Control Strategies of Hybrid Microgrid

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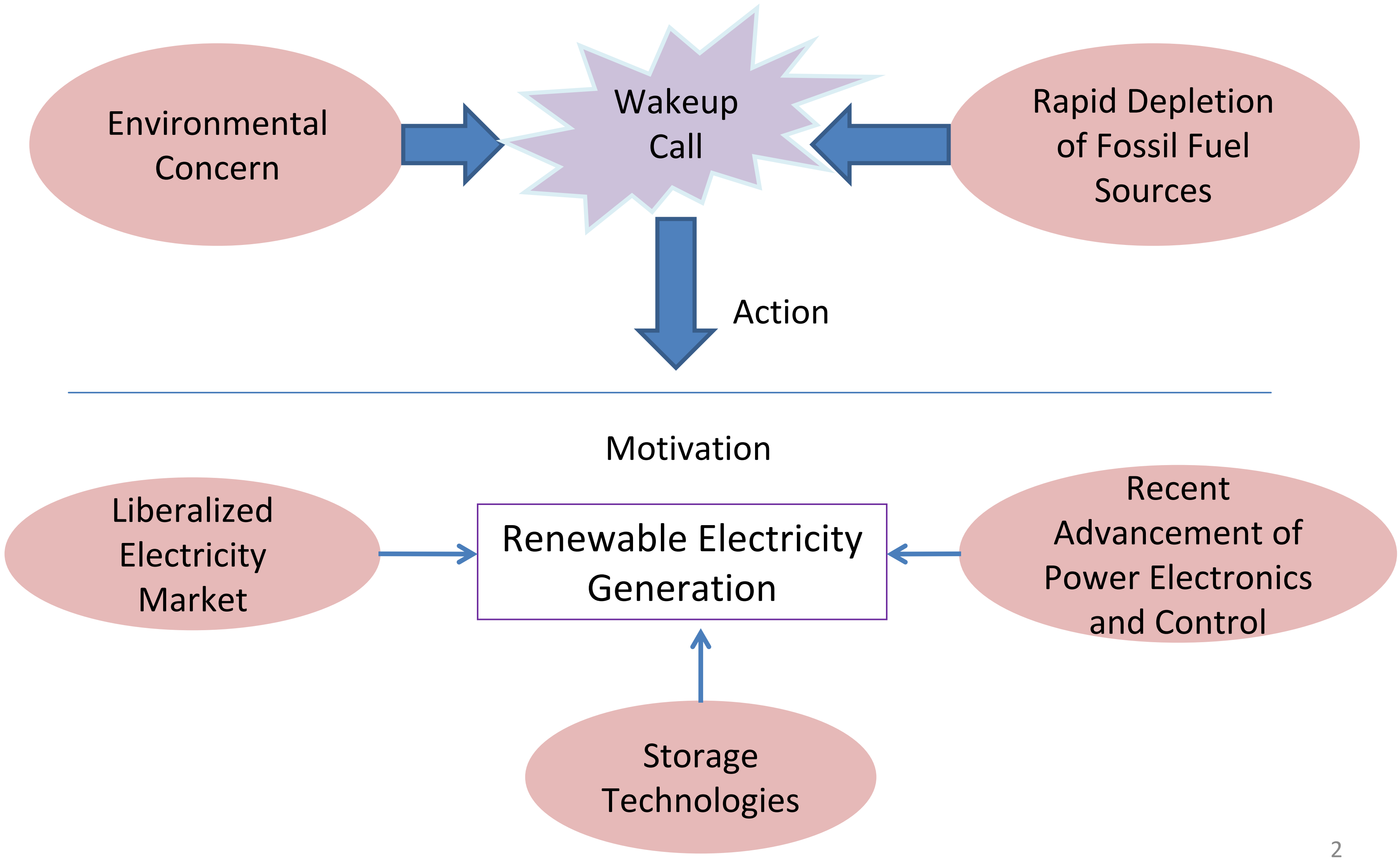
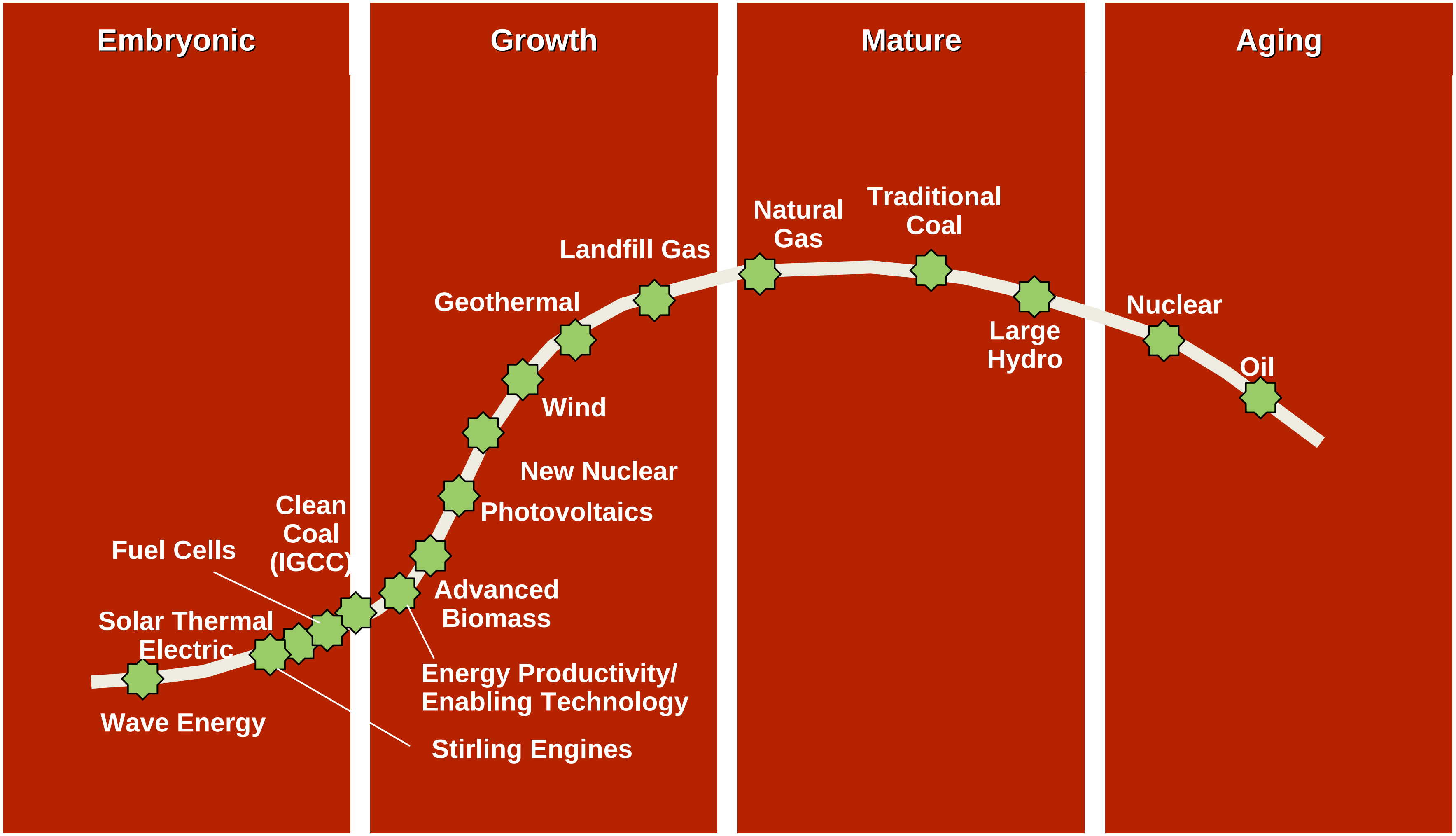
Why Renewable?

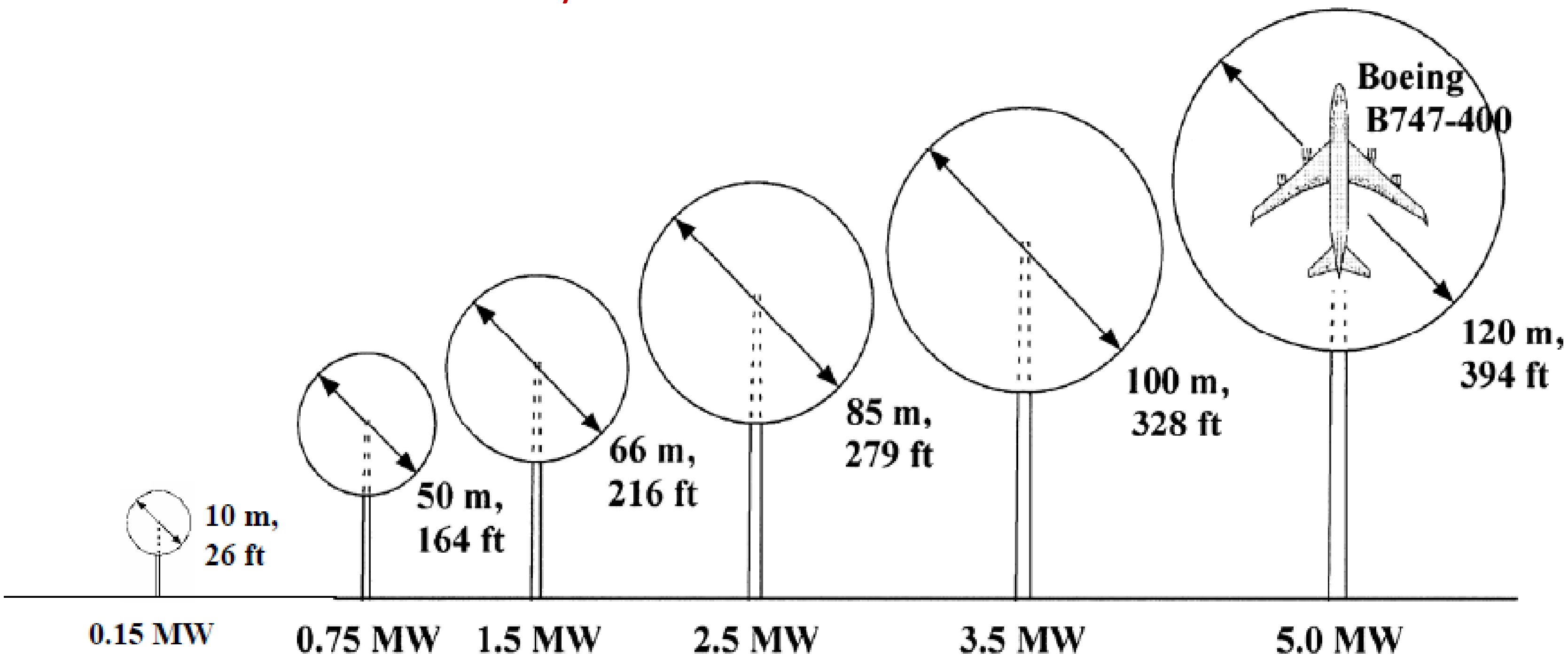


Generation Technologies:



Wind Power

Size of Wind Power System Vs. Time



Source: NREL Report 2008

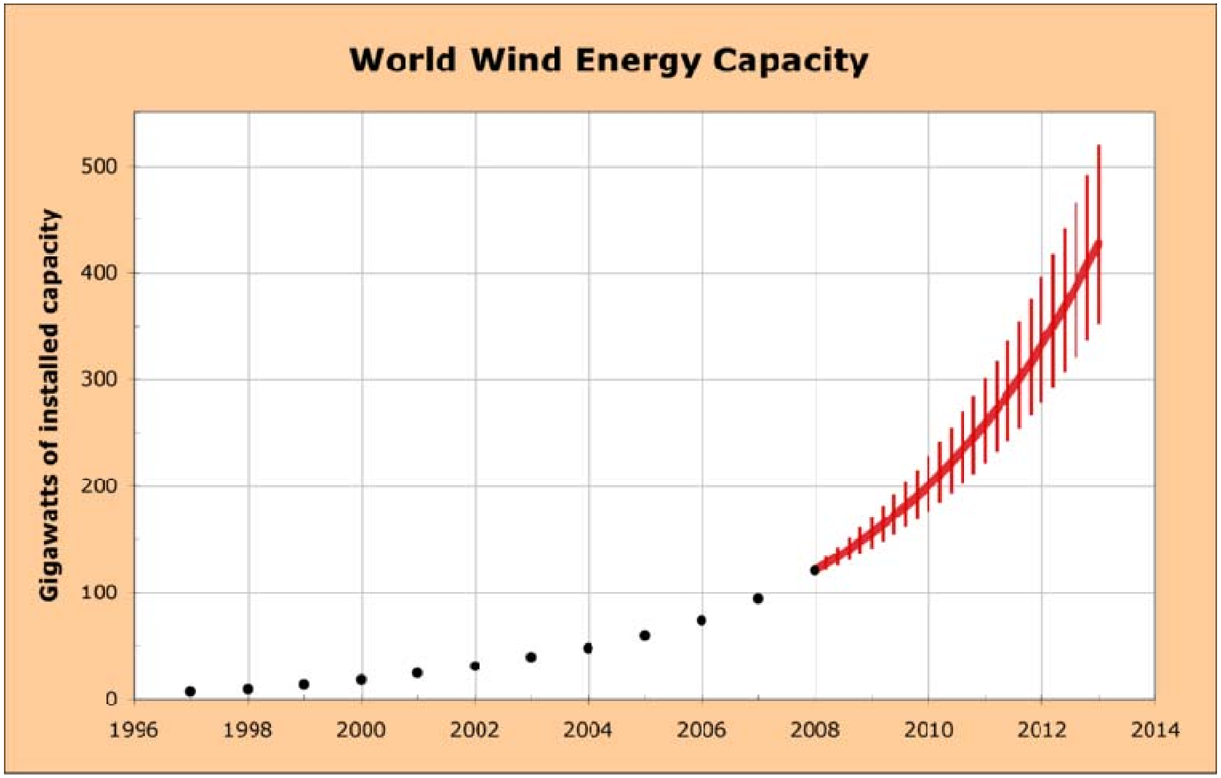
Wind Power Issues

- Wind Energy is one of the Promising RE for Future

- Five fold increase in 2001-2007 and Expected to increased threefold in 2008-2015

- The technology is in advanced stage and Size also getting larger

- Cost

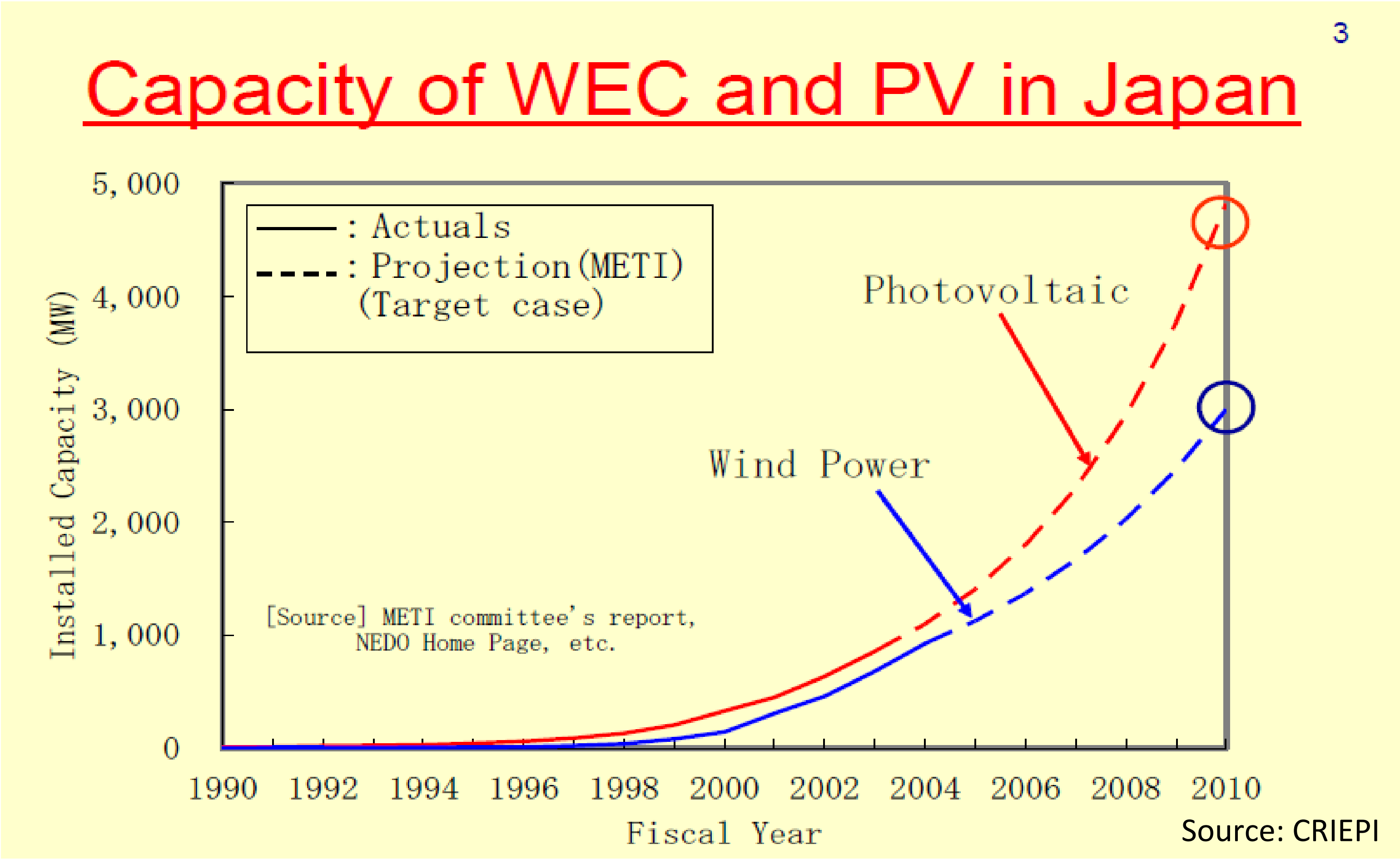


Source: U.S. DOE

1980: 40 cents/kWh

2009: 7- 9 cents/kWh

Wind Power (in Japan)



Recent Declaration of Japanese Government 20% reduction of CO_2 2025 will remarkable change this graph

Wind Power Issues

Until Now (Low Penetration Level)

Negative Load

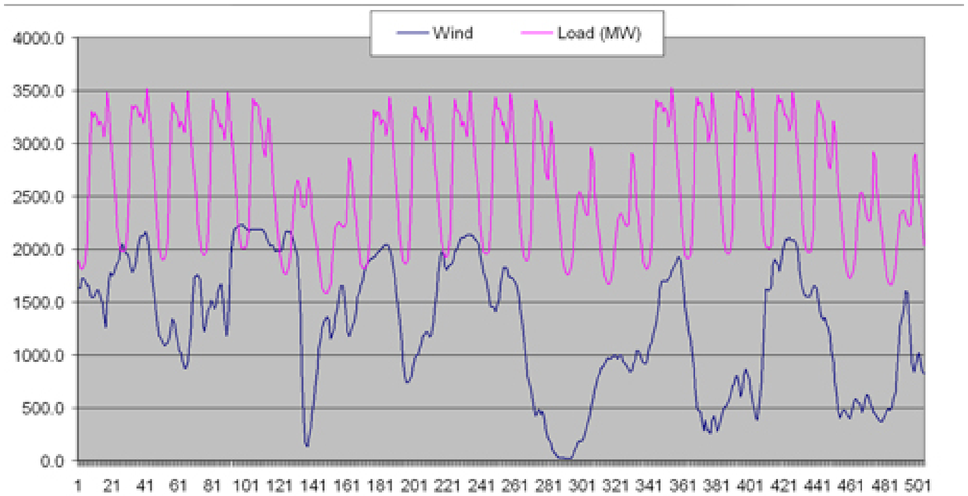
From Now on (High penetration Level)

- *Dispatchable*
- *Ride through capability*
- Regulates Plant Voltage and Power

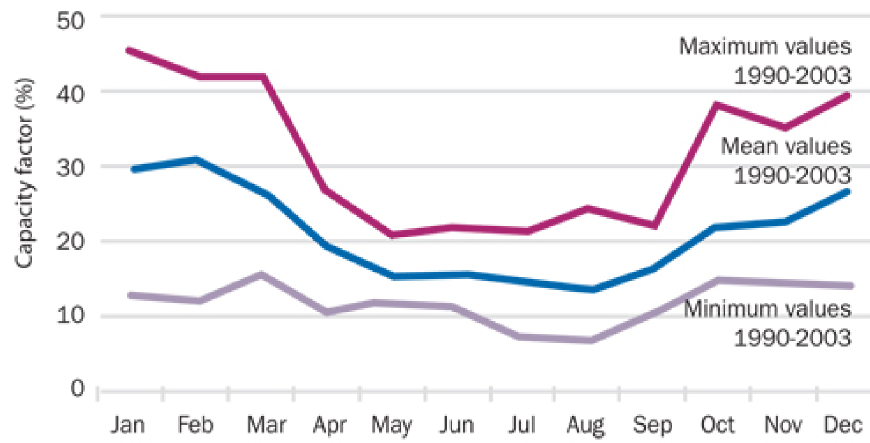
Wind Power

Wind Power Characteristics

✓ **A variable output source embedded in a variable electricity system :** seconds, minutes, hours, days, months, seasons and years



Hourly variation (Source: www.energinet.dk)



Yearly variation (Source: ISET (2004))

✓ Low Capacity factor,

✓ Operational and control Challenges

- Isolated mode and also in Weak grid

→ **Storage**

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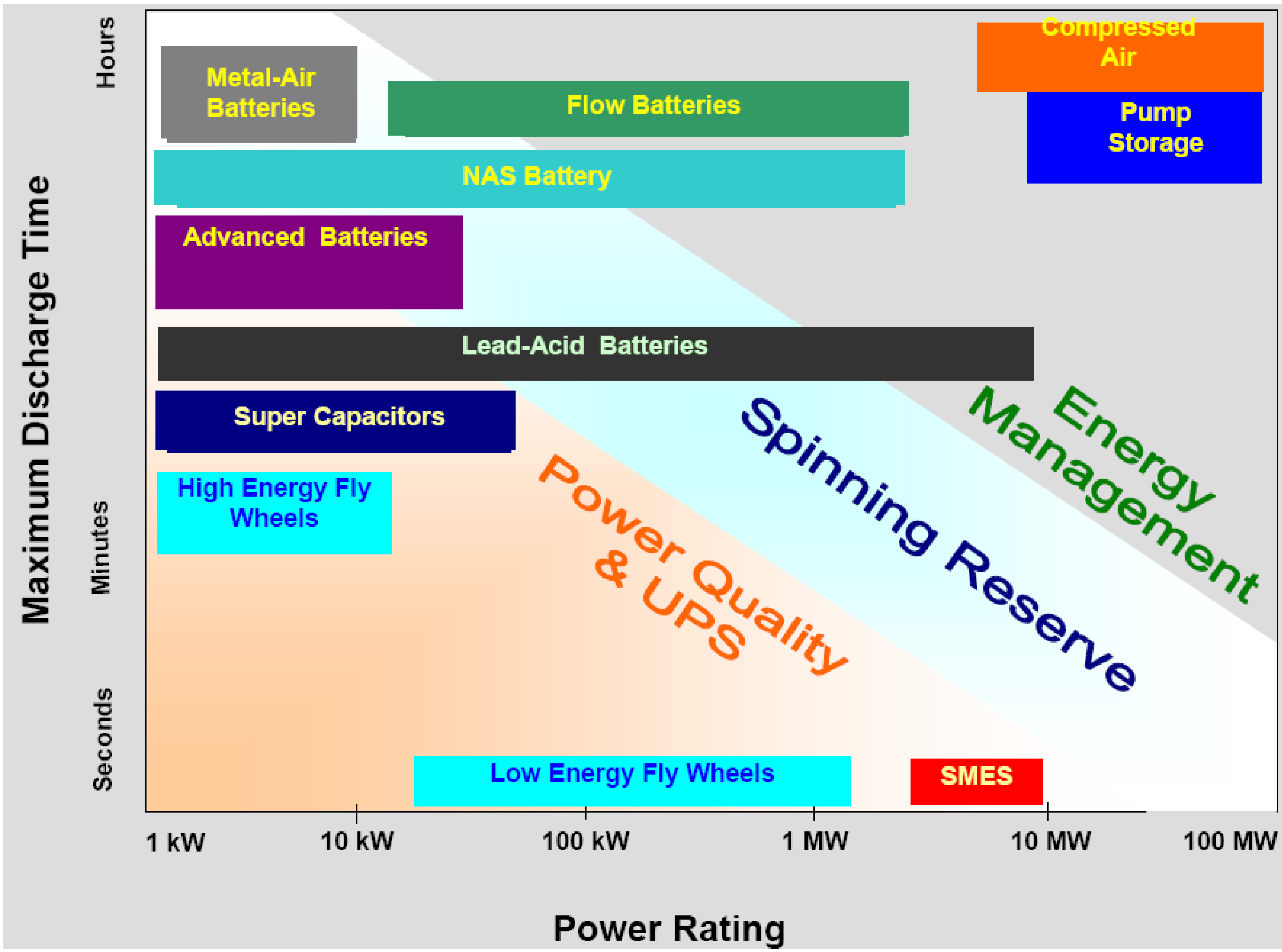
Wind Power and Energy Storage

Short term storage
instantaneous power balance; Buffer storage (ms-s)

Midterm
Spin reserve, Load Shaving etc.
(minutes-hours)

Long term storage
for energy management
(day-month)



Source: ESA 2008

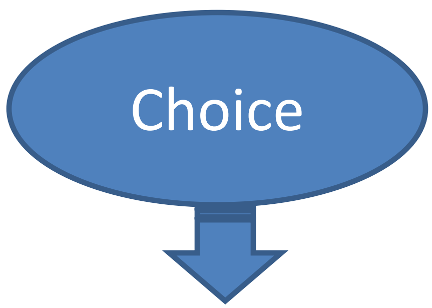
Energy Storage

- Conventional Technology:

  Lead Acid Battery, Pump Storage, Flywheel

- Emerging Technology:

  Ultracapacitor, SMES, H2/Fuel Cell etc.



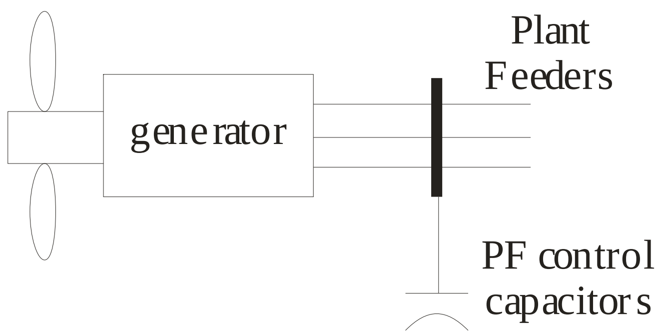
Proposed System:

- H2/ Fuel Cell as Mid term and Long term Storage
- Ultracapacitor as Short term Storage

WTG Standard Models

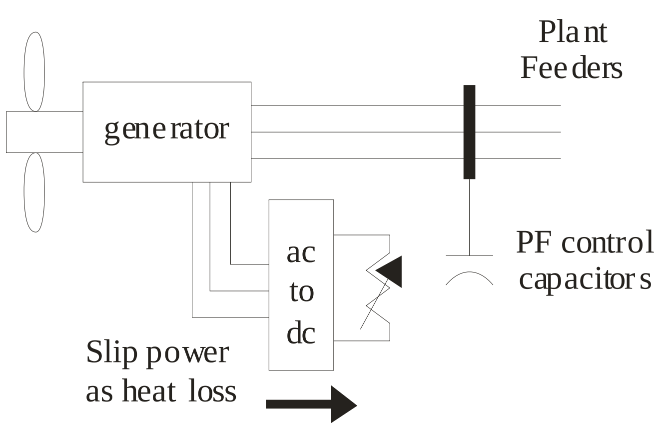
Type A- Fixed speed

(Conventional squirrel caged IG)



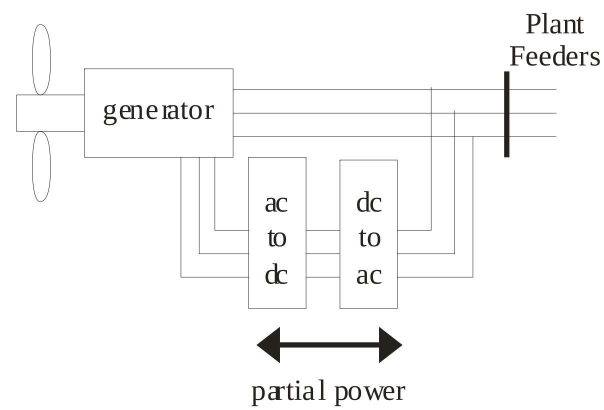
Type-B: Fixed speed

(Wound rotor IG)



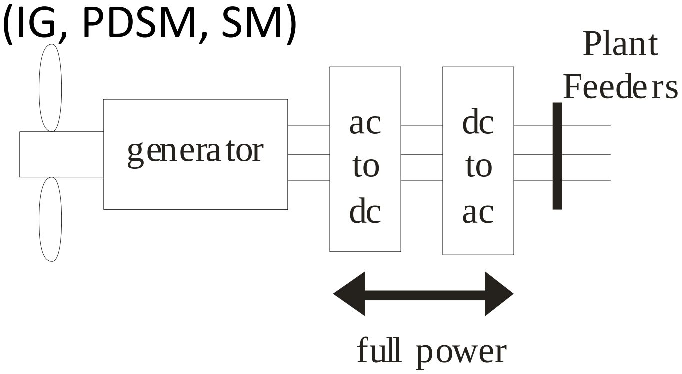
Type C- Variable speed

(doubly-fed induction generator IG)



Type-D: Variable speed

(IG, PDSM, SM)



WTG Model (Contd..)

Aerodynamic characteristics

- Mechanical power (P_m)

  P_m = ½ × (air density) × (swept area) × C_p × (wind speed)^3

- *Rated Power* –

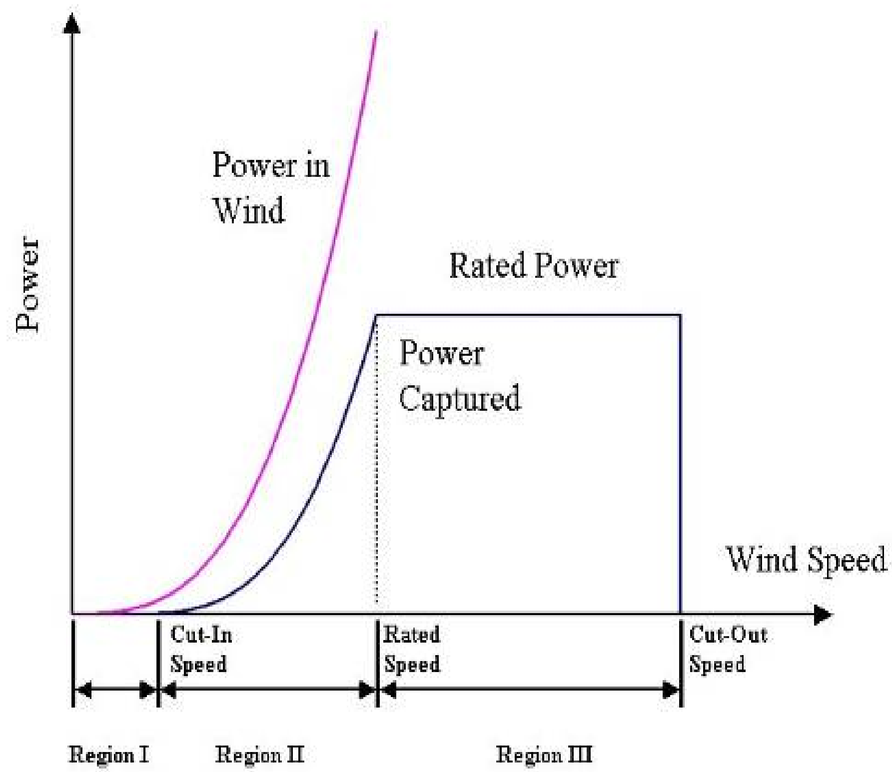
  Maximum power generator can produce.

- C_p (Power Coefficient)

  Function of blade pitch and tip-speed ratio

  (< *Betz Limit* - 59% Max)

- During a typical dynamic simulation, blade pitch and tip speed ratio vary, thus C_p and P_m will also vary
- *Cut-in* wind speed where energy production begins
- *Cut-out* wind speed where energy production ends.



Typical Power Curve

WTG Model (Contd..)

Typical Power vs. Turbine speed Characteristics

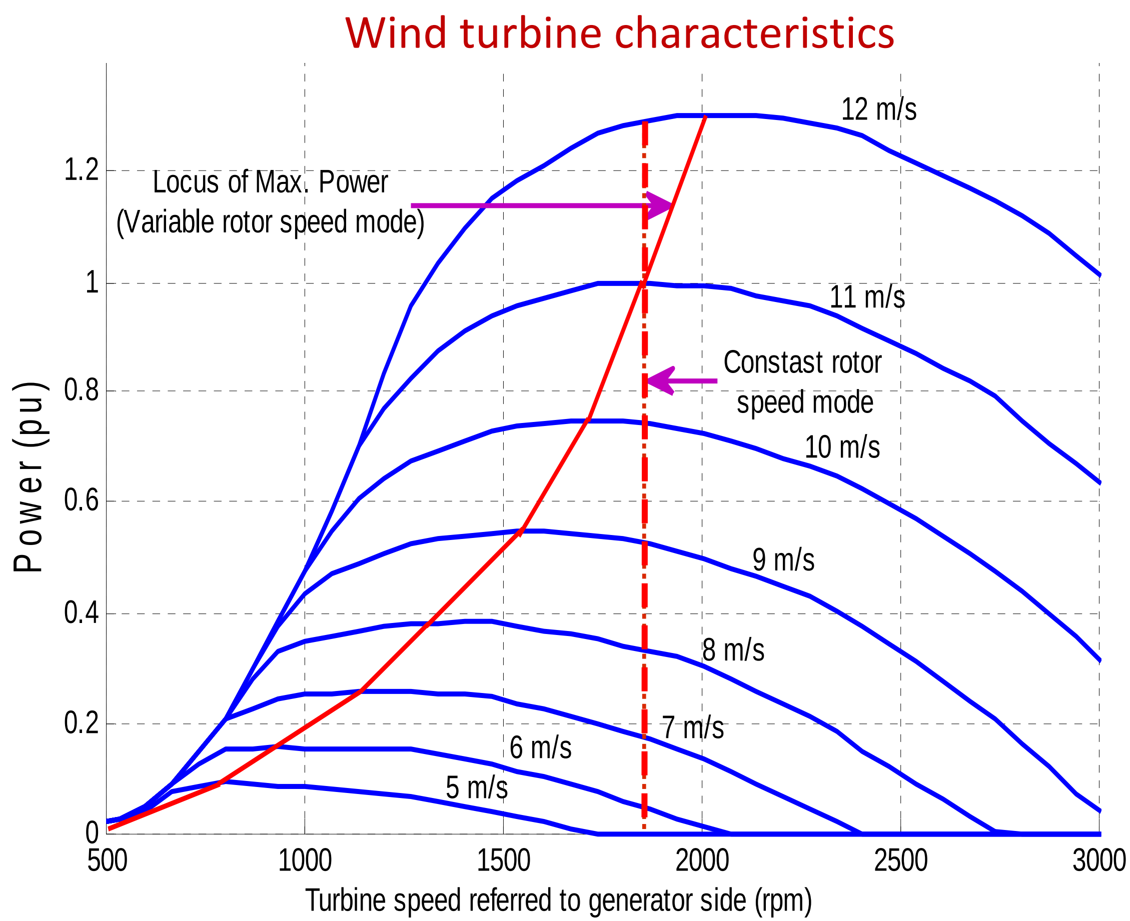
Power - Turbine speed characteristics

•Locus of Max. Power shifts with the turbine speed

Variable WTG system

•Capturing Max. Power available

• Absorption of turbulent power



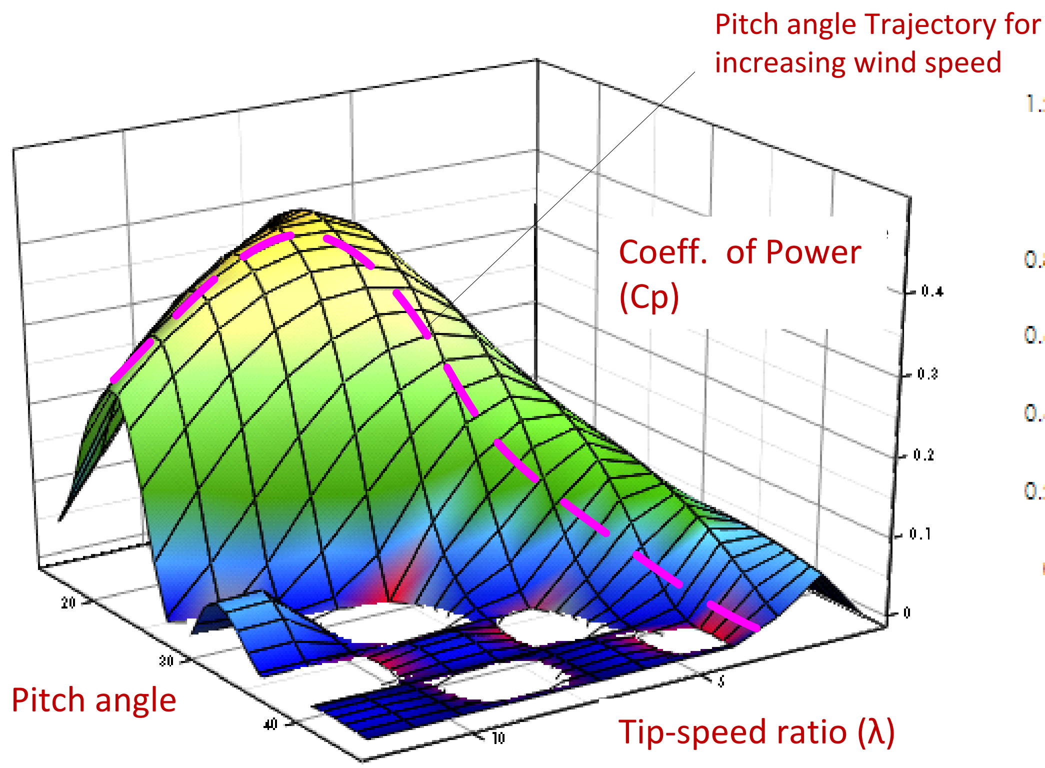
WTG Model (Contd..)

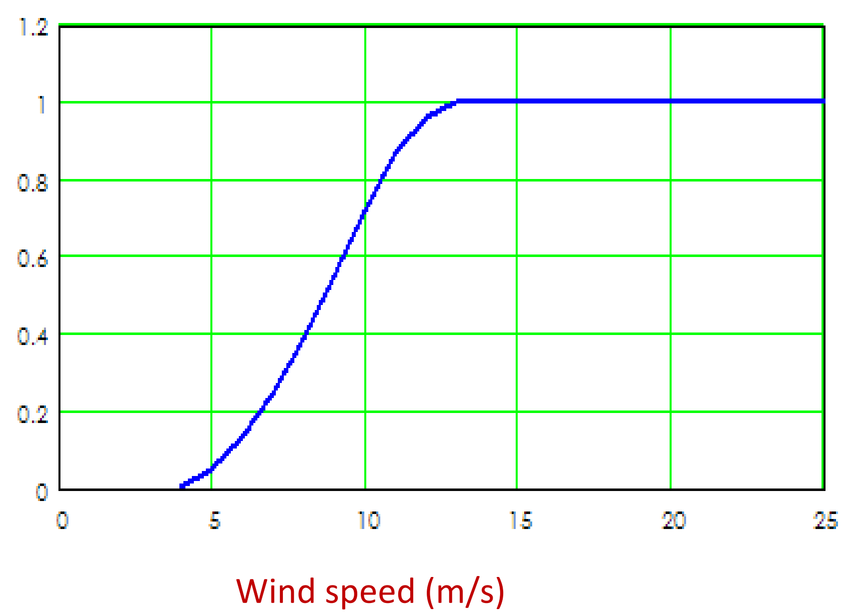
Power coefficient as function of pitch angle and the tip and ratio

- Typical Cp curve (left)

The dashed magenta line shows operating points that correspond to the steady-state power curve (right)

- During a typical dynamic simulation, blade pitch and tip speed ratio vary, thus C_p and P_m will also vary





WTG Model (Contd..)

Mathematical model of WTG (Summarized)

$$P_m = 0.5 c_p(\lambda, \beta) \rho A v_{wind}^3$$

$$c_p(\lambda, \beta) = c_1 \left(\frac{c_2}{\lambda_i} - c_3 \beta - c_4 \right) e^{-\frac{c_5}{\lambda_i}} + c_6 \lambda$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}$$

$$\omega_{gen} = \frac{v_{wind}}{r}$$

$$T_m = \frac{P_m}{\omega_{gen}}$$

$$J \frac{d}{dt} \omega_{gen} + D \omega_{gen} = T_m - T_e$$

where

P_m Mechanical output power of the turbine (W)

C_p Performance coefficient of the turbine

λ Tip speed ratio ($r\omega_{gen}/v_{wind}$)

Air density (kg/m3)

A Turbine swept area (m2)

V_{wind} Wind speed (m/s)

A Tip speed ratio of the rotor blade tip speed to wind speed

β Blade pitch angle (deg)

J Moment of inertia

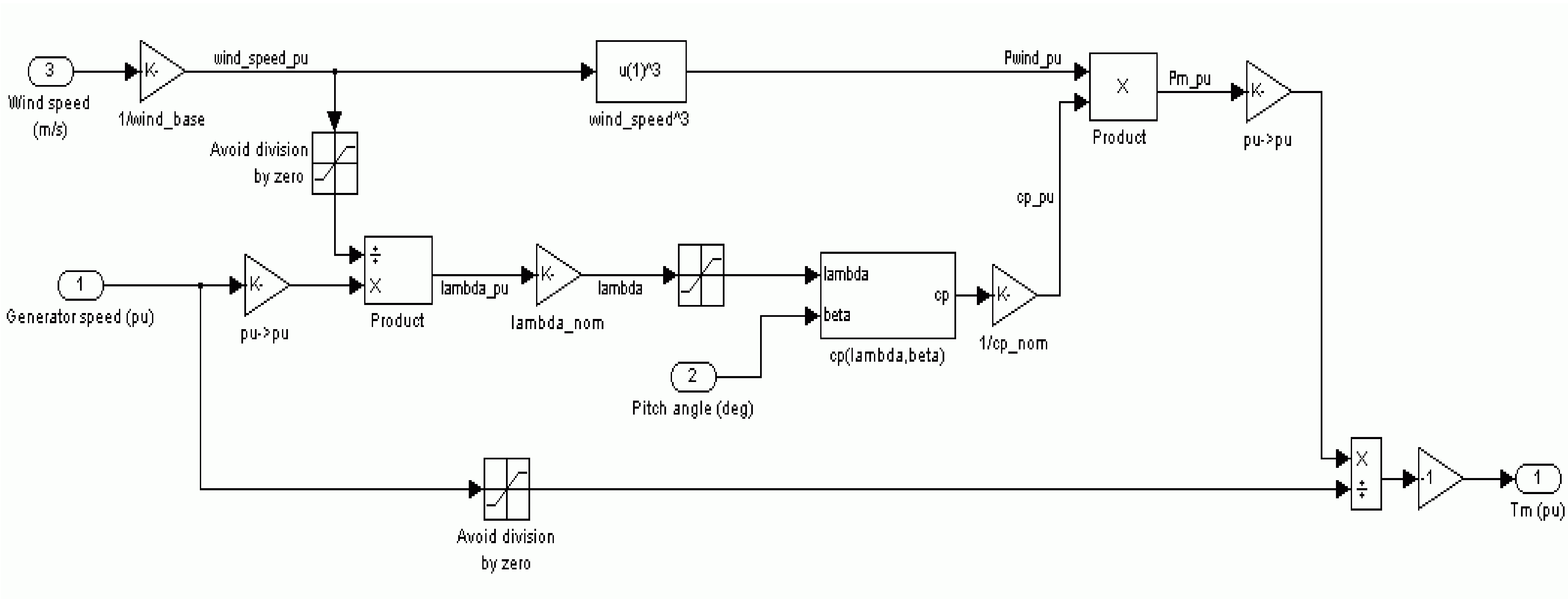
D frictional constant

T_e Electrical torque

r Radius of turbine

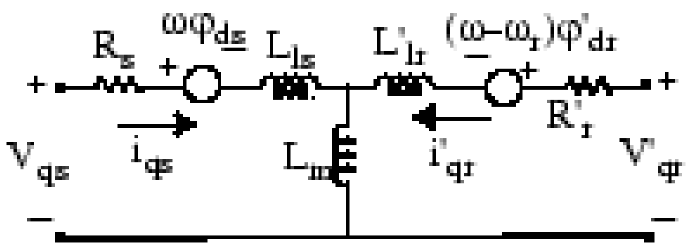
C_i constant coefficient

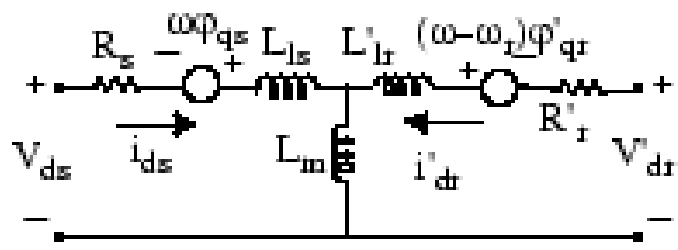
WTG Model (Simulink Model)



WTG Model (Contd..)

Electrical Model of IG (Fifth order model)





$$V_{qs} = R_s i_{qs} + \frac{d}{dt}\varphi_{qs} + \omega\varphi_{ds}$$

$$V_{ds} = R_s i_{ds} + \frac{d}{dt}\varphi_{ds} - \omega\varphi_{qs}$$

$$V'_{qr} = R'_r i'_{qr} + \frac{d}{dt}\varphi'_{qr} + (\omega - \omega_r)\varphi'_{dr}$$

$$V'_{dr} = R'_r i'_{dr} + \frac{d}{dt}\varphi'_{dr} - (\omega - \omega_r)\varphi'_{qr}$$

$$T_e = 1.5\,p(\varphi_{ds} i_{qs} - \varphi_{qs} i_{ds})$$

where

$$\varphi_{qs} = L_s i_{qs} + L_m i'_{qr}$$

$$\varphi_{ds} = L_s i_{ds} + L_m i'_{dr}$$

$$\varphi'_{qr} = L'_r i'_{qr} + L_m i_{qs}$$

$$\varphi'_{dr} = L'_r i'_{dr} + L_m i_{ds}$$

$$L_s = L_{ls} + L_m$$

$$L'_r = L'_{lr} + L_m$$

Fuel Cell Model

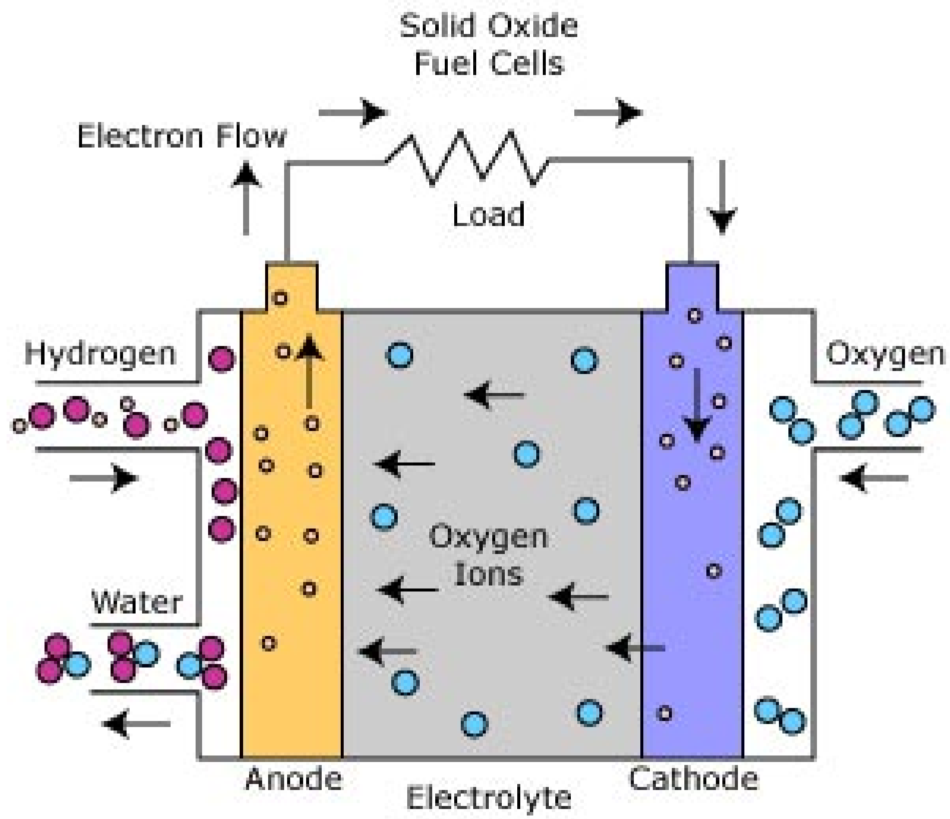
Solid Oxide Fuelcell (SOFC)

•Capable to resist High thermal Stress

•Suitable for high Power application

•High Efficiency

•Allows the internal reforming of gases (Pure H2 is not needed)



Fuel cell Model

Mass Flow/Partial Pressure Dynamics

$$V_a \frac{dp_{H_2}}{dt} = M_{H_2}^{in} - M_{H_2}^{out} - \frac{i}{2F}$$

$$V_c \frac{dp_{O_2}}{dt} = M_{O_2}^{in} - M_{O_2}^{out} - \frac{i}{2F}$$

$$V_a \frac{dp_{H_2O}}{dt} = M_{H_2O}^{in} - M_{H_2O}^{out} + \frac{i}{2F}$$

Here,

p_i *Partial pressure of 'i^th' species*

V_i *Volume of 'i^th' channel*

M_i *Mass flow rate of 'i^th' species*

F *Faraday const.*

Electrochemical Model

$$V_{cell} = E_{Nernst} - V_{act} - V_{ohmic} - V_{act}$$

$$V_{stack} = N_{cell} V_{cell}$$

$$E_{Nernst} = 1.229 - 8.5\times10^{-3}(T_{fc} - 298.15) + \frac{RT_{fc}}{2F} \ln\left[p_{H_2}\left(p_{O_2} / p_{H_2O}\right)^{0.5}\right]$$

$$V_{act} = -A \ln(i / i_0)$$

$$V_{con} = B \ln(1 - i / i_l)$$

$$V_{ohm} = iR_{in}$$

Here,

V_{act} *Activation loss*

V_{ohm} *Ohmic loss*

V_{con} *Concentration loss*

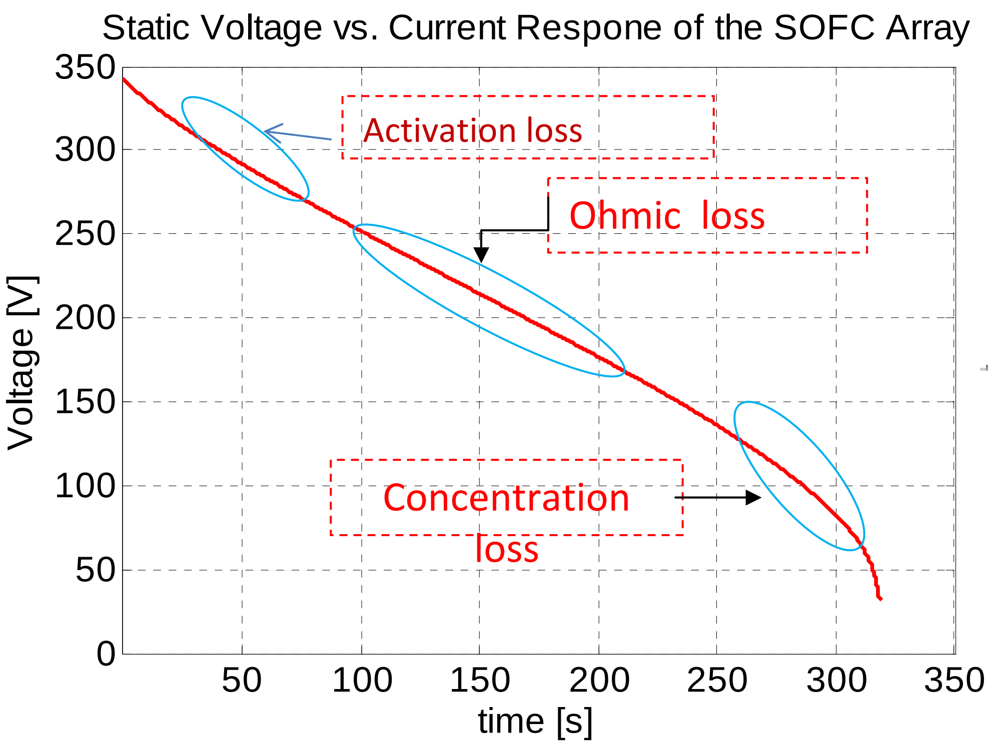
A, B *Cons tan ts*

I_l *Limiting current*

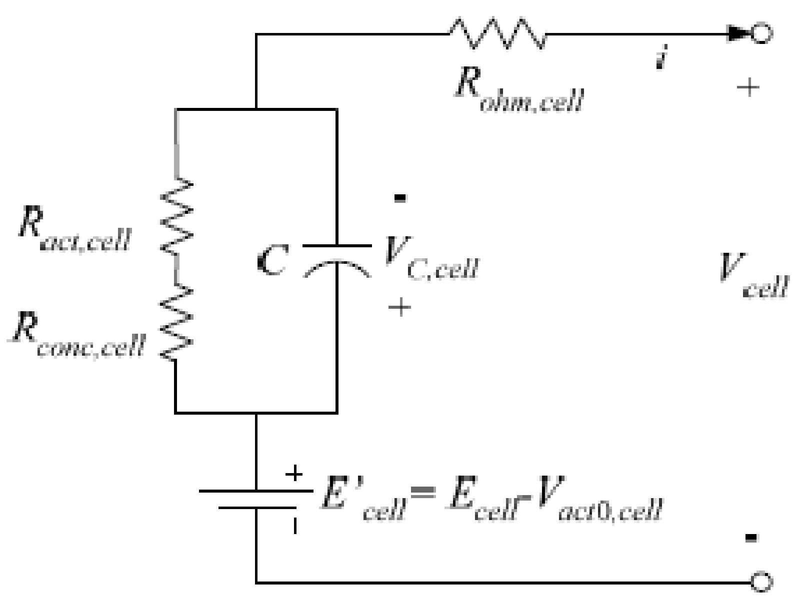
I_0 *Exchange current*

Fuel Cell Model (Contd..)

Static V-I Characteristics of SOFC



Equivalent Electrical Model



Power Interface Model

Simplified Model of single Ultracapacitor

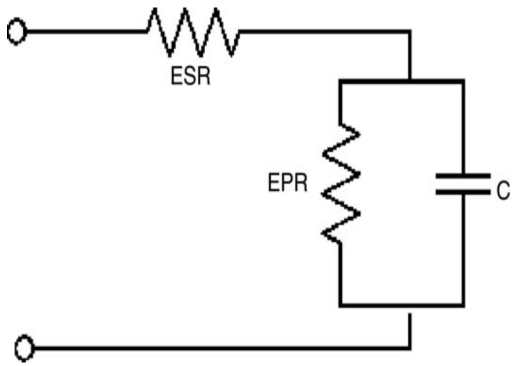
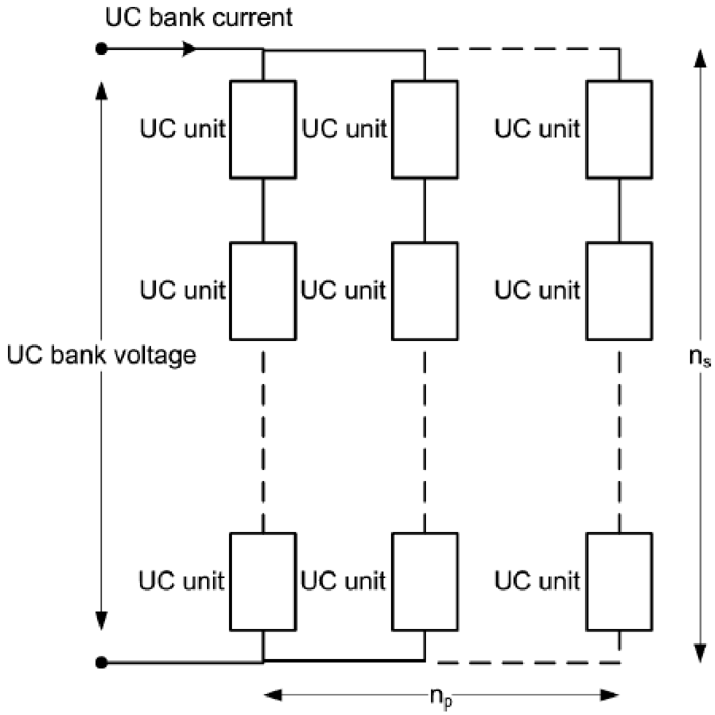


TABLE I
MAXWELL BOOSTCAP PC2500 UC CHARACTERISTICS [24]

UC Parameters	Value
Capacitance	2700 ± 20% [F]
Internal Resistance (dc)	0.001± 25% [Ω]
Leakage current	0.006 [A], 72 hours, 25ºC
Operating Temperature	-40ºC to 65ºC
Rated Current	100 [A]
Voltage	2.5 [V]
Volume	0.6 [l]
Weight	0.725 [kg]

Source: BOOTCAP Double layer UC
Available: http://www.maxwell.com/pdf/uc/datasheets/PC2500.pdf

UC in series-parallel



$$R_{\mathrm{UC-total}} = n_{\mathrm{s}} \frac{\mathrm{ESR}}{n_{\mathrm{p}}}$$

$$C_{\mathrm{UC-total}} = n_{\mathrm{p}} \frac{C}{n_{\mathrm{s}}}.$$

Power Interface Model

DC-DC Boost converter

$$\frac{dx}{dt} = Ax + Bv_{dd\_in}$$

$$v_{dd\_out} = C^T x$$

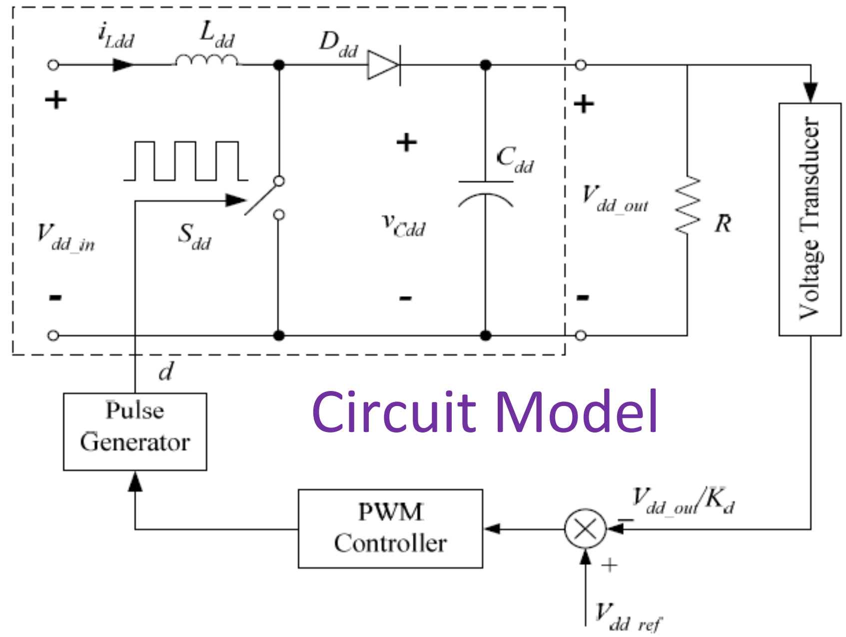
$$where,$$

$$x = [i_{l\_dd} \quad v_{dd\_out}]^T$$

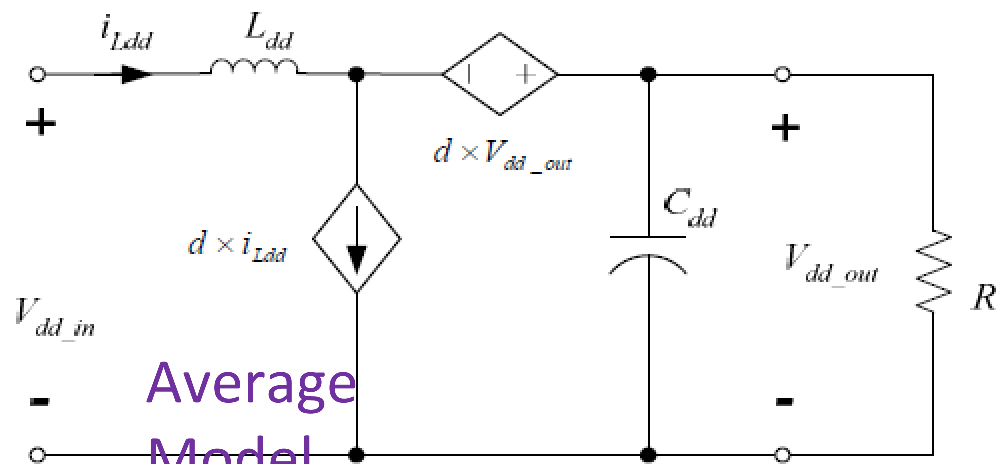
$$A = \begin{bmatrix} 0 & \frac{-(1-d)}{L_{dd}} \\ \frac{-(1-d)}{C_{dd}} & \frac{-1}{RC_{dd}} \end{bmatrix}$$

$$B = \begin{bmatrix} 1/L_{dd} \\ 0 \end{bmatrix}, C = \begin{bmatrix} 0 & 1 \end{bmatrix}$$

State Space equation



Circuit Model



Average Model

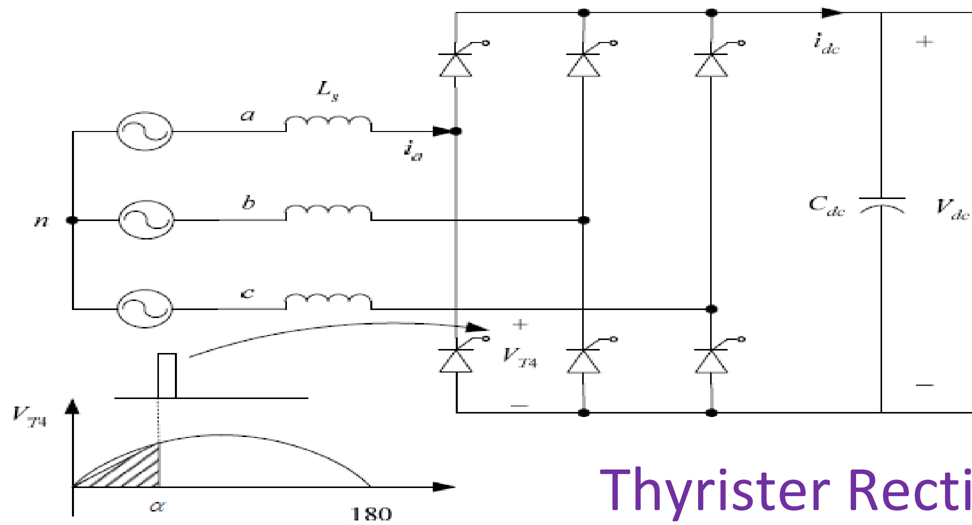
Power Interface Model (contd..)

State Space models :

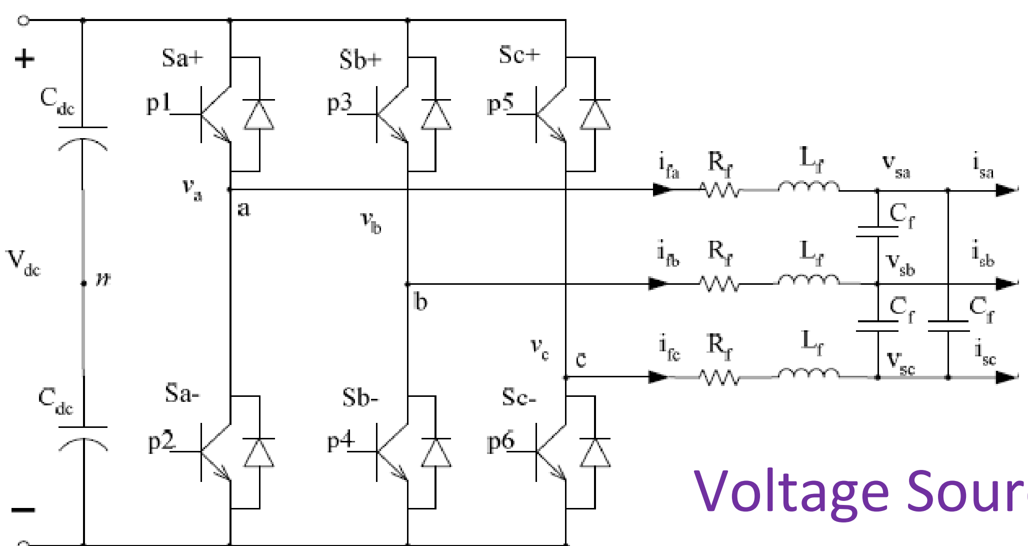
$$V_{dc} = \frac{3}{\pi}\sqrt{2}V_{LL}\cos(\alpha)$$

$$\begin{cases} v_{an} = \dfrac{d_1^*}{2}V_{dc} \\ v_{bn} = \dfrac{d_2^*}{2}V_{dc} \\ v_{cn} = \dfrac{d_3^*}{2}V_{dc} \end{cases}$$

$$\begin{cases} v_a = L_f \dfrac{di_{fa}}{dt} + R_f i_{fa} + v_{sa} \\ v_b = L_f \dfrac{di_{fb}}{dt} + R_f i_{fb} + v_{sb} \\ v_c = L_f \dfrac{di_{fc}}{dt} + R_f i_{fc} + v_{sc} \end{cases}$$



Thyrister Rectifier



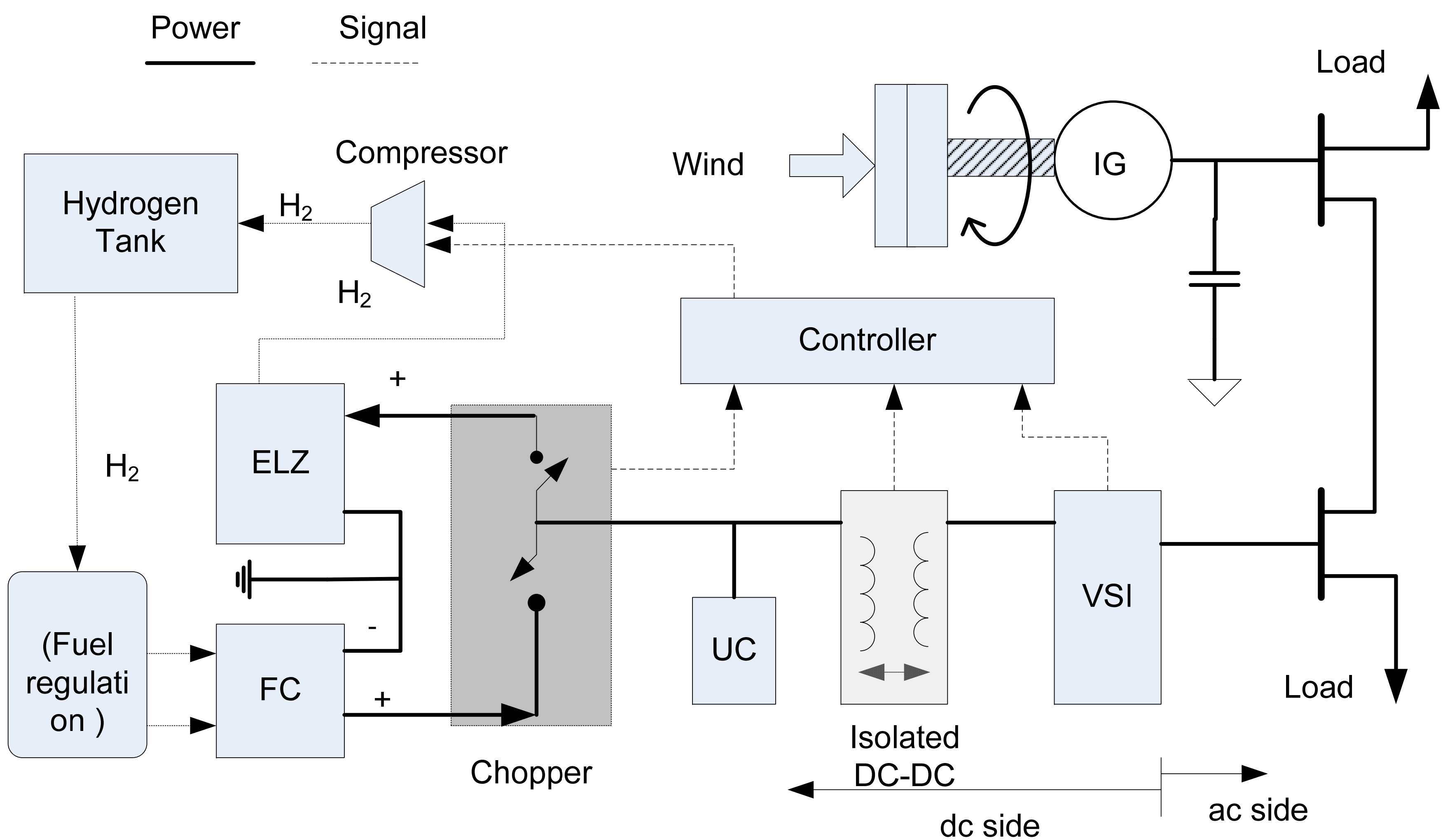
Voltage Source Inverter

Proposed System

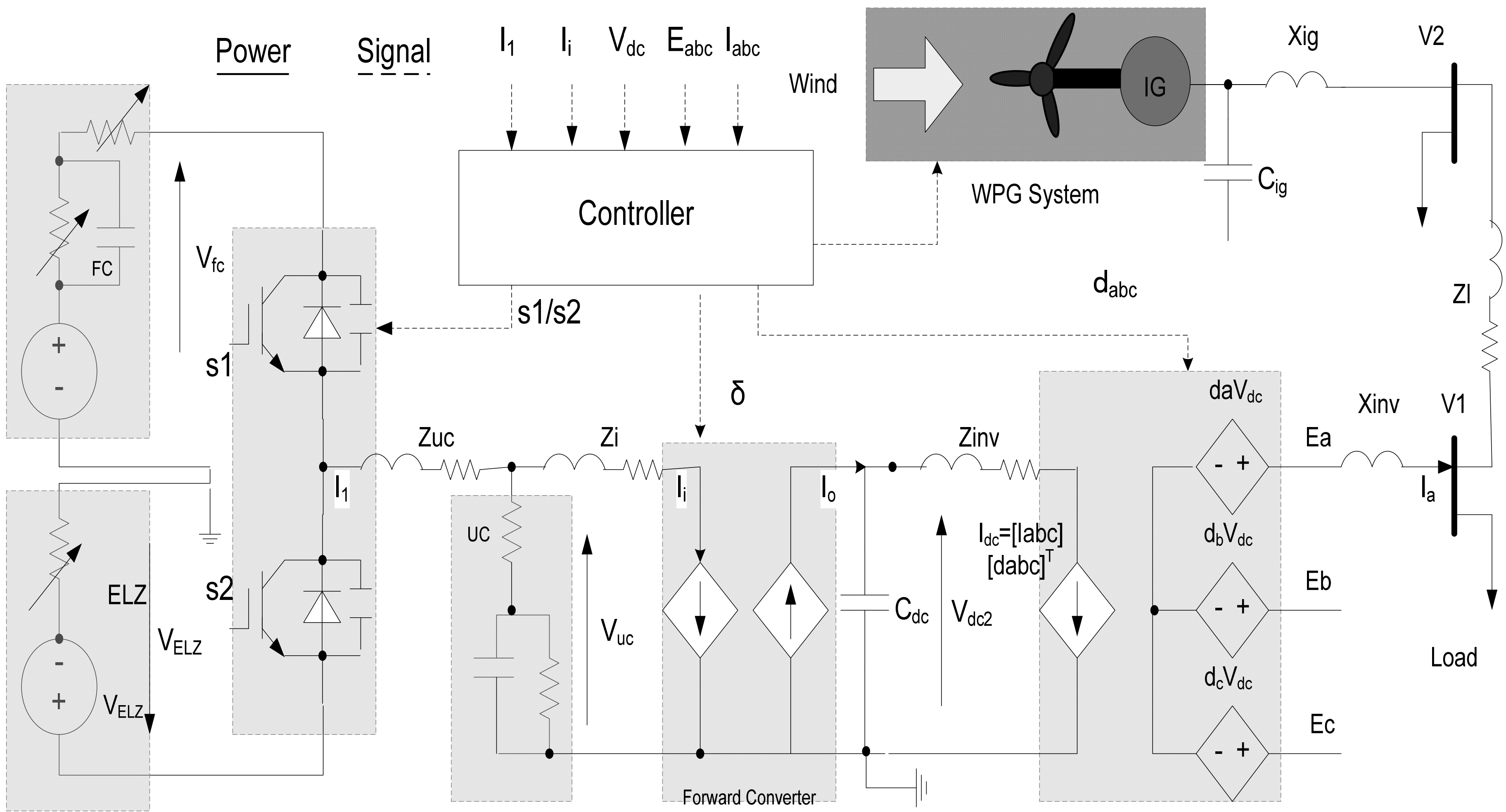
System Components

- Wind Turbine Generator (WTG) System
  - Wind Turbine and Generator
  - Power electronics interfaces (ac/dc to dc/ac)
- Electrolyzer/Fuel cell/ Ultracapacitor system
  - Hydrogen Storage and regulation
  - Oxygen flow regulation
  - DC/DC interfaces
  - DC/Ac interfaces

Proposed System



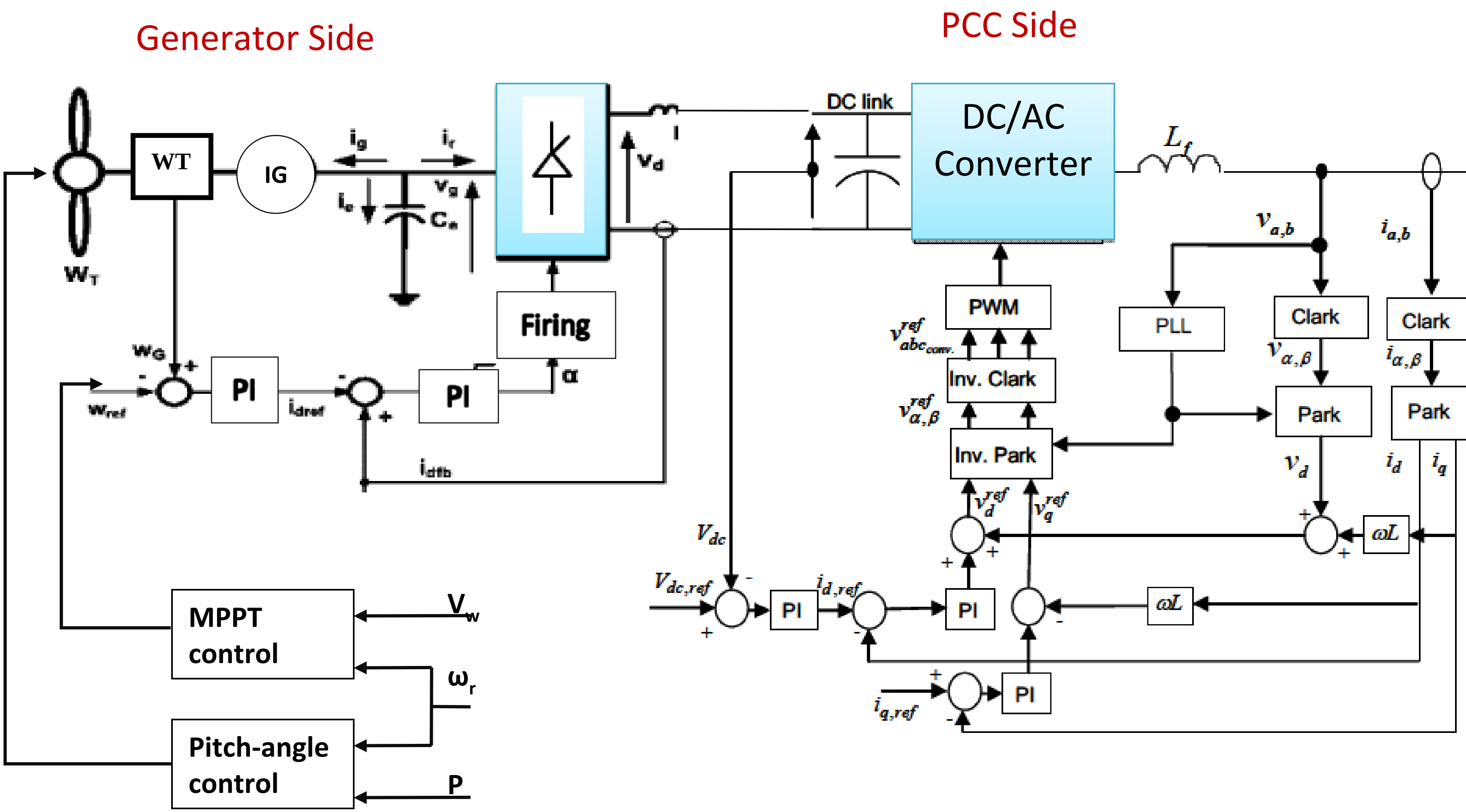
Proposed Scheme



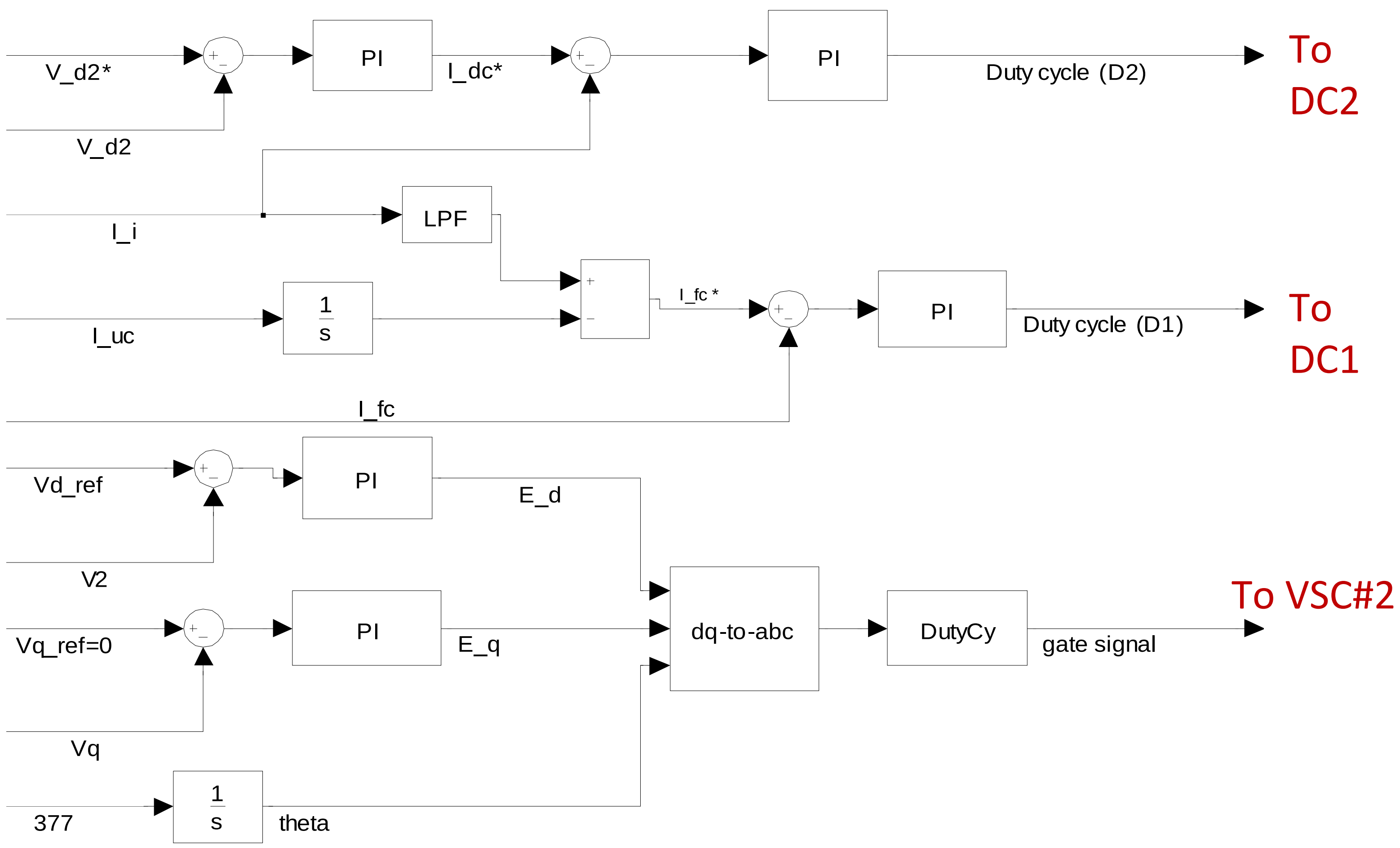
Modeling and Design of Controller

1. **WTG Controller**
   – Pitch angle control
   – Rotor speed control (MPPT)
   – DC voltage control
   – AC voltgae/Reactive power control
2. **ELZ/FC/UC Controller**
   – DC voltage control
   – AC bus voltage control
   – Frequency regulation
   – ELZ/FC current control
   – UC charge control

WTG Controller

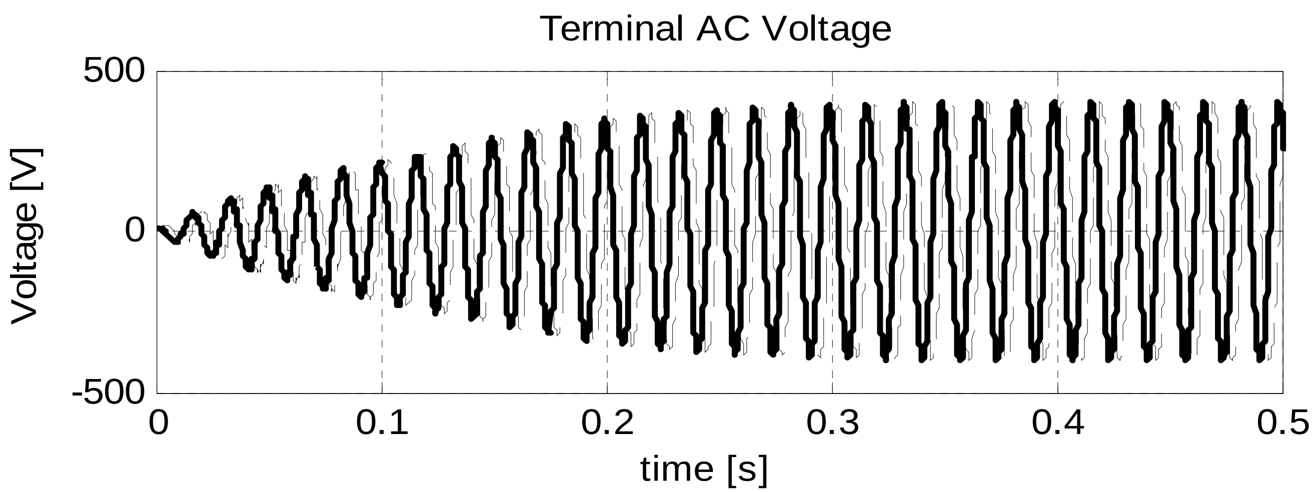


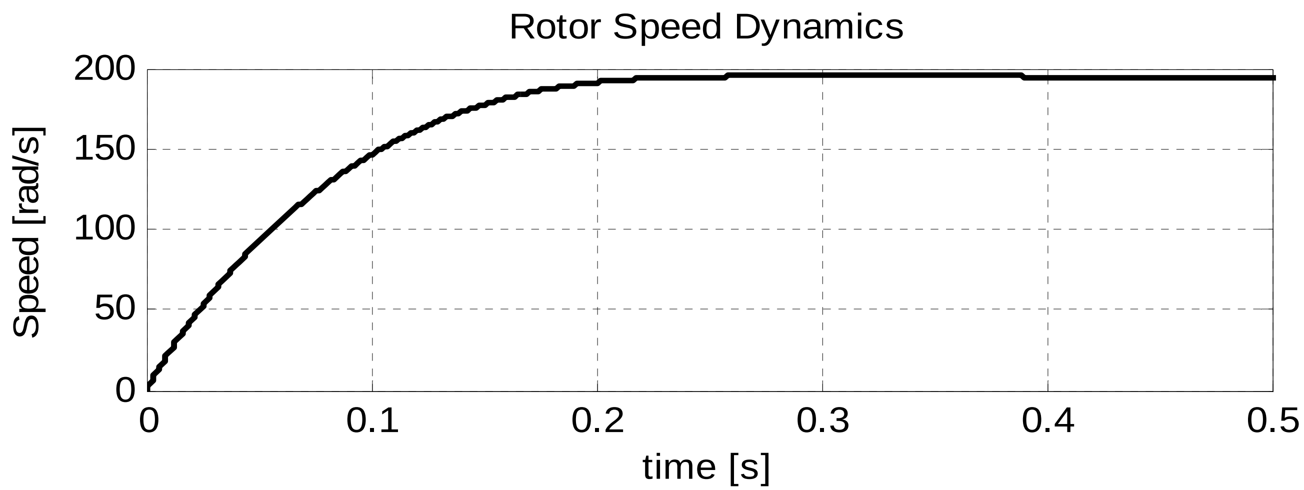
FC/UC Controller



Simulation

IG Voltage and Current Built-up Process





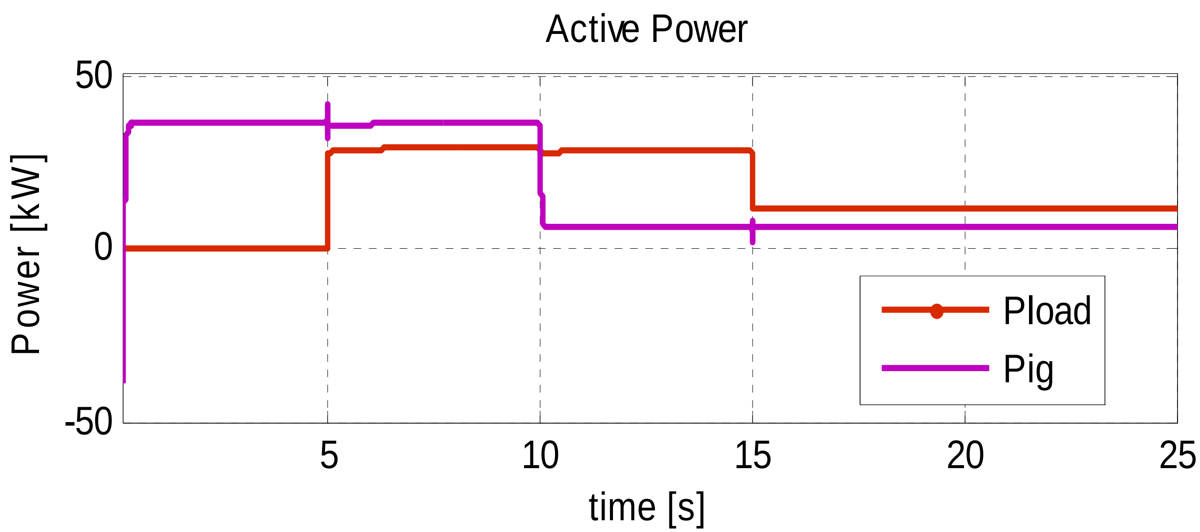
Simulation (Power Flow Dynamics)

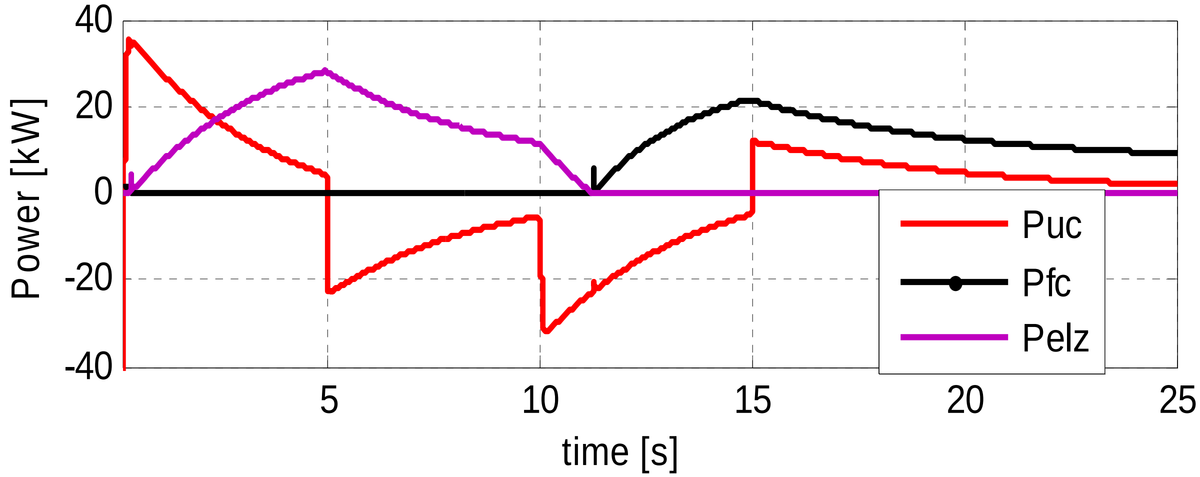
Sequence of disturbance

- t=5 s, load of 30 kW is introduced

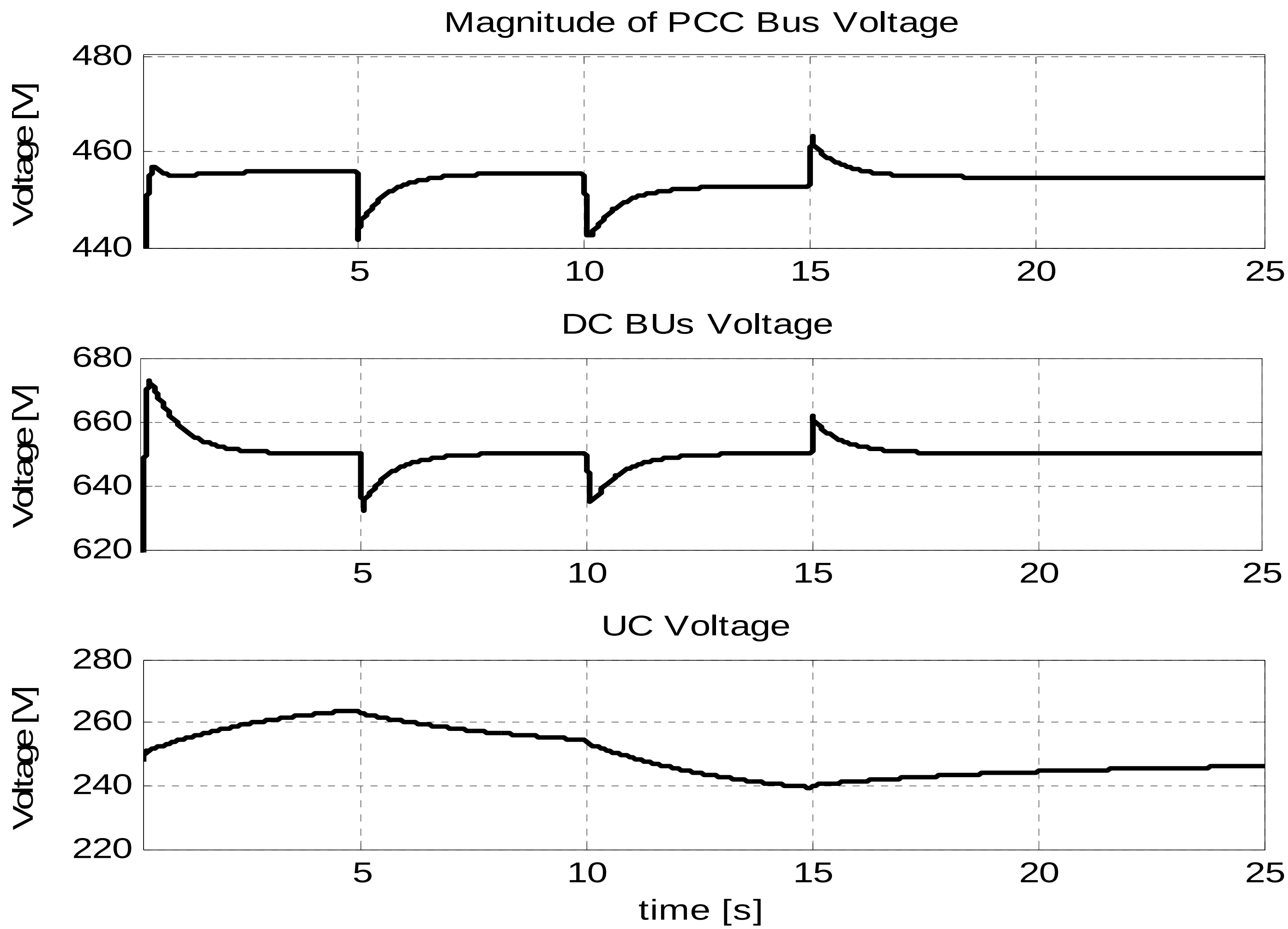
•t=10s, wind velocity increased from 7m/s to 10m/s.

•t=15 s, 15 kW load is released

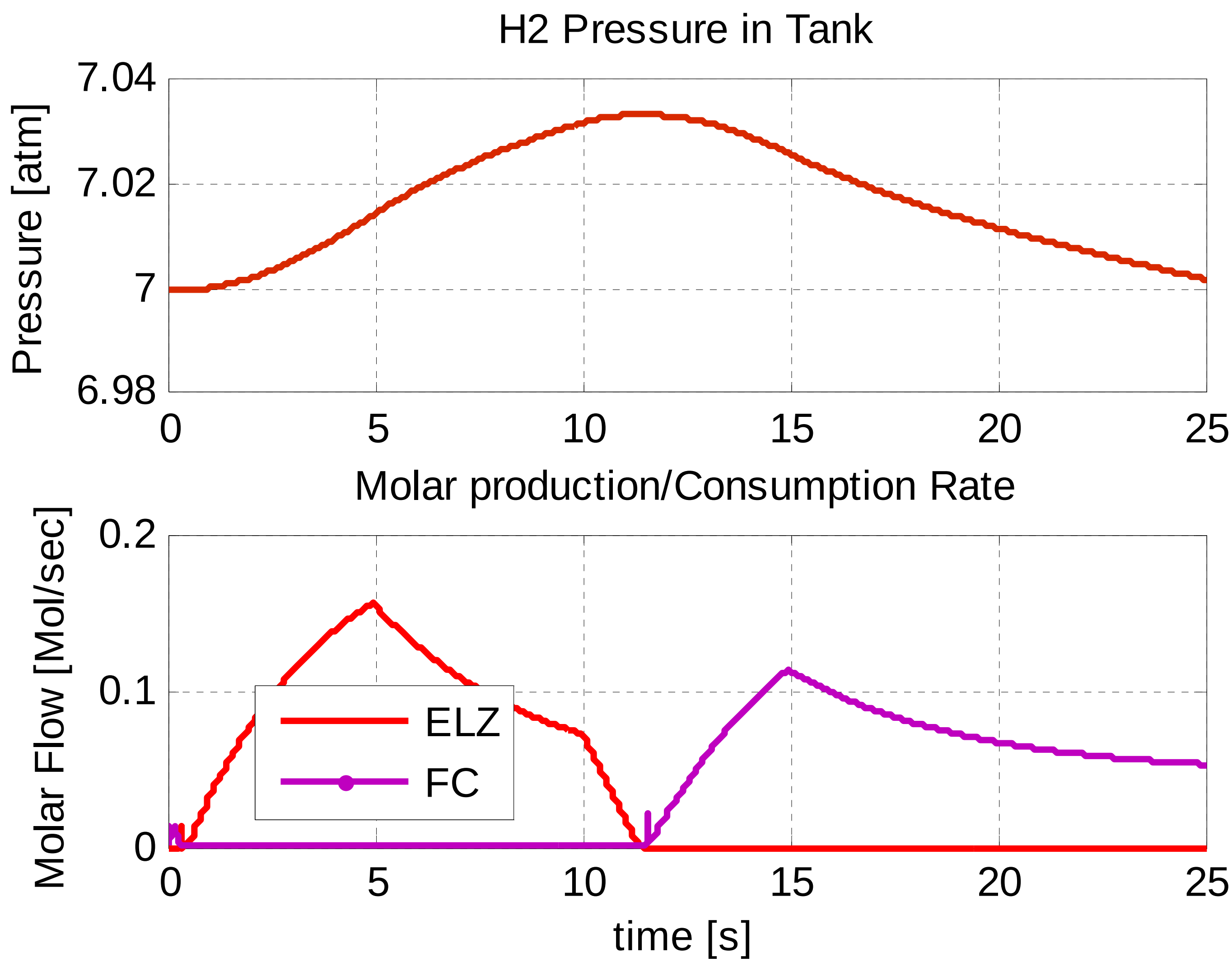




Simulation (Voltage Dynamics)

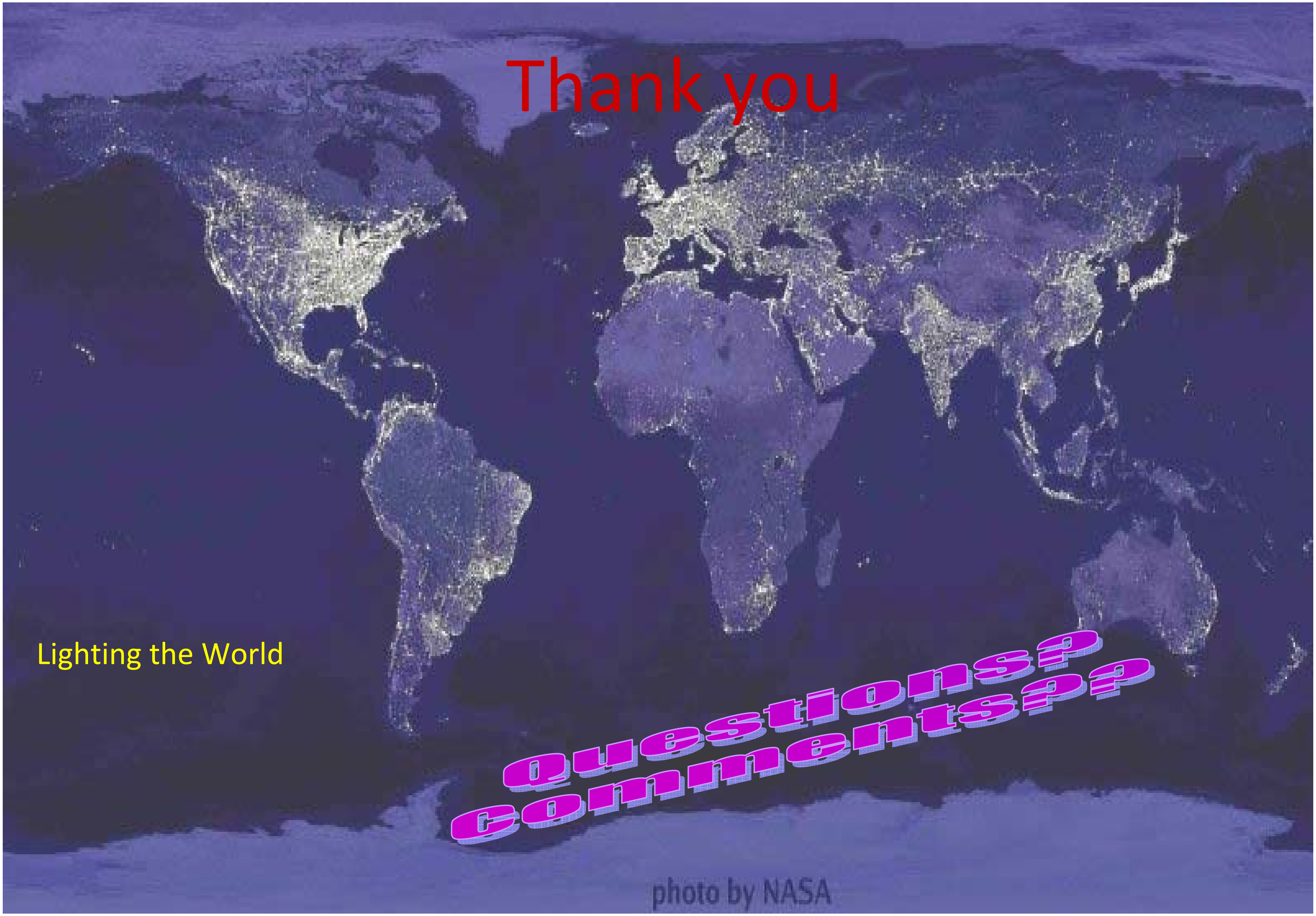


Simulation (Partial Pressure Dynamics)



Conclusion

- Wind power being non-dispatchable in nature, long-term, medium-term and short-term energy storage system are necessary for power and energy management.
- In a hybrid /stand-alone system, fuel-cell/hydrogen storage/electrolyzer can be used as mid-term and long-term energy storage and UC as Transient Load Mitigation.
- Simulation Results show that effective voltage and frequency regulation is achieved while fulfilling the operational requirements. Thus they validates the applicability of the proposed scheme in the real system
- Further simulation on worst case scenario and model Validation with real/experimental system is suggested to get further insight of the scheme
- The constraints for utilization of UC and FC/H_2 /ELZ with wind power system is the cost conversion effiecieny. The research on these technologies are going on, and in future, the cost effective and efficient solution is expected to achieve.


Thank you
Lighting the World
Questions?
Comments??
photo by NASA