Inertial control of a DFIG based WPP considering the kinetic energy of the wind generators

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Wind energy Grid-Adaptive Technology Research Center

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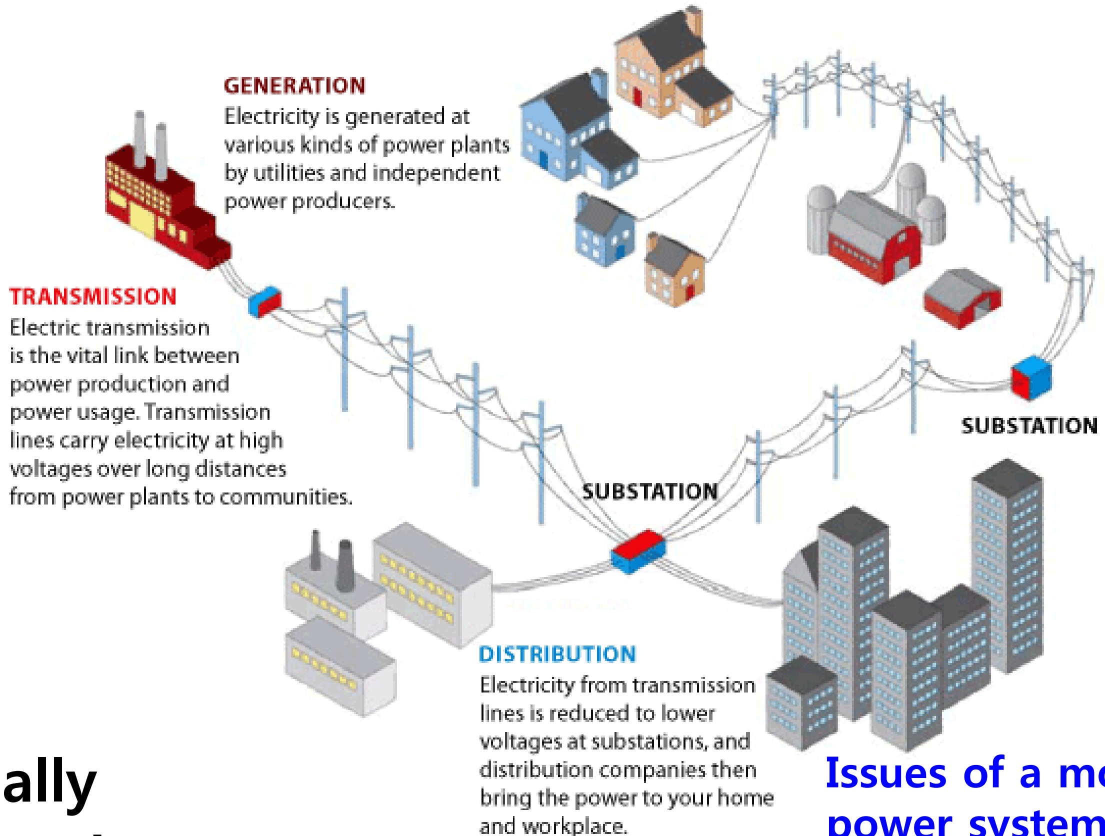
Power system or power grid



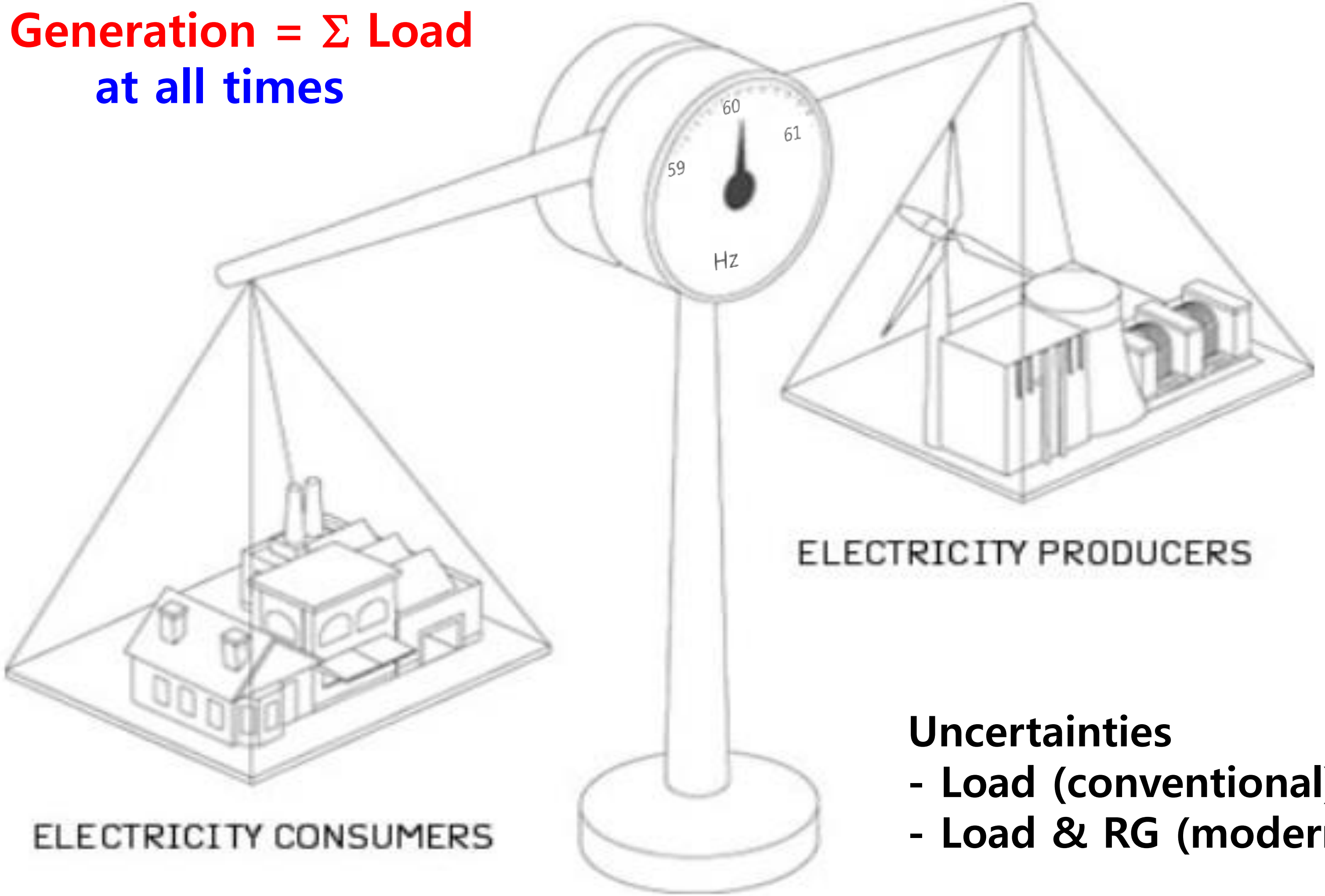
Reciprocally Interdependent system

Issues of a modern power system

- Reliable power
- Affordable power
- Renewable power

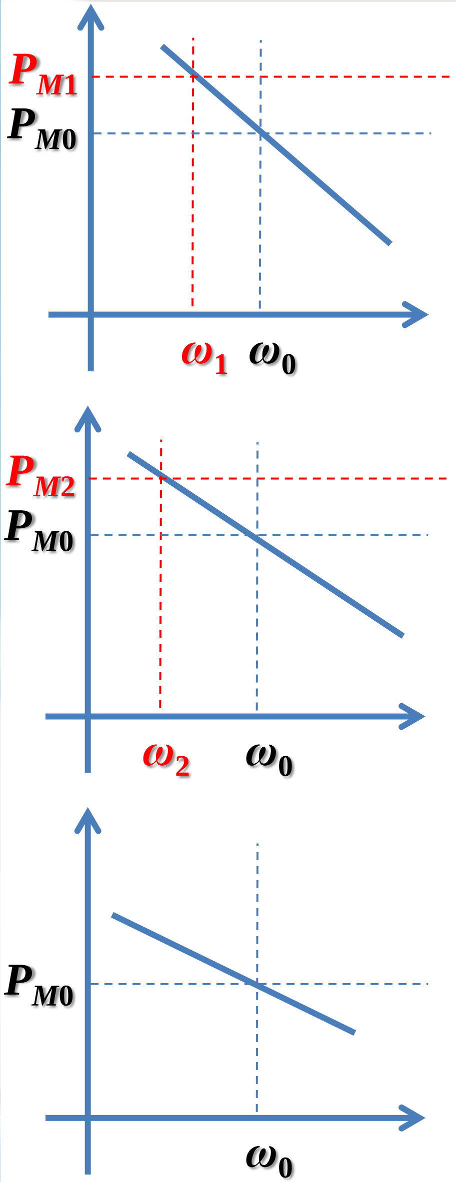
Operation of a power system: Balance between generation and consumption

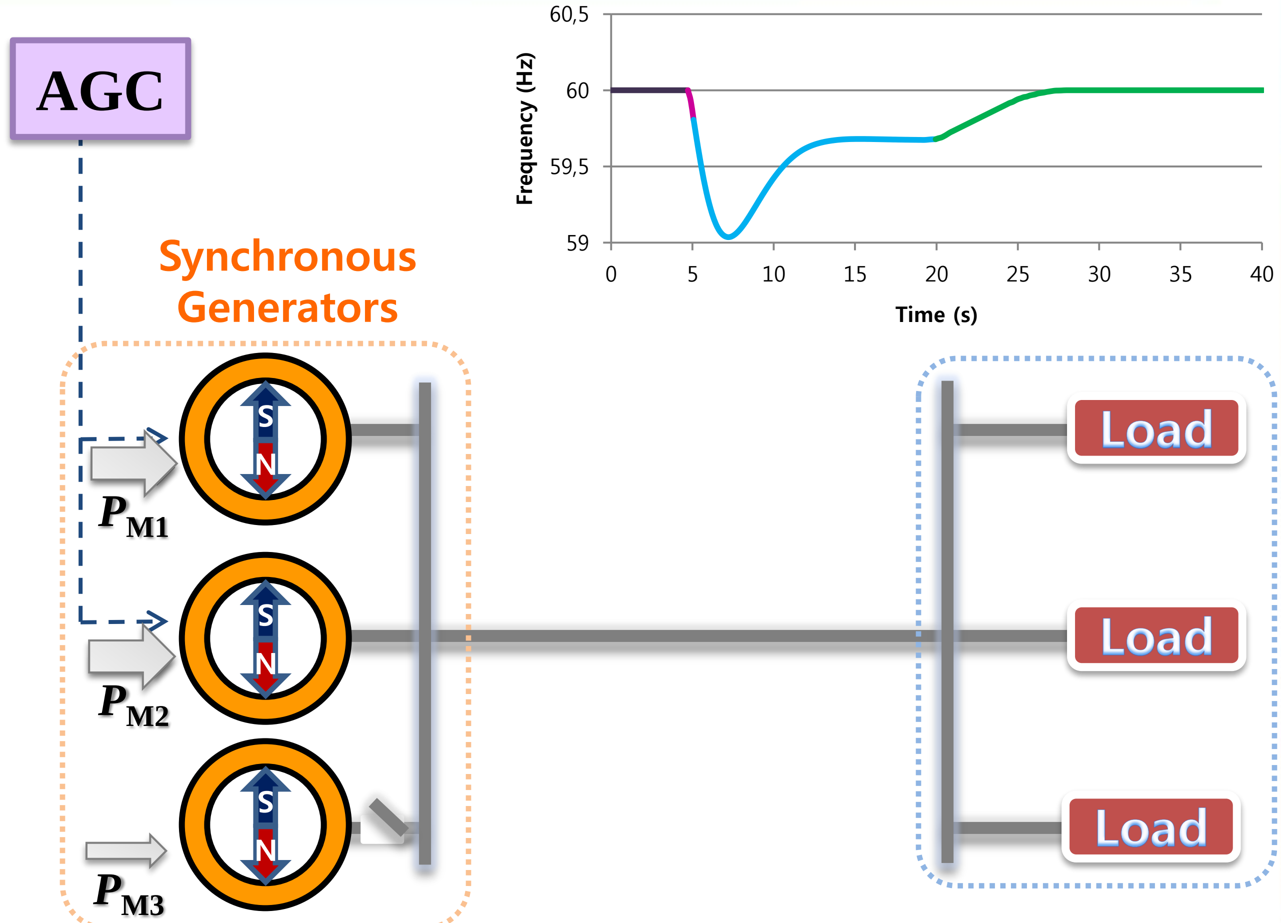
Σ Generation = Σ Load
at all times



Uncertainties
- **Load (conventional)**
- **Load & RG (modern)**

Synchronously operating power system





Inertial response: Gen trip → Decrease in Freq of each Gen

Primary control: Increase in P_M based on droop of each Gen

Secondary control: **AGC** from system opertor

Statistics of the Korean power system

World ranks of installed capacity & wind generation (GW)

Ranks	Country	GDP Ranks	Capacity	Wind Generation	Ranks	Country	GDP Ranks	Capacity	Wind Generation
1	USA	1	1,025	60.0 (2)	8	France	5	119	7.6 (8)
2	China	2	878	75.3 (1)	9	Brazil	7	106	2.5 (15)
3	Japan	3	285	2.6 (13)	10	Italy	9	101	8.1 (7)
4	Russia	8	225		11	Spain	13	96	22.8 (4)
5	India	11	189	18.4 (5)	12	UK	6	88	8.3 (6)
6	Germany	4	147	31.3 (3)	13	Korea	15	81	0.5 (27)
7	Canada	10	132	6.2 (9)	14	Mexico	14	59	1.2 (22)

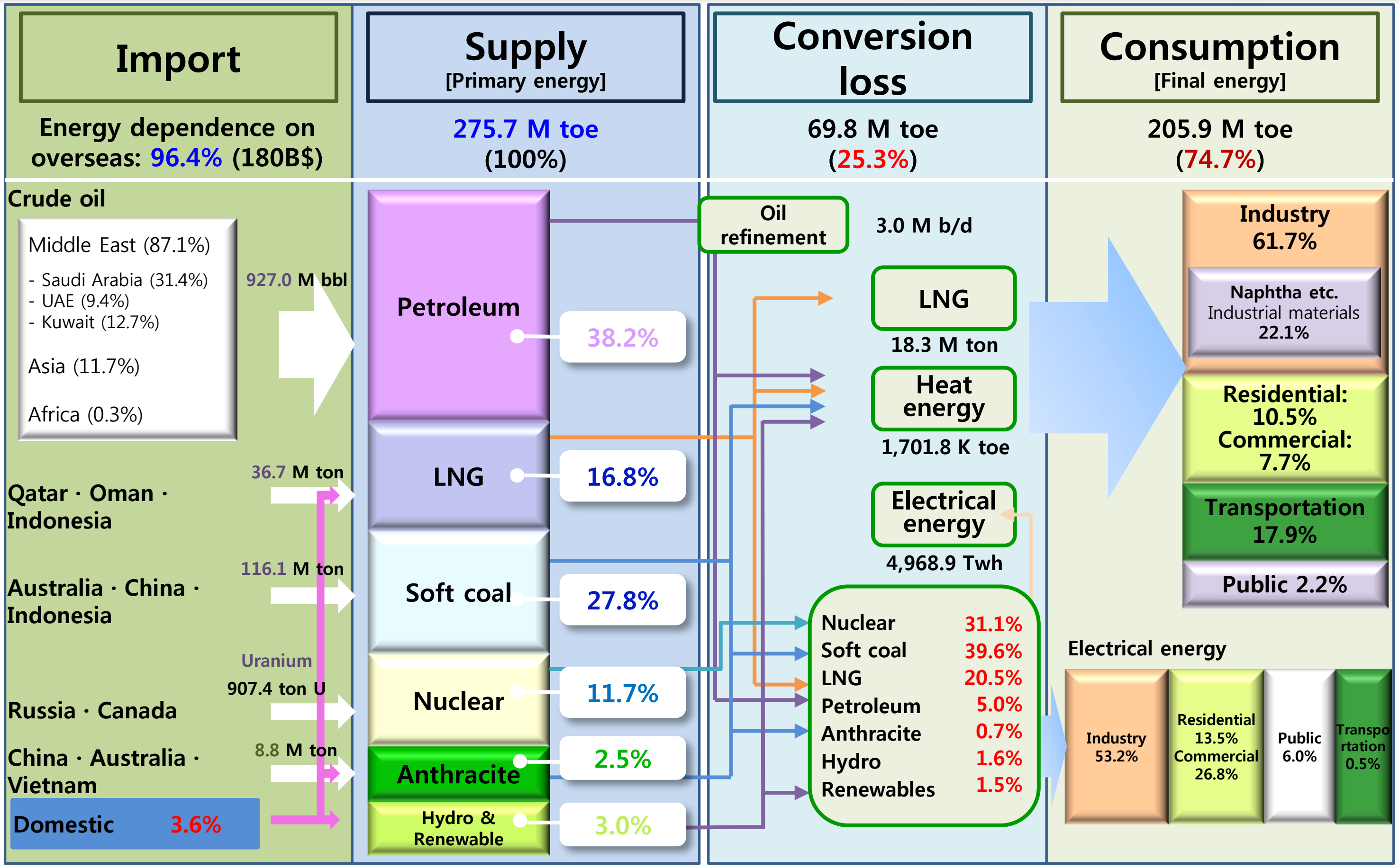
Source: CIA the world Factbook 2012, USA

World ranks of electricity consumption (TWh) & wind energy penetration

Ranks	Country	GDP Ranks	Consumption	WEP(%)	Ranks	Country	GDP Ranks	Consumption	WEP(%)
1	China	2	4,693	2.0	6	Germany	4	510	7.7
2	USA	1	3,889	3.5	7	Canada	10	505	2.8
3	Japan	3	860	0.5	8	Korea	15	455	0.2
4	Russia	8	808		9	France	5	451	
5	India	11	638		10	Brazil	7	438	

Source: CIA the world Factbook 2012, USA

Korea's energy balance flow in 2011



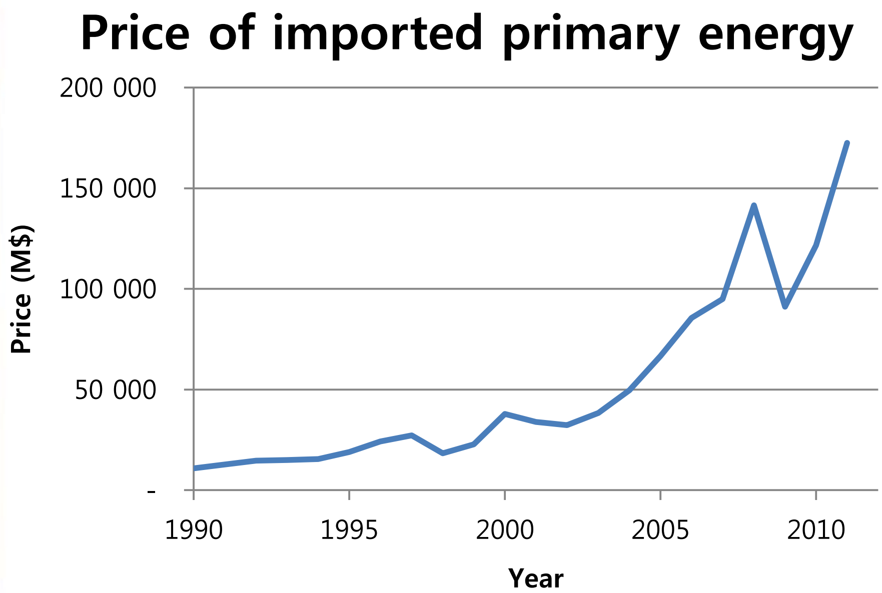
Source: MKE, Korea

Every Korean
Income: 60$/day
Energy: 10$/day

Electrical energy: main cause of conversion loss

- 60B$: 33% of imported primary energy price
- 100 Mtoe: 36% of total primary energy

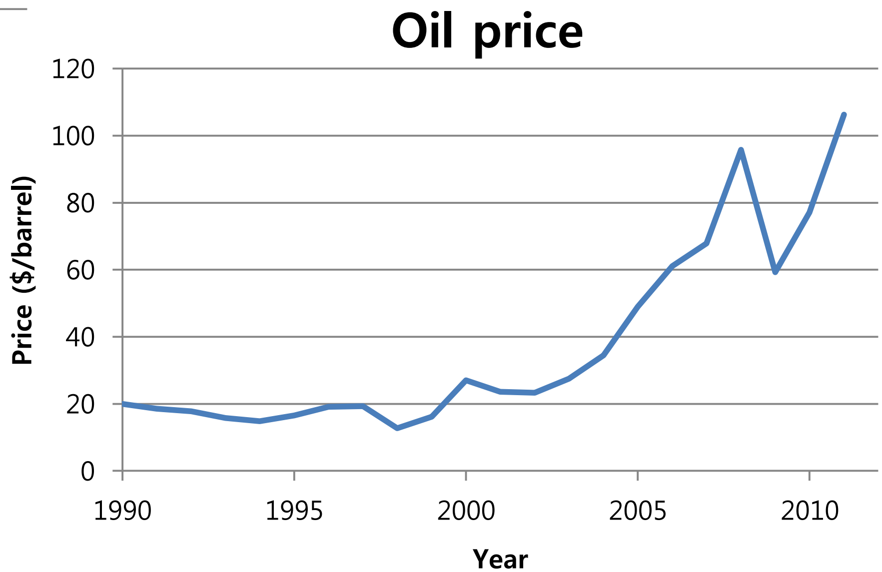
Energy security in Korea



2010 → 2011

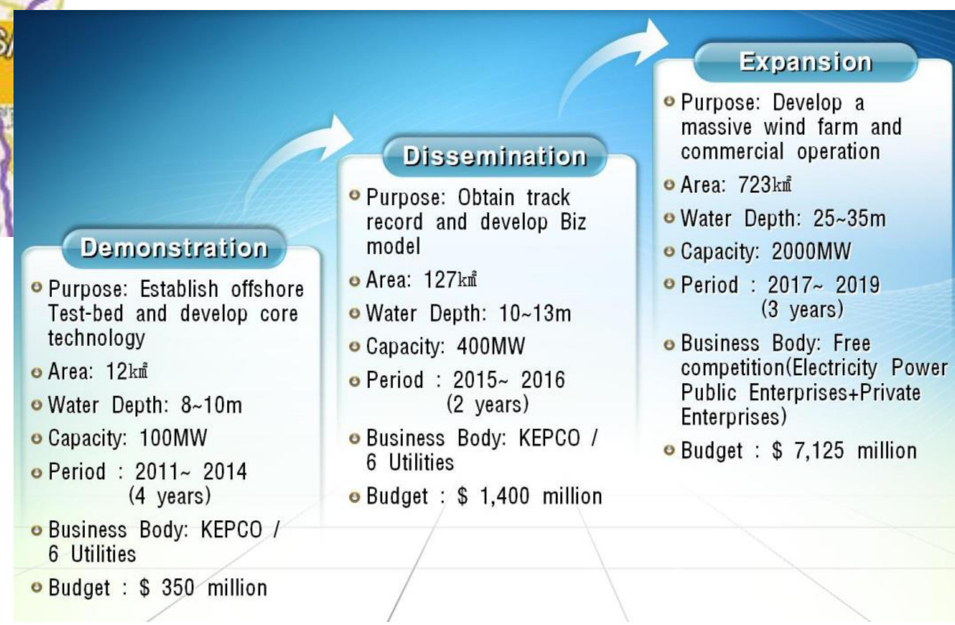
- **Imported primary energy: 3% ↑**
- **Price: 50% ↑ (120B$ → 180B$)**

Average oil price for the last 5 years:
4+ times than before 20C



Source: MKE, energy statistics 2012

2.5 GW Korea's ongoing offshore WPP project



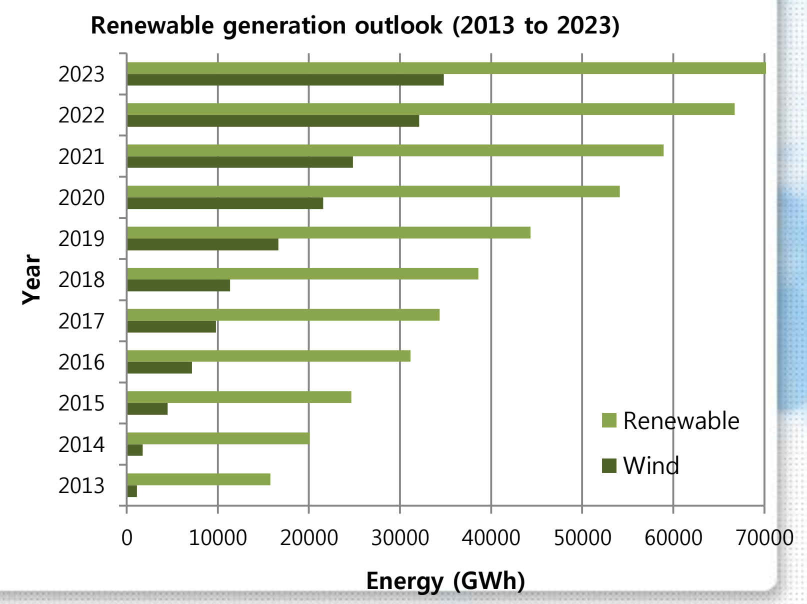
Korea's policy on renewable energy

Introduction of Renewable Portfolio Standard (RPS)

Year	'12	'13	'14	'15	'16	'17	'18	'19	'20	'21	'22
Share (%)	2.0	2.5	3.0	3.5	4.0	5.0	6.0	7.0	8.0	9.0	10.0

2020 Targets for RE and WE of Korea

- In 2010: RE (5.9TWh, 1.3% of EE), WE (13% of RE)
- By 2020:
  - RE (54TWh): 8.6% of EE (631TWh)
  - WE (22TWh): 40% of RE, 3.4% of EE
  - 10GW of WG



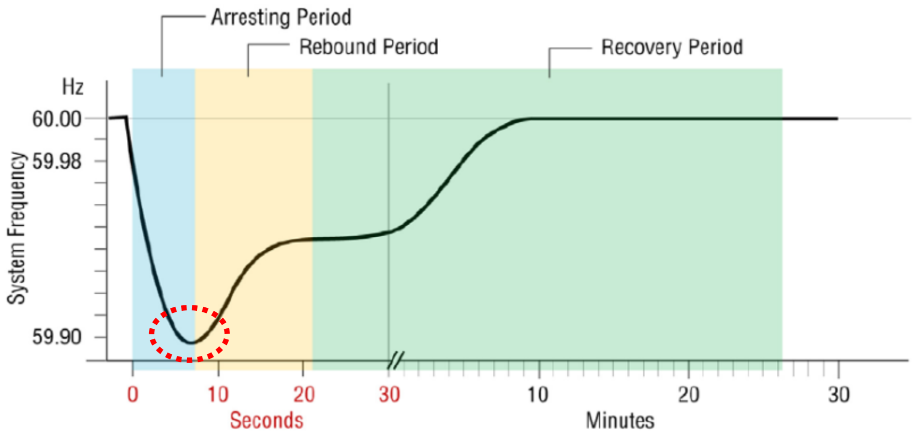
Source: The 6th basic plan of electricity supply, MKE, Korea

Frequency control of a power system

Frequency control

- Recovers the reduced frequency to the nominal value when a disturbance occurs

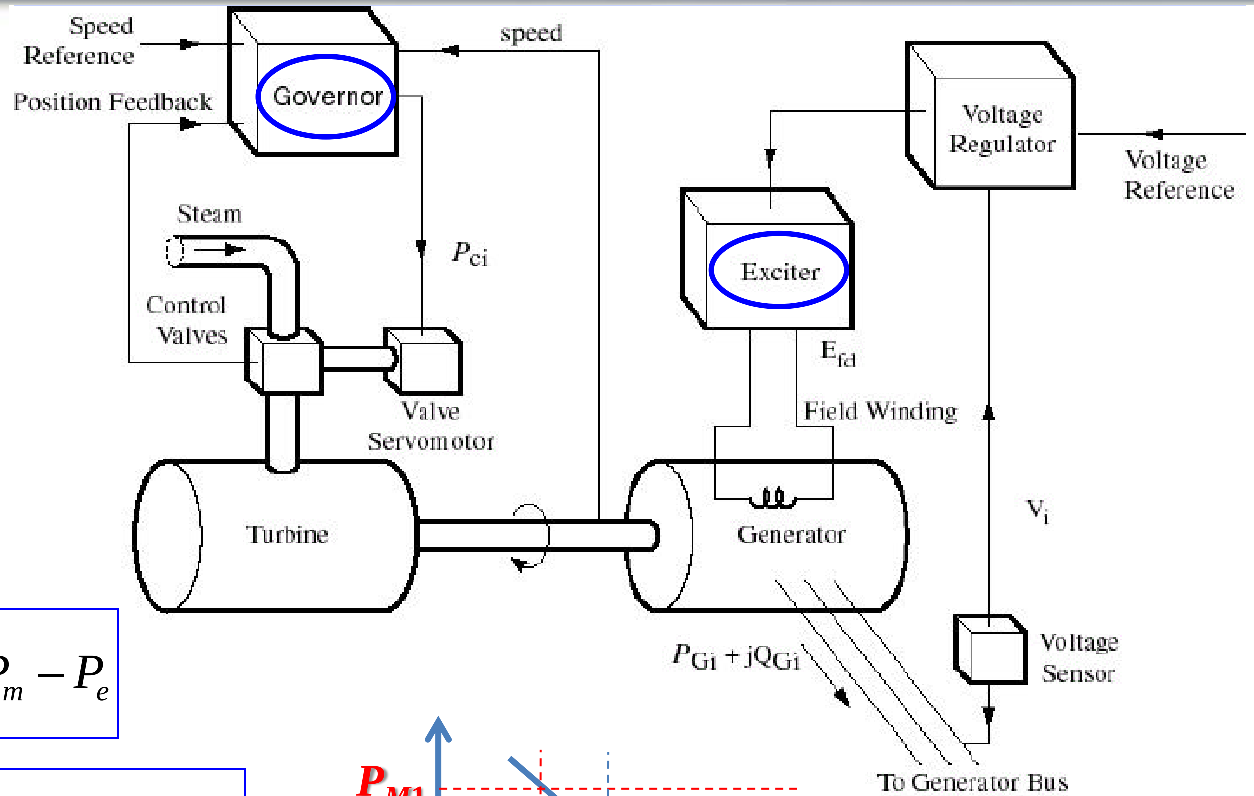
	Time frame	Features
Inertial response	2–3 sec.	Naturally releasing the kinetic energy, Uncontrollable
Governor response (Primary response)	10–60 sec.	Droop control using the spinning reserve
AGC response (Secondary response)	1–10 min.	Re-dispatching from the SO



Frequency nadir

- **Criteria for the system reliability**
- **Under Frequency Load Shedding: sheds 6% of load in every 0.2 Hz from 59.0 Hz**
- **Disconnection of SGs (from 58.5~57.5Hz)**

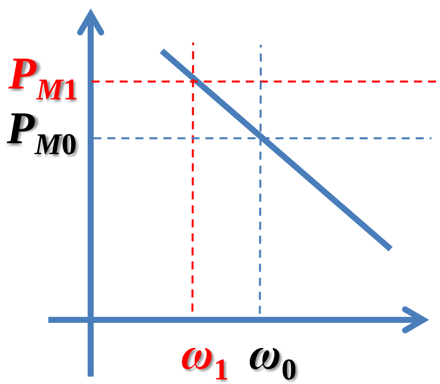
Primary control of a synchronous generator



$$J\omega\frac{d\omega}{dt} = P_m - P_e$$

$$P_m = -\frac{1}{R}(\omega - \omega_0) + P_m^0$$

$$\frac{P_m - P_m^0}{\omega - \omega_0} = -\frac{1}{R}$$

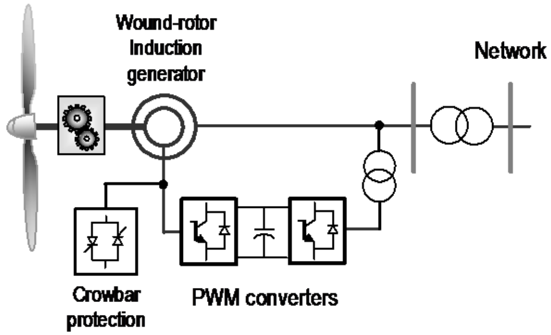


Smaller R → Larger ΔP

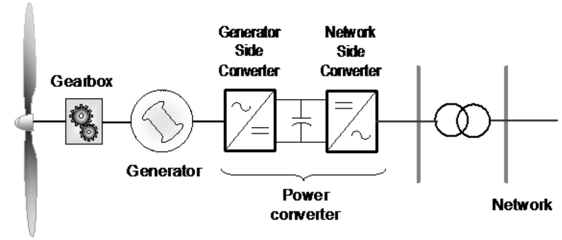
Variable speed wind generator (WG)

- **Configuration of variable speed WG**

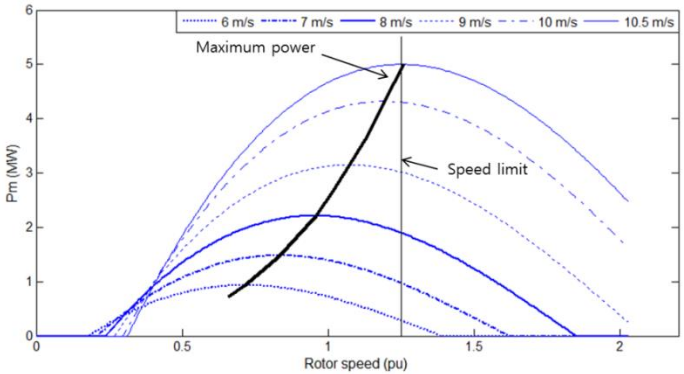
Doubly fed induction generator (DFIG)



Fully-rated converter WG (FRC)

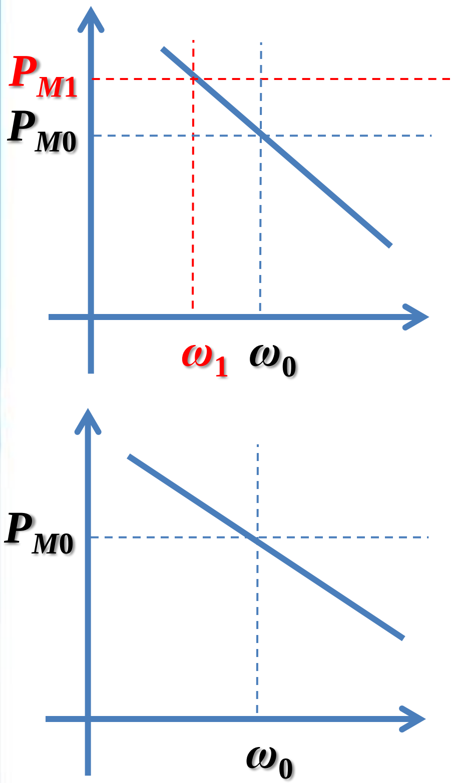


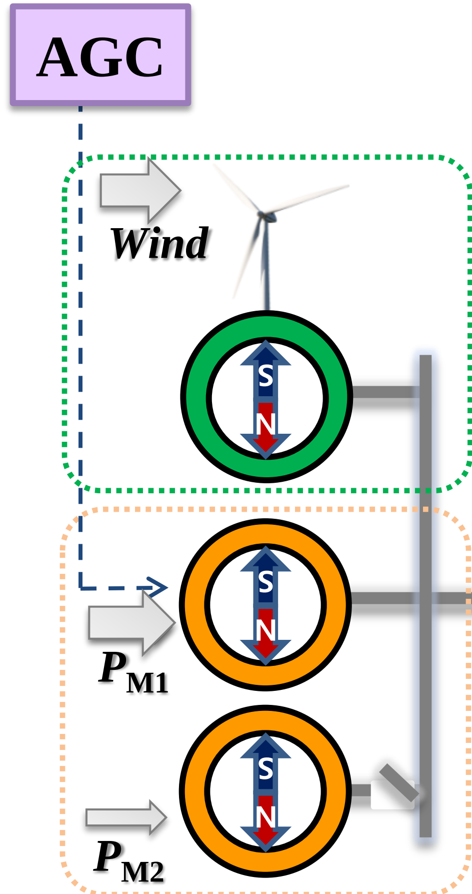
- **Maximum power point tracking (MPPT) operation**
  - Keeps the rotor speed to the optimum value

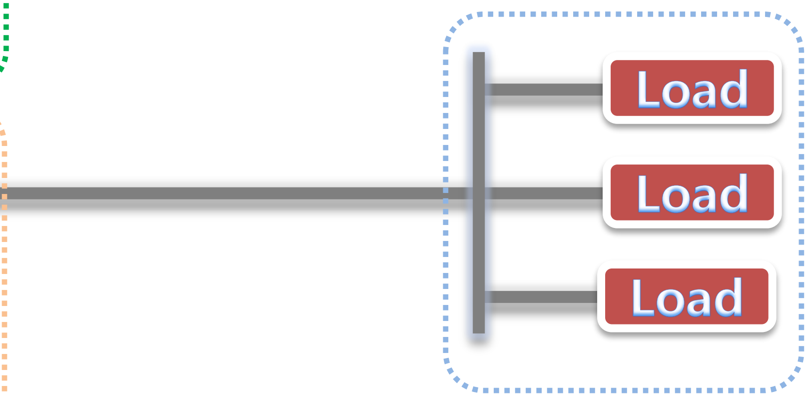


→ only depending on the wind condition

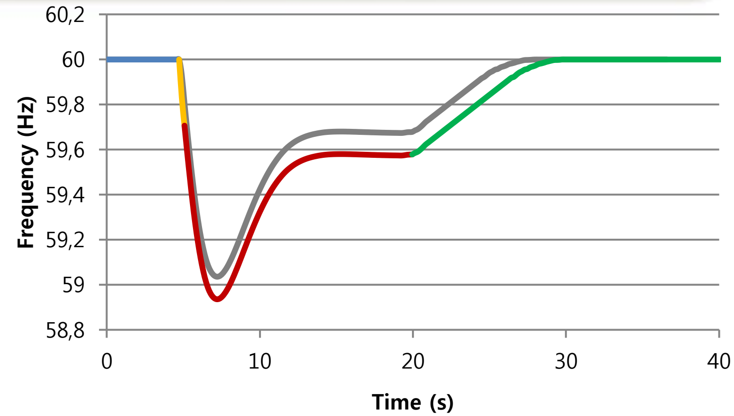
Frequency control in a power system with wind







Synchronous Generators



- Decreasing the system inertia because of the MPPT control of WG
- Necessity of the inertial control of WG

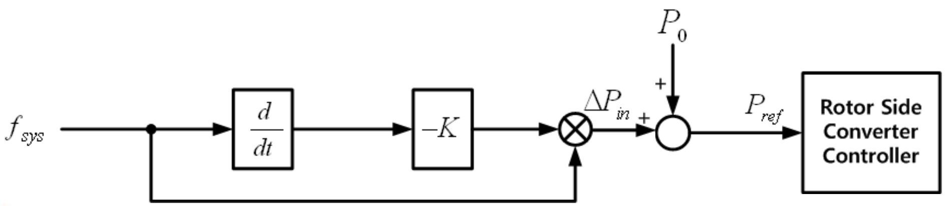
Inertial control of a wind power plant

Conventional inertial control 1

- Inertial control using the rate of change of frequency (ROCOF)

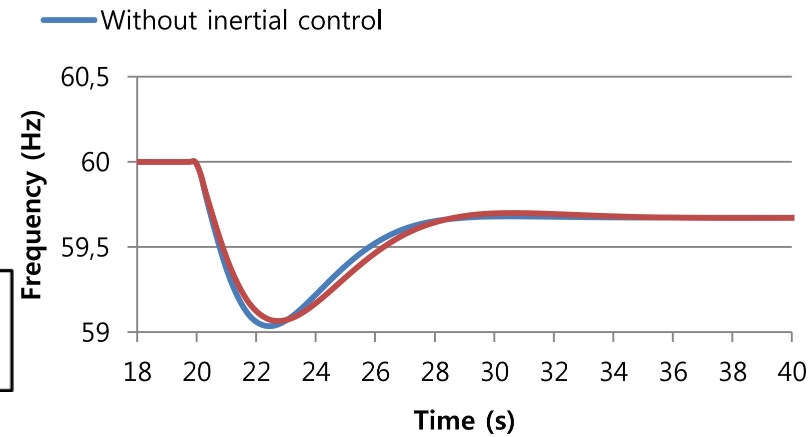
J. B. Ekanayake, L. Holdsworth, and N. Jenkins, "Control of doubly fed induction generator (DFIG) wind turbine," *IEE, Power Eng.*, vol. 17, no. 1, pp. 28–32, Feb. 2003.

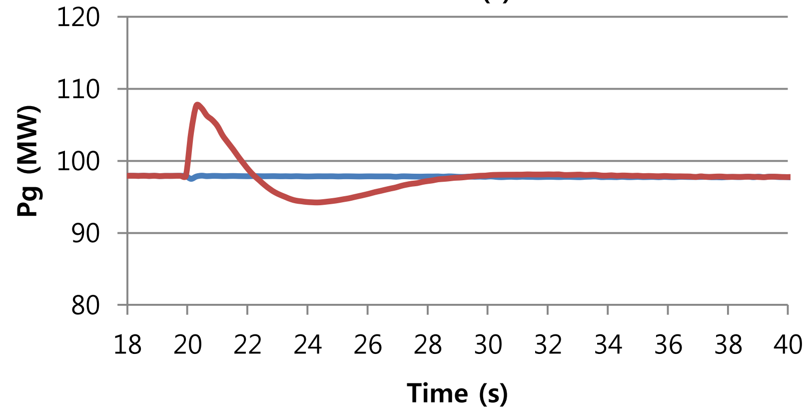
$$P_m - P_e = K_{sys} \times f_{sys} \times \frac{df_{sys}}{dt} \Rightarrow \Delta P_{in} = K \times f_{sys} \times \frac{df_{sys}}{dt}$$



$$P_{ref} = P_0 + \Delta P_{in}$$

- **Advantage:**
  - Increase of the system inertia and the frequency nadir
- **Disadvantages:**
  - Reduction of the additional power as the ROCOF decreases
  - Negative contribution after the frequency rebound

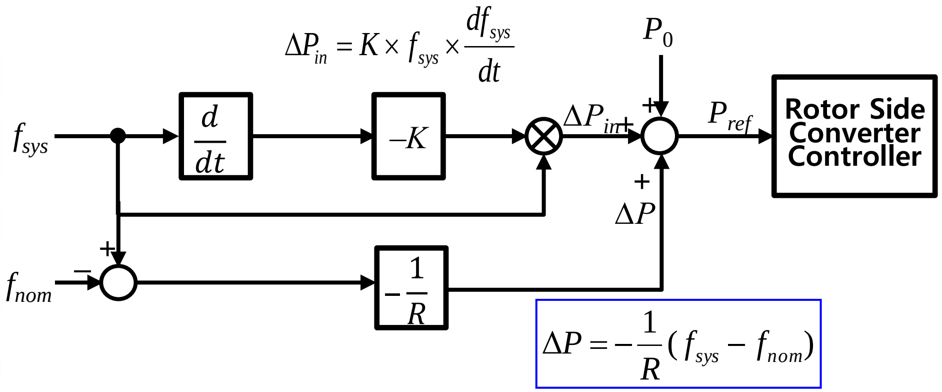




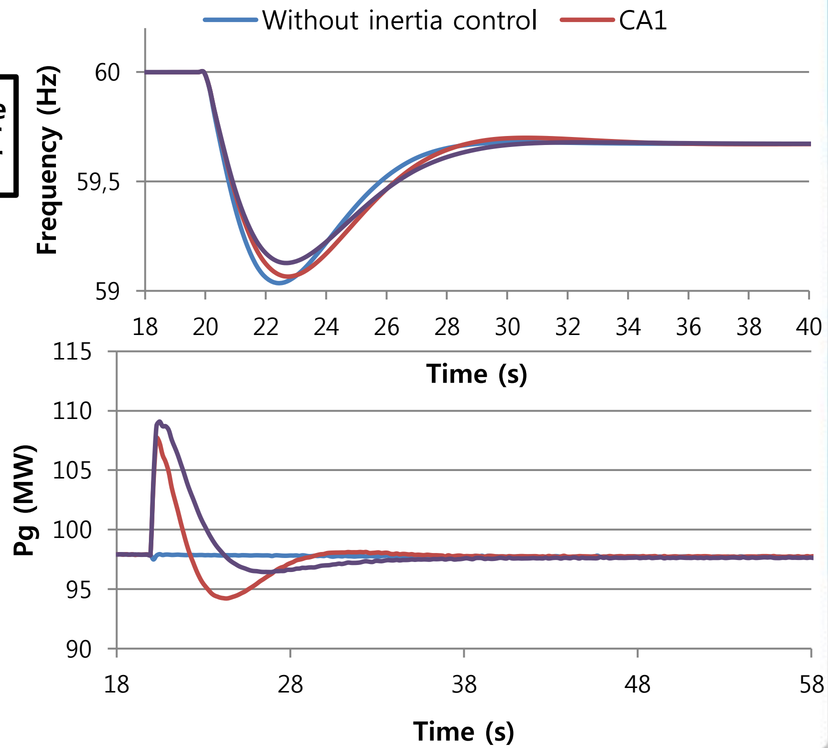
Conventional inertial control 2

Inertial control using ROCOF & Droop

- G. Ramtharan, J. B. Ekanayake, and N. Jenkins, "Frequency support from doubly fed induction generator wind turbines," *IET, Renew. Power Gen.*, vol. 1, pp. 3-9, 2007.
- Z. Zhang, Y. Sun, J. Lin, and G. Li, "Coordinated frequency regulation by doubly fed induction generator-based wind power plants," *IET Renew. Power Gener.*, vol. 6, no. 1, Jan. 2012, pp. 38–47.



$$P_{ref} = P_0 + \Delta P_{in} + \Delta P$$



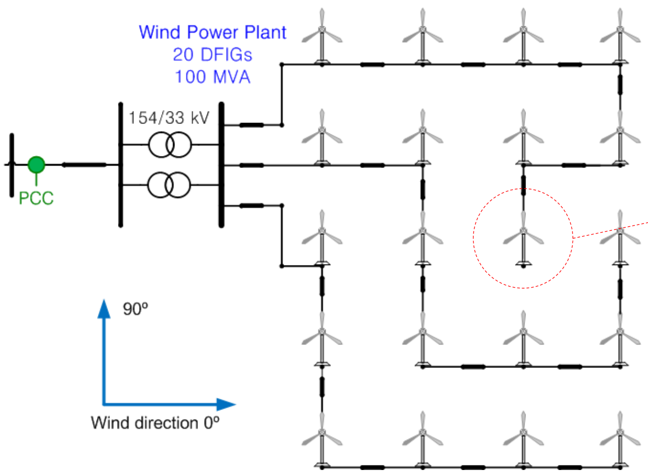
- **Advantage:**
  - More increase of the frequency nadir
- **Disadvantage:**
  - Gradual reduction of the additional power
  - Slower recovery than MPPT after frequency rebound

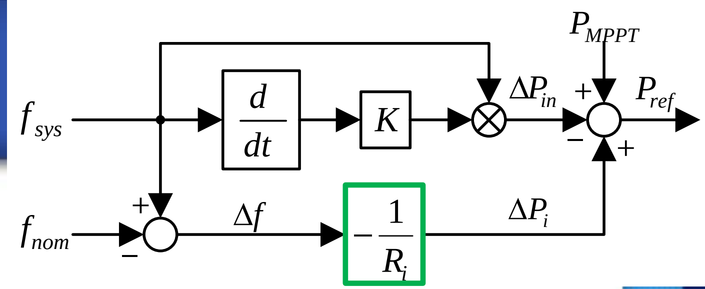
Inertial control considering the kinetic energy stored in a WPP

- **Wake effect**
  - Reduced average wind speed after the wind passing through the upstream WGs

    Wake effect → different wind and rotor speed → different kinetic energy stored in each WG

- **Inertial control to release more kinetic energy depending on the kinetic energy**





Assignment of control gain

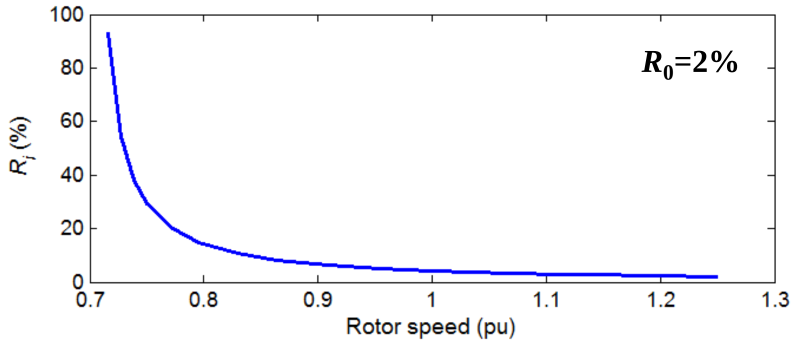
- Droop (R_i)
  - Control gain of the frequency deviation loop for inertial control
- Droop assignment considering the kinetic energy
  - Assigning smaller droop to the WG operating at a higher rotor speed

$$\Delta \overline{P}_i = -\frac{1}{R_i}\left(\bar{f}_{sys} - \bar{f}_{nom}\right) \qquad R_i = R_0 \times \frac{E_{\max}}{E_i}$$

$$\frac{\Delta \overline{P}_i}{\overline{f_{sys} - f_{nom}}} = -\frac{1}{R_i}, \quad i = 1, \ldots, n$$

$$\Delta \overline{E}_i R_i = -1 \qquad \Delta \overline{E}_i R_i = \Delta \overline{E}_{\max} R_0$$

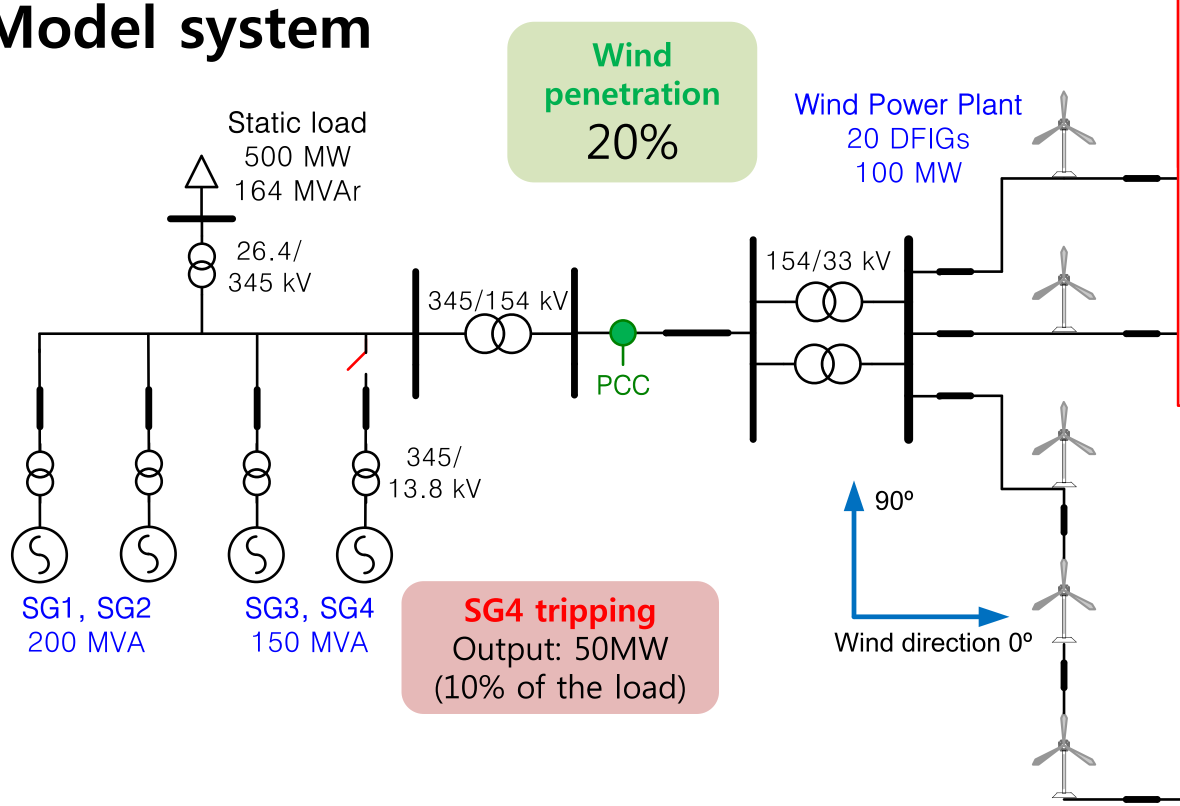
$$E_i = \frac{1}{2} J(\omega^2 - \omega_{\min}^2)$$



E_i: Kinetic energy to be released from WG_i
$E_{\max}$: Kinetic energy to be released from the WG operating in maximum rotor speed
R_0: Reference droop determined to the WG operating in maximum rotor speed

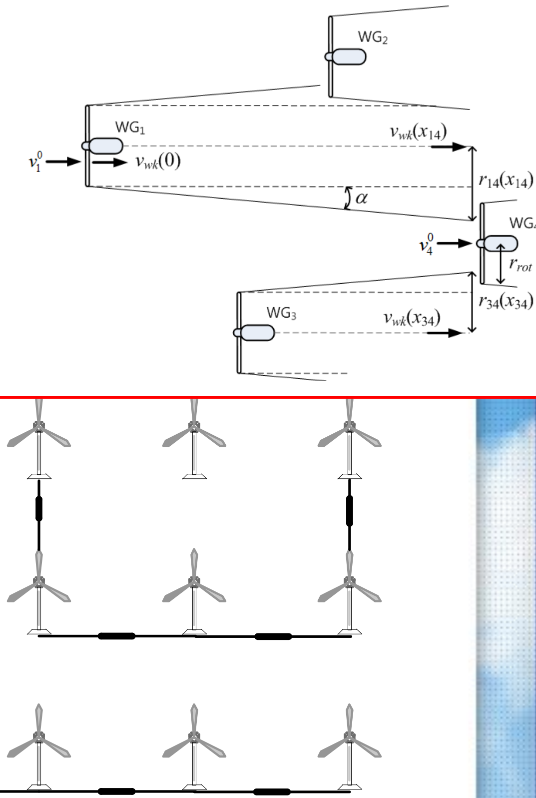
Case studies

Model system



- **N. O. Jenson's wake model**

$$v_j = v_j^0 - \sqrt{\sum_{\substack{i=1 \\ i \neq j}}^{n} \beta_i^2 \cdot \left(v_{wk}(x_{ij}) - v_j^0\right)^2}$$



- **Total generation**
  800 MVA
- **Load consumption**
  500 MW

- **Steam turbine SG**
  IEEEG1 model (5% droop)
  150 MVA × 2
  200 MVA × 2

- **WPP/WG**
  Rated power: 100 MVA
  5 MW DFIG × 20
  Rated speed: 11 m/s

- **SG tripping at 40 s: 50 MW (10% of total consumption)**
- **Studied cases**

	Wind speed (m/s)	Wind direction (deg.)
1	9	0
2	11	90

Input wind speed of WGs for each case (m/s)

Case 1			
9.0	8.3	7.5	6.6
9.0	8.3	7.5	6.6
9.0	8.3	7.5	6.6
9.0	8.3	7.5	6.6
9.0	8.3	7.5	6.6

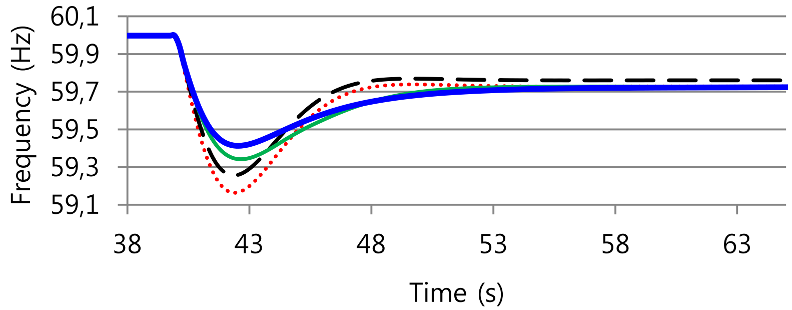
Case 2			
7.4	7.4	7.4	7.4
8.6	8.6	8.6	8.6
9.6	9.6	9.6	9.6
10.3	10.3	10.3	10.3
11.0	11.0	11.0	11.0

- Control algorithms in the case

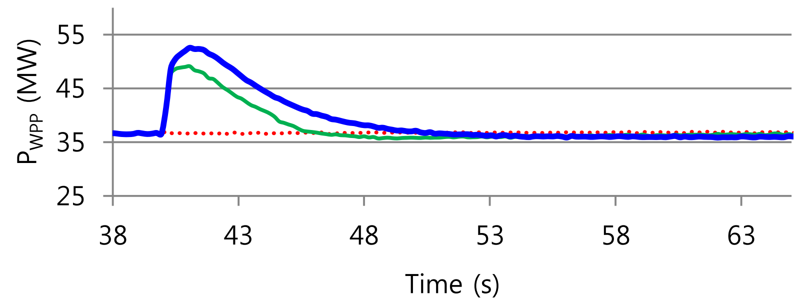
Algorithm	Features
Proposed	Assigning the rotor speed-based droop (R_i)
Conventional	Applying the same R to all WGs (R=avg(R_i))
Only SGs	A 100 MW SG instead of the WPP
No inertial	Operating in MPPT control mode

Case 1: *wind speed 9 m/s, wind direction 0°*

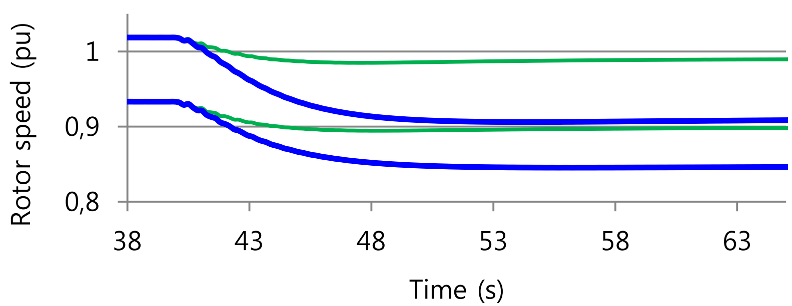
System frequency (Prop./Conv./SGs/No inertial)



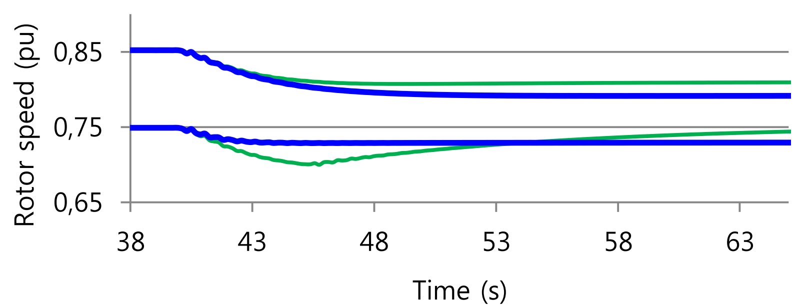
Active power of a WPP (Prop./Conv./SGs/No inertial)



Rotor speed of 1st, 2nd WGs (Prop./Conv.)



Rotor speed of 3rd, 4th WGs (Prop./Conv.)



- **Frequency nadir**
  Proposed: 59.41Hz
  Conventional: 59.34Hz
  SGs: 59.25Hz
  MPPT: 59.17Hz

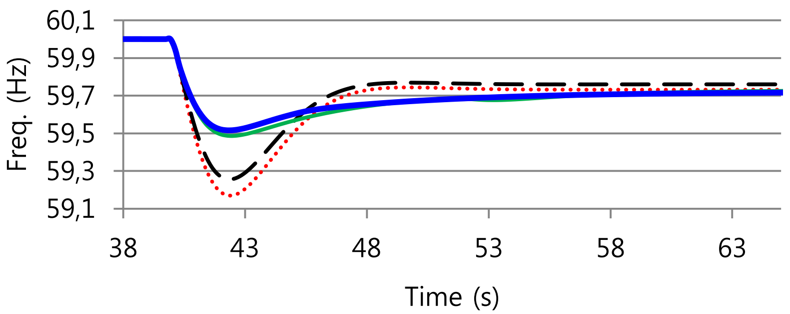
- **NBFR**
  Proposed: 8.47MW/0.1Hz
  Conventional: 7.58MW/0.1Hz
  Only SGs: 6.67MW/0.1Hz
  No inertial: 6.02MW/0.1Hz

- **Assigned R_i**
  1st, 2nd column: 3.9%, 5.6%
  3rd, 4th column: 9.1%, 30.3%
- **Average R**
  Conventional algorithm: 12.2%

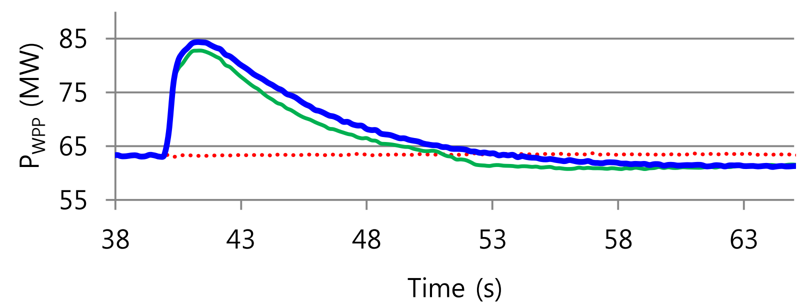
* NBFR (Nadir-based Frequency Response)=Capacity of tripped SG/Maximum frequency deviation

Case 2: *wind speed 11 m/s, wind direction 90°*

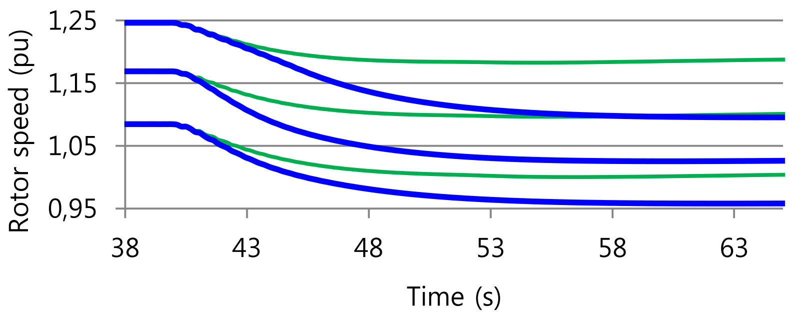
System frequency (Prop./Conv./SGs/No inertial)



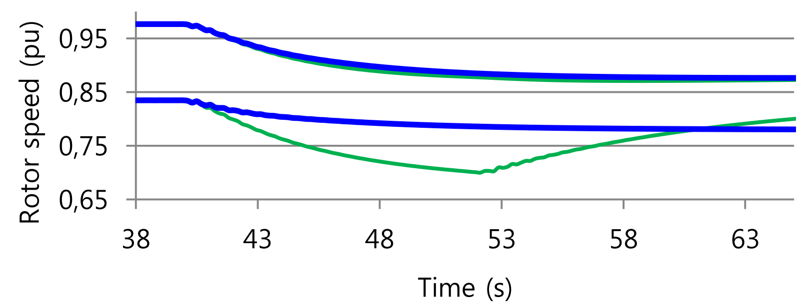
Active power of a WPP (Prop./Conv./SGs/No inertial)



Rotor speed of 5th, 4th, 3rd WGs (Prop./Conv.)



Rotor speed of 2nd, 1st WGs (Prop./Conv.)



- **Frequency nadir**
  - Proposed: 59.52Hz
  - Conventional: 59.49Hz
  - SGs: 59.25Hz
  - MPPT: 59.17Hz

- **NBFR**
  - Proposed: 10.42MW/0.1Hz
  - Conventional: 9.80MW/0.1Hz
  - Only SGs: 6.67MW/0.1Hz
  - No inertial: 6.02MW/0.1Hz

- **Assigned R_i**
  - 5th, 4th, 3rd row: 2.0%, 2.4%, 3.1%
  - 2nd, 1st row: 4.6%, 10.4%
- **Average R**
  - Conventional algorithm: 4.5%

Conclusions

- **Inertial control of a WPP releasing more kinetic energy stored for WGs with a higher wind speed**
  - Assigns the droop gain depending on the rotor speed
    - Smaller/larger droop for the WG with larger/smaller rotor speed

- **Inertial control of a WPP can give more contribution than SGs by controlling the kinetic energy stored in the WGs**

- **WG of 5 MW has similar kinetic energy to a SG of 100 MW**

- **A power system with high wind penetration has larger system inertia in terms of frequency stability**

Wind energy Grid-Adaptive Technologies

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