# *PSE Challenges in Solar Research*

***CAPD Review Sunday March 11, 2012***

***B. Erik Ydstie***

| | |
|---|---|
| Solar grade silicon | (J. Du) |
| Float Process for Silicon Wafers | (G. Oliveros |
| Dye Sensitized Solar cells | (R. Panella |
| Solar and wind on the Grid | (J. Liu) |

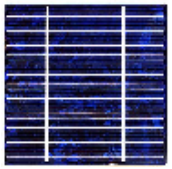
# Supply Chain for Silicon Solar Cells

PV System = Solar cell module + Balance of system (BOS)

*50% of system cost*

*30% of module cost*

Crystalline silicon → Wafer production → Cell fabrication



Solar-grade silicon

**REC Silicon, Moses Lake, WA**

***Fluidized Bed Si Production:***

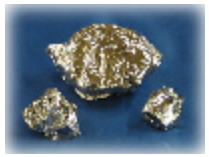
| | |
|---|---|
| 2002–2005 | Pilot plant |
| 2005–2007 | Demonstration scale |
| 2008 | Commercial scale |

*Aim: $20/kg*

*$40-60/kg*

IC supply chain

Metallurgical grade silicon → $SiCl_3H$ distillation → Decomposition Crystallization → Wafer → Integrated circuit



*$3-5/kg*

*$40-60/kg*

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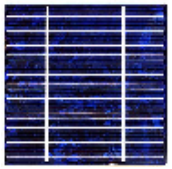

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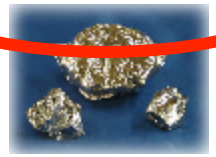

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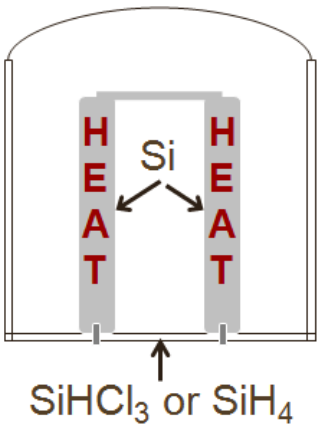
# Design and Control of Solar Silicon FBR process*From Silane to Solar Silicon*

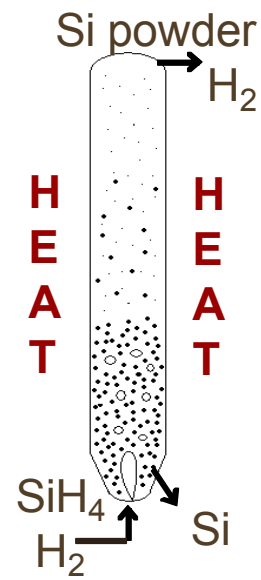
*Ron Reis REC Silicon, Paul Ege Reactech*
*2 PhD students*




Siemens Reactor
Batch Process
1100°C (TCS)
650 °C (Silane)

$$SiH_{4(g)} \rightarrow Si_{(s)} + 2H_{2(g)}$$

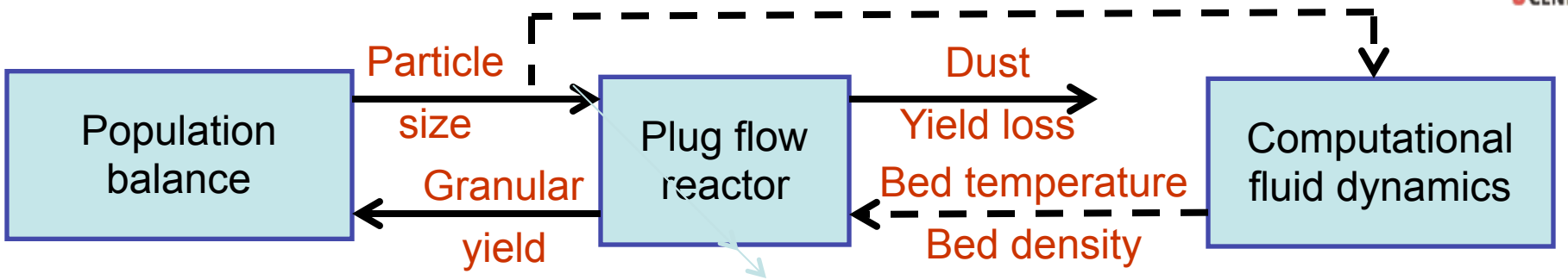
increase throughput
Reduce energy cost




Fluid Bed Reactor
Continuous Process
Large surface area
650 C

**Goal: develop scale-up and control models to optimize granular yield and control particle size.**

# Multi-scale Modeling Approach




*Particles are well-mixed*

Integrate over time for particle size distribution

*Gas and powder are plug flow*

Integrate over height for granular yield

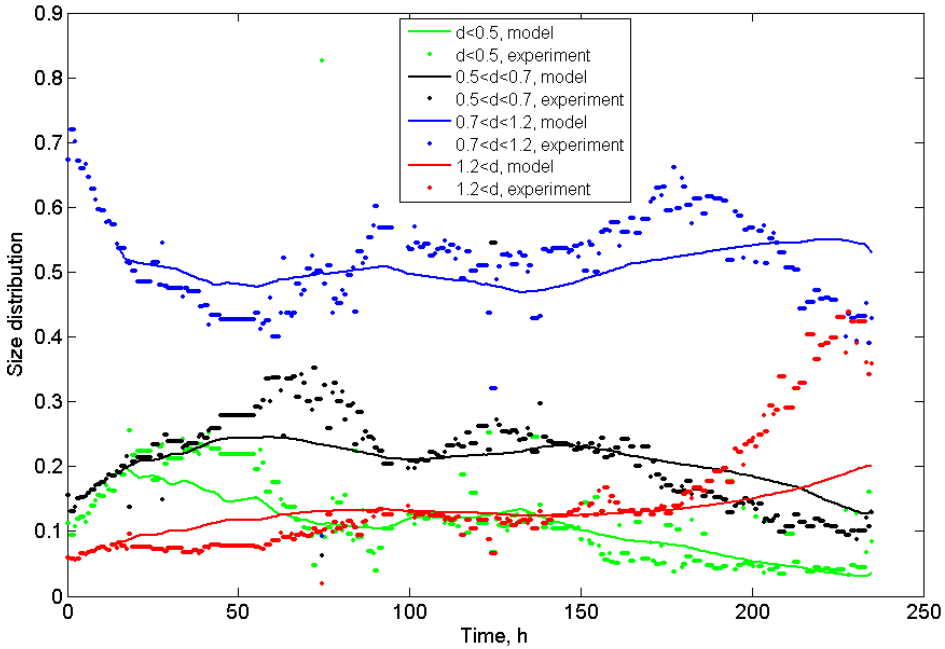
*Control fluidization regime*

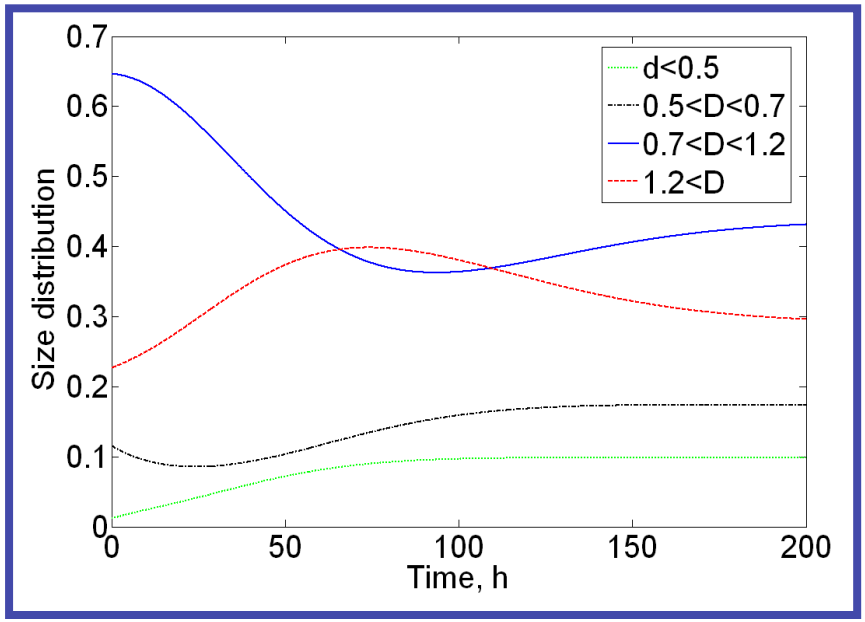
Simulate to obtain model input

**Operation challenges**

- Fast dynamics – fluidization, reaction
- Slow dynamics – particle size distribution
- Distributed parameters
  - *Particle size distribution*
  - *Chemical reaction, yield loss*
  - *Bed fluidization*

# Model Verification using Pilot Plant Data



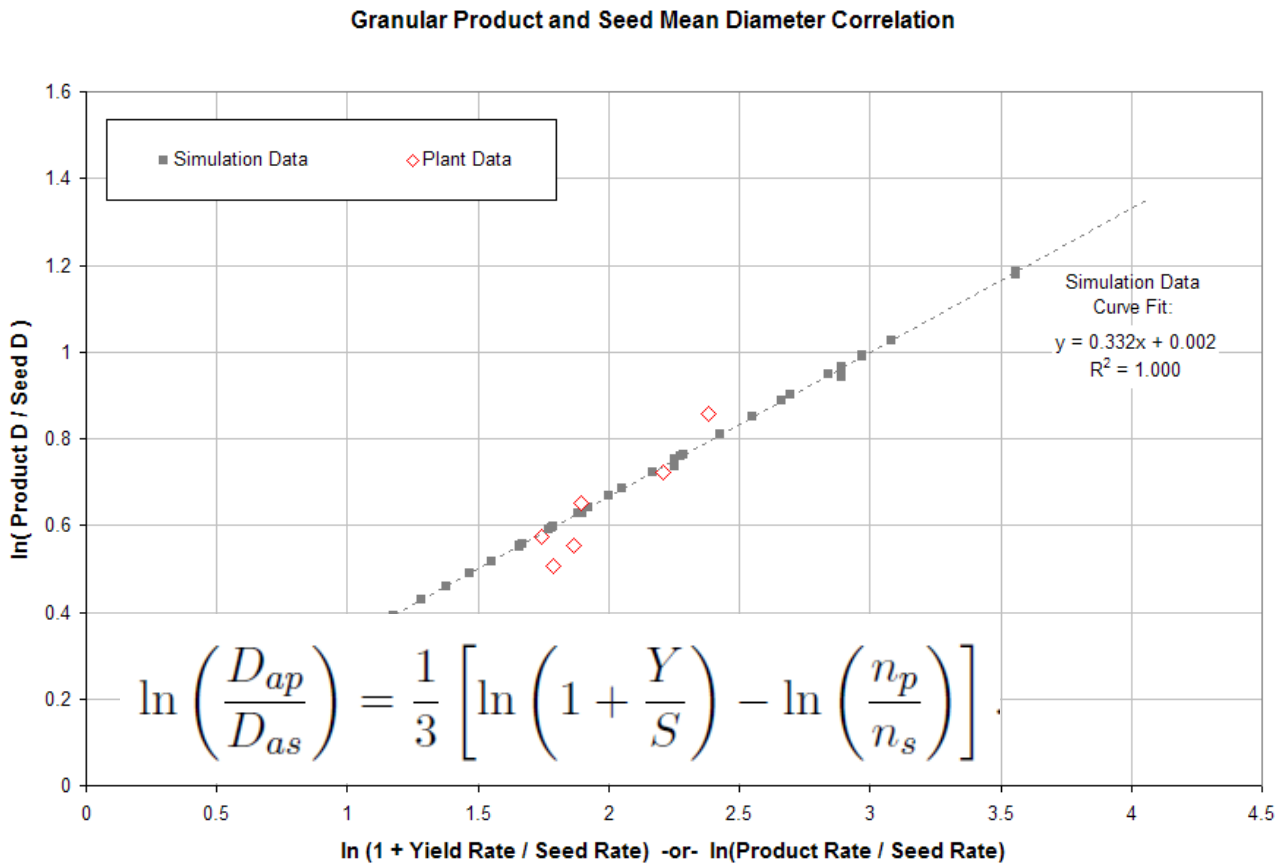




Time constant for particle size distribution about 50 hours.

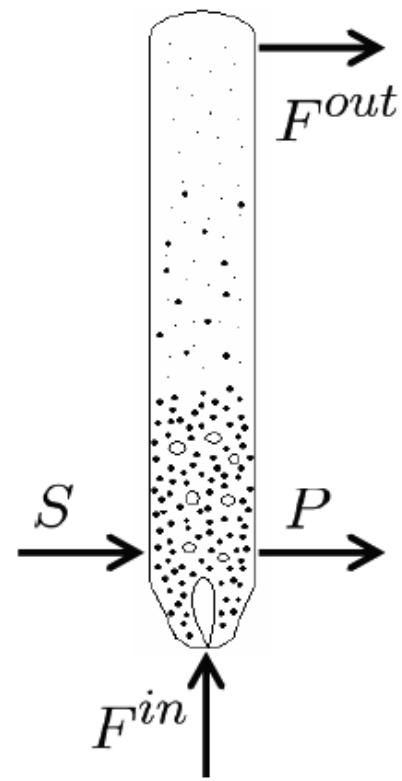
Weak control of distribution function

Difficult to control yield loss (sensitive system)

# Scale-up models: from pilot to demonstration plant




$$\ln\left(\frac{D_{ap}}{D_{as}}\right) = \frac{1}{3}\left[\ln\left(1+\frac{Y}{S}\right) - \ln\left(\frac{n_p}{n_s}\right)\right]$$




**Y-Yield**
**S-silane feedrate**
**D- average diameter(p - product, s-feed)**
**n- particle feedrate (p -product, s-feed)**

**Full Scale Production on Moses Lake in 2009**

- Multi-scale modeling
  - Captures physics of system (CFD, Chemistry, Population balance)
  - Useful for scale-up and design
  - Predicts process dynamics
- "Natural Discretization" of population balance
- New closure relation
- Stability and control (Juan Du)
- **REC Silicon's $970 million expansion project** in Moses Lake houses 24 fluid bed reactors to produce 6,500 metric tons of polysilicon per year
- Christy's Thesis has been "sold" from the library


Ground Breaking August 2006

Mar. 2008

Sept. 2008

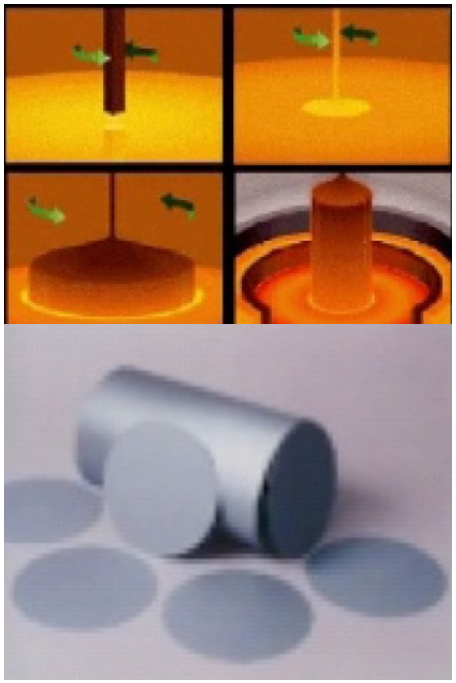
Production Nov. 2009

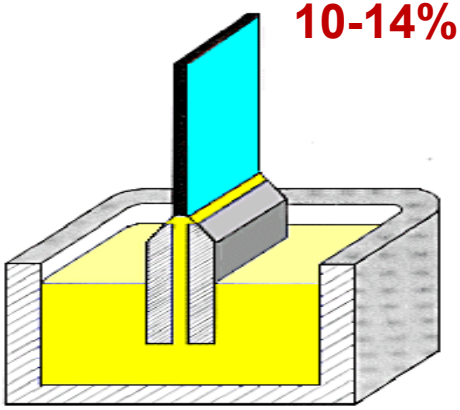
- NSF Graduate Research Fellowship Program
- REC Silicon
- Reactech Process Development Inc.

# Silicon Wafers using Float Process

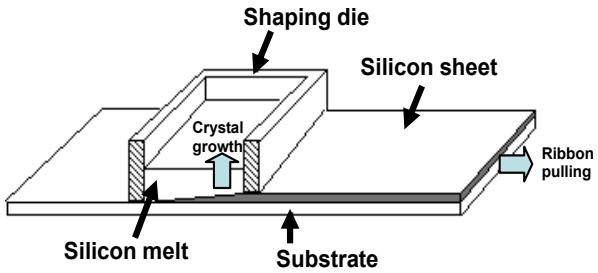
**Current methods are carried out in batch**
**Continuous processes yield inferior product**

| | |
|---|---|
| **Single crystalline** | **18-20%** |
| **Multi-crystalline** | **14-16%** |
| **EGF etc** | **10-14%** |





Edge-Defined Film
Fed Growth (EFG)





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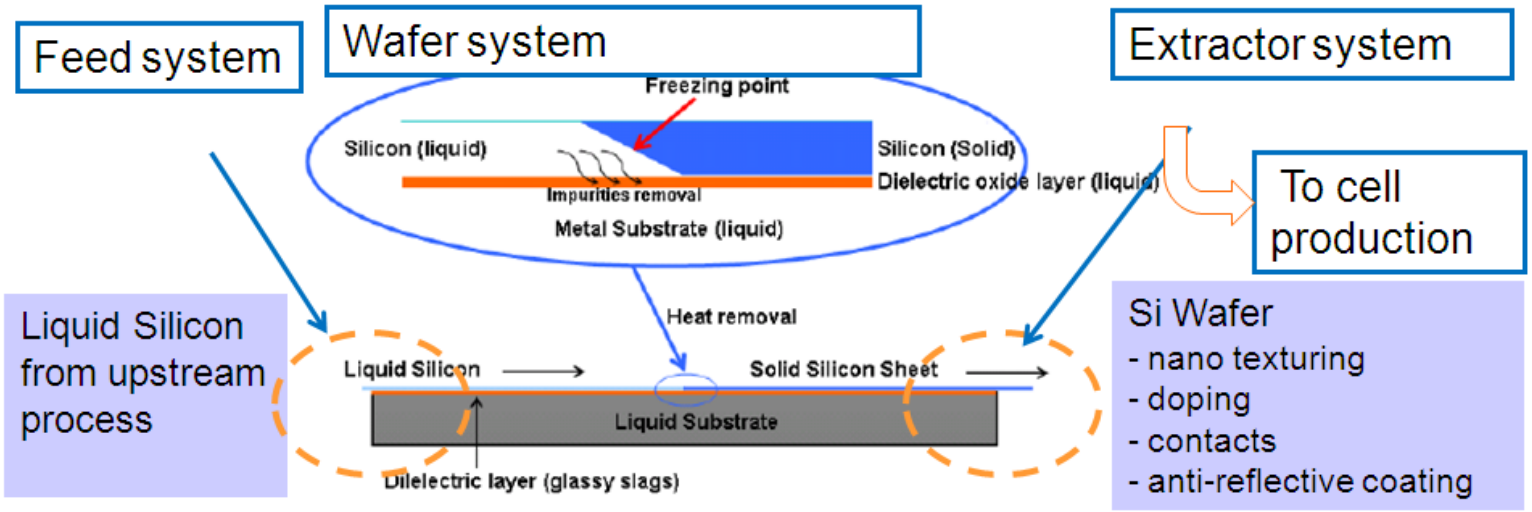
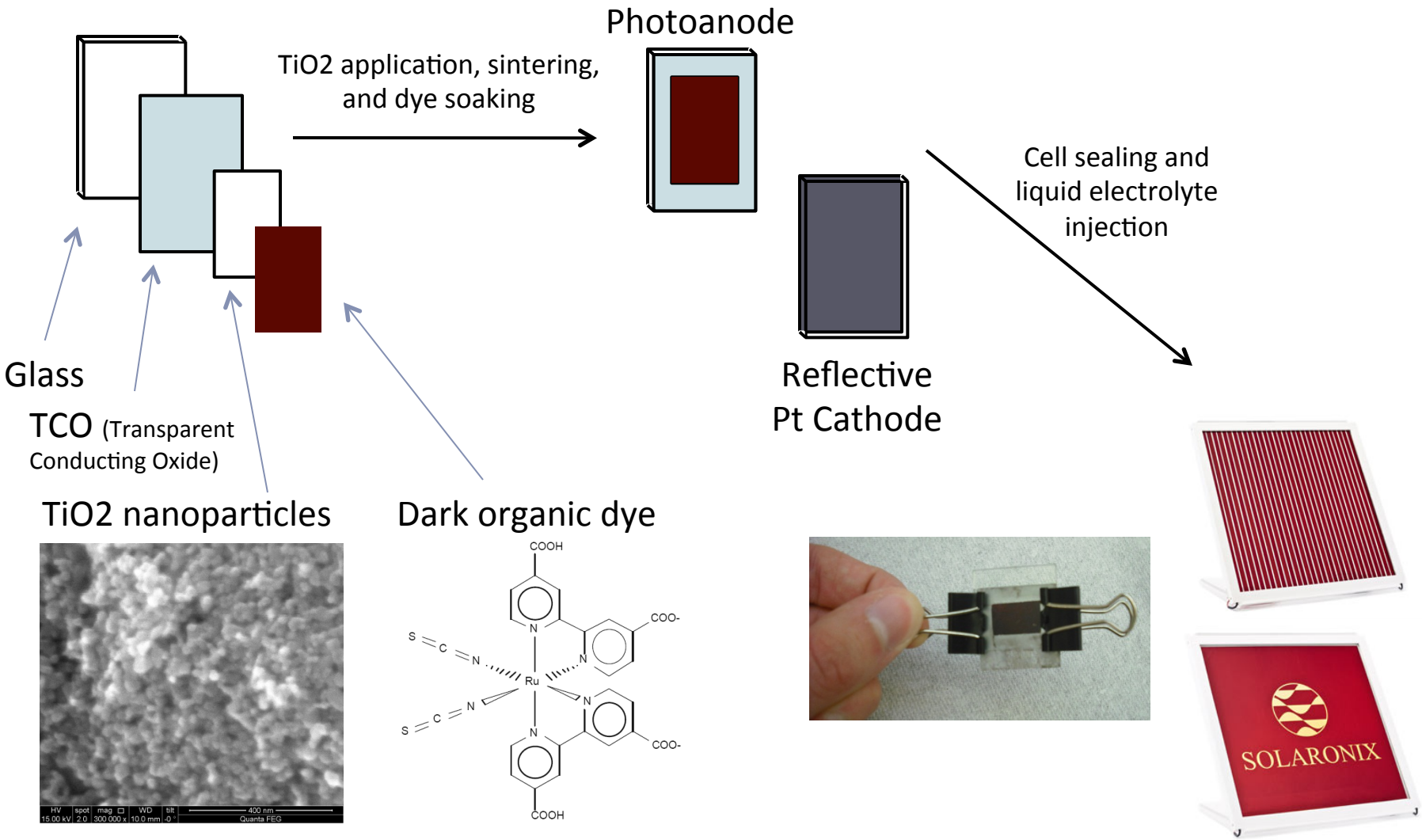
# Float Process for Silicon Wafers




**2009-2013 NSF and PA Nano grants to study**

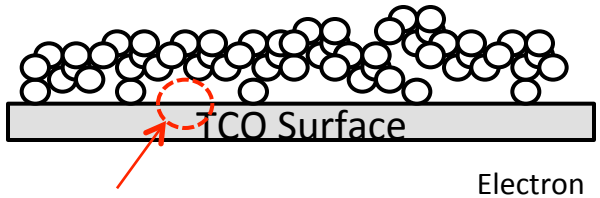
crystallization
fluid flow and heat flow
process scale-up and detailed design
process control
commercialization

# Dye Sensitized Solar Cell – Simple Construction



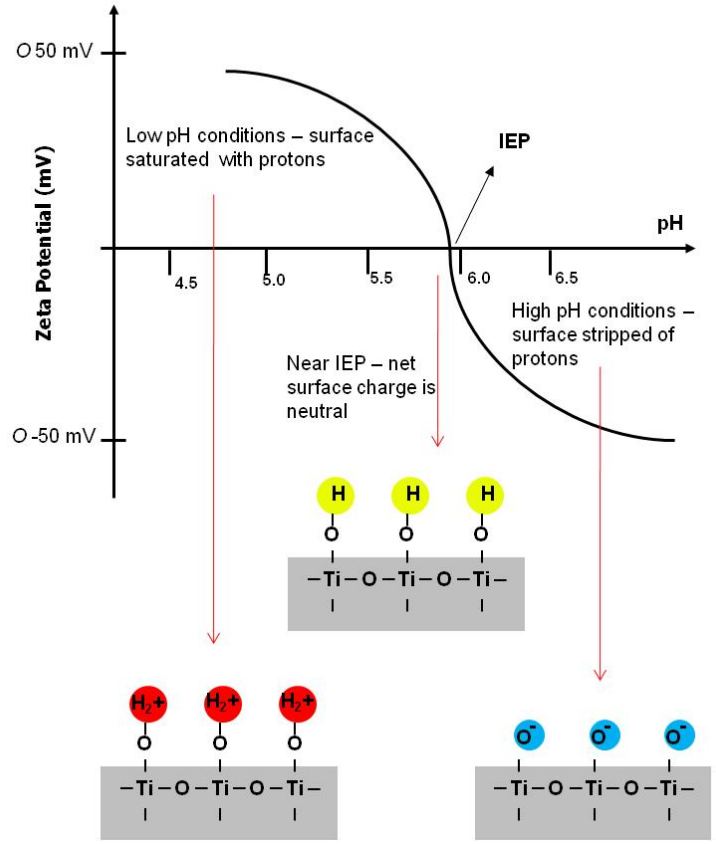
# Dye Solar Cell Issues – TCO Recombination

- Undesirable electrolyte interactions with TCO surface

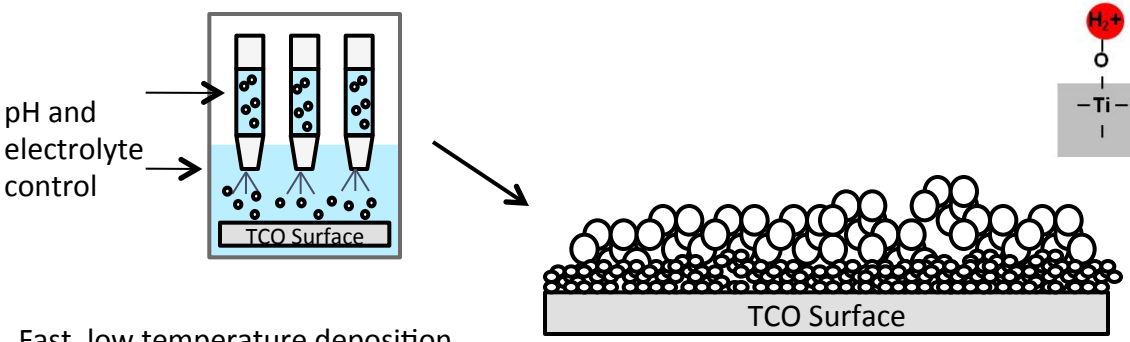



$2TCO^* + I_3^- \rightarrow 2TCO + 3I^-$

Electron recombination at TCO/ electrolyte interface

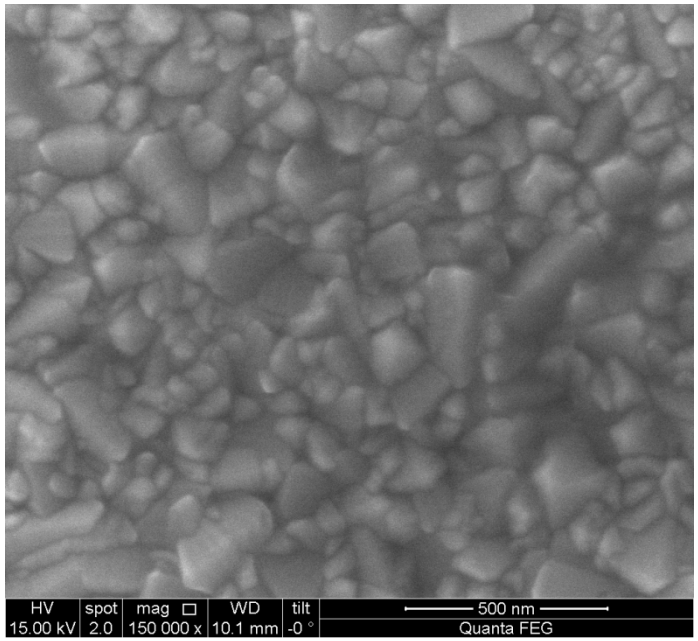



- Stop recombination by applying smaller titania nanoparticles under aqueous conditions

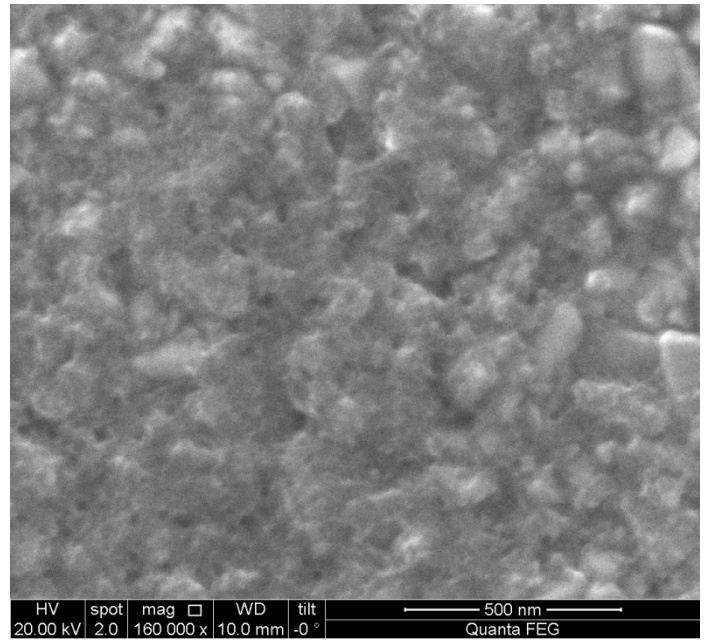



Fast, low temperature deposition

# Application of Deposited Particles to Operating Cells



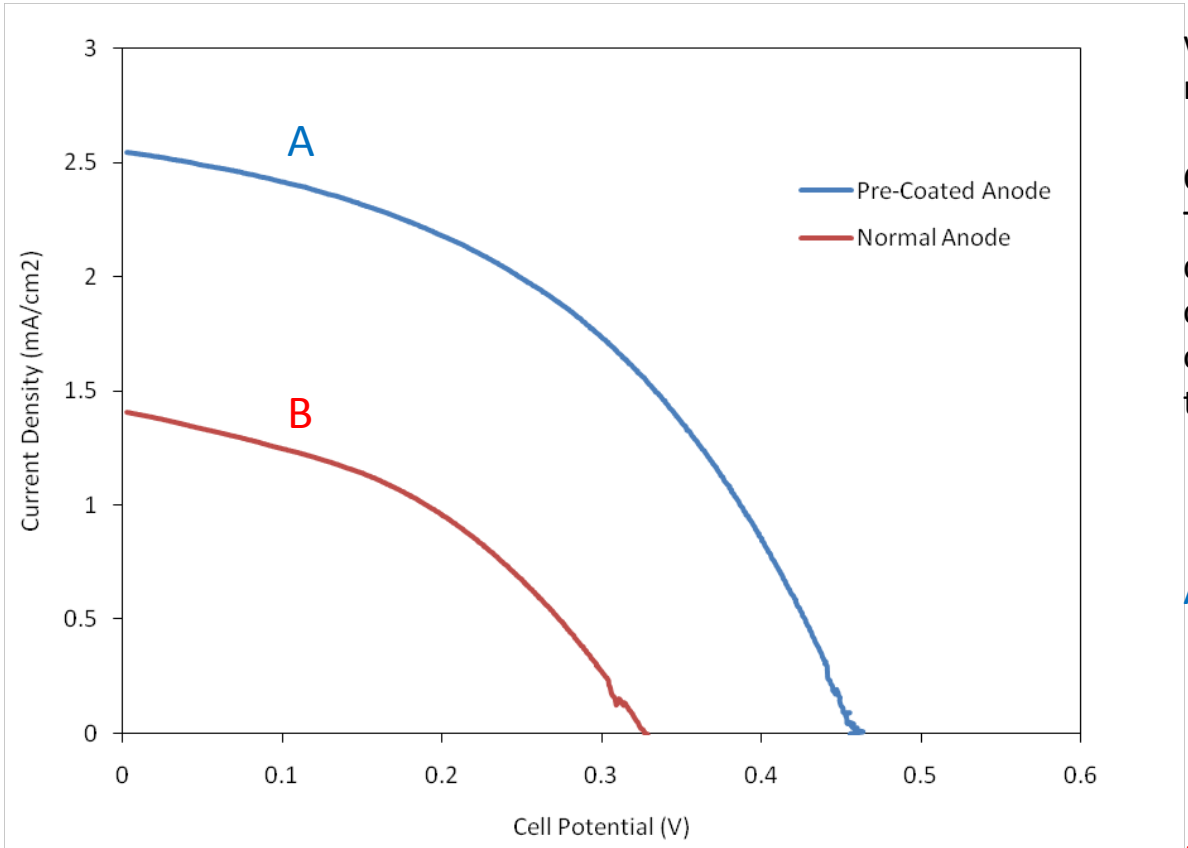

10 Ω/□ FTO under 150k magnification SEM
Crystalline nature encourages light scattering




10 Ω/□ FTO which has been exposed to $TiO_2$ nanoparticles under adsorbing conditions

Small, 10 nm particles are able to strongly adsorb to the FTO surface

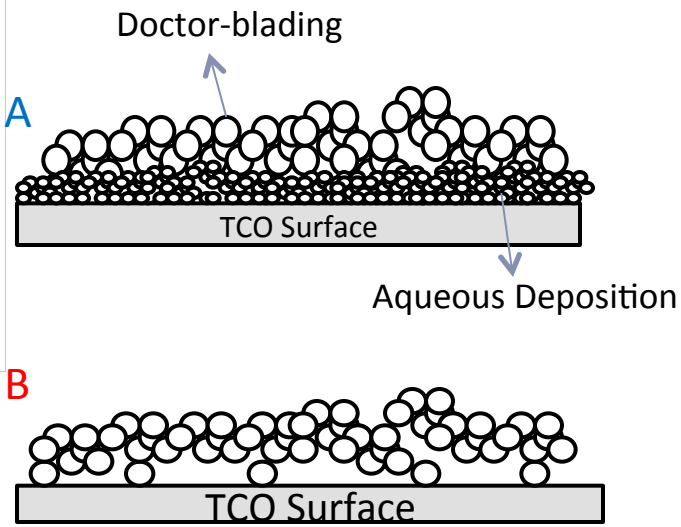
# Solar Results




| | I (short circuit) mA/cm2 | V (open circuit) | Fill Factor | IPCE |
|---|---|---|---|---|
| "Pre" Coated Cell | 2.55 | 0.46 | 0.441 | 0.52% |
| Standard Cell | 1.41 | 0.33 | 0.417 | 0.19% |

The pre-coated anode has been treated with an impinging jet with 10 nm $TiO_2$ nanoparticles.

On top of this, a ~30 µm layer of 25 $TiO_2$ particles has been applied by doctor-blading and drying a concentrated slurry. The normal anode only has the doctor-bladed layer, not the 10 nm layer.



# Frequency Control in Systems with Wind Power

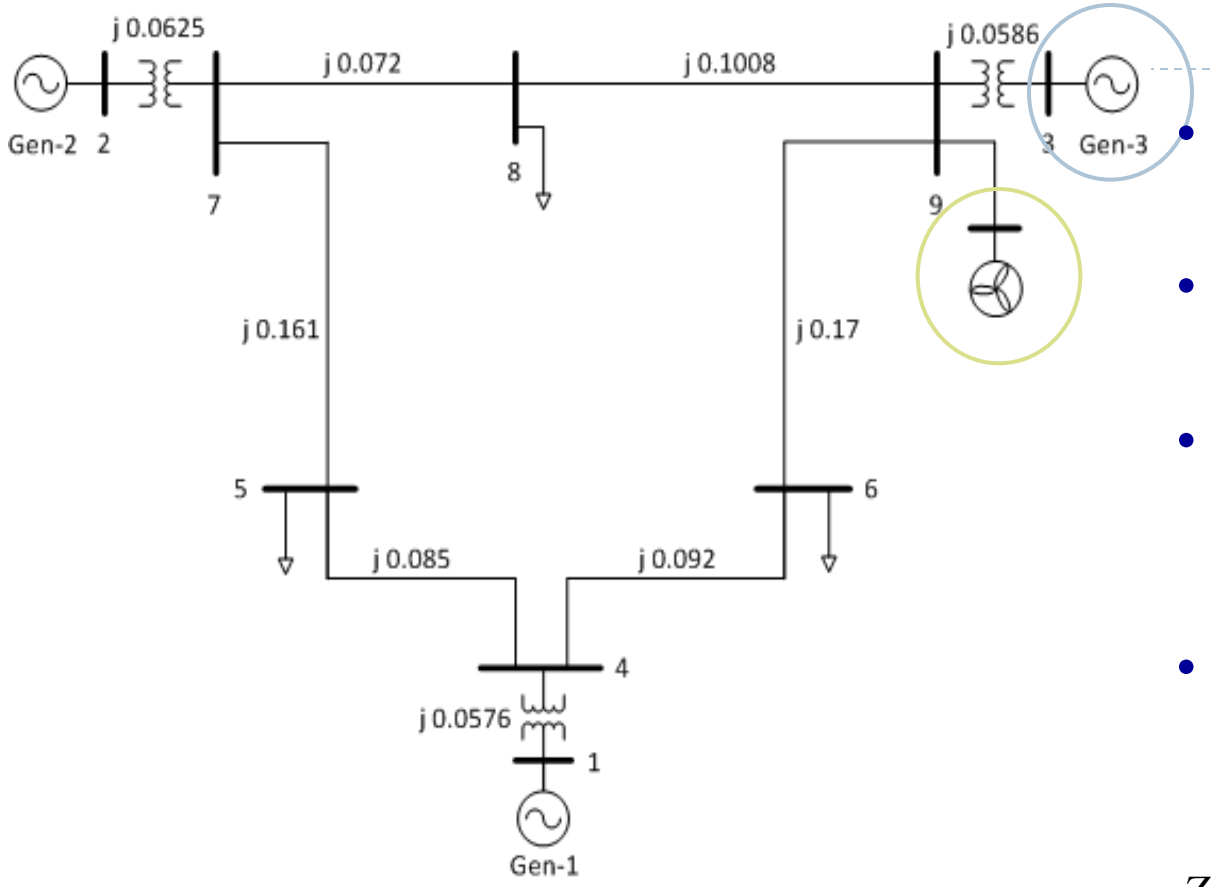
***Project with PITA***

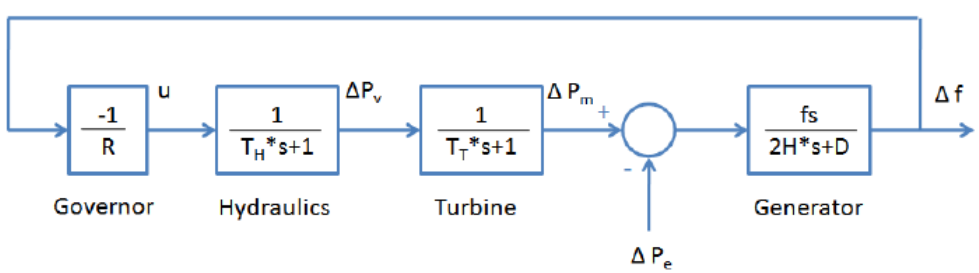
***Juhua Liu (PhD), Bruce Krogh (ECE)***

- 2.5% of worldwide electricity at the end of 2010
- 2.3 % (41.4GW) in USA
- Rapid growth worldwide (27.6% over past 5 years)
- High expectation (U.S. 20% by 2030)

- Wind fluctuations → deviation from 60Hz.
- Conventional generation compensates (slow
- Need for decentralized approaches for stability analysis and design
- Our Approach: Use thermodynamic stability analysis ***(entropy as "Lyapunov function")***

# IEEE WECC 9-Bus Test Case



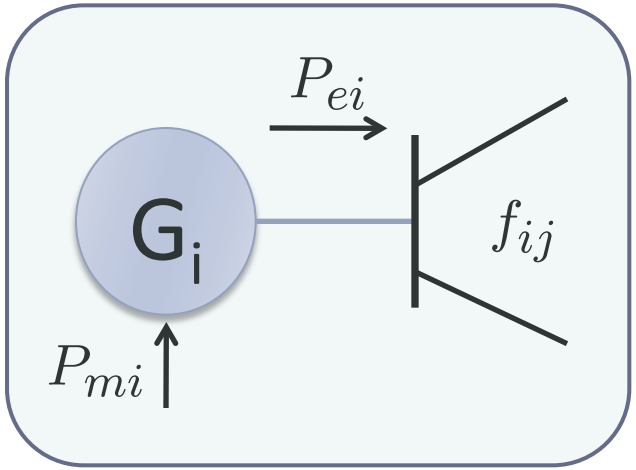

- Wind farm about 25% of system capacity
- Wind power fluctuation ±5% of average power
- Redesign Gen-3's governor for frequency control
- The system is passive

$$Z = \frac{1}{2} J\omega^2$$ Kinetic energy

$$S = -\frac{2}{3}\sqrt{\frac{2}{J}} Z^{\frac{3}{2}}$$ Entropy

$$\frac{\partial S}{\partial Z} = \pm\omega$$ Angular velocity

## Generator Model: Swing Equations (per unit)



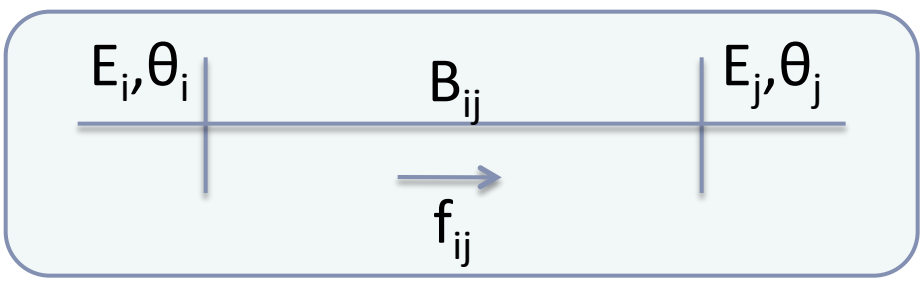

$$\dot{\theta}_i = \omega_i - \omega_0$$

$$\frac{2H_i}{\omega_0}\dot{\omega}_i = T_{mi} - T_{ei} - K_{Di}(\omega_i - \omega_0)$$

$$\omega_0 = 2\pi 60 \ rad/s \qquad P_{mi} = T_{mi}\omega_i/\omega_0$$

$$P_{ei} = T_{ei}\omega_i/\omega_0 \qquad P_{ei} = \sum_{j=1, j\neq i}^{n} f_{ij}$$

## Network Model: DC Power Flow




$$f_{ij} = E_i E_j B_{ij} \sin\left(\theta_i - \theta_j\right)$$

$$f_{ij} \approx E_i E_j B_{ij}\left(\theta_i - \theta_j\right)$$

$$f_{ij} = -f_{ji}$$

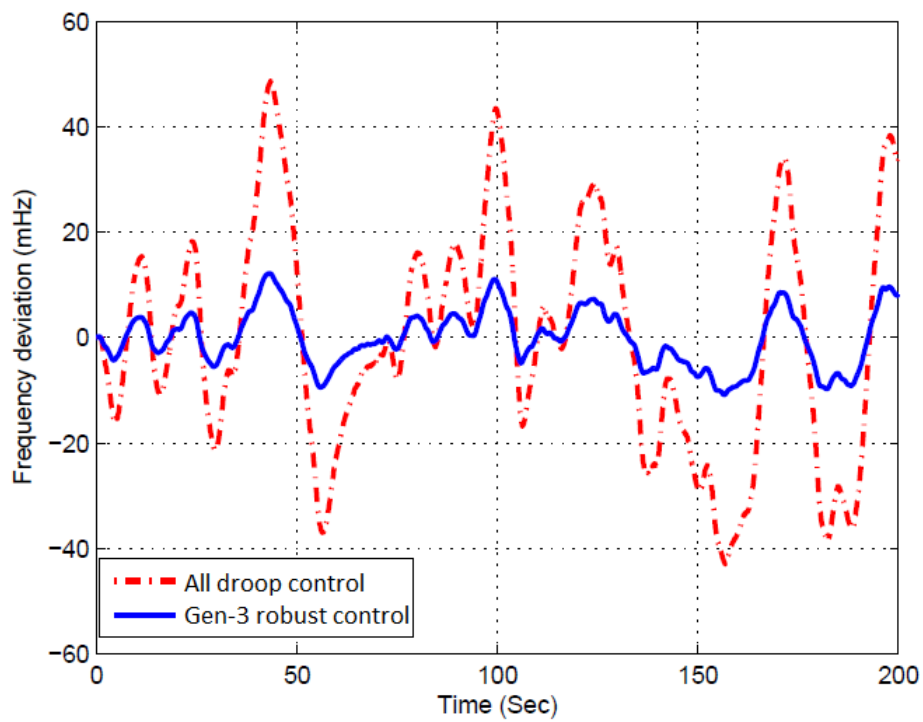
$B_{ij}$: susceptance

# Performance Evaluation

- Gen-3 on robust $H_{infinity}$ control, others on droop control (PI)

$$G_{C3} = \frac{8460s^2 + 5579s + 2.411E5}{s^3 + 6349s^2 + 1.444E5s + 2.284E5}$$

Frequency deviation




Closed-loop gain from $P_W$ to $\omega_3$