Wind Power Application: Integration problems of wind power sources to transmission and distribution networks

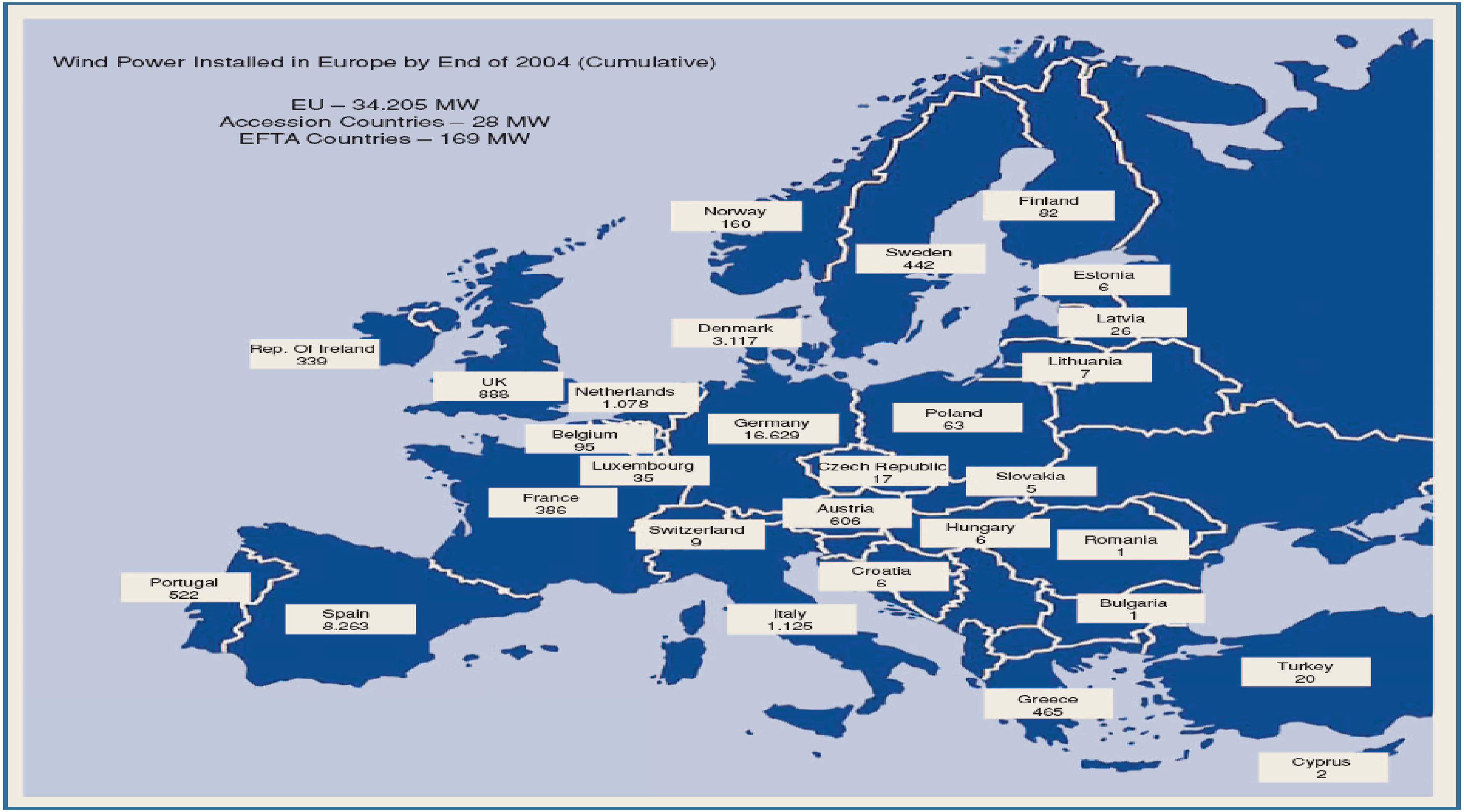
July , 2007

Kwang Y. Lee
Department of Electrical and Computer Engineering
Baylor University
Waco, Texas
Kwang_Y_Lee@baylor.edu

Outline

1. Status of wind power
2. Key wind integration issues
3. Grid code for wind generation
4. HVDC and wind power (Gotland)
5. Critical clearing time for network connected to wind generation system

Total installed capacity of wind power in Europe



Wind Power in USA (2004)

Installed capacity(2005) : 8,957 MW

State	Installed capacity of 2004 (MW)	State	Installed capacity of 2004 (MW)
California	2,045	West Virginia	66
Texas	1,396	Wisconsin	53
Minnesota	577	Illinois	105
Iowa	632	New York	49
Wyoming	284	South Dakota	44
Oregon	261	Hawaii	2
Washington	244	Nebraska	15
Colorado	229	Vermont	6
New Mexico	266	Ohio	8
Pennsylvania	129	Tennessee	29
Oklahoma	176	Alaska	1
Kansas	113	Massachusetts	1
North Dakota	66	Michigan	3
sum			6,800

Key figures of the power system in Germany, Spain, Ireland, and Denmark

		Germany	Spain[2]	Ireland	Denmark (W + E)[1]
Peak demand 2004	GW	77.2	38.2	4.5	3.7 + 2.6
Minimum demand 2004	GW	38	15.3	1.65	1.2 + 0.9
Interconnection transfer capability 2005	GW	16.6	1.8–2.8	0.5	2.7 + 2.4
Wind power 2004	GW	16.6	8.3	0.3	2.4 + 0.7
	TWh	25	14.5	0.7	6.2 + 1.7
Max penetration level (Installed wind power/ minimum demand)		44%	54.2%	18.2%	W: 200% E: 77%
Max penetration level with interconnection [installed wind power/(minimum demand+ interconnection)]		30%	48.5%–45.8%	13.9%	W: 61.5% E: 21.2%
	Year	2020	2011	2010	2020
Targets for wind power.	GW	50.3	13.0	1.0	3.6 + 1.2

[1] For the western and eastern part of Denmark, respectively.
[2] For the Spanish Peninsular.

Occupation rate of wind power in Europe

country	Occupation rate in 2005(%)
Denmark	19.70%
Spain	7.70%
Germany	5.40%
Ireland	3.80%
Portugal	3.60%
Greece	2.90%
Netherlands	2.10%

PENNSTATE

Classification of wind power generation

❑ Structure

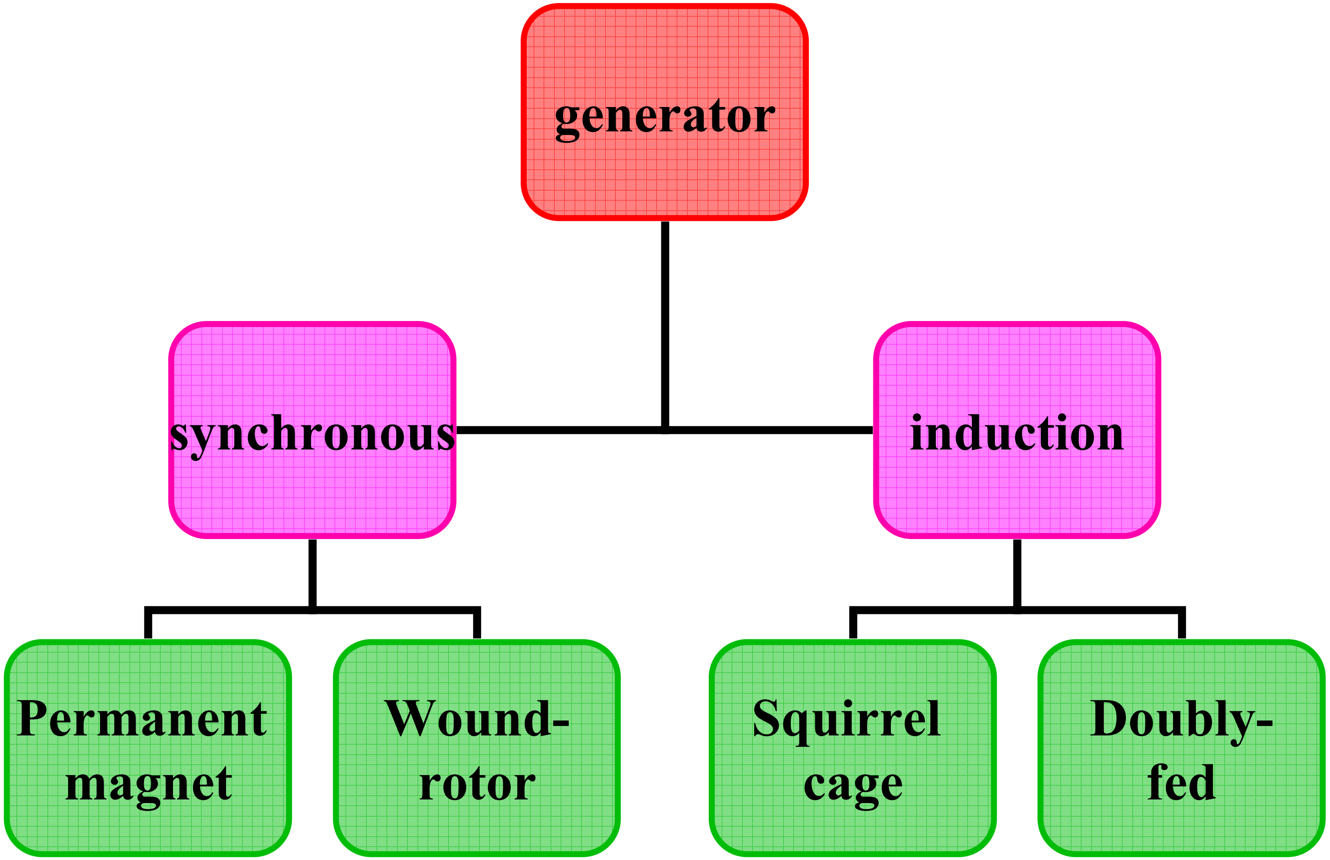
Vertical axis

Horizontal axis

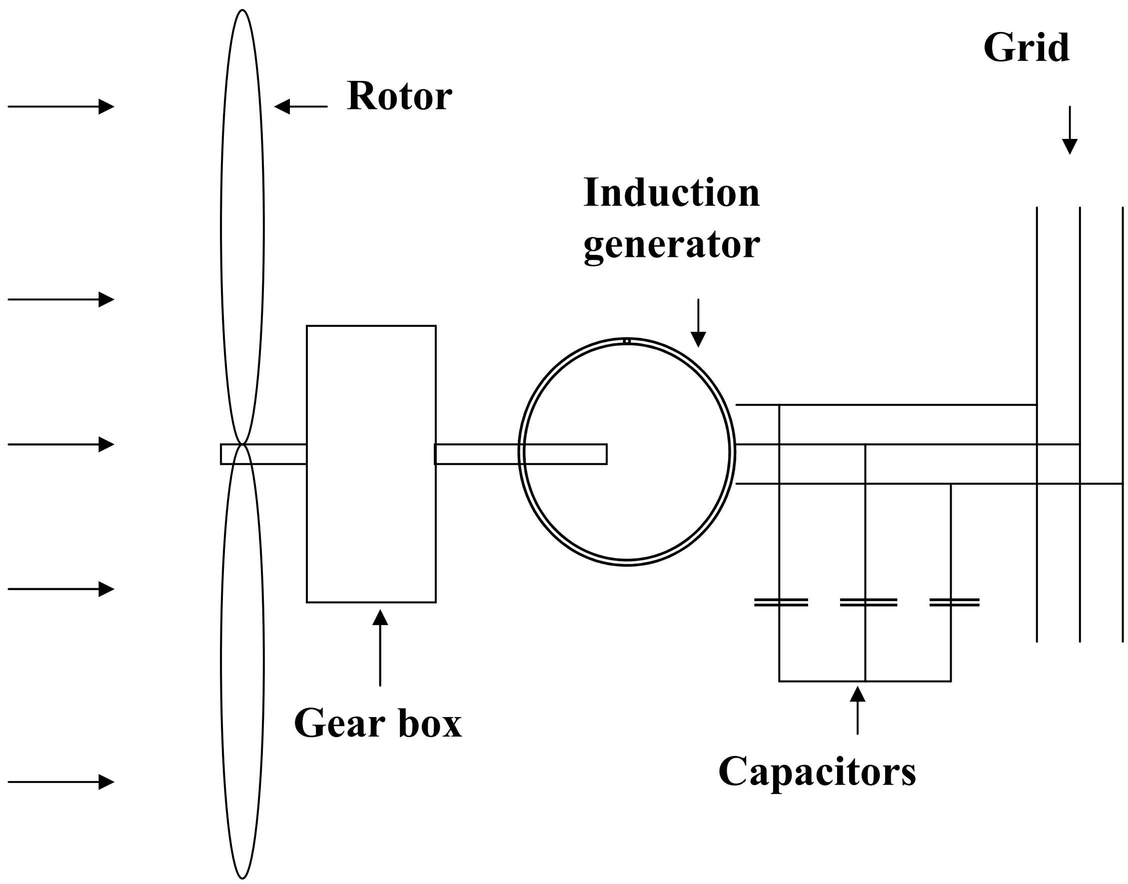
❑ Opertaion

- Grid-connected operation
- Stand-alone operation

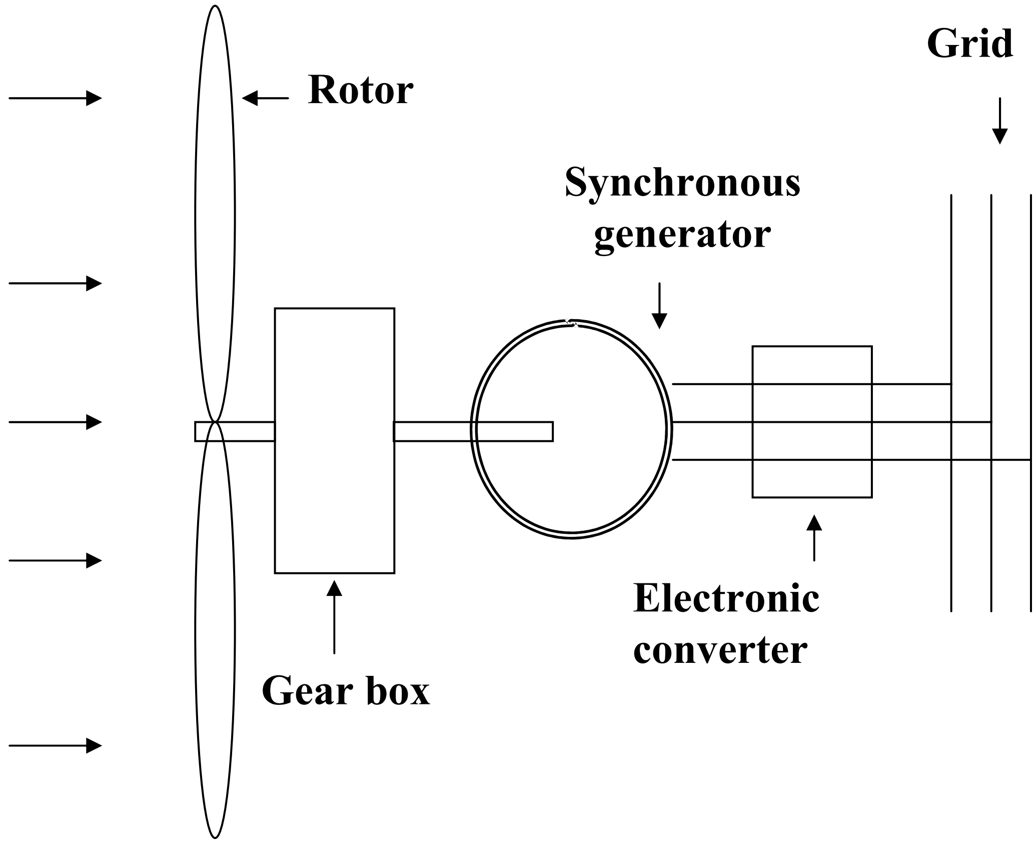
Wind power generator



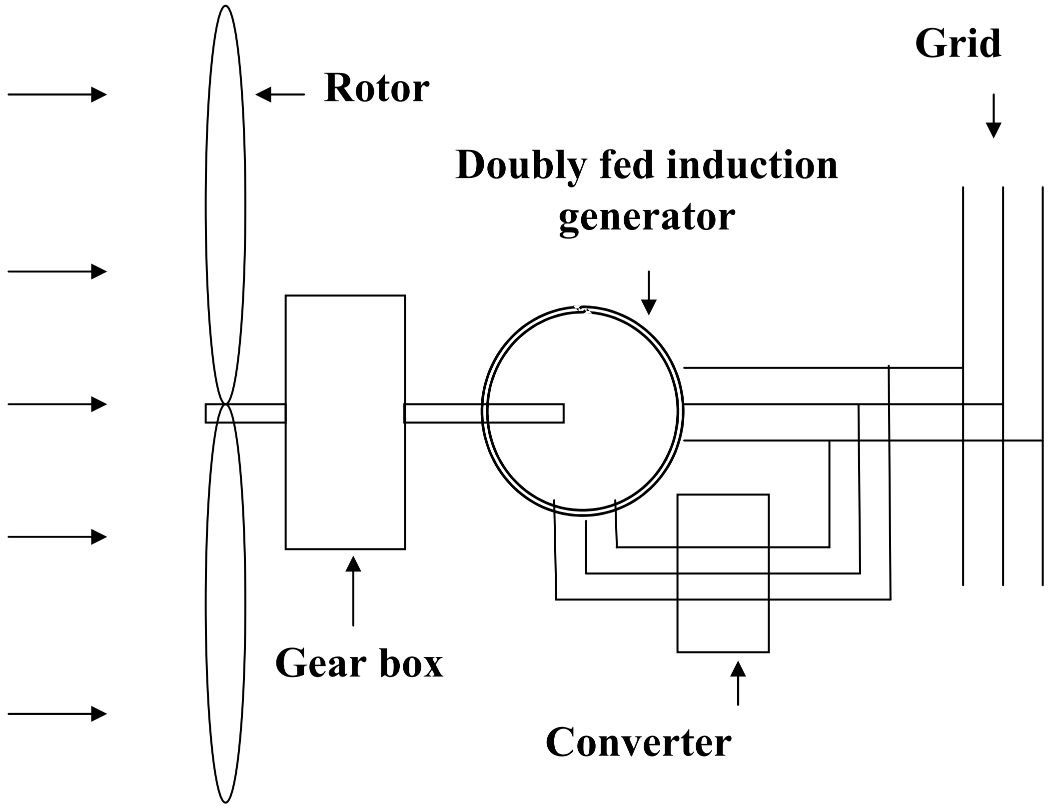
Fixed speed operation of wind turbine



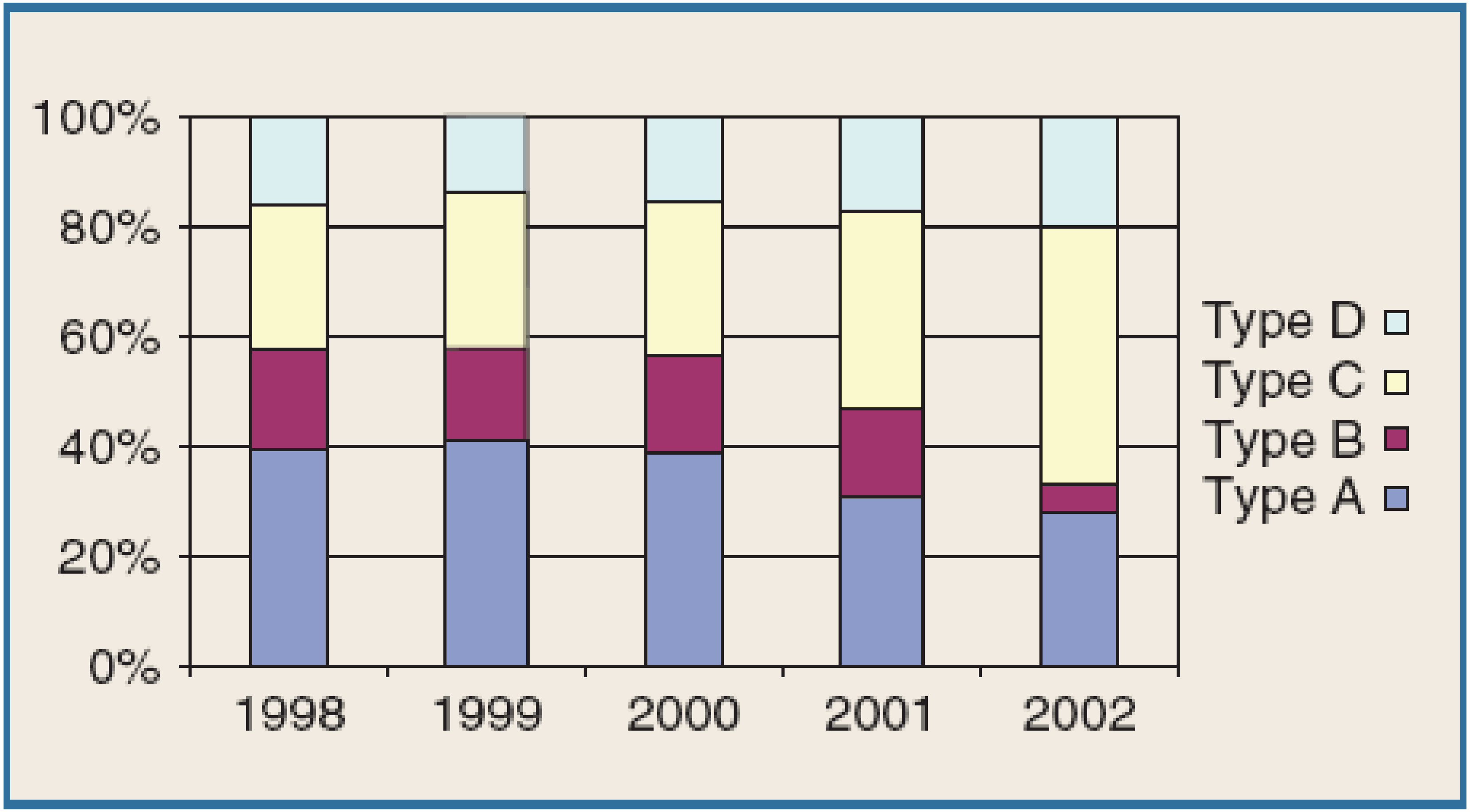
Variable speed wind turbine with synchronous generator



Variable speed wind turbine with doubly fed induction generator



World market share of wind turbine (1998-2002)



- ✓ **Type A: fixed speed wind turbine with a asynchronous squirrel induction generator**
- ✓ **Type B: variable speed wind turbine with wound rotor induction generator**
- ✓ **Type C: variable speed wind turbine with a doubly fed induction generator (DFIG)**
- ✓ **Type D: variable speed, pitch controlled wind turbine**

Key Wind Integration Issues

- ✓ **What are the impacts of wind's *variability* on system operating cost?**
- ✓ **How should wind plant *capacity credit* (or value) be determined?**
- ✓ **How has wind affected *system operating strategies*?**

Impacts of wind's variability on operating cost

- ✓ **a few seconds – one minute:**

  frequency regulation

- ✓ **a few minutes – a couple of hours:**

  load following

- ✓ **several hours – one or more days:**

  unit commitment

Wind impacts on system operating costs

Study	Wind capacity penetration(%)	Regulation cost (US$/MWh)	Load-following cost (US$/MWh)	Unit commitment cost (US$/MWh)	Gas supply cost (US$/MWh)	Total operating cost impact (US$/MWh)	System operating cost savings (US$/MWh)
Xcel-UwiG	3.5	0	0.41	1.44	NA	1.85	na
Xcel-MNDOC	15	0.23	0	4.37	NA	4.60	na
CAISO	4	0.59	0	na	NA	na	na
We Energies	4	1.12	0.09	0.69	NA	1.90	na
We Energies	29	1.02	0.15	1.75	NA	2.92	na
PacifiCorp	20	0	1.6	3.0	NA	4.6	na
Xcel-PSCo	10	0.20	0	2.26	1.26	3.72	na
Xcel-PSCo	15	0.20	0	3.32	1.45	4.97	na
GE-NYISO	10	na	na	na	NA	na	$350 million

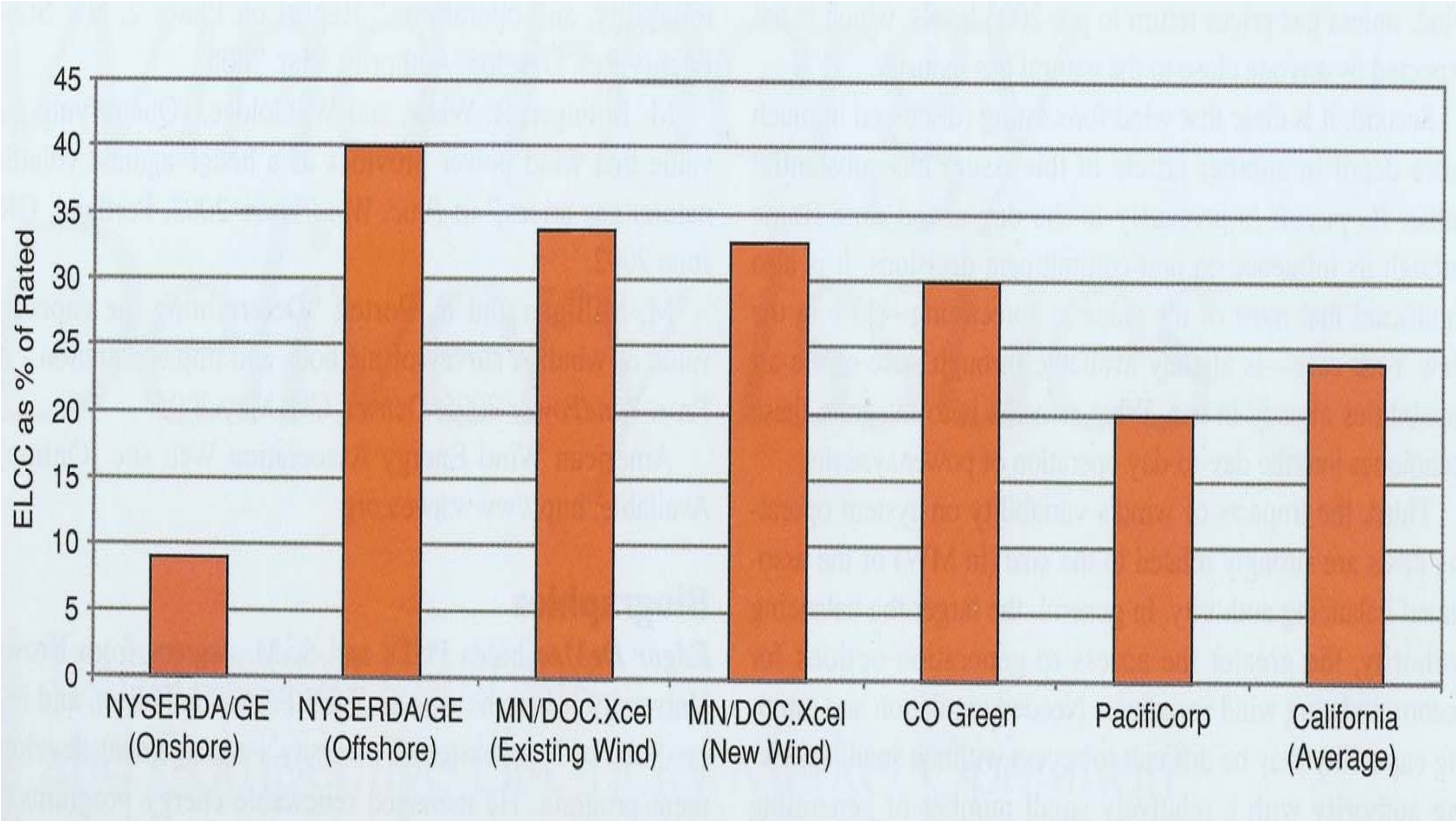
Capacity Value of Wind Plants

- ✓ The addition of a wind plant will generally decrease the statistical loss of load probability (LOLP)
- ✓ Some wholesale power markets include a capacity component with associated payments to generators
- ✓ ELCC (Effective Load-Carrying Capability): established measure for estimating capacity contributions for system-expansion and resource-adequacy planning

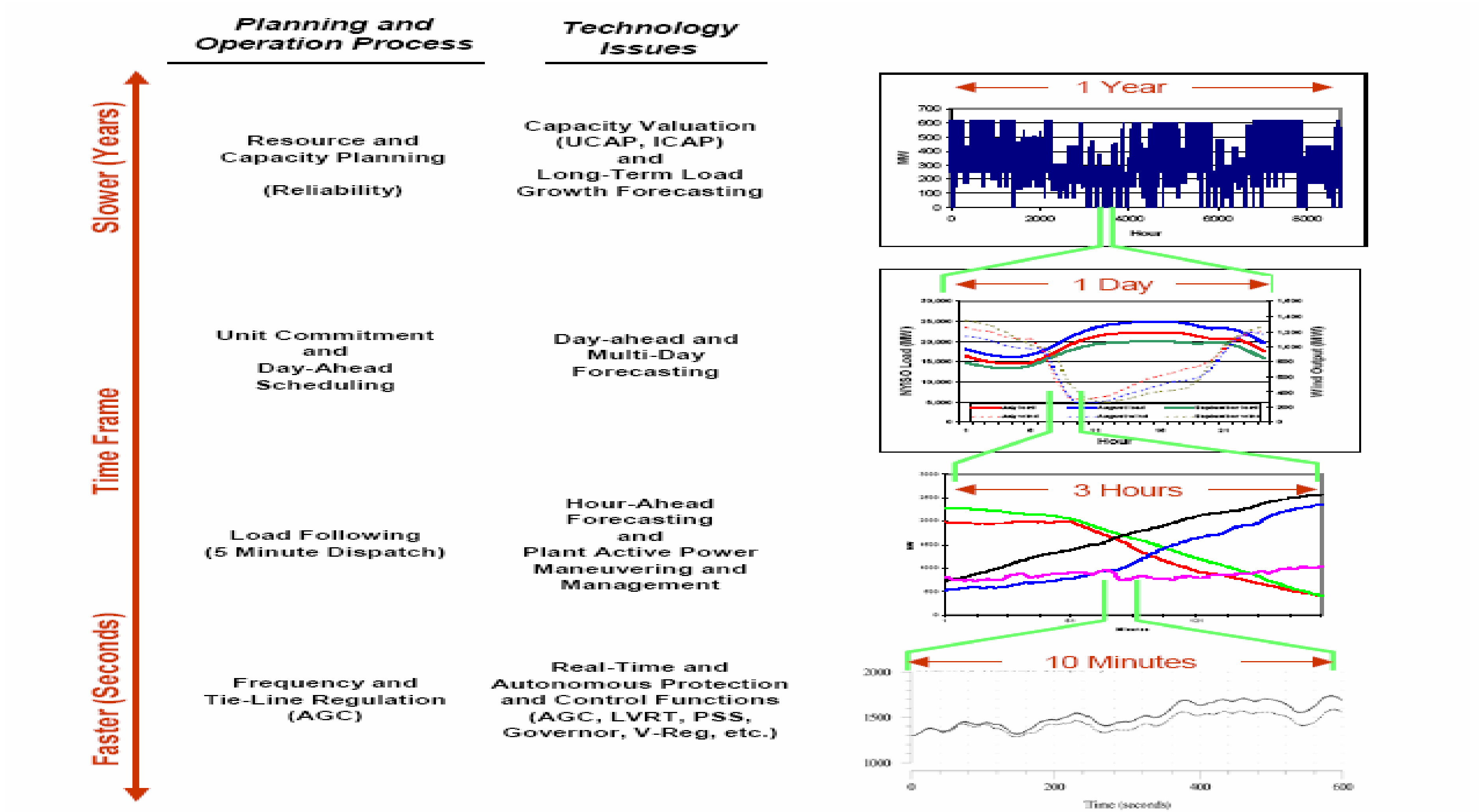
Effective Load-Carrying Capability (ELCC)

- ✓ Reliability-based method to calculate the capacity value of a generator
- ✓ Estimation of the equivalent capacity of a reference unit that would provide the same annual reliability level as the wind plant in question
- ✓ Need of hourly wind generation data and a reliability model of the system to be evaluated
- ✓ California: the range of 23%-25% of rated capacity
- ✓ Onshore capacity value in New York about 9%
- ✓ Offshore (Long Island) in New York: about 40%

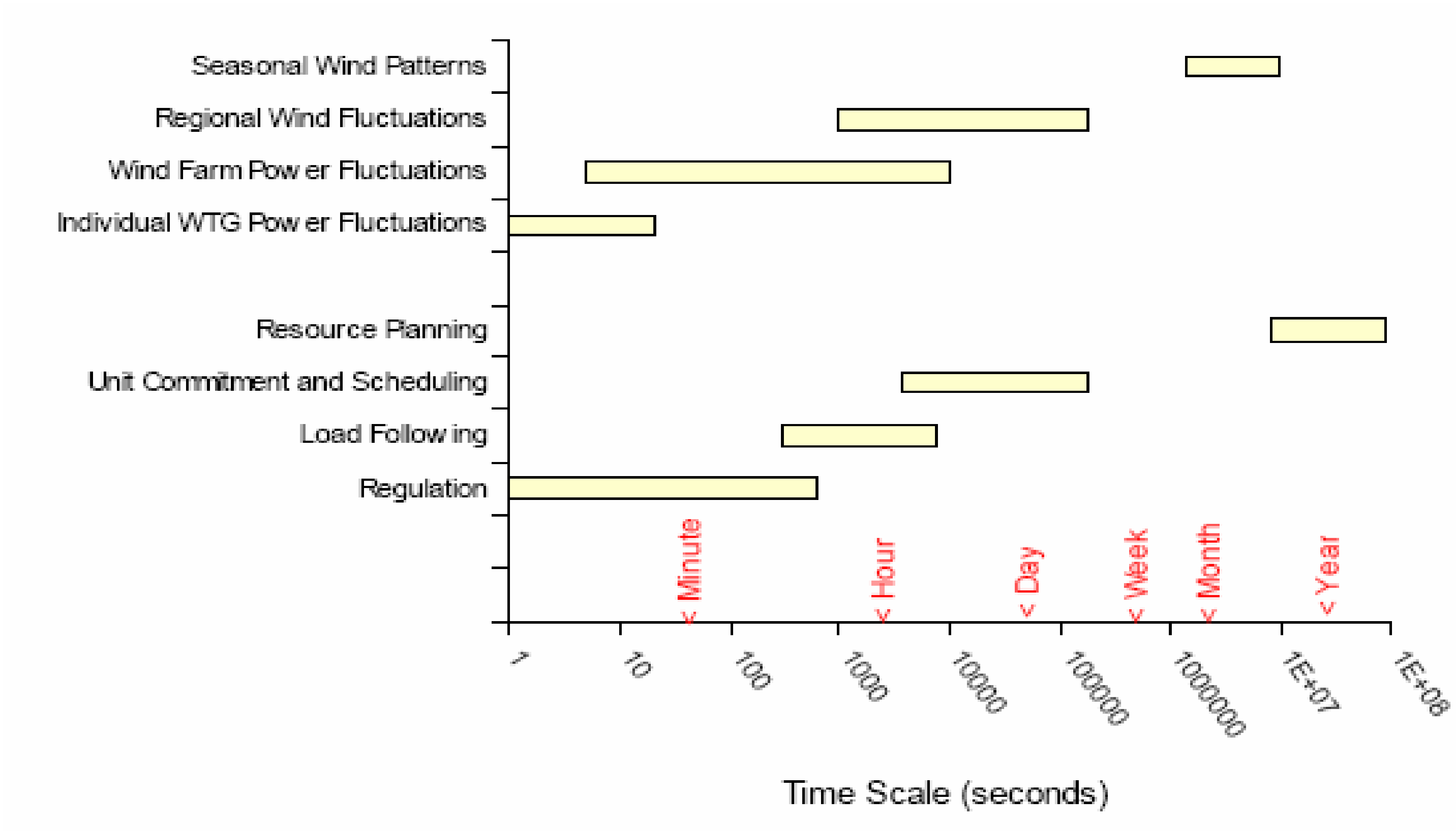
Effective load-carrying capabilities from several recent studies



Time scales for system planning and operation processes (NYISO)

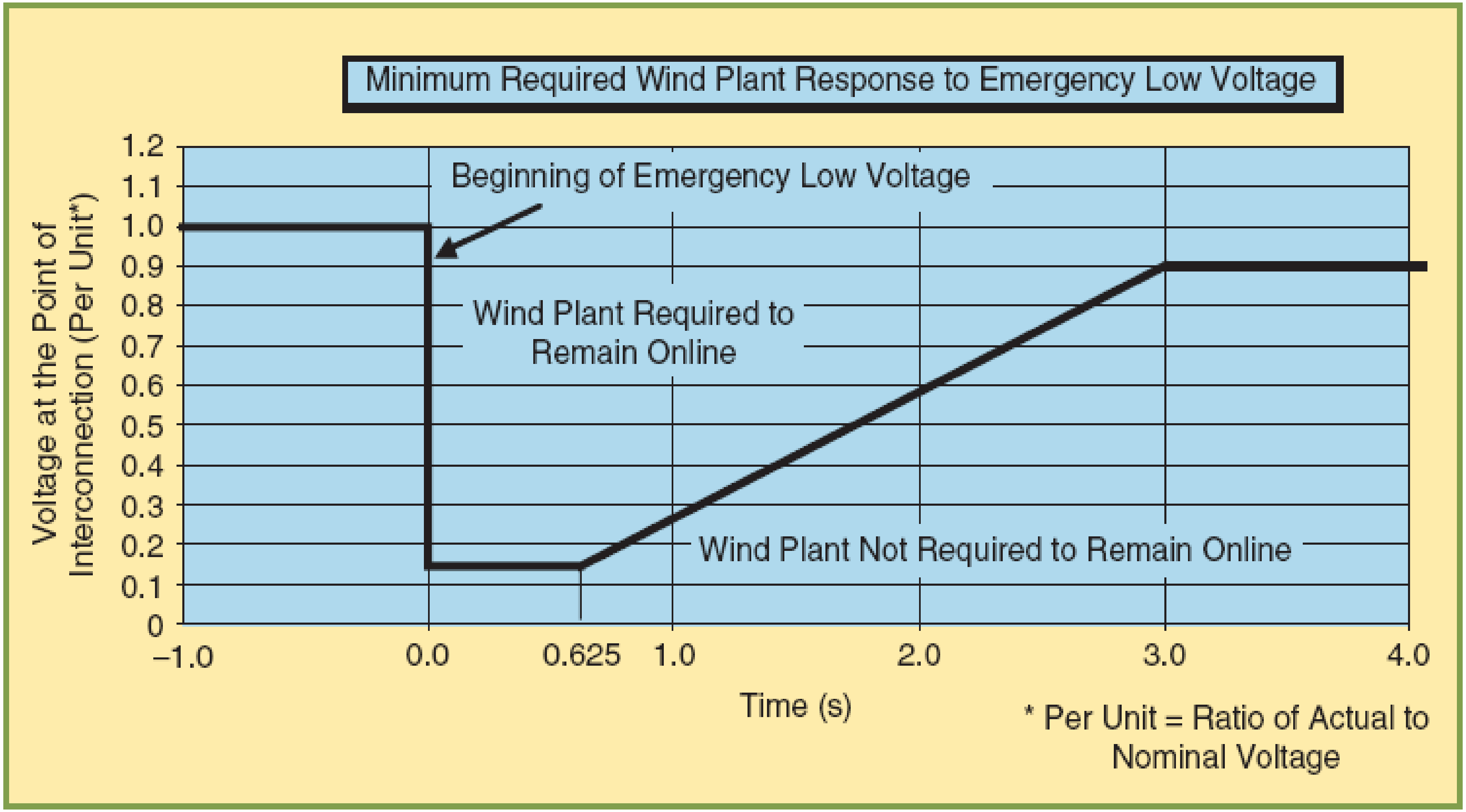


Wind variability and impact on system operation



Grid code for wind generation

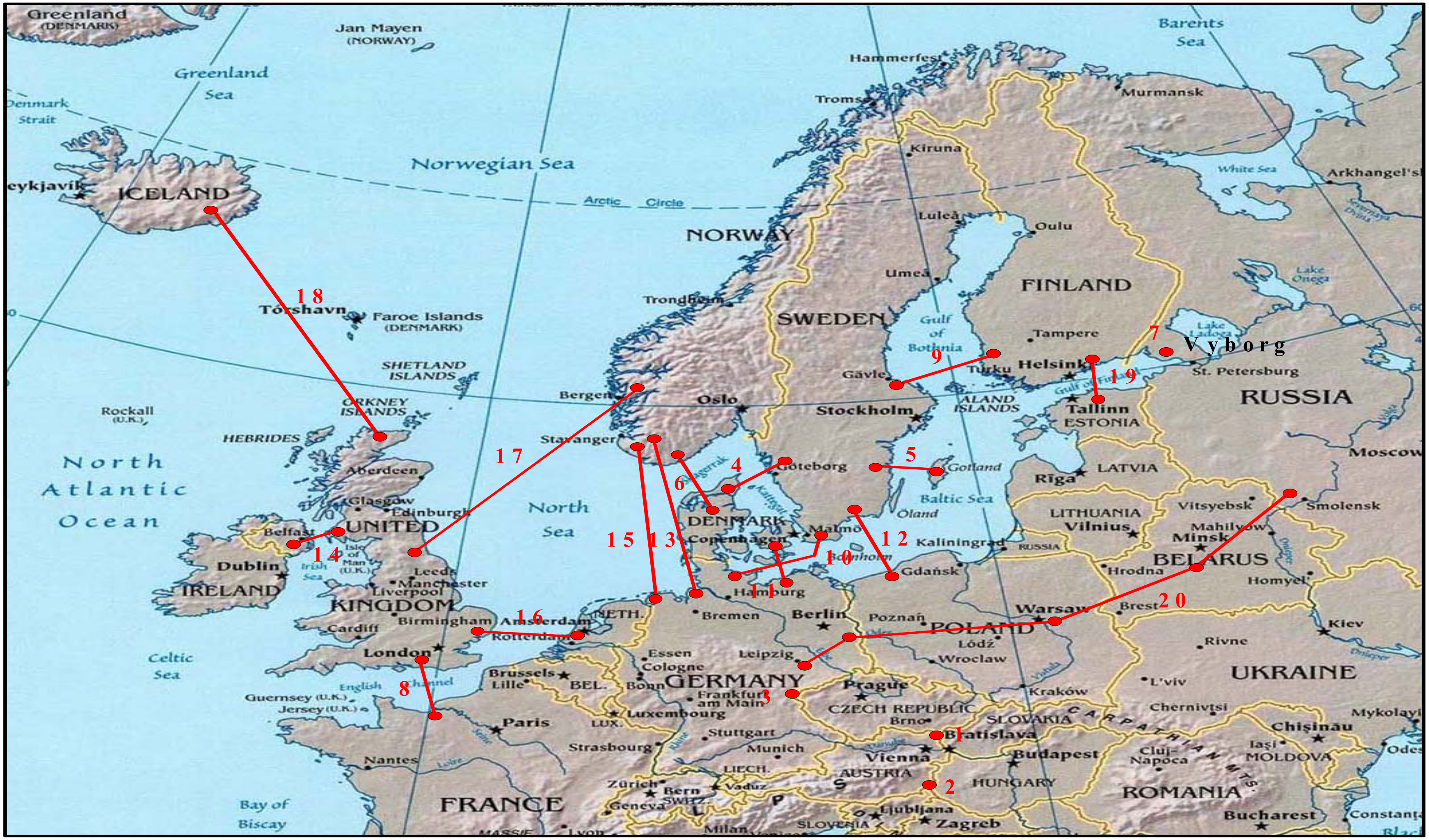
- ✓ **LVRT (Low Voltage Ride-Through) capability: the machines stay connected for voltages at the terminals as low as 15% of nominal per unit for approximately 0.625sec**


Minimum Required Wind Plant Response to Emergency Low Voltage
Beginning of Emergency Low Voltage
Wind Plant Required to Remain Online
Wind Plant Not Required to Remain Online
Voltage at the Point of Interconnection (Per Unit*)
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
–1.0
0.0
0.625
1.0
2.0
3.0
4.0
Time (s)
* Per Unit = Ratio of Actual to Nominal Voltage

PENNSTATE

- ✓ **Supervisory control and data acquisition (SCADA) equipment for remote control**
- ✓ **Reactive power capability: wind plants connected to the transmission system is capable of operating over a power factor (PF) range of lagging 0.95 - leading 0.95**

HVDC system in Europe and Gotland Island



Mainland ↔Gotland   about 90 kM

Gotland Island

Year 1954: LCC HVDC 15MW-> 30MW

Year 1983: 150MW NEW LCC HVDC replacement

→One way

Year 1999: 65 MW VSC type HVDC

Year 2002: Change to Bidirectional HVDC

Year 2003: Maximun load: 160 MW, minimum load: 40 MW
Gas turbine: Synchronous generator for backup

Year 1984: 3 MW wind power capacity

Year 1994: 15 MW wind power capacity

Year 2003: 90 MW wind power capacity

Planning to 300 MW

Map of Gotland Island

PENNSTATE

Wind power generation system in Gotland

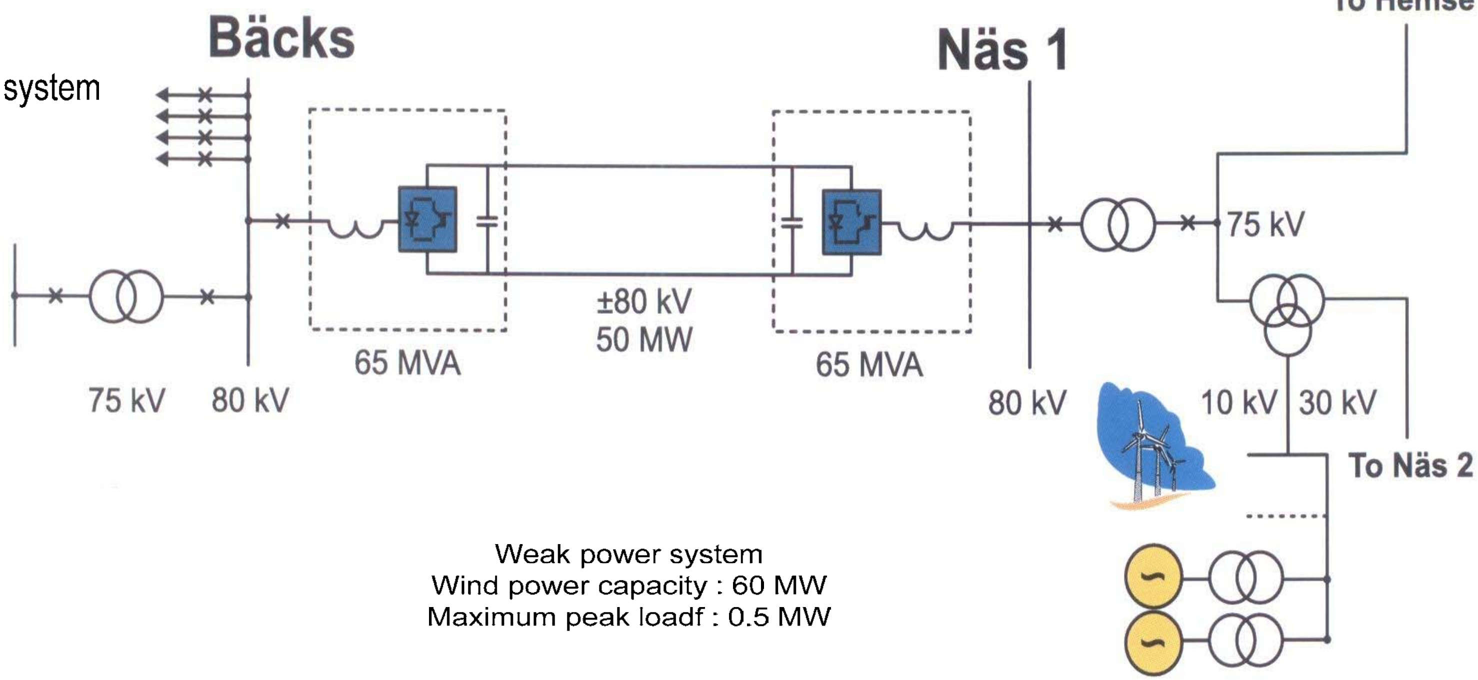
Windmill park at the southern tip of Gotland

PENNSTATE

HVDC and wind power system in Gotland

Nortth area of
Gotland

Strong power system



Weak power system
Wind power capacity : 60 MW
Maximum peak loadf : 0.5 MW

CRITICAL CLEARING TIME FOR NETWORK CONNECTED TO WIND GENERATION SYSTEM

CONCEPT OF CRITICAL CLEARING TIME

✓ **Swing equation:**

$$\frac{d^2\delta}{dt^2} = \frac{\omega_s}{2H}(Pm - Pe)$$

Where

ω_s **: Angular frequency**

t **: Time**

H **: Inertia constant of the rotating mass**

- ✓ **After fault clearing, the oscillation of the speed (and consequently the rotor angle) continues for a while, but eventually they settle to a new steady-state condition**
  → stable
- ✓ **The rotor angle continues to increase further and generator losses synchronism with the network**
  → unstable
- ✓ **Maximum rotor angle below which the synchronous generator can retain a stable operation**
  → critical clearing angle
- ✓ **Corresponding maximum clearing time**
  → critical clearing time (CCT)

✓ In case of induction generator

$$J\frac{d\omega}{dt} = Tm - Te$$

Where

J : Moment of inertia of the rotating mass

Tm : Mechanical torque applied on the rotor of the associated wind turbine

ω : Rotor speed

✓There is a maximum time for the fault to be cleared, otherwise, induction generators lose their stability

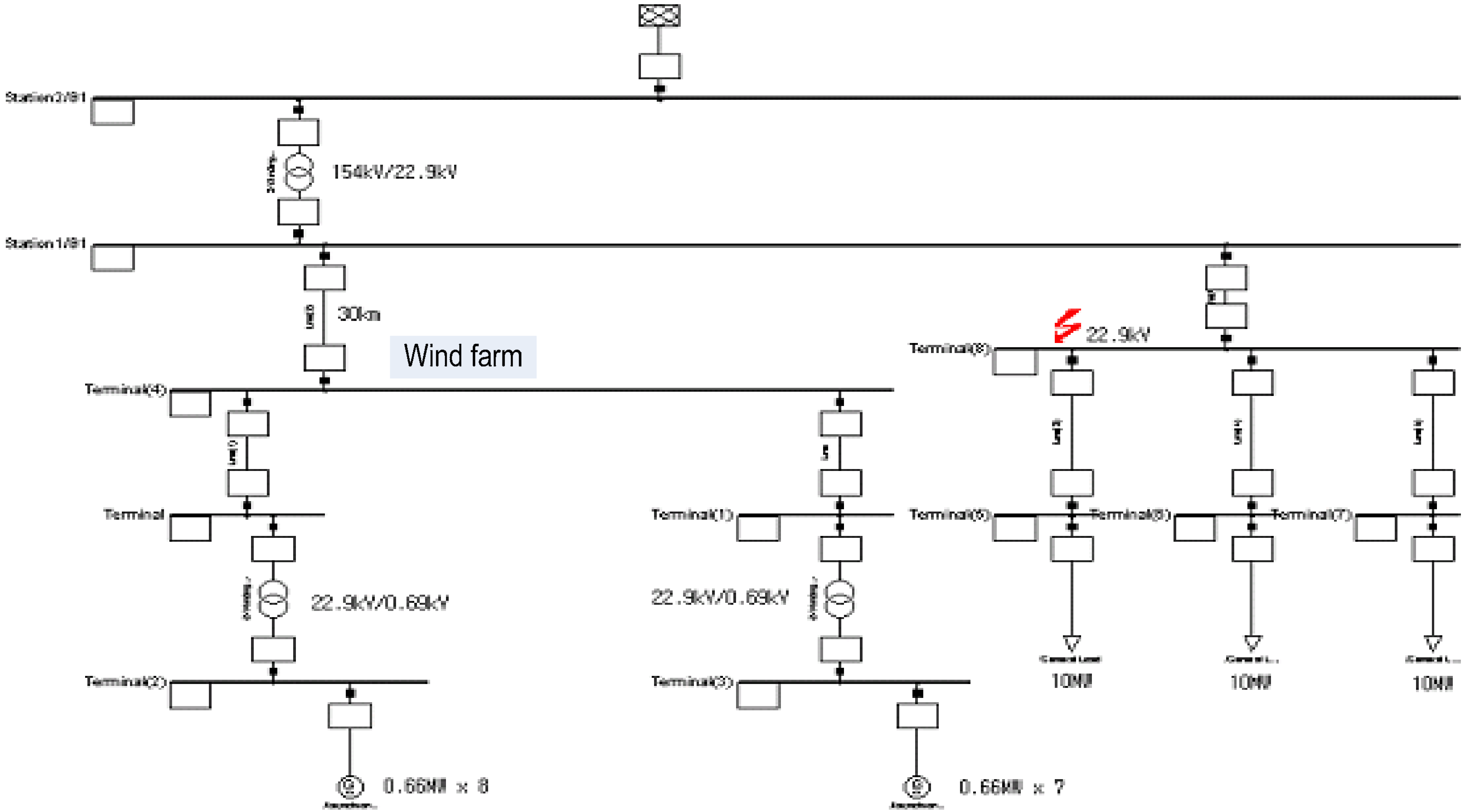
→ CCT for induction generator

INVESTIGATED CASES

- ✓ Distribution network with embedded generators
- ✓ Generators are integrated into the distribution network at 22kV voltage level through a 22kV interfacing link
- ✓ Wind farm is assumed to have fifteen wind turbine generator units, each of 660kW with a nominal voltage of 690V
- ✓ Investigation that examines the effect on the value of the CCT of a wind farm
- ✓ Factors such as load variation, power factor, wind generation capacity and length of the interfacing line
- ✓ Simulation with Digsilent Power Factory program

PENNSTATE

Schematic diagram of the investigated network



PENNSTATE

Network data for simulation

Generator capacity (pf)	Length of the interfacing line	Load capacity (pf)
660[kW](0.9) $\times$ 15	ACSR (160[mm2]) 30[km] $R = 0.2024[\Omega / km]$ $X = 0.3891[\Omega / km]$	30[MW](0.9)

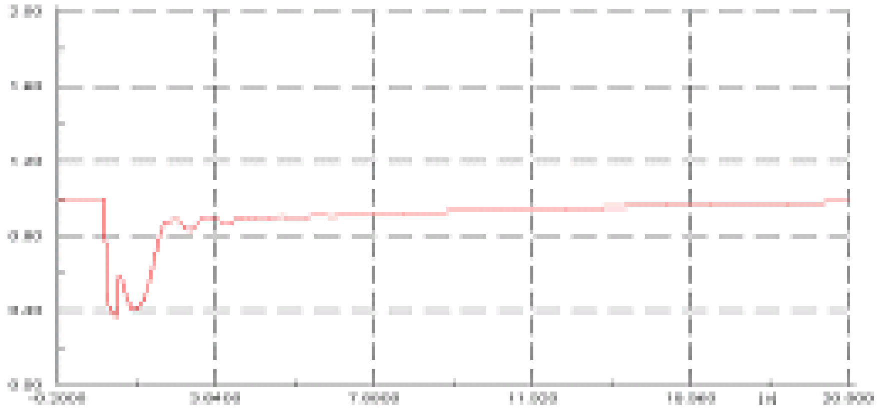
Comparison of CCT for synchronous and asynchronous (induction) generator

- ✓ **Three phase fault is assumed on load terminal (22kV bus)**
- ✓ **In case of synchronous generator, fault durations are assumed as 306ms and 307ms**

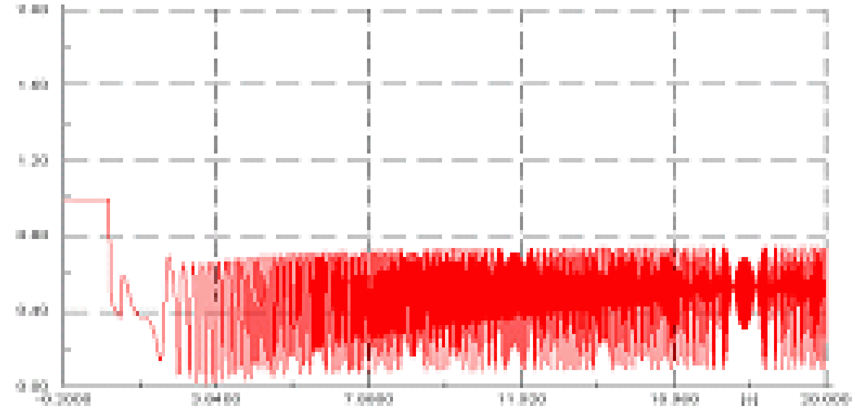
  → CCT is 306ms
- ✓ **For embedded induction generator following a three-phase fault with durations of 90ms and 91ms**

  → CCT is 90ms

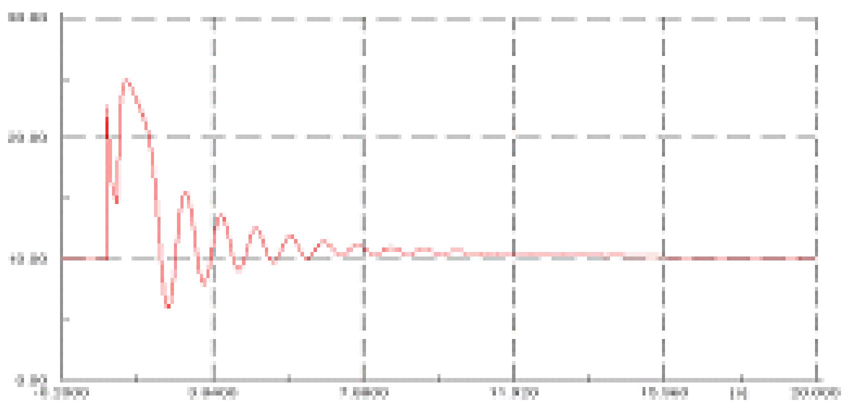
wind farm bus voltage (306ms)



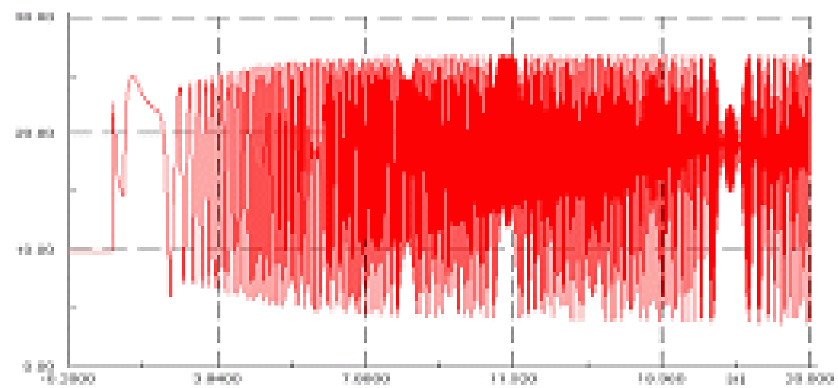
wind farm bus voltage (307ms)



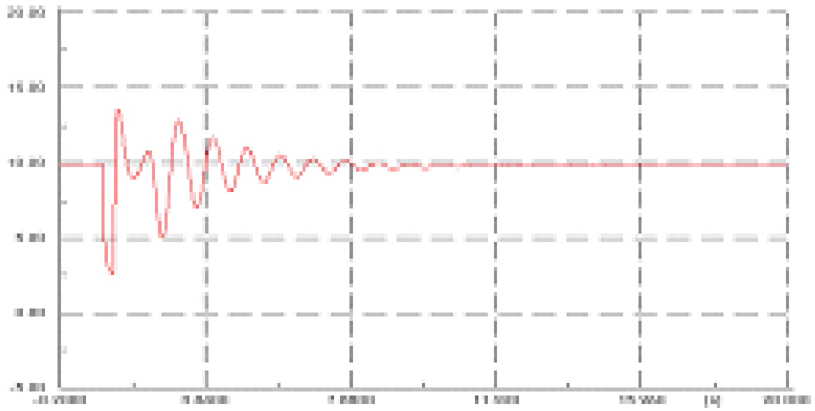
wind farm bus current (306ms)



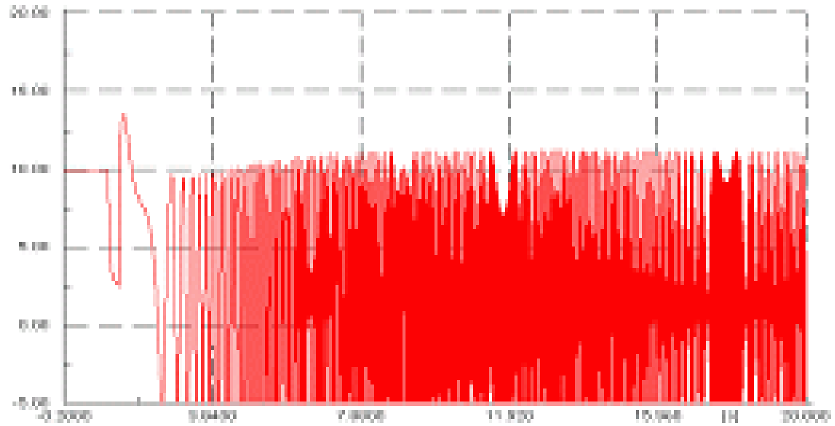
wind farm bus current (307ms)



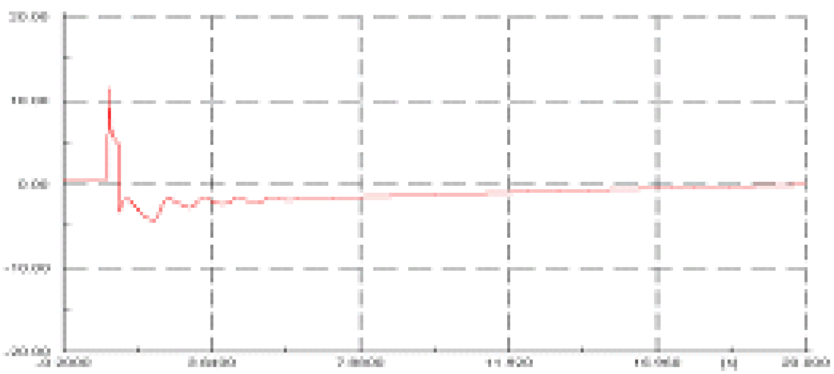
wind farm active power (306ms)



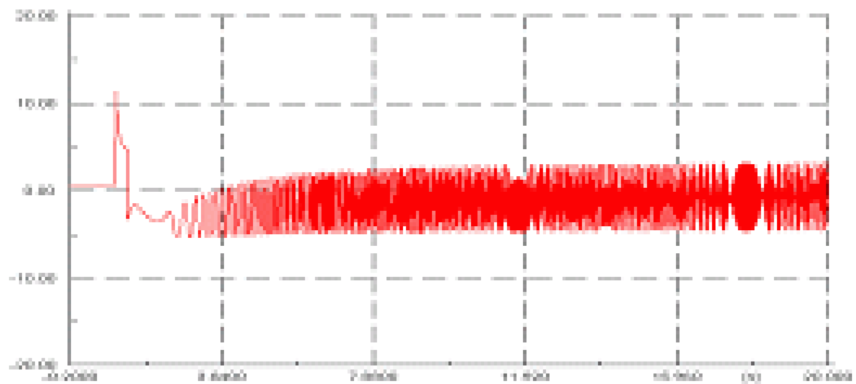
wind farm active power (307ms)



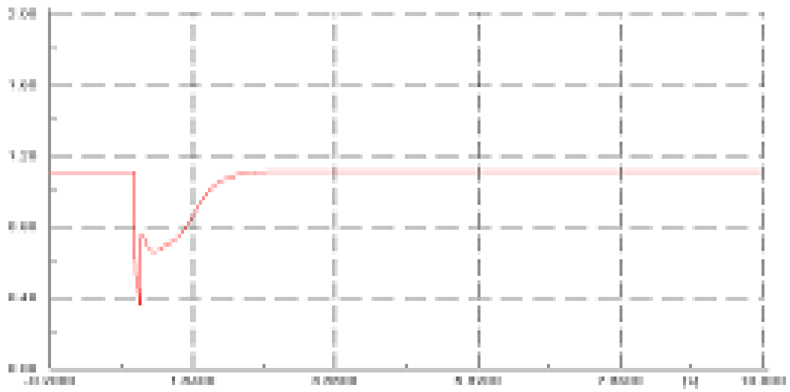
wind farm reactive power (306ms)



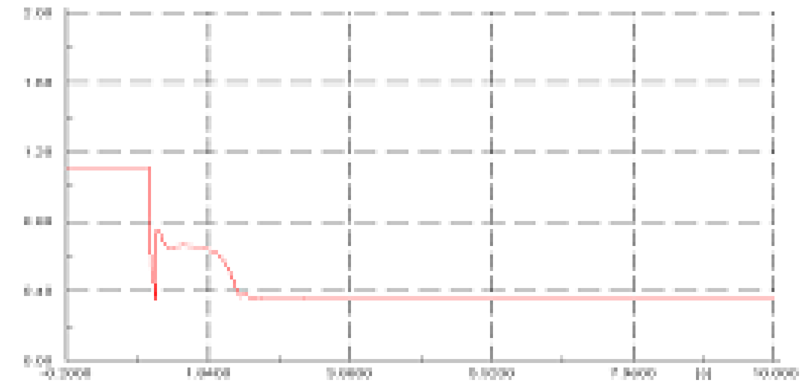
wind farm reactive power (307ms)



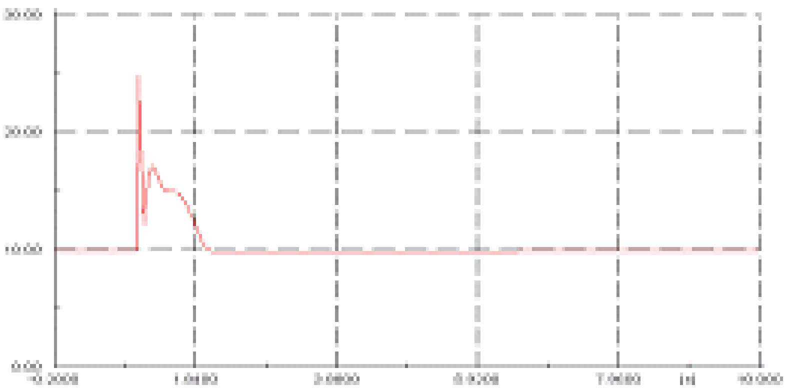
wind farm bus voltage (90ms)



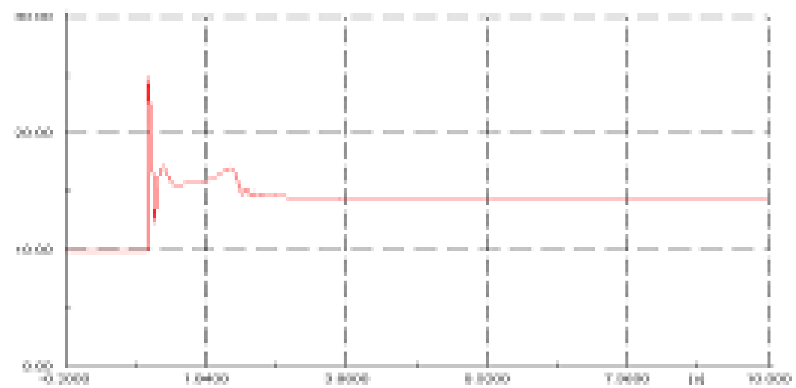
wind farm bus voltage (91ms)



wind farm bus current (90ms)

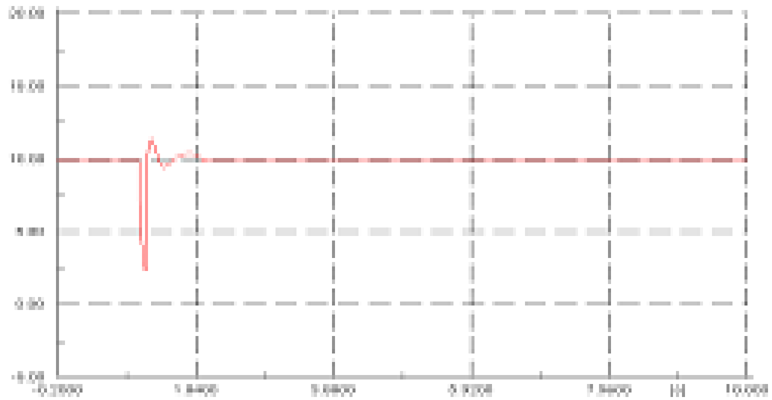


wind farm bus current (91ms)

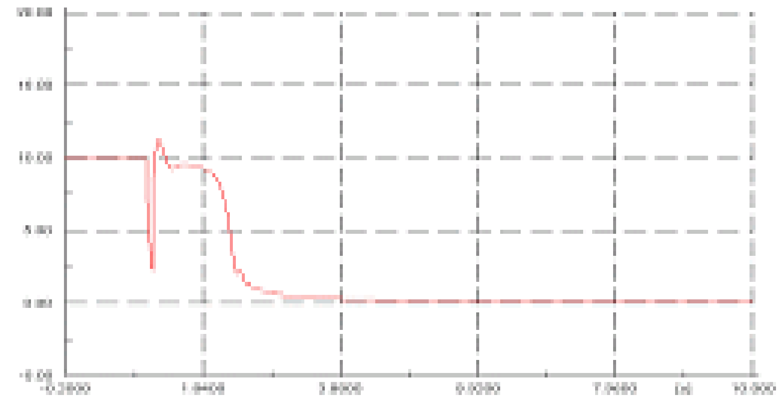


PENNSTATE

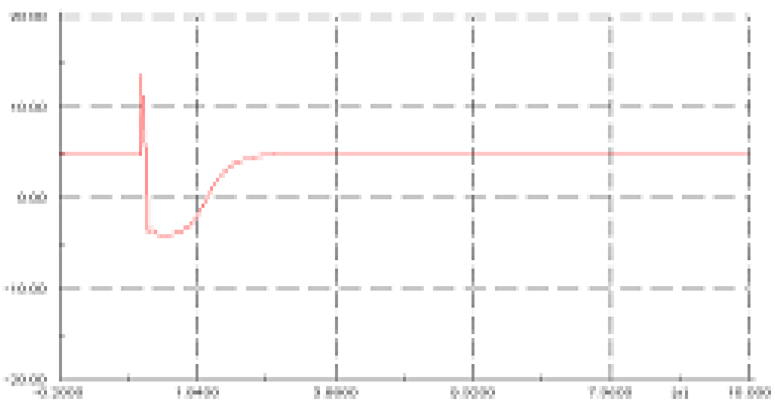
wind farm active power (90ms)



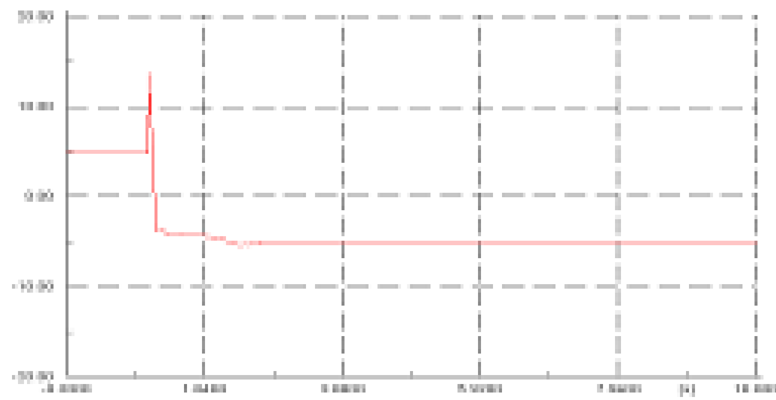
wind farm active power (91ms)



wind farm reactive power (90ms)



wind farm reactive power (91ms)

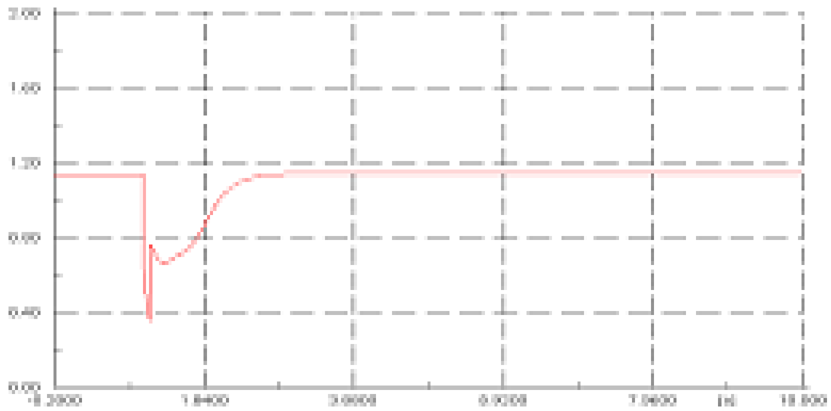


Effect on CCT according to load variation

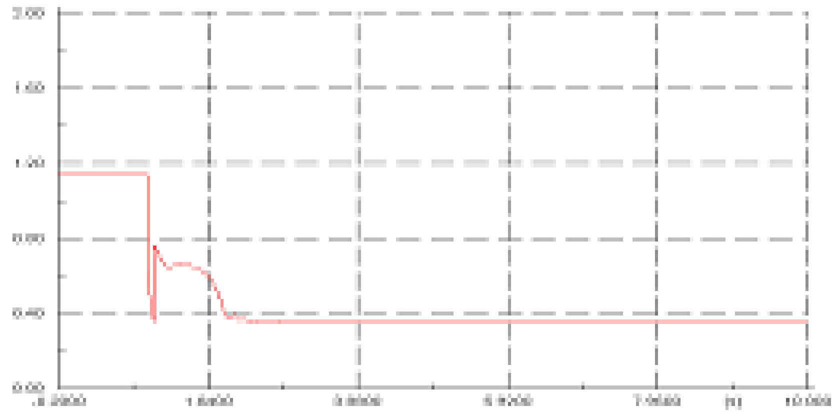
- ✓ Load variation to 20MW, 30MW and 40MW
- ✓ By increasing load from 20MW to 40MW, the CCT value decreases from 92ms to 86ms.
- ✓ Effect of load variation on wind farm CCT

Load (MW)	Wind farm CCT (ms)
20	92
30	90
40	86

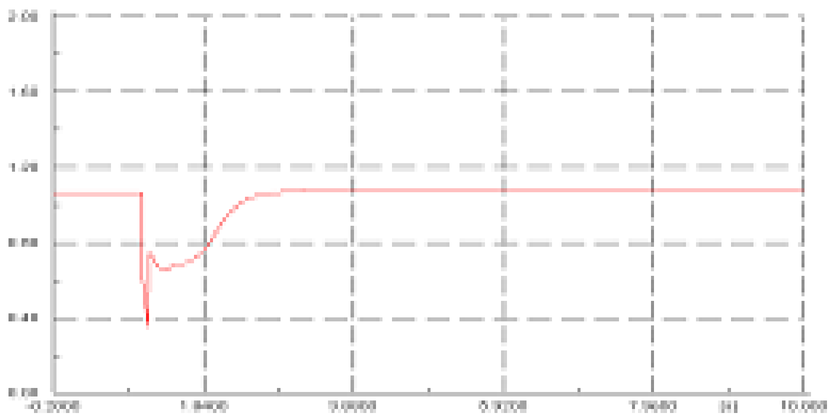
wind farm bus voltage (92ms, 20MW load)



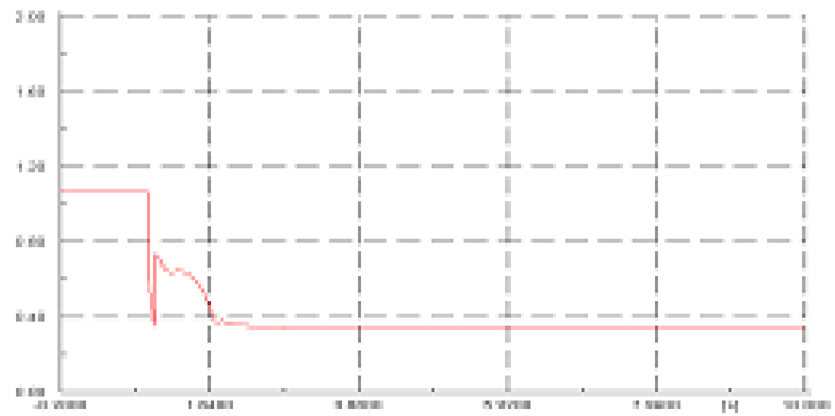
wind farm bus voltage (93ms, 20MW load)



wind farm bus voltage (86ms, 40MW load)



wind farm bus voltage (87ms, 40MW load)



Effect on CCT according to power factor

- ✓ By increasing load power factor from 0.8 to 1.0, the CCT value increases from 81ms to 105ms
- ✓ Effect of load power factor on wind farm CCT

Load pf	Wind farm CCT (ms)
0.8	81
0.85	85
0.9	90
0.95	96
1.0	105

Effect on CCT according to wind generation power

- ✓ By increasing wind generation power from 11MW to 14MW, the CCT value decreases from 90ms to 42ms
- ✓ Effect of wind generation power on wind farm CCT

Wind generation power (MW)	Wind farm CCT (ms)
10	90
11	76
12	65
13	51
14	42

Effect on CCT according to length of interfacing line

- ✓ By increasing length of interfacing line from 0km to 30km, the CCT value decreases from 380ms to 10ms
- ✓ Effect of length of interfacing line on wind farm CCT

Length of the line [km]	Wind farm CCT [ms]
0	380
1	350
5	250
10	165
15	105
20	65
25	35
30	10

Conclusions

- ✓ The presence of embedded generator greatly affects the CCT of wind farm
- ✓ CCT of embedded synchronous generator is much higher than that of embedded induction generator
- ✓ The transient stability of a wind farm is affected by the type of embedded generator, load variation, power factor, wind generation power and the length of interfacing line


Thank you
Kwang Y. Lee
Professor of Electrical and Computer Engineering
Baylor University
Kwang_Y_Lee@baylor.edu