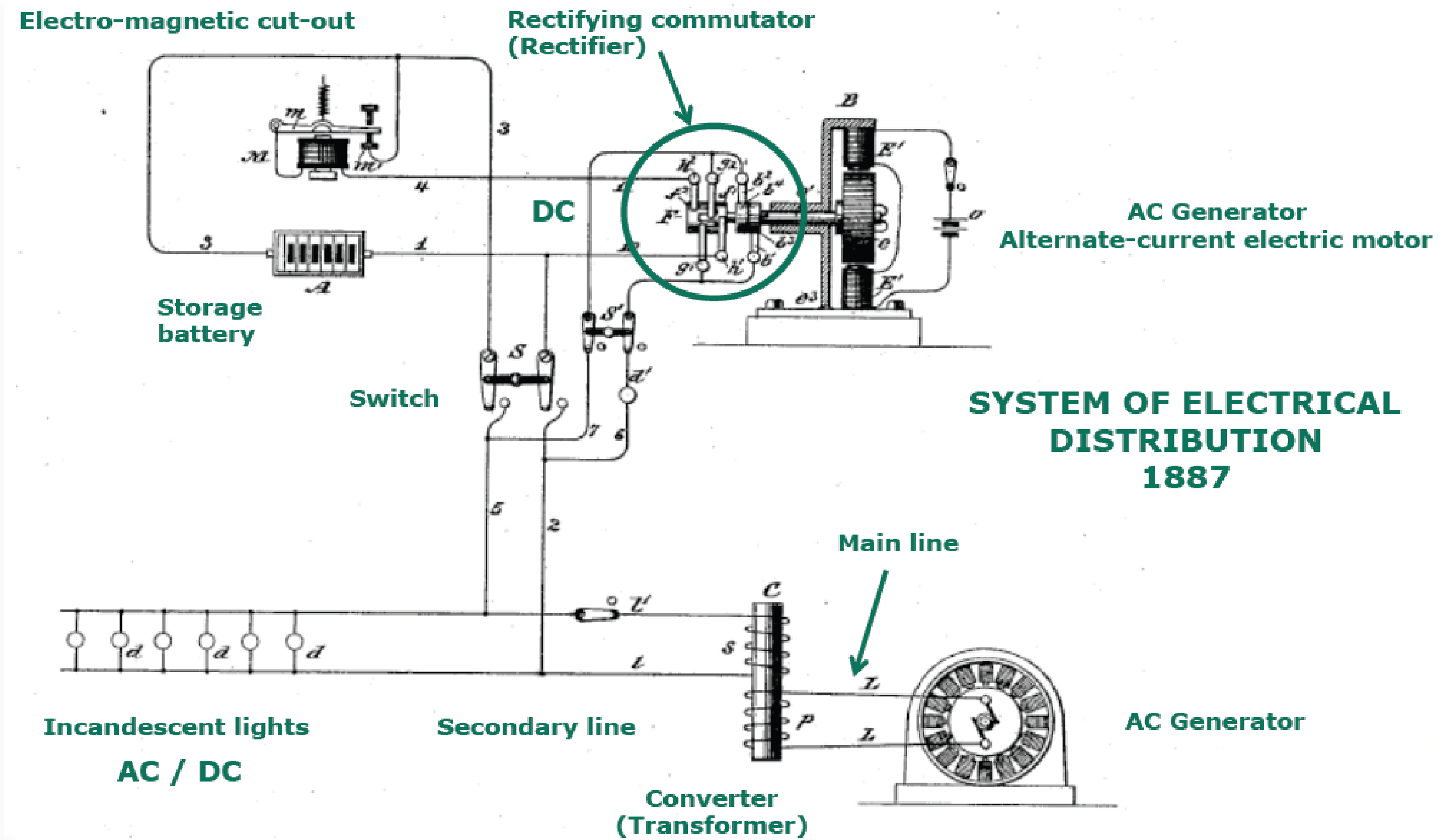
GEORGE WESTINGHOUSE, JR., OF PITTSBURG, PENNSYLVANIA.

SYSTEM OF ELECTRICAL DISTRIBUTION.

SPECIFICATION forming part of Letters Patent No. 373,035, dated November 8, 1887.

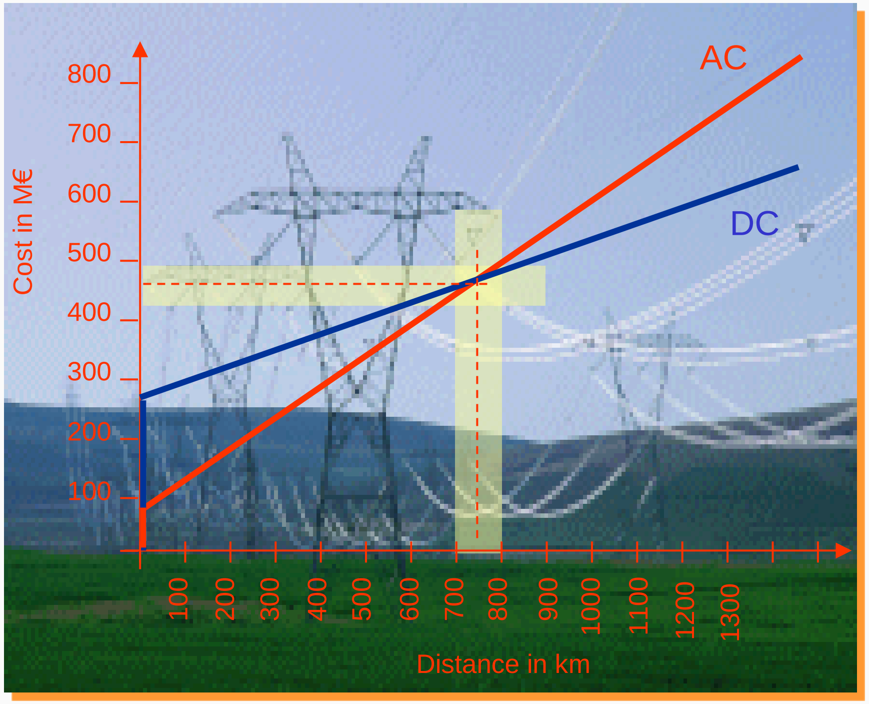
Application filed February 4, 1887. Serial No. 226,498. (No model.)

AC-DC Origins…



HVDC - Costs and Solutions

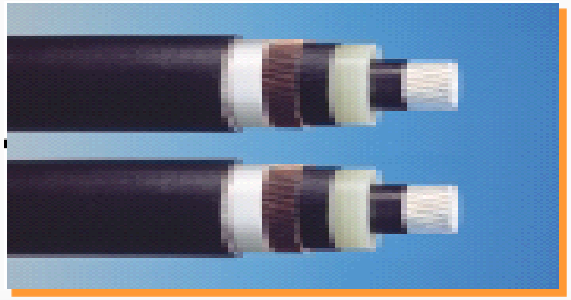
Cost estimation of a 2GW link overhead lines



High Voltage Direct Current. To transfer power from one point to another or to connect asynchronous grids.

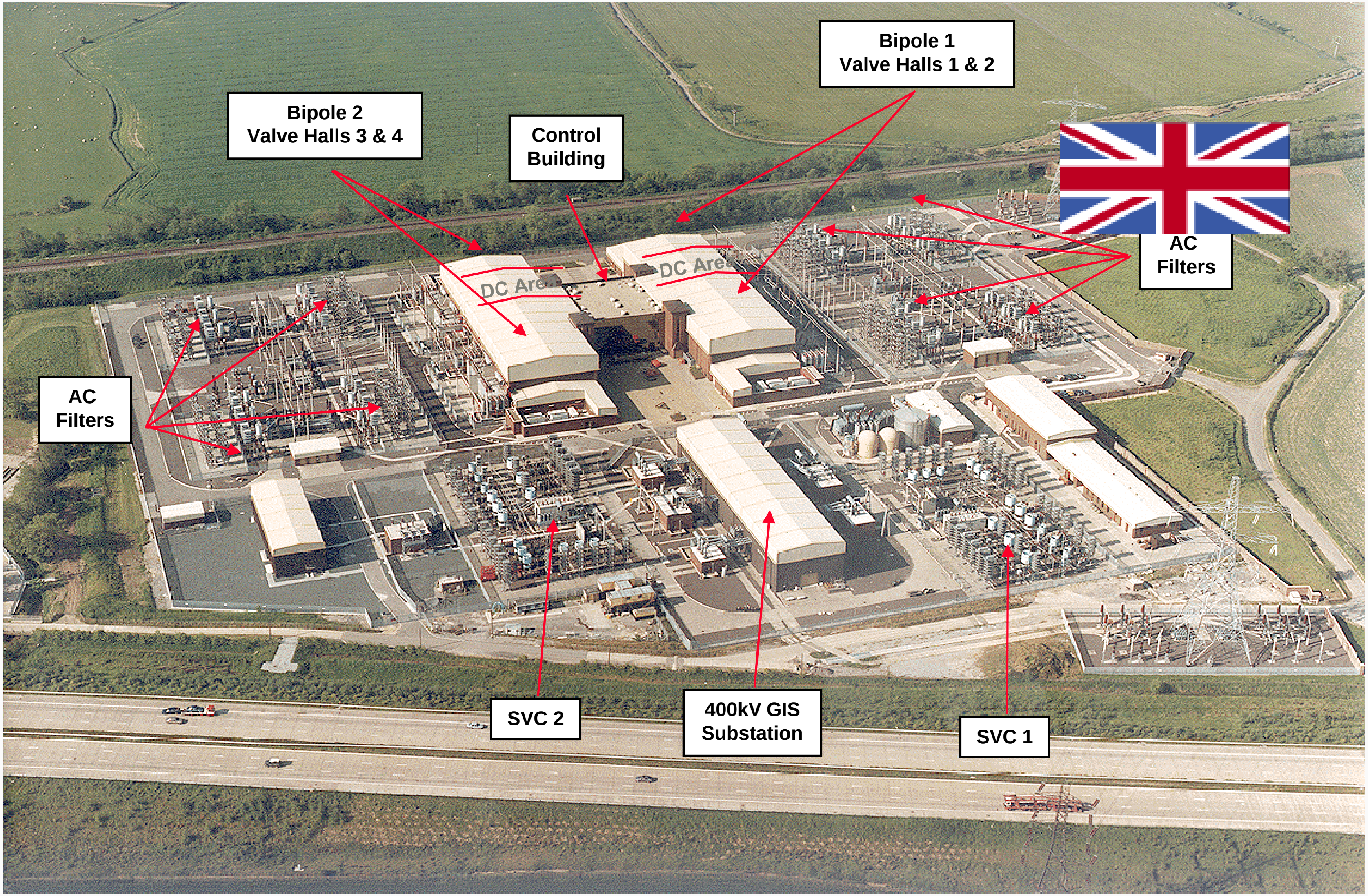
Some hundreds installation in the world: it is a mature technology, for thyristor based solutions.

For Sea cables, the point of equality between AC and DC is obtained for shorter distances, as small as 30 km.



Courtesy: Alstom

Interconnexion France Angleterre - IFA2000
English side - SELLINDGE

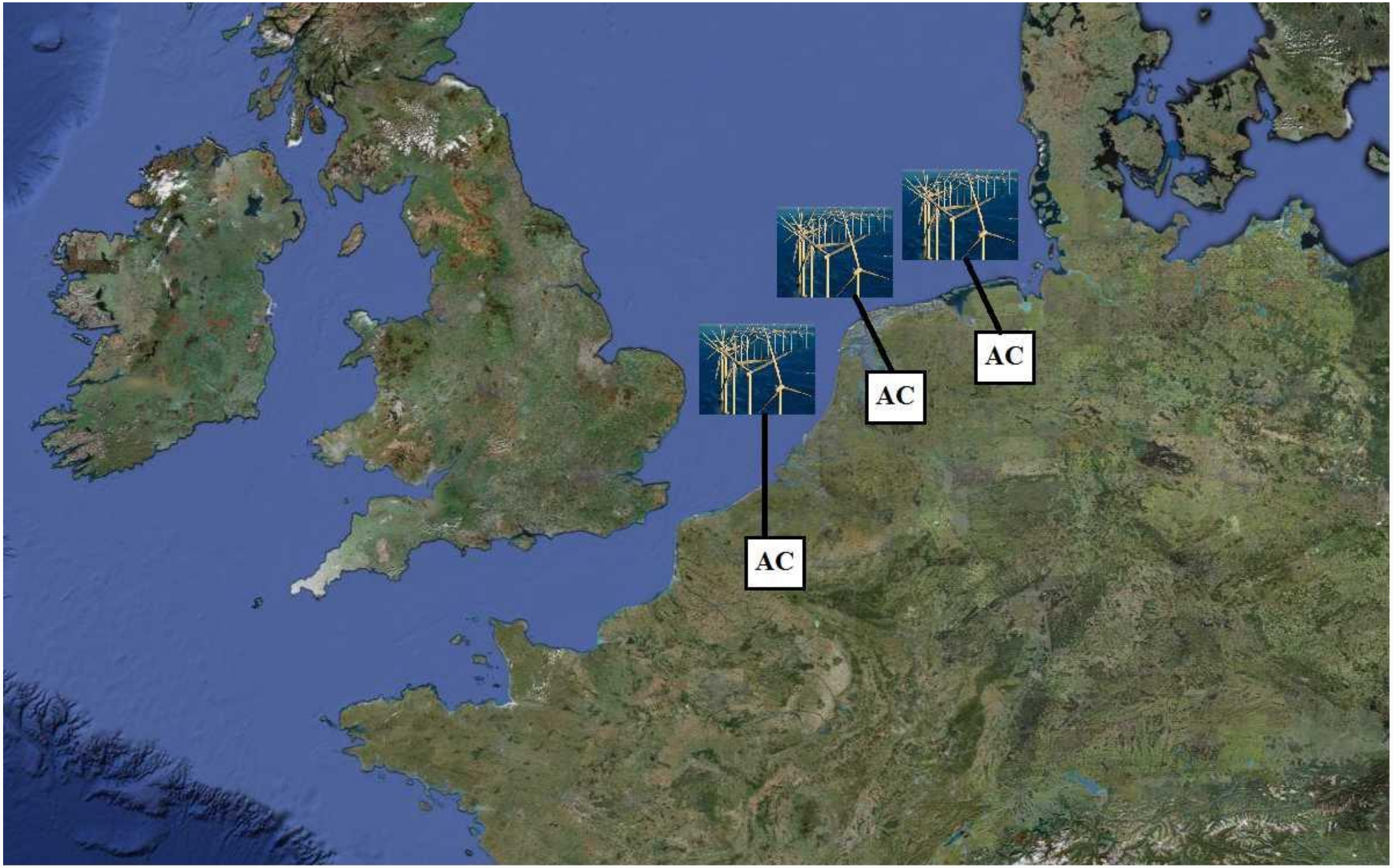


Courtesy: Alstom

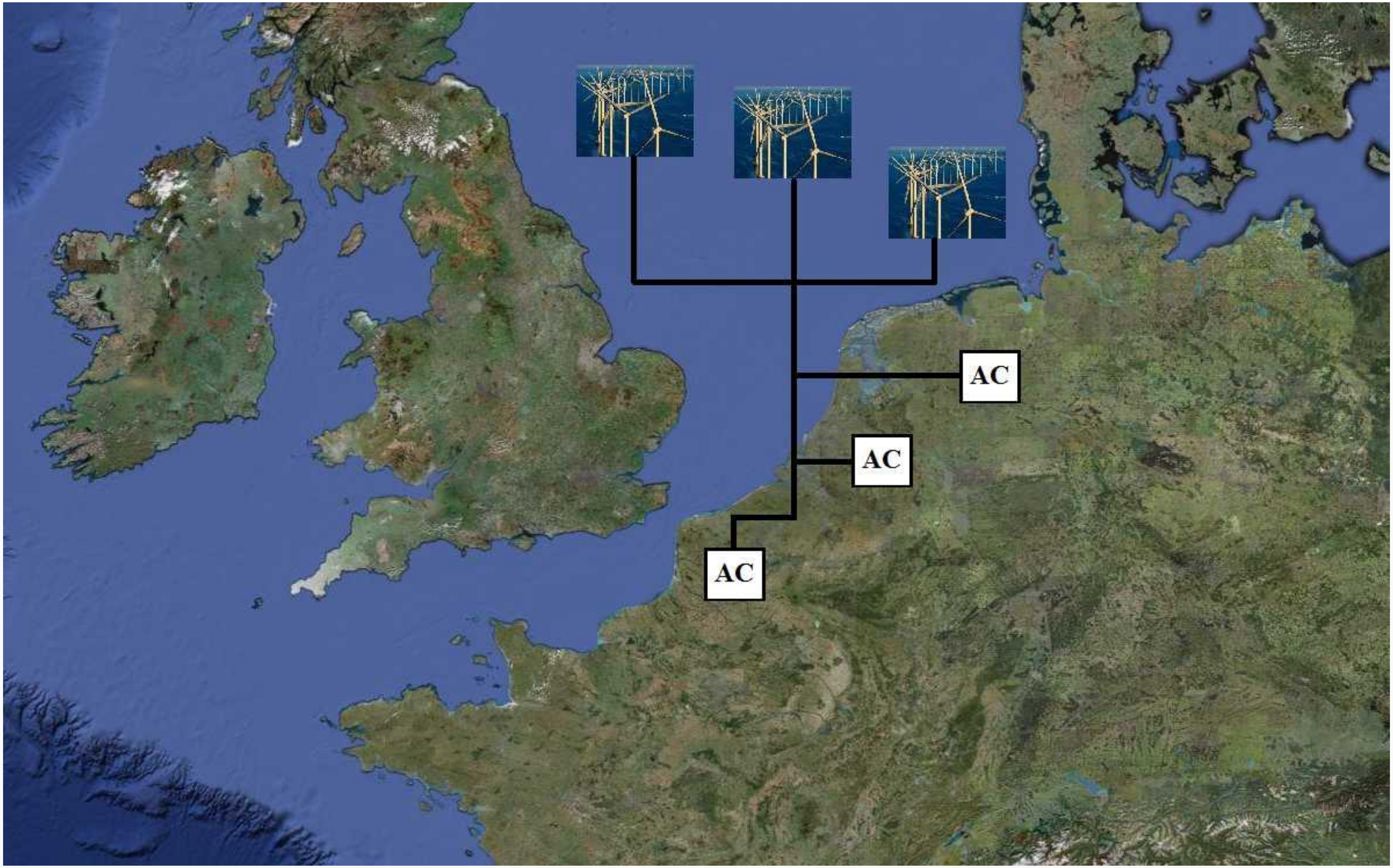
Winpower

Multi-point HVDC

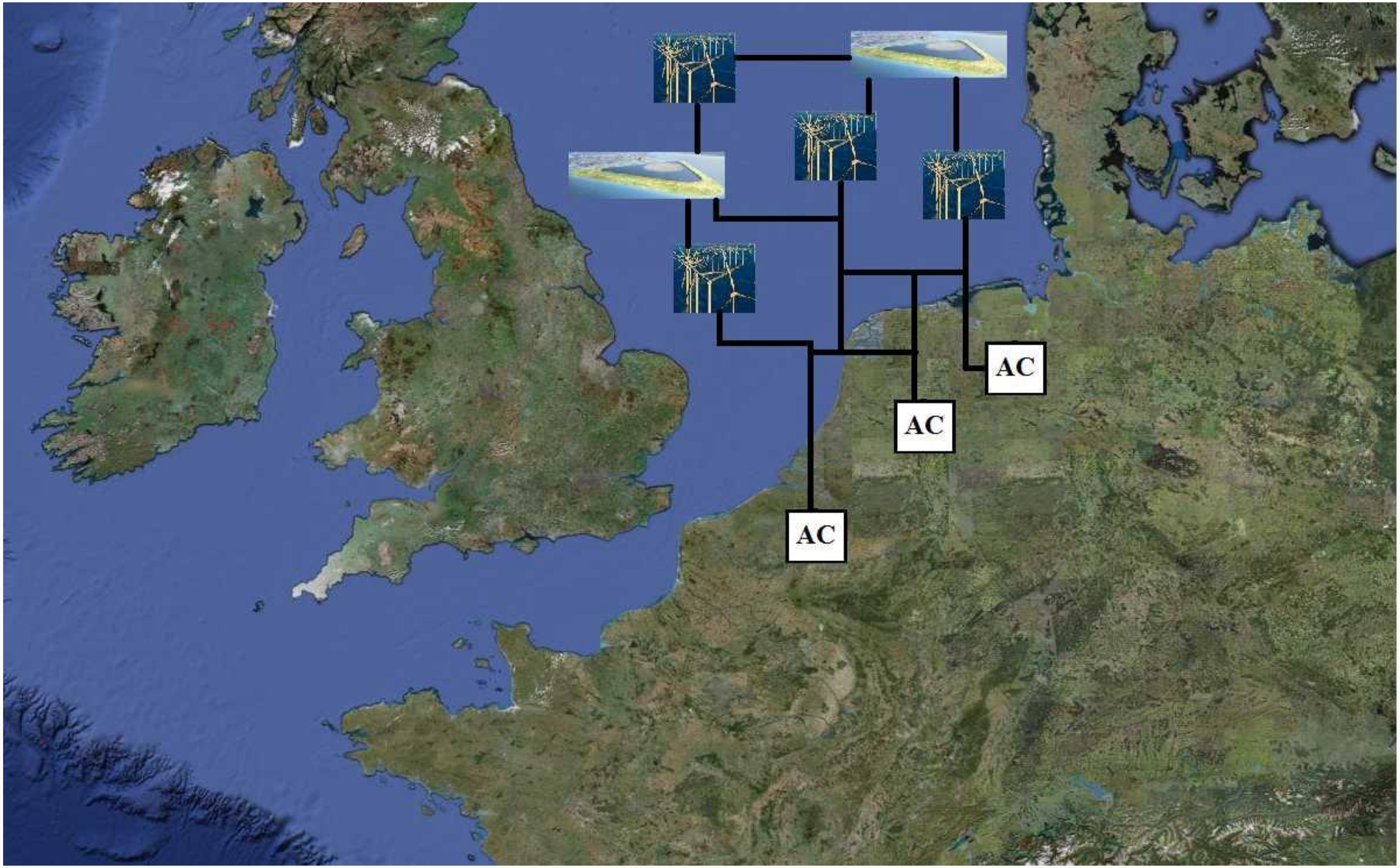
Multi-point HVDC



Multi-point HVDC



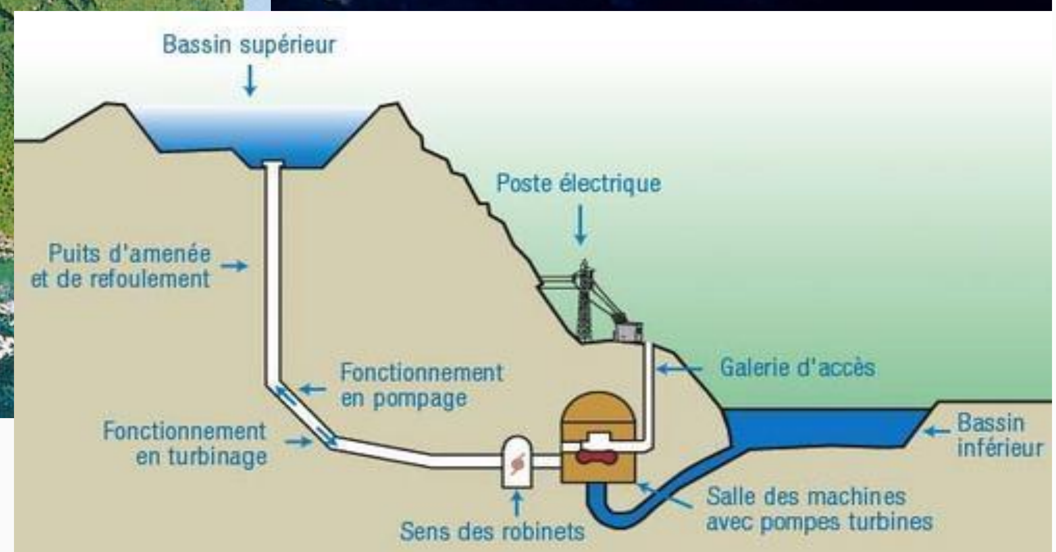
Multi-point HVDC



Multi-point HVDC - Converters

Storage – present → pumped water

Station en Okinawa

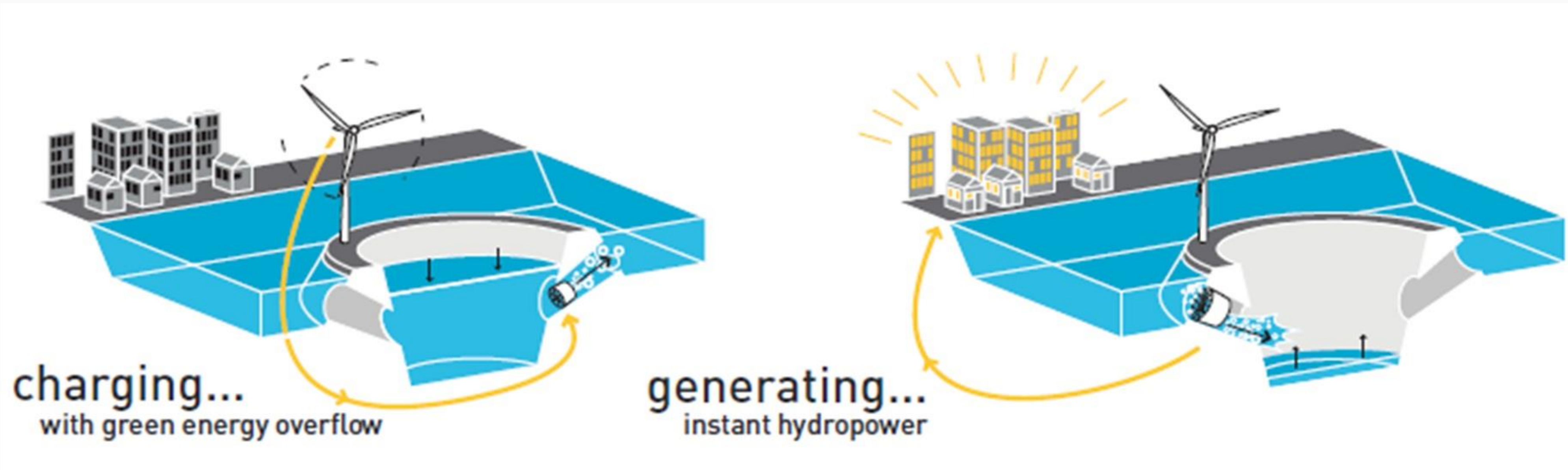


Storage – future?

Project in Denmark

Project in Floride

Principle


charging...
with green energy overflow
generating...
instant hydropower

Main ideas of Winpower: Model and control of meshed DC networks based on AC networks

- **«Think globally, act locally »**
  - – Main idea behind AC network deployment since the 30's
  - – Complex models (chaotic, fractals, distributed…)
  - – System of systems
- **Approach plug & play**
  - – Adapt the system in real time
  - – Different spatial-temporal scales for decoupling and system's hierarchy
  - – Reconstruct an equivalent to inertia on DC by power electronics and storage
- **Winpower method – strong industrial academia combination and partnership**
  - – Continuous evolution of simulation models and softwares
  - – Modularity
  - – Integration of sub-systems and their control laws in these modules

Design a control strategy based on the same concepts of AC grids → easier compatibility and integration

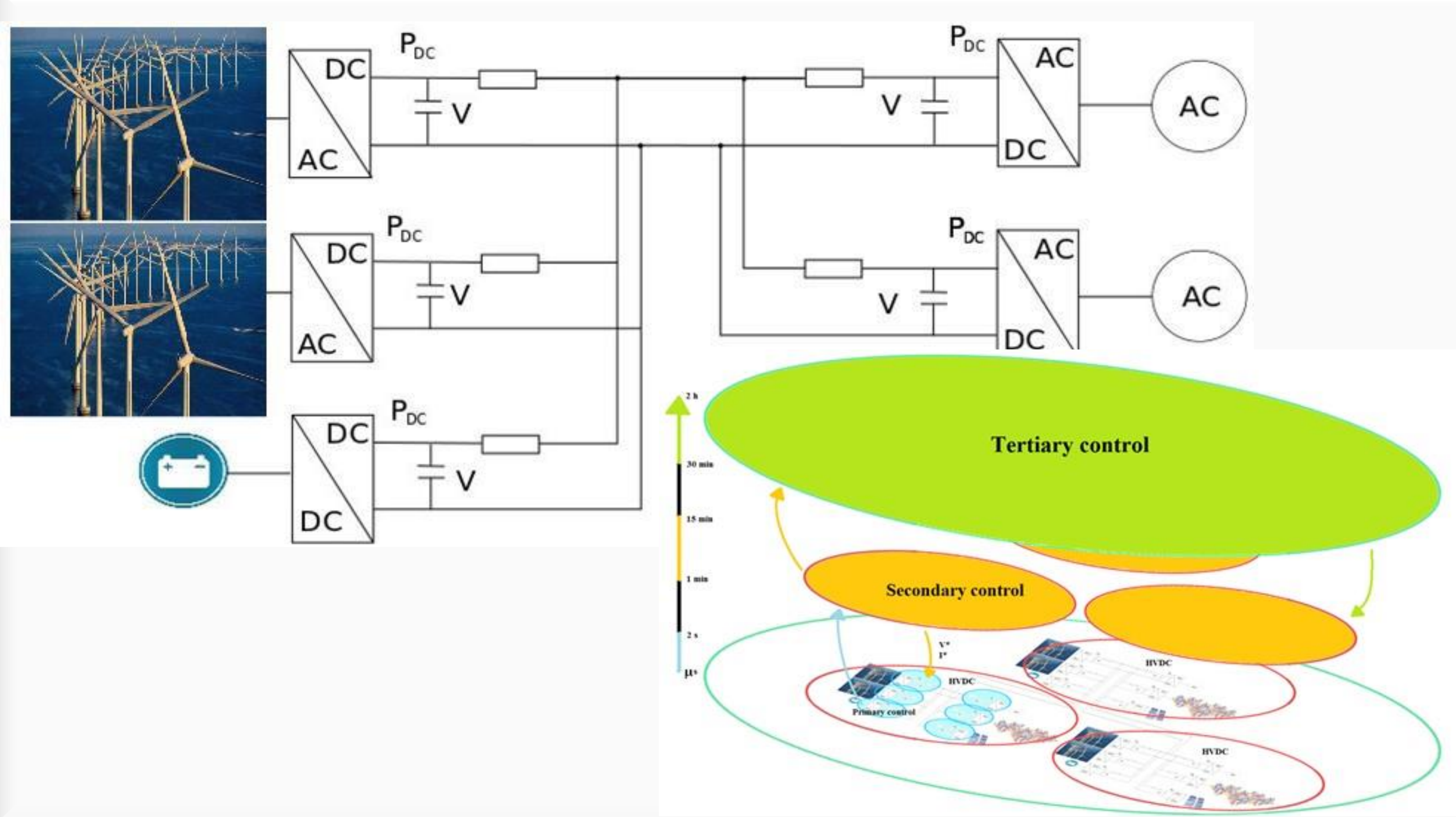
AC Transmission Network frequency control & tools (same for voltage control)

Local control (ms) - Generator control, node
Primary control (s) – global control but applied in a distributed way
Real time control via droop – each generator (node) is assigned with static gain (ki) and is assigned (by higher level) an amount of power to inject into the grid ➔ $\Delta P = ki \times \Delta F$
Secondary control (mn) – global control – for $F=F_{ref}$, new references calc. ➔ Pi=P'i
Tertiary – dispatching and Load shedding

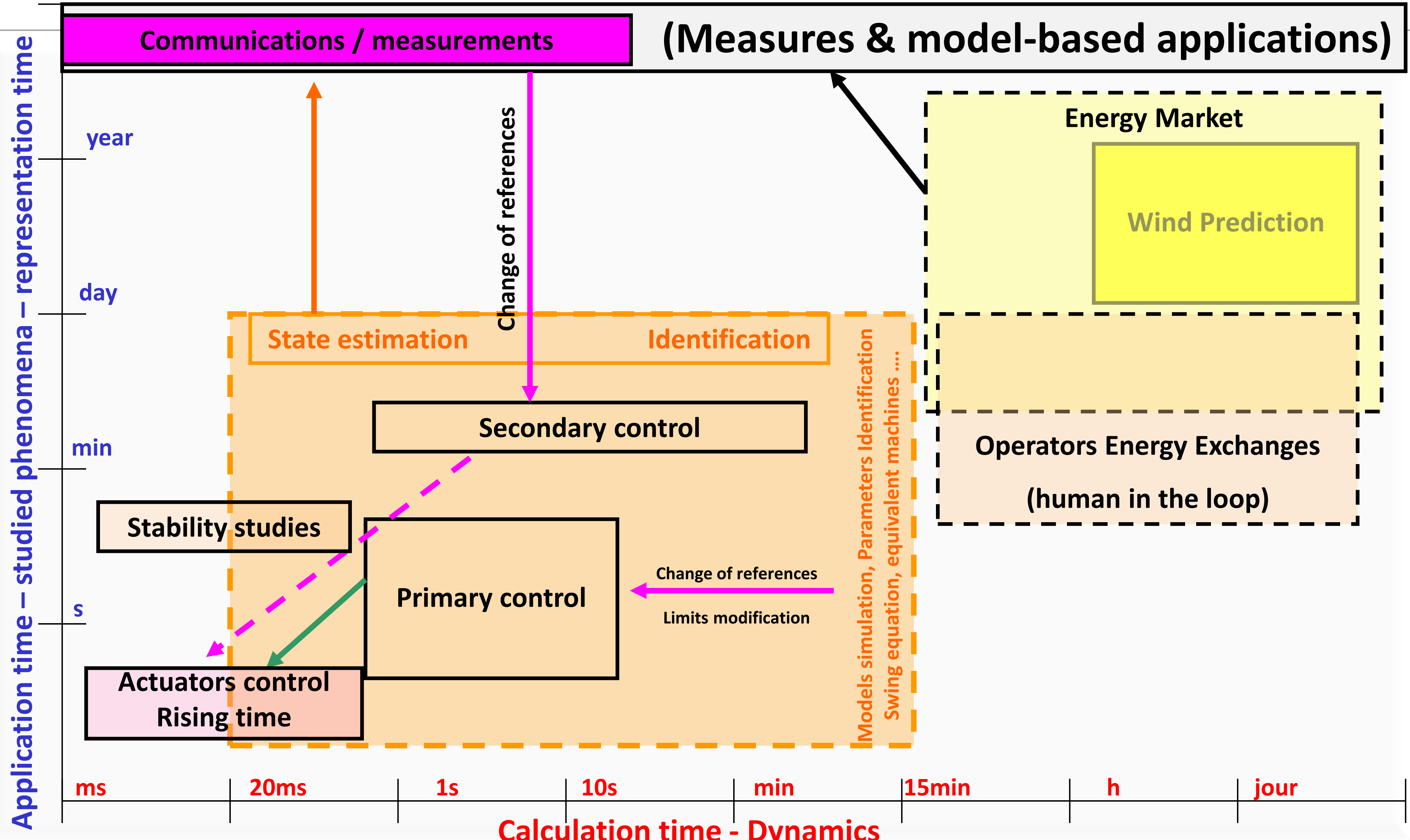
Plug & Play system already exists in AC network

Use of AC control design and tools

- ✓ Modeling large-scale systems – complex systems
- ✓ Machine equivalent model – swing equation/frequency for AC – capacitors and power electronics/voltages for DC


DC
AC
P_{DC}
V
DC
AC
P_{DC}
V
DC
DC
P_{DC}
V
P_{DC}
AC
DC
V
AC
P_{DC}
AC
DC
V
AC
2 h
30 min
15 min
1 min
2 s
µs
Tertiary control
Secondary control
V*
I*
HVDC
Primary control
HVDC
HVDC

Time scale decoupling



Control of MT-HVDC Networks

Operation of MTDC with loss minimization: Secondary control strategies

LEVEL CONTROL	AC definition	WINPOWER definition
Level 3 *(15 mn)*	Tertiary	Tertiary
Level 2 *(~ mn)*	Secondary Control **(U,Φ)**	Secondary Control **(~ mn)**
	Primary Control **(Droop)**	Droop Control **(P, I)**
Level 1 *(~ 10-20 ms)*	Local control **(PSS/ AVR of rotors, filters)**	Local control (U) **(converters, influence of cables, etc.)**
Level 0	Protection	Protection *(Outside of the study of Winpower)*

Secondary control objectives

- ***Follow tertiary planning references (who has already considered weather forecast ,electricity market ...).***
- ***Optimal Power flow coordination.***
  - ***Optimized to minimize power losses in the lines***
  - ***Optimized to minimize line congestion***
  - ***Optimize to maximize profit***
  - ***Optimize to reduce voltage variations***
  - ***…***
- ***Storage management.***
- ***Prevent congestion on lines.***

<u>After disturbance:</u>

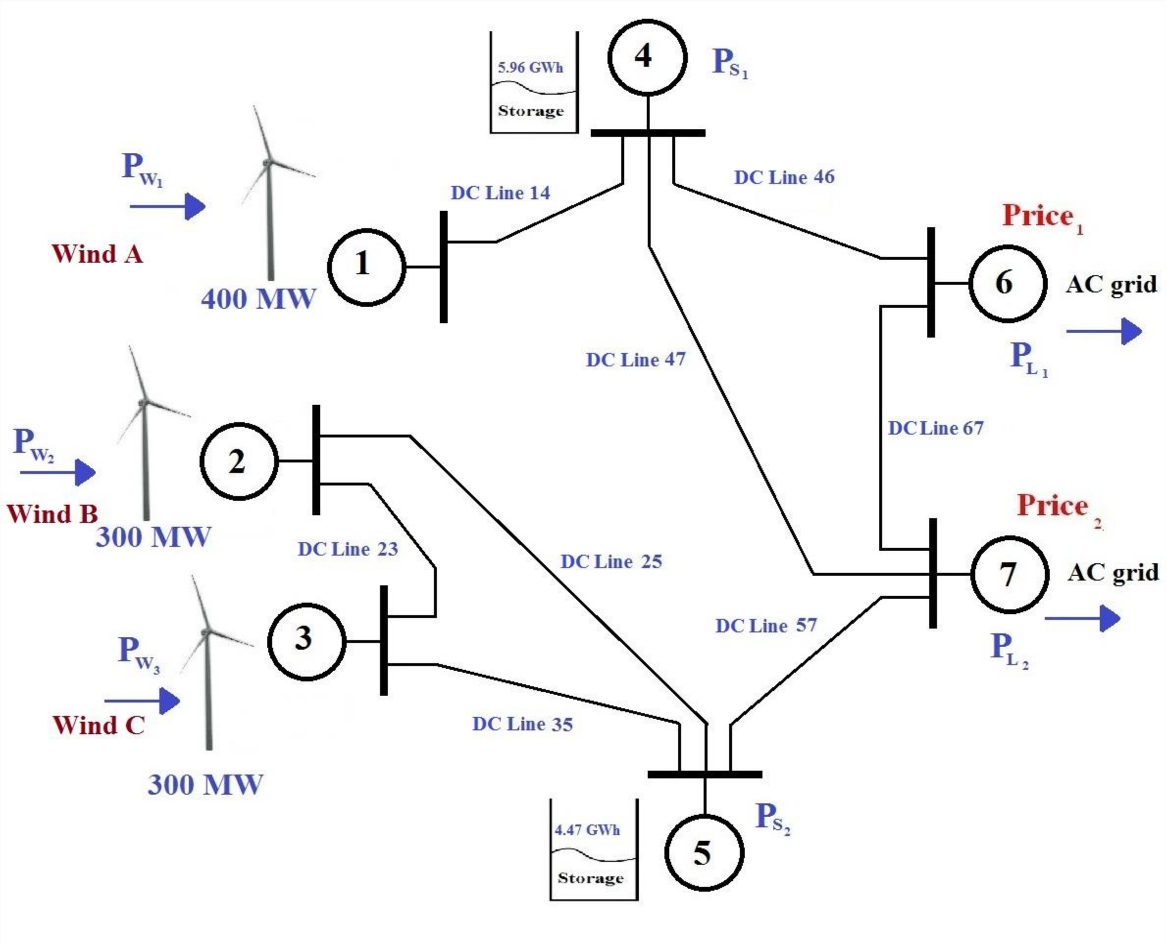
- ***Get a level of stable non-degraded operation state***
  Determine a new level of voltage
- ***Restore energy capacity of each storage node***
- ***Re-dispatch the parameters of nodes in primary control (redistribute droop gains for each concerned node)***

⬇

Communication is required between nodes.

Model predictive control

Multi-point HVDC



Secondary control

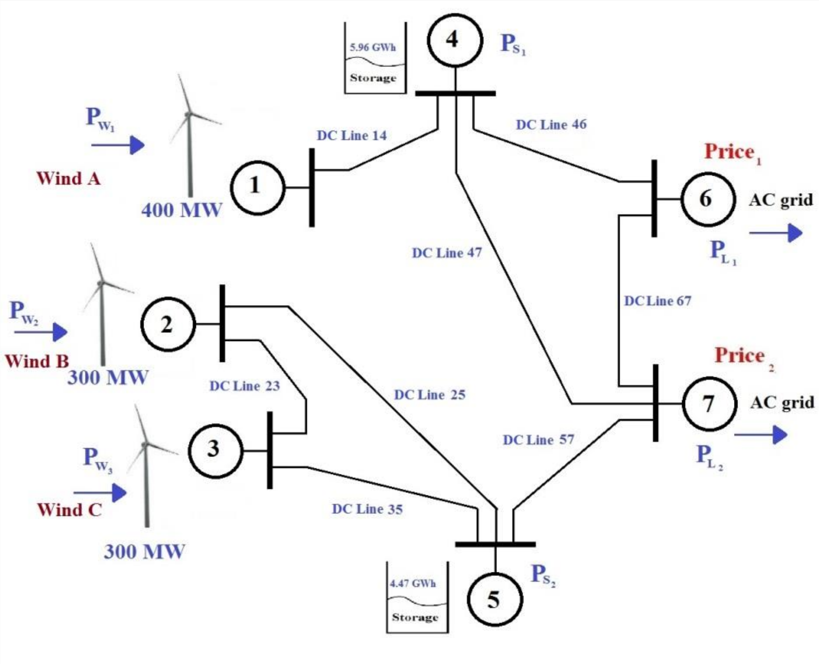
- *Secondary Control will command power flow within the network.*
- *Actuation time between 1 and 15 min.*
- *Storage size and response characteristics will determine the overall system performance.*

Model Predictive control

Objective function

$$min\left(\sum P_i\right) = \min([u]^t \cdot [Y] \cdot [u])$$

Subject to:



a) $j \in \mathrm{A, B, E, F} / P_j = [u]^t \cdot [Y]_j^{\ *} \cdot [u]$

b) $P_{A,B} - P_{E,F} = P_{C,D} + P_{Losses}$

$P_{A,B}$ ≡Generator nodes

$P_{C,D}$ ≡Storage nodes

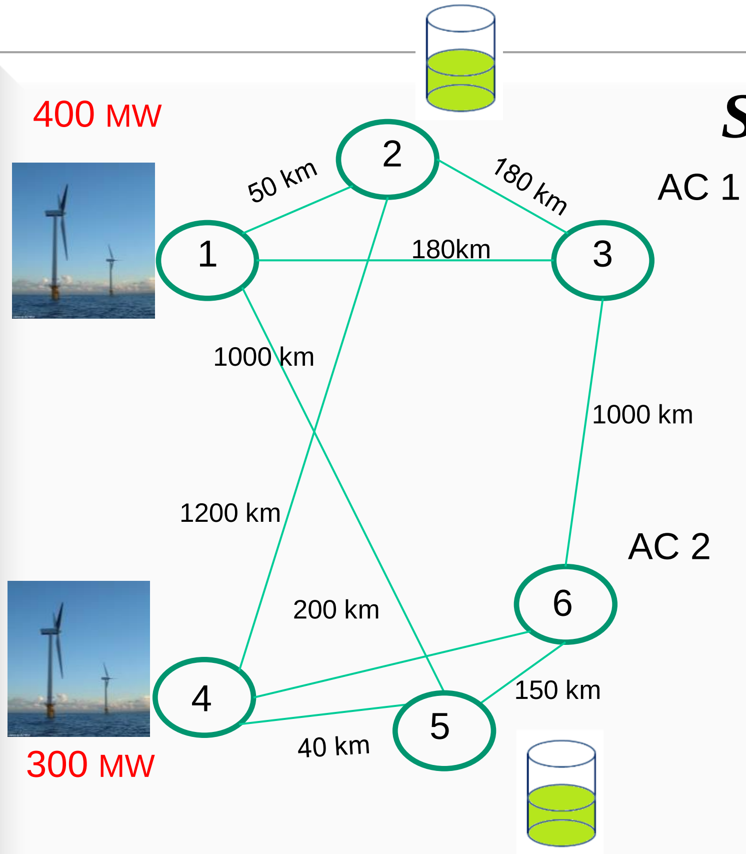
$P_{E,F}$ ≡Consumption nodes

c) $\frac{|u_i - u_j|}{R_{ij}} \leq I_{\max\, line\, ij}$

d) $u_{i,min} \leq u_i \leq u_{i,max}$

e) $P_{C,D\, min} \leq P_{C,D} \leq P_{C,D\, max}$

Secondary control - Results



Simulations parameters

Line	Ω/km
1-2	0.0121
1-3	0.0121
1-5	0.0121
2-3	0.0121
2-4	0.0121
3-6	0,0121
4-5	0.0121
4-6	0.0121
5-6	0.0121

Nominal voltage grid
$100\ kV$

Base power
$400\ MW$

Imax
1 $p.u.$

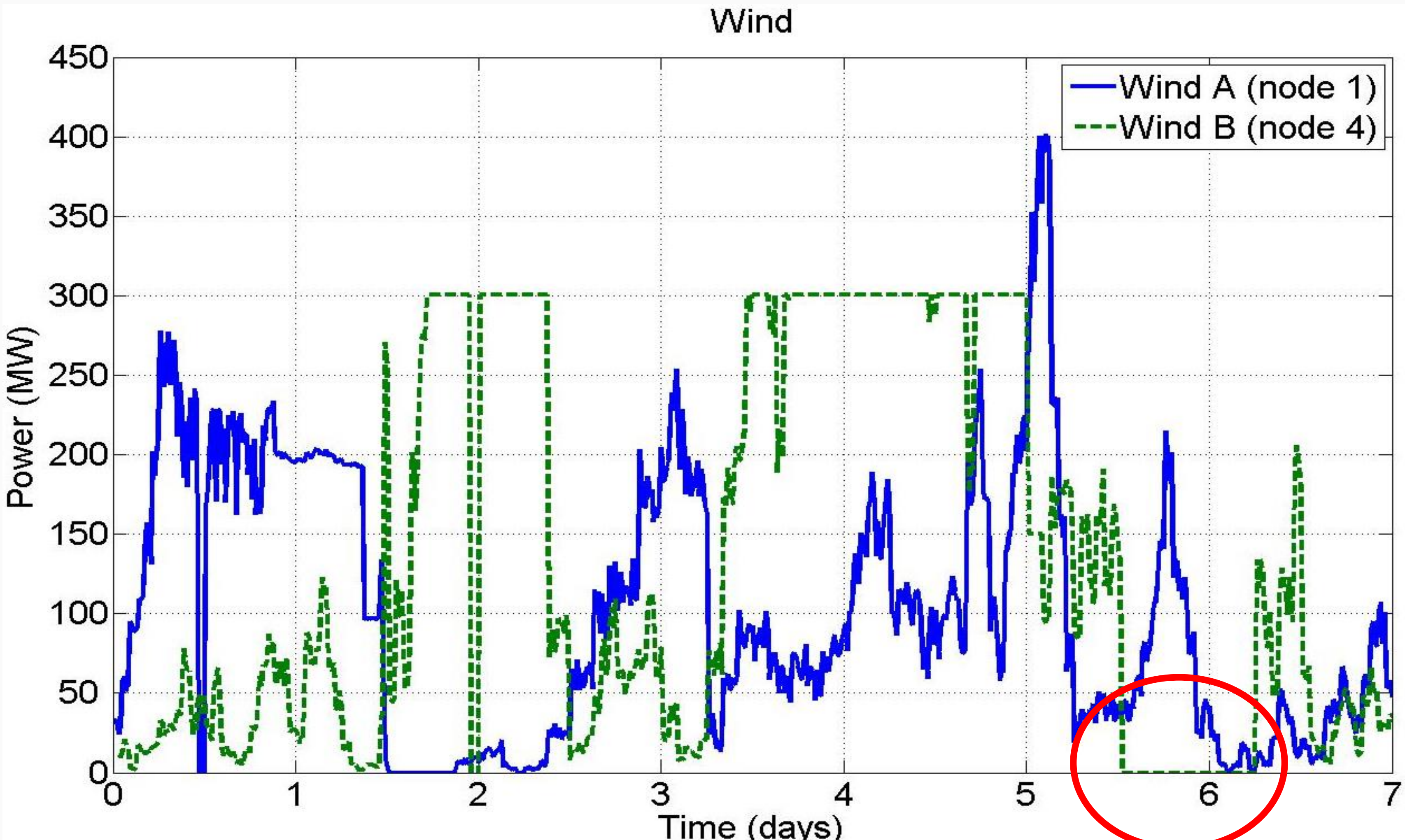
Voltage
$0{,}9 \leq u_i \leq 1{,}1 \quad (p.u.)$

N_p	T
2 hours	5 minutes

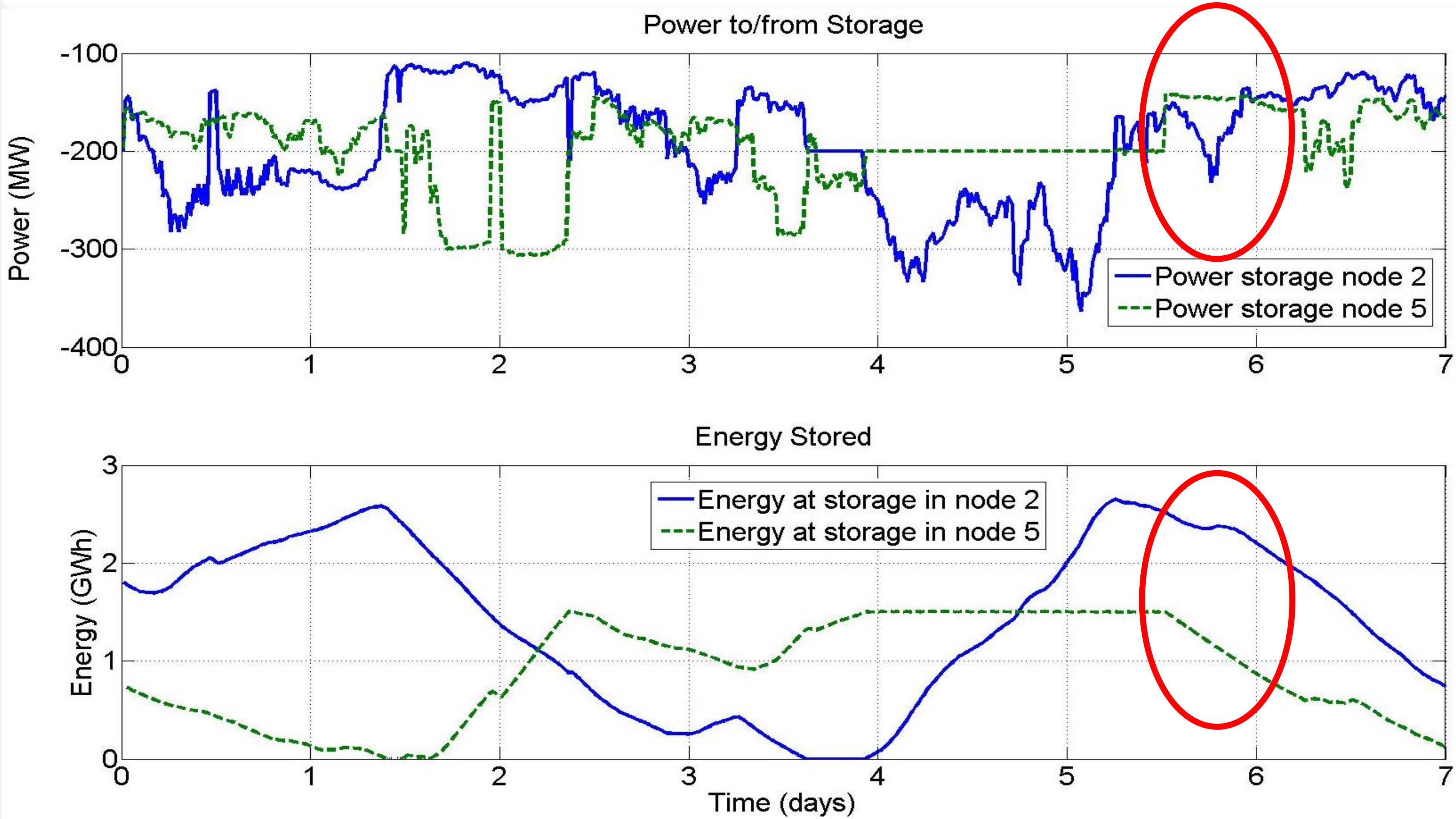
	Storage node 2	Storage node 5
Initial energy	60 %	50%
Maximum energy	10 GWh	3 GWh
Maximum power charging	350 MW (η=0,8)	220 MW (η=0,8)
Maximum power discharging	300 MW (η=0,85)	200 MW (η=0,85)

Secondary control. Results.

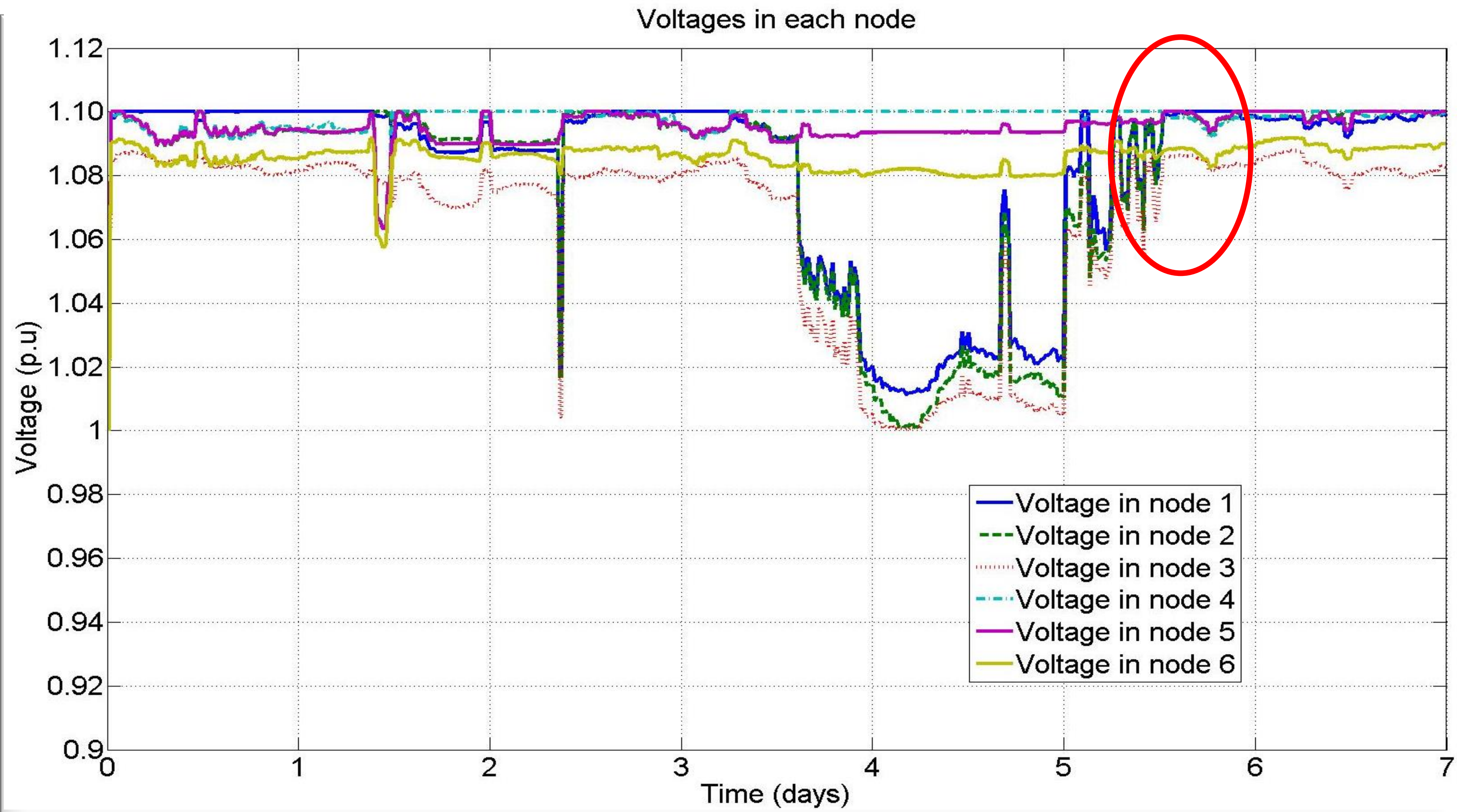
Simulations (b). Loss of generator node



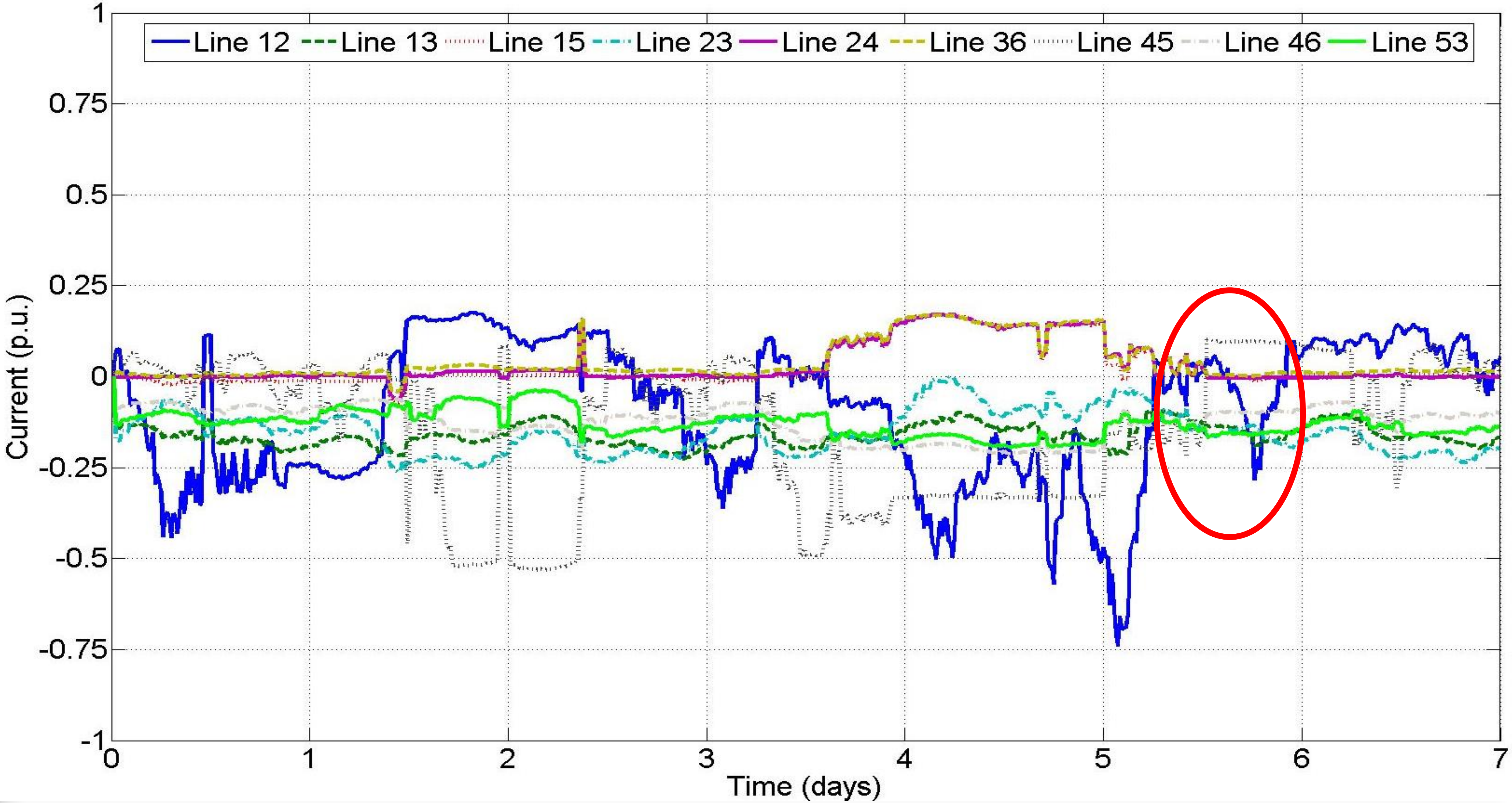
Secondary control. Results.



Secondary control. Results.

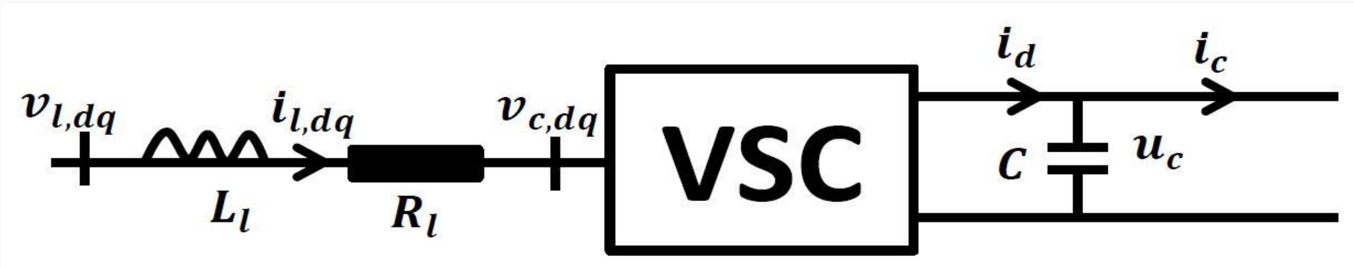


Secondary control. Results.



Local Control of VSC converters – Stability analysis, methodologies

Specification of a converter



- A synchronous d-q reference frame is applied in stead of abc frame;
- i_{ldq}: phase reactors currents; v_{ldq}: connected AC area voltage; v_{cdq}: converter voltage; C: DC capacitors; R_l, L_l: series connected phase reactors; u_c: DC voltage
- i_c: measureable DC current representing an active demand or supply

Modeling of a VSC-HVDC terminal

State space model

$$\frac{di_{ld}}{dt} = -\frac{R_l}{L_l} i_{ld} + \omega i_{lq} - \frac{1}{2L_l} M_d u_c + \frac{v_{ld}}{L_l}$$
$$\frac{di_{lq}}{dt} = -\frac{R_l}{L_l} i_{lq} - \omega i_{ld} - \frac{1}{2L_l} M_q u_c + \frac{v_{lq}}{L_l}$$
$$\frac{du_c}{dt} = -\frac{1}{C} i_c + \frac{1}{C}\frac{3}{4}(M_d i_{ld} + M_q i_{lq})$$

$$P_l = \frac{3}{2} v_{ld} i_{ld}$$
$$Q_l = -\frac{3}{2} v_{ld} i_{lq}$$

- State variables: i_{ld} i_{lq} u_c;
- Control variables: M_d M_q(modulation index)
  $v_{c,dq} = \frac{1}{2} M_{dq} u_c$
- External signal: i_c
- System known parameters: R_l L_l $v_{l,dq}$ and C

dq reference frame make: $v_{ld} = v_{l,rms}$ and $v_{lq} = 0$

Control objective

- **Develop different control structures :**
  - Make the DC voltage u_c and the reactive power Q_l track their desired values $u_c{}^*$ and $Q_l{}^*$ if i_c is subjected to certain changes
  - Providing $i_{lq}{}^*$ instead of $Q_l{}^*$

- Control methods:
  - Backstepping-like nonlinear controller
  - Static/dynamic feedback linearization controller
  - Globally stable passive controller

❖Backstepping-like nonlinear controller

Control variables M_{dq}

$$\begin{cases} M_{di} = \frac{2L_{li}}{u_{ci}}\left(-\frac{R_{li}}{L_{li}} i_{lid} + \omega_i i_{liq} + \frac{1}{L_{li}} v_{lid} - u_{id}\right) \\ M_{qi} = \frac{2L_{li}}{u_{ci}}\left(-\frac{R_{li}}{L_{li}} i_{liq} - \omega_i i_{lid} + \frac{1}{L_{li}} v_{liq} - u_{iq}\right) \end{cases}$$

State feedback control law

$$\begin{cases} u_{id} = \frac{di_{lid}}{dt} = \frac{d\tilde{i}_{lid}}{dt} + \frac{di^*_{lid}}{dt} \\ u_{iq} = \frac{di_{liq}}{dt} = \frac{d\tilde{i}_{liq}}{dt} + \frac{di^*_{liq}}{dt} \end{cases}$$

Eliminate the error fast dynamics $\tilde{i}_{lid}, \tilde{i}_{liq}$

$$\begin{cases} \dot{\varphi}_{id} = \tilde{i}_{lid} \\ \dot{\tilde{i}}_{lid} = -k_{id}\tilde{i}_{lid} - \lambda_{id}\varphi_{id} \end{cases}$$

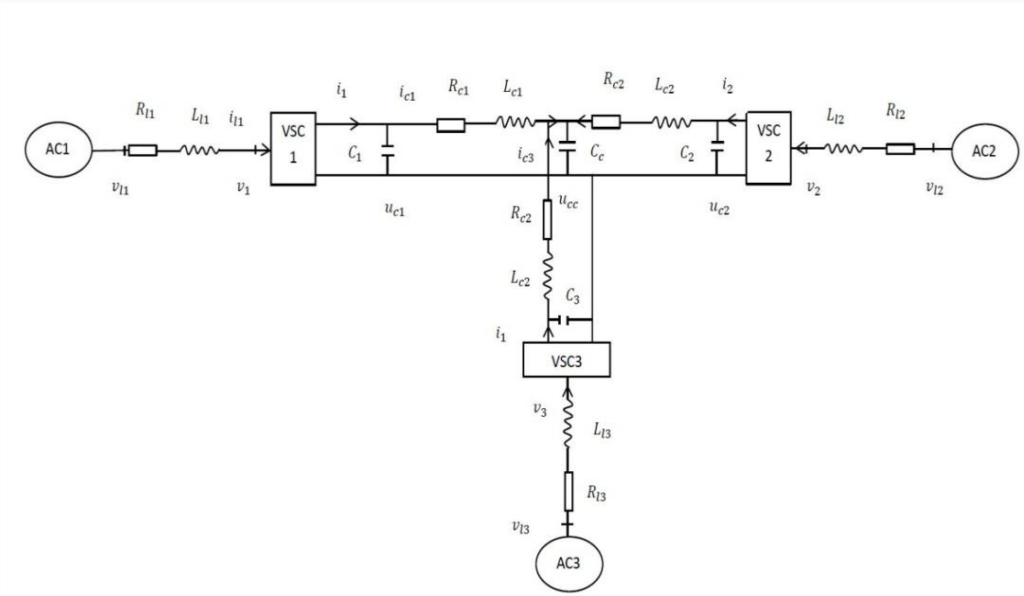
$$\begin{cases} \dot{\varphi}_{iq} = \tilde{i}_{liq} \\ \dot{\tilde{i}}_{liq} = -k_{iq}\tilde{i}_{liq} - \lambda_{iq}\varphi_{iq} \end{cases}$$

Reactive power control offers $i_{liq}{}^*$

$$i^*_{liq} = -\frac{2}{3}\frac{Q^*_{li}}{v_{lid}}$$

DC voltage control offers $i_{lid}{}^*$

$$\frac{di^*_{lid}}{dt} = -\frac{2}{3}\frac{u_{ci}}{i_{lid}}\frac{Ci}{L_{li}}\left(-k_{ci}\tilde{u}_{ci} - \lambda_{ci}\varphi_{ci} + \frac{i_{ci}}{C_i}\right) + \frac{u_{ci}}{2L_{li}}\frac{i_{liq}}{i_{lid}}M_{qi} + \left(-\frac{R_{li}}{L_{li}} i_{lid} + \omega_i i_{liq} + \frac{v_{lid}}{L_{li}} + k_{id}\tilde{i}_{lid} + \lambda_{id}\varphi_{id}\right)$$



Terminal	R_{li}	L_{li}	R_{ci}	L_{ci}
1	13.79 Ω	31.02 mH	0.2085 Ω	2.4 mH
2	12.79 Ω	33.02 mH	0.2 Ω	1 mH
3	13.57 Ω	40.02 mH	0.235 Ω	3.5 mH

Table 2.1: Parameter values of the terminals.

A three-terminal VSC-HVDC transmission system

Remark:

1. ${Q_{l1}}^*$, ${Q_{l2}}^*$ and ${Q_{l3}}^*$ are set up to zero.
2. The feedback control gains:

k_{id} = 100, λ_{id} = 100, k_{iq} = 100, λ_{iq} = 100, k_{ci} = 25, λ_{ci} = 5

3. Other parameters: $\omega_i = 314, C_i = 12\mu F, v_{li} = 230KV$

Simulation results

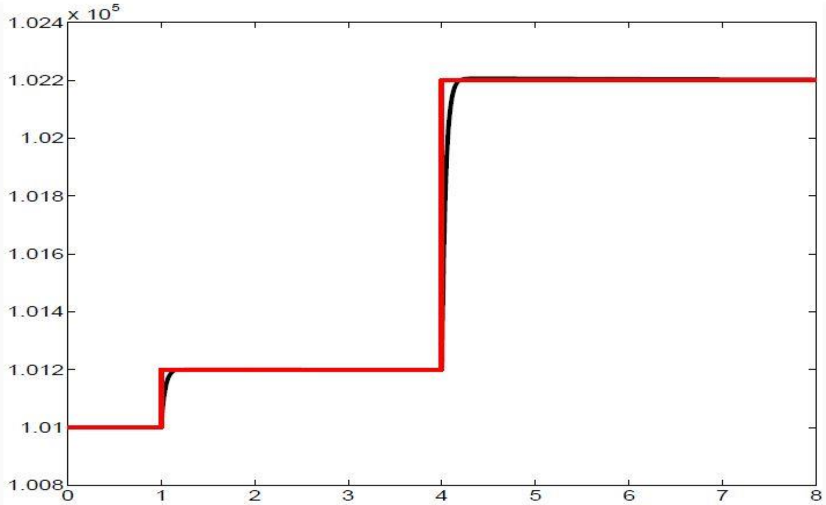


Fig. 4. u_{c1} response.

Time (s)	Event
0	u^*_{c1} = 101 kV, u^*_{c2} = 100 kV, u^*_{c3} = 99.8 kV
1	u^*_{c1} = 101.2 kV, u^*_{c2} = 101 kV, u^*_{c3} = 99.9 kV
4	u^*_{c1} = 102.2 kV
5	u^*_{c2} = 102.0 kV
6	u^*_{c3} = 100.9 kV

TABLE II

SEQUENCE OF EVENTS APPLIED TO THE SYSTEM.

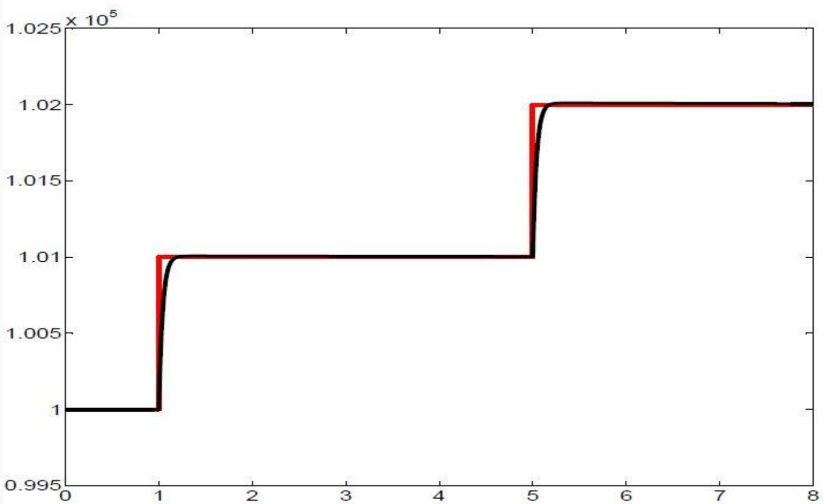


Fig. 6. u_{c2} response.

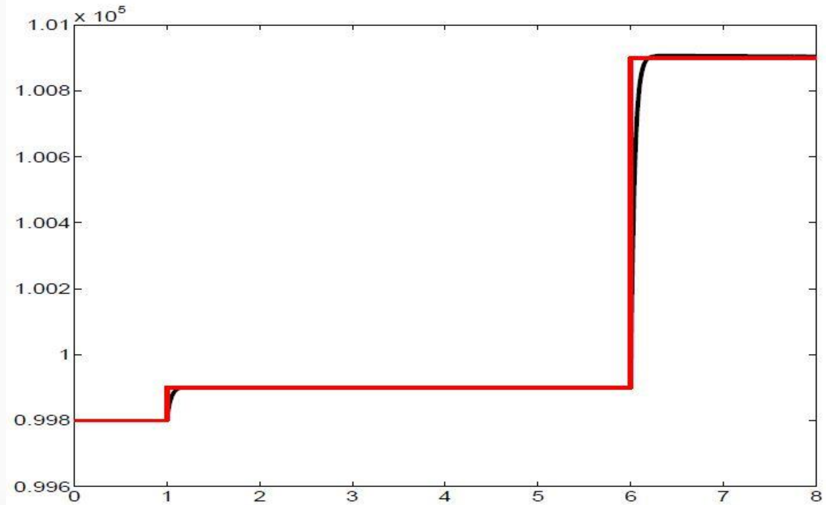


Fig. 8. u_{c3} response.

❖ Static/dynamic feedback linearization controller

$i_c < 0$ (inversion mode): static feedback linearization

Control variables M_{dq}

$$\begin{pmatrix} M_d \\ M_q \end{pmatrix} = J^{-1} \begin{pmatrix} v_q - (-\frac{R_l}{L_l} i_{lq} - \omega i_{ld} + \frac{v_{lq}}{L_l}) \\ v_u - (-\frac{i_c}{C}) \end{pmatrix}$$

$$J^{-1} = \begin{pmatrix} \frac{2L_l}{u_c} \frac{i_{lq}}{i_{ld}} & \frac{4C}{3 i_{ld}} \\ -\frac{2L_l}{u_c} & 0 \end{pmatrix}$$

$$J = \begin{pmatrix} L_{g_d}(i_{lq}) & L_{g_q}(i_{lq}) \\ L_{g_d}(u_c) & L_{g_q}(u_c) \end{pmatrix}$$

$$L_{g_d}(i_{lq}) = 0$$
$$L_{g_d}(u_c) = \frac{3 i_{ld}}{4C}$$
$$L_{g_q}(i_{lq}) = -\frac{u_c}{2L_l}$$
$$L_{g_q}(u_c) = \frac{3 i_{lq}}{4C}$$

Additional inputs v_{qu}

$$v_q = \frac{d i^*_{lq}}{dt} + k_{pq}(i^*_{lq} - i_{lq})$$
$$v_u = \frac{d u^*_c}{dt} + k_{pu}(u^*_c - u_c)$$

Zero dynamics:

$$A = \frac{1}{L_l} \frac{\frac{2}{3} u^*_c i_c - R_l (\bar{i}_{ld})^2}{(\bar{i}_{ld})^2} < 0$$

❖ Static/dynamic feedback linearization controller

$i_c > 0$ (recfication mode): dynamic-like feedback linearization

Control variables
M_{dq}

Additional inputs
v_{dq}

$i_{ld}{}^*$

$$\begin{pmatrix} M_d \\ M_q \end{pmatrix} = \frac{2L_l}{u_c}\begin{pmatrix} (-R_l i_{ld} + \omega L_l i_{lq} + v_{ld}) - v_d \\ (-R_l i_{lq} - \omega L_l i_{ld} + v_{lq}) - v_q \end{pmatrix}$$

$$v_d = \frac{d i_{ld}{}^*}{dt} + k_{pd}(i_{ld}{}^* - i_{ld})$$
$$v_q = \frac{d i_{lq}{}^*}{dt} + k_{pq}(i_{lq}{}^* - i_{lq})$$

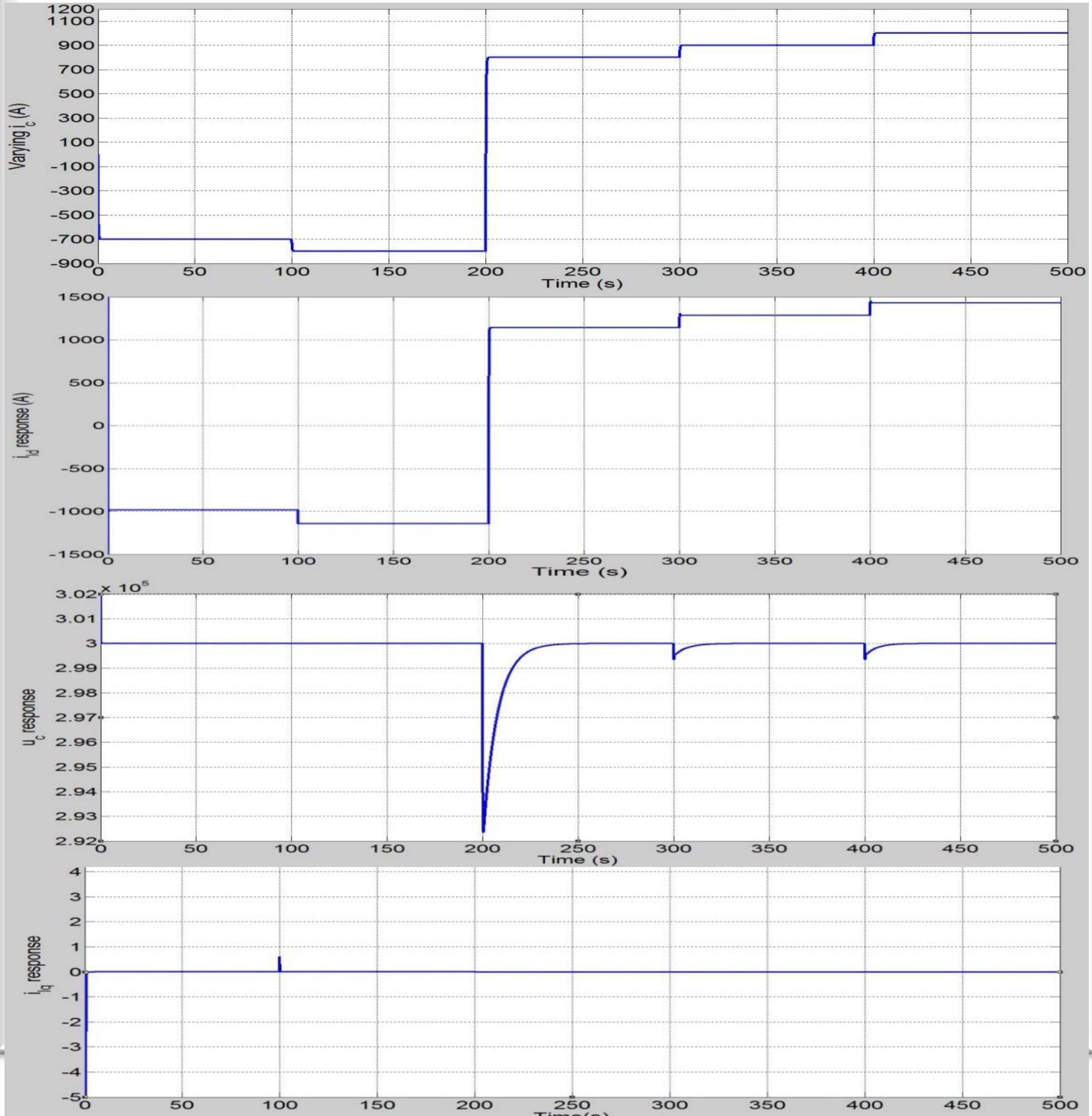
$$\frac{di_{ld}^*}{dt} = \frac{[-L_{f_0}^2(u_{c,re}) - c_1(u_{c,re} - u_c^*) - c_2 z_2]}{L_{g_0}L_{f_0}^1(u_{c,re})}$$

$$L_{f_0}^1(u_{c,re}) = -\frac{i_c}{C} + \frac{3}{2C}\times \frac{(-R_l i_{ld}^{*2} + v_{ld} i_{ld}^*) + (-R_l i_{lq}^{*2} + v_{lq} i_{lq}^*)}{u_{c,re}}$$

$$L_{f_0}^2(u_{c,re}) = -\frac{3\dot{u}_{c,re}}{2C}\frac{(-R_l i_{ld}^{*2} + v_{ld} i_{ld}^* + -R_l i_{lq}^{*2} + v_{lq} i_{lq}^*)}{u_{c,re}^2}$$

$$L_{g_0}L_{f_0}^1(u_{c,re}) = \frac{3}{2C}\frac{1}{u_{c,re}}(-2R_l i_{ld}^* + v_{ld})$$

Simulation results



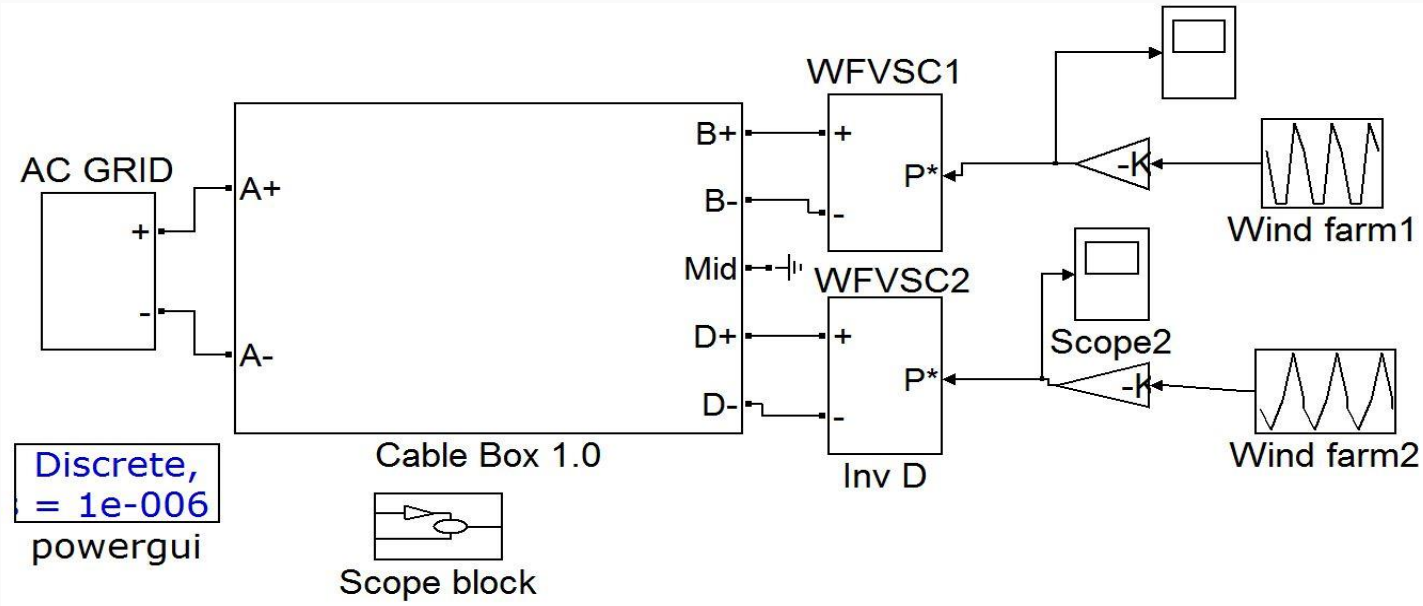
Terminal	R_l	L_l	v_{ld}	C	f
	0.05 Ω	40e-3 H	140 kV	20e-3 F	50 Hz

TABLE I

PARAMETER VALUES OF THE VSC TERMINAL.

Conclusion:

- Linear control theory can be applied to position new poles
- Control structure requires to switch between two control laws in different operation mode.

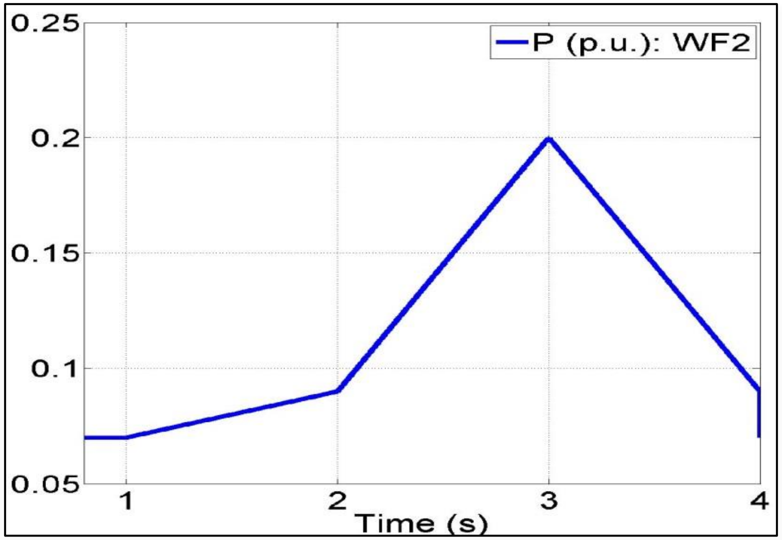


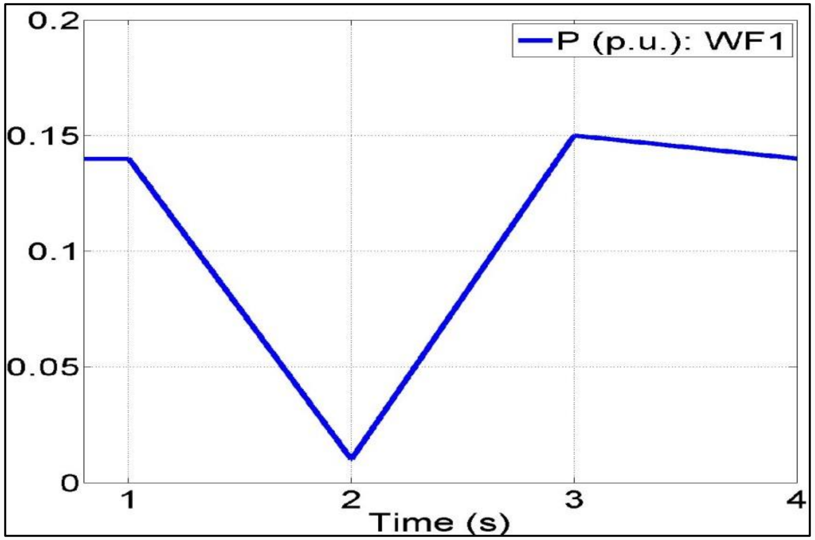
A three-terminal VSC-HVDC transmission system

Remark:

- Three VSC: two WFVSC and one GSVSC;
- GSVSC: regulate DC bus voltage level with the proposed control law (k_d = k_q=0,25) ;
- WFVSC: send the power generated from WF.

Simulation results





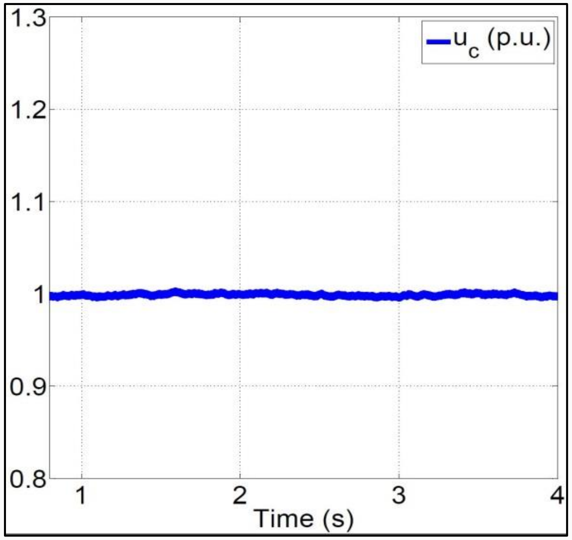
- **Power flows from WFs varying with respect to the wind speed**

Active power generated by wind farms

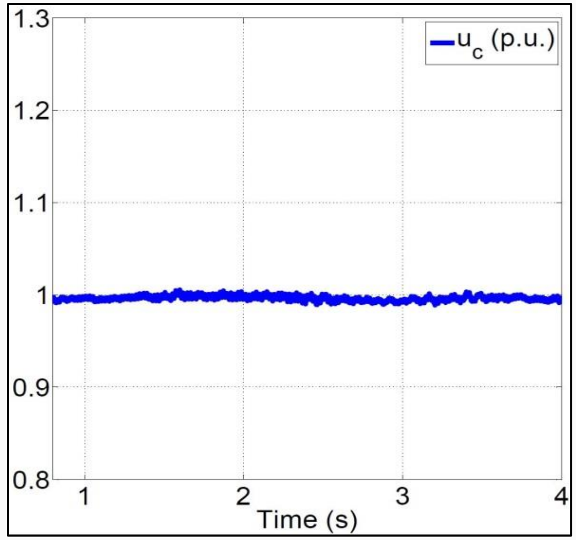
Control objective:

- Make all reactive powers follow the reference $Q_l^* = 0$;
- Enable to tolerate the variations in plow flows and always guarantee the DC voltage transmission level at the desired value $u_c^* = 1$ p.u..
- Ensure the power flows generated by WFs being totally transferred.

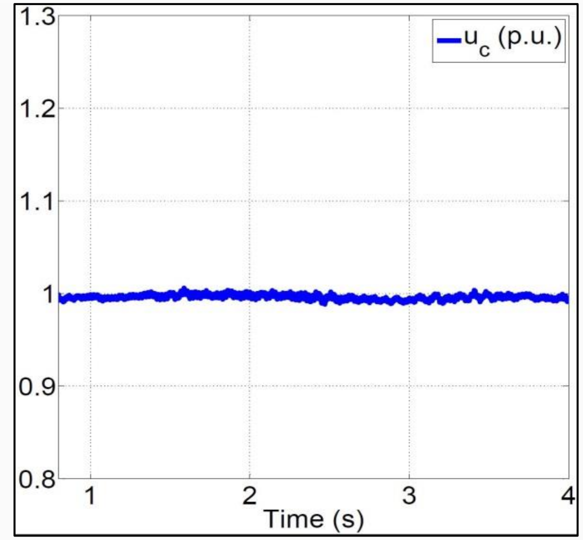
Simulation results



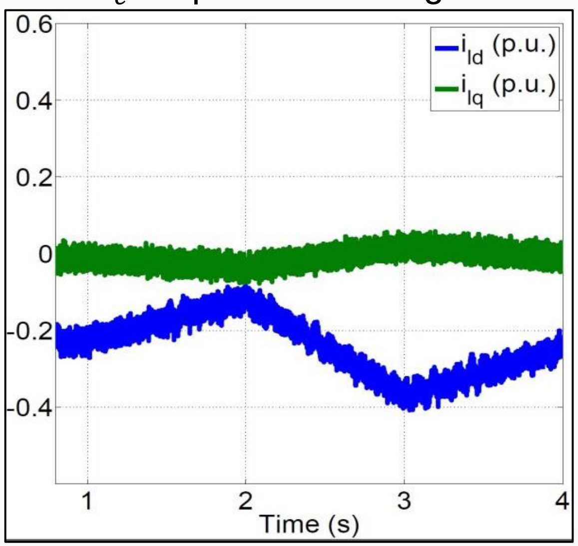
u_c responses of AC grid



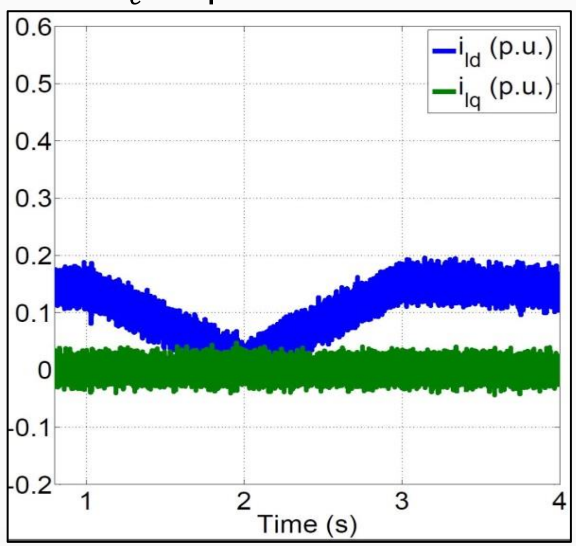
u_c responses of WF1



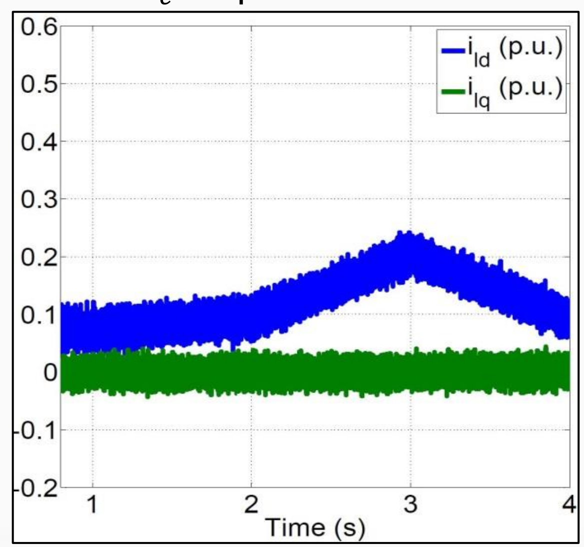
u_c responses of WF2



$i_{l,dq}$ responses of AC grid



$i_{l,dq}$ responses of WF1



$i_{l,dq}$ responses of WF2

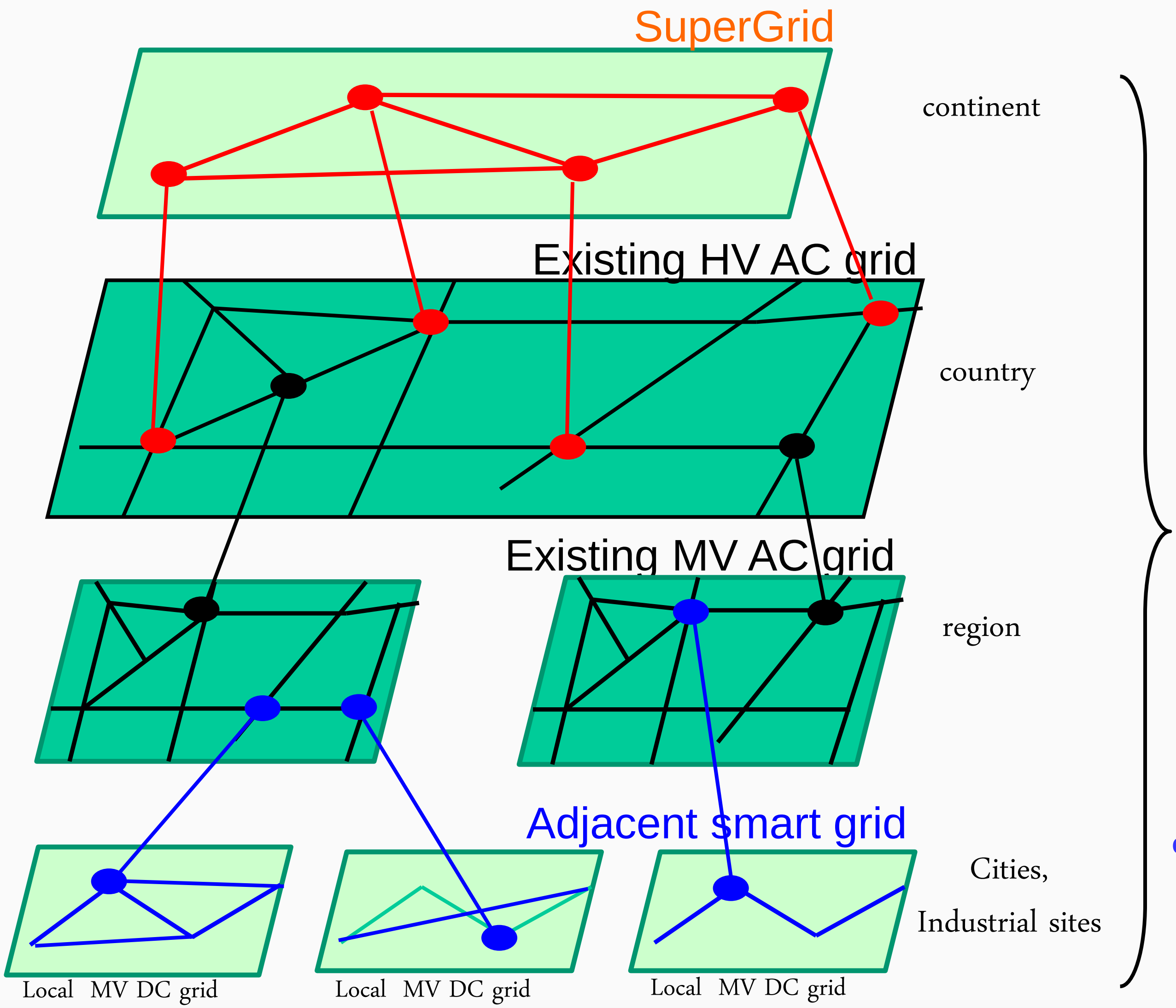
Comparison between different approaches

	Backstepping-like nonlinear controller	Static/dynamic feedback linearization controller	Globally stable passive controller
Stability:	Local	Local	Global
Power direction	Unidirectional	Bidirectional	Bidirectional
Linear system theory	Applicable	Applicable	Non applicable
Need equilibrium point in advance	No need	No need	Need

Even further steps

Constructing a SuperGrid

2020 vision: Supergrid & Adjacent Smartgrid



SuperGrid

- Meshed DC Grid
- Redundant lines
- Converters only at interface between AC and DC grids

⇨ Reduced Losses

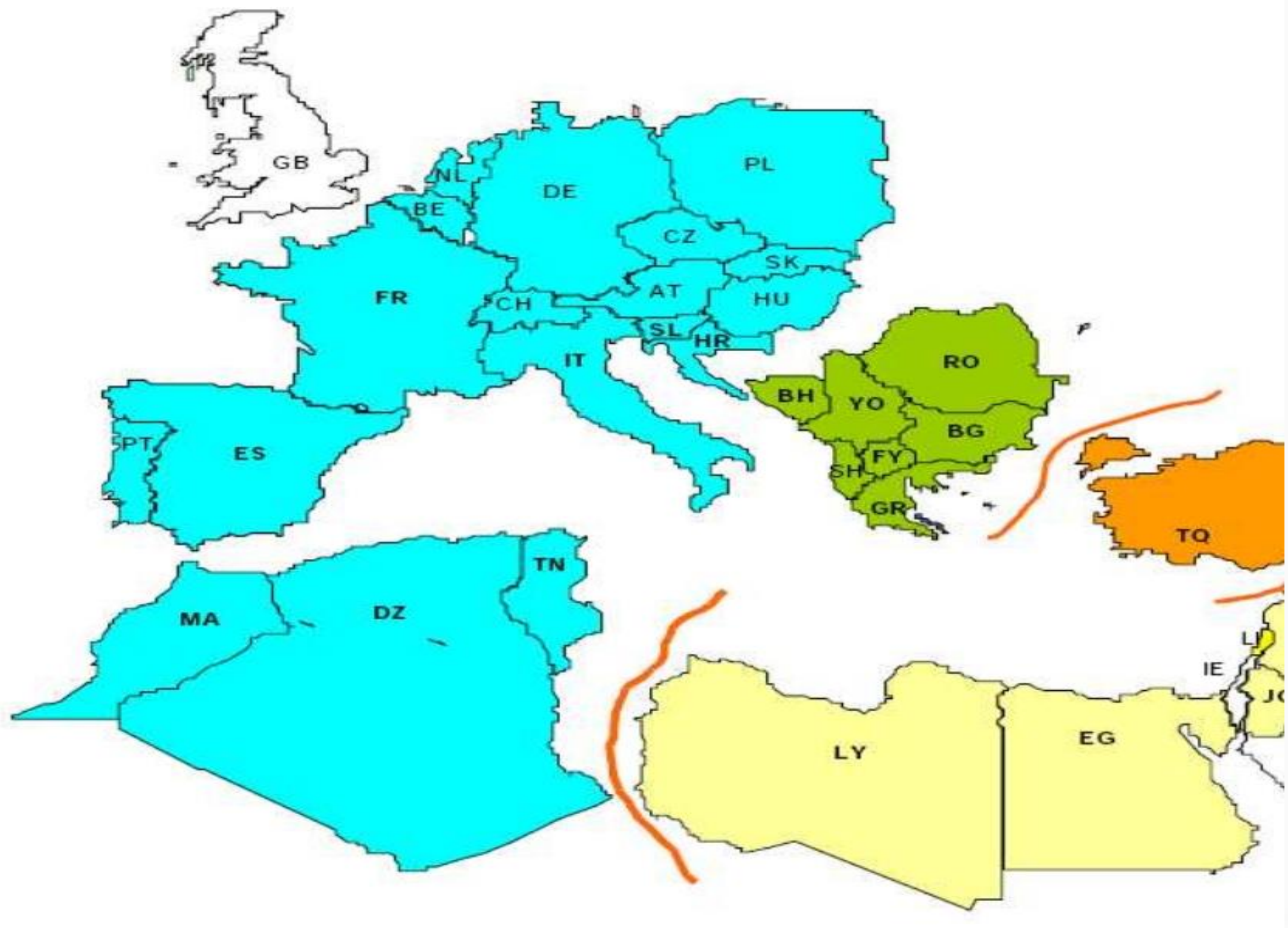
Superimposed layers

Adjacent smartgrid

- Local DC loops
- DC/DC converters to connect renewable, storage & loads in local loops and DC/AC converters at interface between AC and DC grids

⇨ Reduced Losses

Mediterranean Ring

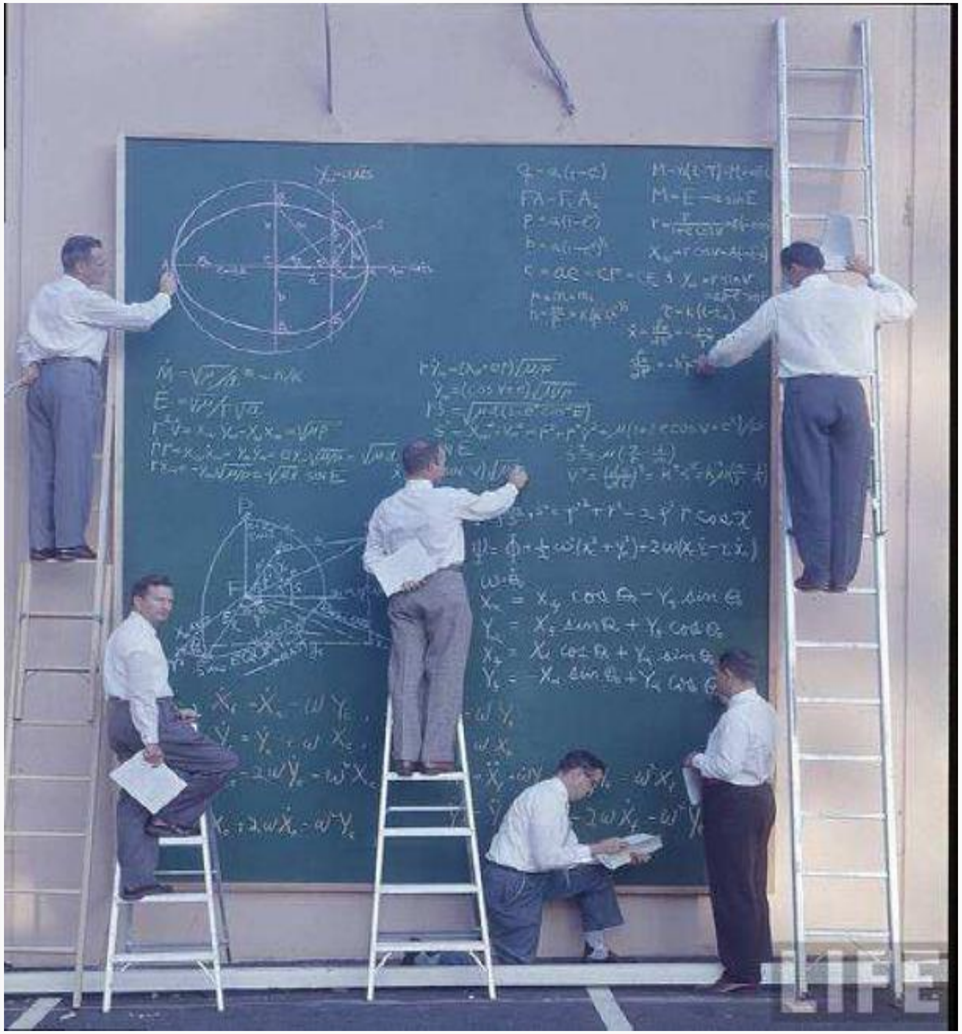


Conclusions

- ✓ Yet much to be done!!!!

- ✓ Hierarchical full control strategy under development
- ✓ Based on AC background, but merging with new knowledge from power electronics
- ✓ Multi-disciplinary → Much more could be presented!
- ✓ Plug-and-play
- ✓ Time scale separation

WINPOWER philosophy: Team work



References

- Y. Chen, G. Damm, A. Benchaib, F. Lamnabhi-Lagarrigue, “A globally stable passive controller for a VSC terminal in a multi-terminal HVDC grid”, in proc. ACC’14, Portland, USA, 4 - 6 June 2014.
- Y. Chen, G. Damm, A. Benchaib, F. Lamnabhi-Lagarrigue, “Control induced explicit time-scale separation to attain DC voltage stability for a VSC-HVDC terminal”, IFAC World Congress 2014.
- Y. Chen, G. Damm, A. Benchaib, F. Lamnabhi-Lagarrigue, “A new control strategy based on static and dynamic feedbacklinearization for a VSC-HVDC terminal”, in proc. ECC’14, Strasbourg, France, 24 - 27 June 2014.
- Y. Chen, J. Dai, G. Damm, F. Lamnabhi-Lagarrigue, et al., “Nonlinear control design for a multi-terminal VSC-HVDC system,” in Proceedings of the European Control Conference, 2013.
- M. Jimenez Carrizosa, G. Damm, A. Benchaib, M. Netto and F. Lamnabhi-Lagarrigue, “Bilinear and nonlinear control algorithms for a DC/DC converter for multi-terminal HVDC networks” 19th World Congress of the International Federation of Automatic Control . August 2014, Cape Town, South Africa.
- M. Jiménez Carrizosa, F. Dorado Navas, G. Damm , A. Benchaib and F. Lamnabhi-Lagarrigue, “Optimal power flow operation of a multi terminal HVDC with energy storage” 12th IEEE International conference on Industrial informatics - INDIN 2014 Porto Alegre, Brazil July 27-30 2014
- M. Jiménez Carrizosa, A. Benchaib, P. Alou and G. Damm, “DC transformer for DC/DC connection in HVDC network” 15th European Conference on Power Electronics and Applications September 2013, Lille, France.
- M. Jiménez Carrizosa, J. Cortés, A. Benchaib, P. Alou, G. Damm, J. A. Cobos and F. Lamnabhi-Lagarrigue, “DC / DC converters as DC circuit-breakers in HVDC networks operation” 16th European Conference on Power Electronics and Applications August 2014, Lappeenranta, Finland.
- M. J. Carrizosa, F. Dorado Navas, G. Damm , A. Benchaib and F. Lamnabhi-Lagarrigue, “Optimal power flow in multi-terminal HVDC grids with offshore wind farms and storage devices” (submitted) International Journal of Electrical Power and Energy Systems.

References

- Damm, G., Lamnabhi-Lagarrigue, F., Marino, R. et Verrelli, C.-M., Transient Stabilization and Voltage Regulation of a Synchronous Generator, chapter in the book Taming Heterogeneity and Complexity of Embedded Control, Chapter 13, pp. 211-226, Eds F. Lamnabhi-Lagarrigue, S. Laghrouche, A. Loria and E. Panteley, ISTE Hermes and Lavoisier, 2006 .
- G. Damm, F. Lamnabhi-Lagarrigue, R. Marino, C. M. Verrelli, Transient stabilization and voltage regulation of a synchronous generator, in "Taming Heterogeneity and Complexity of Embedded Control", Editors: F. Lamnabhi-Lagarrigue, S. Laghrouche, A. Loria and E. Panteley, International Scientific and Technical Encyclopedia (ISTE), London, pp. 211-225, 2007.
- A. Benchaib, DC Grids in Power Network of the Future : Time scales consideration as key tool for control and operations of such complex system, Plenary presentation, 5èmes Journées Doctorales / Journées Nationales MACS, 11-12 July 2013, Strasbourg, France
- A. Benchaib, HVDC grid: from actuators distributed control to global stability of the network, HYCON2 Workshop on Energy, 3-4 September 2012, Brussels, Belgium. http://hycon2-ad2-wks.sciencesconf.org/resource/page/id/2
- A. Benchaib, Power Network: Multi-terminal DC grid Control, European Institute of Innovation and Technology, Summer School, August 2013, Paris, France
- A. Benchaib, DC system of systems - The future of power grids? : The complex systems observed in the social organisations of the natural world could hold the key to stable plug-and-play DC grids that use control functions on different timescales and system levels to integrate the energy from wind and other renewable energy sources, Alstom Grid Magazine, think grid #11 – Spring/summer 2013 http://www.alstom.com/grid/fr/actualites-et-evenements/thinkgrid/
- P. Kundur, Power System Stability and Control. New York, McGraw-Hill, 1993, pp. 581-592.
- A.R. Bergen, and V. Vittal, Power systems analysis, Prentice Hall, Upper Saddle River, 2000.
- P.M. Anderson, and A.A. Fouad, Power system control and stability, Wiley-IEEE Press, 2002.
- P.W. Sauer, and M.A. Pai, Power system dynamics and stability, Prentice Hall, 1997.