Carnegie Mellon

Electric Energy Systems Group

Electrical & Computer ENGINEERING

A Modeling and Control Approach to Ensuring Intra-Dispatch Regulation Power Reserves

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System Balancing

A Two-Step Approach

Scheduling
Unit Commitment
Dispatch (LHD/ALM)

Error Balancing
Power Balancing
Stabilization

Intra-Dispatch Real Power Balancing

Load Following

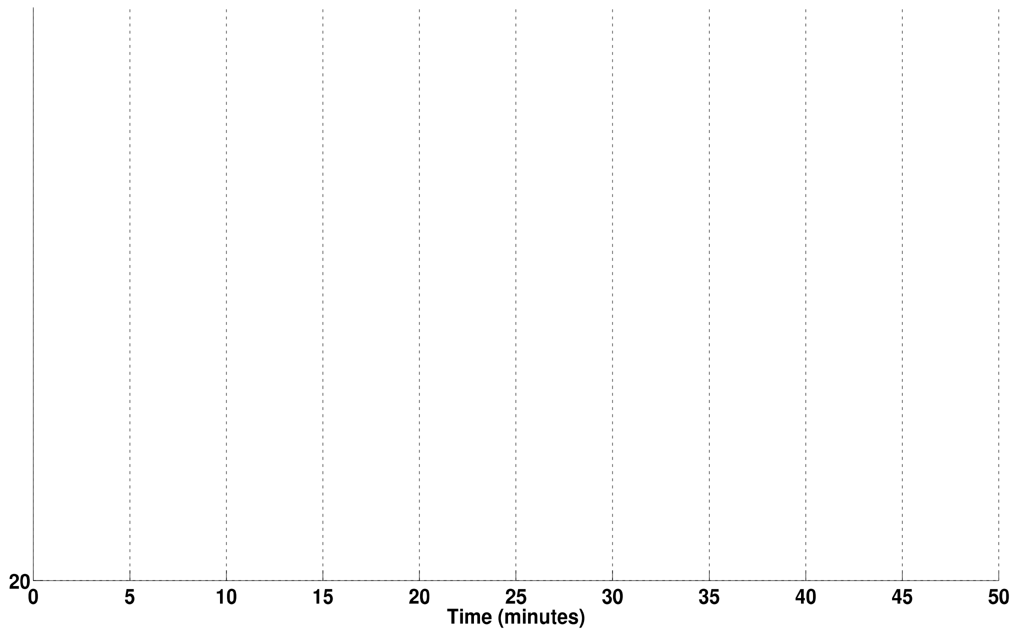
- *Prediction Error in Load*
- *Intra-Dispatch Variations in Load*

Conventional Approach

- *Hour Ahead Load Curve projected- Data-History*
- *Generators are Ramped Up*
- *Remaining Error picked-up by AGC*

Granularity of Scheduling & Balancing Wind

- Flores Island



How Wind affects Intra-Dispatch Balancing?

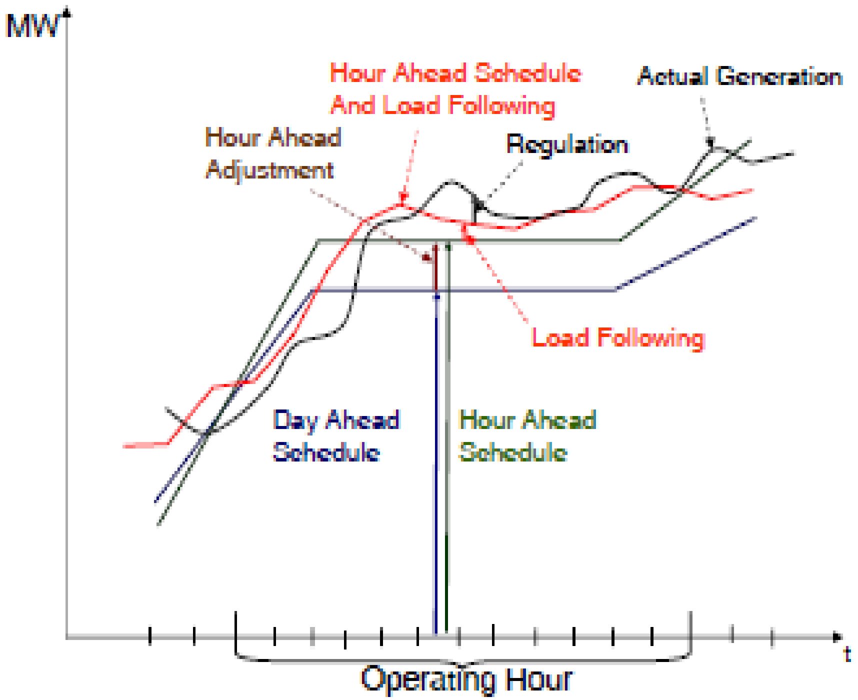
Following System Imbalances under Wind Penetration

- *Increased Variability in Intra-Dispatch time-frame*
- *Wind Speed: Lack of Rich Data History*
- *Short-Term Forecasting Error Prone*
- *Inconsistent Correlation with Load Swings*

Consequences

- *Increase in Load/Wind following Requirements*
- *Hard-to-define Ramp Rates for Wind*
- *Large Error left-over for AGC*

Power Balancing: Conventional Approach

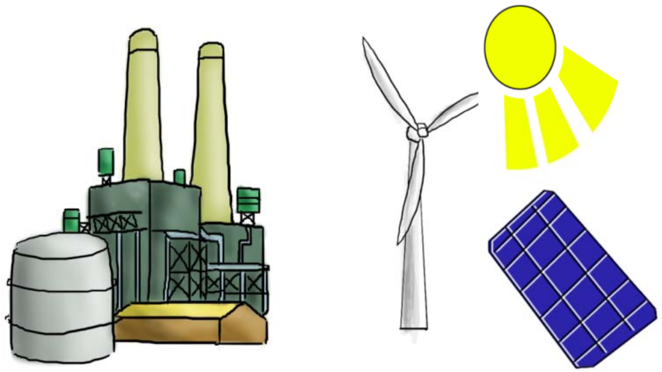


SOURCE: Y. Makarov, C.Loutan, J. Ma, P. Mello, S. Lu 'Impacts of Wind Generation on Regulation and Load Following Requirements in the California System' PES General Meeting-Conversion & Delivery of Electrical Energy in 21st Century 2008 IEEE

Managing Heterogeneity

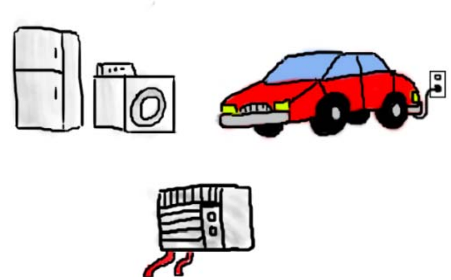
Sources & Sinks of Energy

- **Sources**



- *Controllable*
- *Dispatchable*
- *Time-Scale of Technology (Combustion/Hydro/Wind)*

- ***Sinks***



- *Controllable*
- *Responsive*
- *Size & Time-Scale Type (Inductive or Resistive)*
- *Residential/Commercial/Industrial*

Intra-Dispatch Power Balancing

Proposed Approach

- *Automated Feedback Control*
- *Based on Quasi Stationary Concept*
- *Formal Mathematical Model for Quasi-Stationary Power Balancing*
- *Power Imbalance: Feedback Signal*
- *AGC responds to Frequency Offsets*

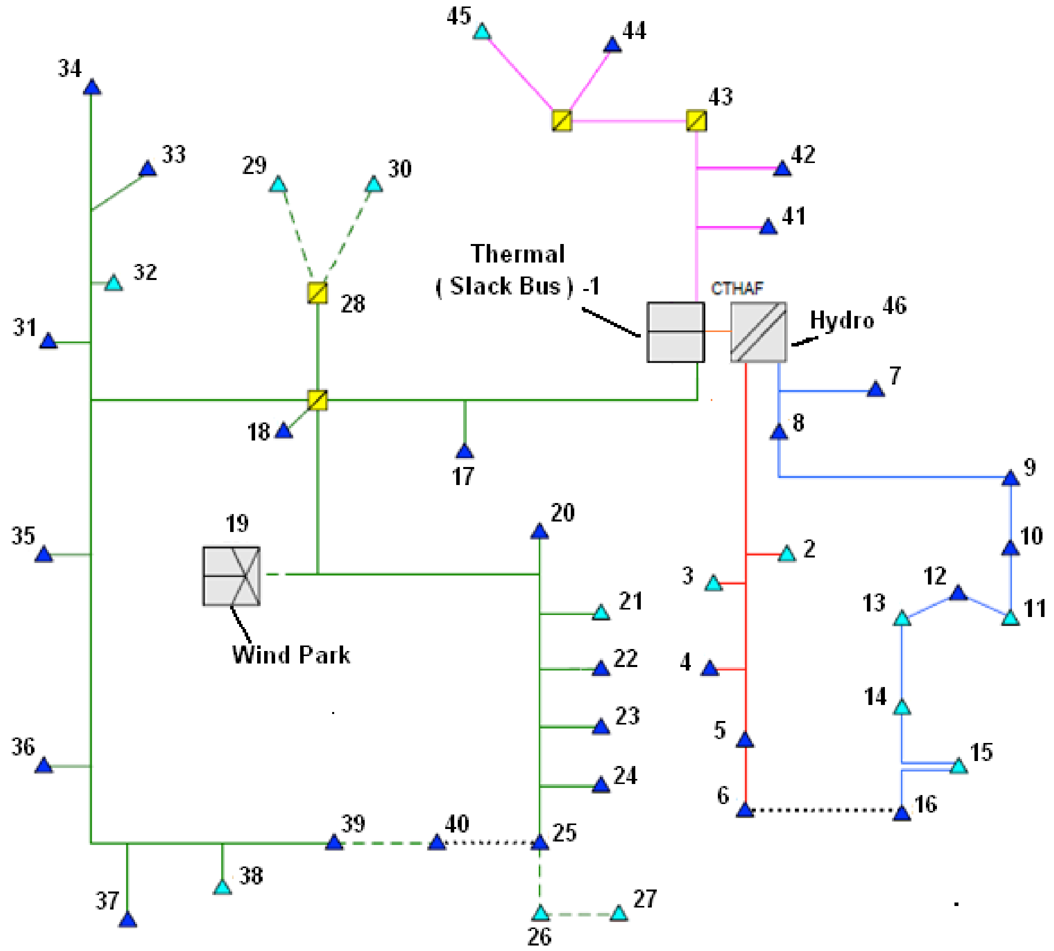
Flores Island Network

Network

- *45-Bus Radial*
- *2 MW Demand*
- *Mix of Generation: 4-Hydro (1.7 MW), 4-Diesel (2.5 MW), 2-Wind (0.66 MW)*

Wind

- *Wind ~ 14% Installed Capacity*
- *Scheduled Wind ~ 21% Total Demand*



Generation Dynamics of Energy Resources

- ***Hydro***

0

$$\begin{bmatrix}\dot{\omega}_G\\ \dot{q}\\ \dot{v}\\ \dot{a}\end{bmatrix} = \begin{bmatrix} -\frac{(e_h+D_h)}{M_h} & k_q & 0 & -k_w \\ [illegible] & [illegible] & [illegible] & [illegible] \\ 0 & 0 & -\frac{1}{T_e} & \frac{r'}{T_e} \\ -\frac{1}{T_s} & 0 & \frac{1}{T_s} & -\frac{(r_h+r')}{T_s}\end{bmatrix}\begin{bmatrix}\omega_G\\ q\\ v\\ a\end{bmatrix} + \begin{bmatrix}0\\ 0\\ 0\\ \frac{1}{T_s}\end{bmatrix}\omega_G^{ref} + \begin{bmatrix}-\frac{1}{M_h}\\ 0\\ 0\\ 0\end{bmatrix}P_G$$

- ***Diesel***

0

$$\begin{bmatrix}\dot{\omega}_G\\ \dot{V}_{CE}\\ \dot{W}_F\\ \dot{W}_{Fdot}\end{bmatrix} = \begin{bmatrix} -\frac{D_d}{M_d} & 0 & \frac{c}{M_d} & 0 \\ [illegible] & [illegible] & [illegible] & [illegible] \\ 0 & 0 & 0 & 1 \\ 0 & \frac{a}{\alpha} & -\frac{\gamma}{\alpha} & -\frac{\beta}{\alpha}\end{bmatrix}\begin{bmatrix}\omega_G\\ V_{CE}\\ W_F\\ W_{Fdot}\end{bmatrix} + \begin{bmatrix}0\\ [illegible]\\ 0\\ 0\end{bmatrix}\omega_G^{ref} + \begin{bmatrix}-\frac{1}{M_d}\\ 0\\ 0\\ 0\end{bmatrix}P_G$$

N. Popli, M. Ilić, Modeling & Control Framework to Ensure Intra-Dispatch Regulation Reserves, Book-Chapter, The Case of Low-Cost Green Azores Islands

Generator's Steady State Droop

Steady State Gain/Steady State Droop

$$G\,\omega_G[K] = \frac{1}{\sigma_G}\omega_G[K] = -P_G[K]$$

Gain

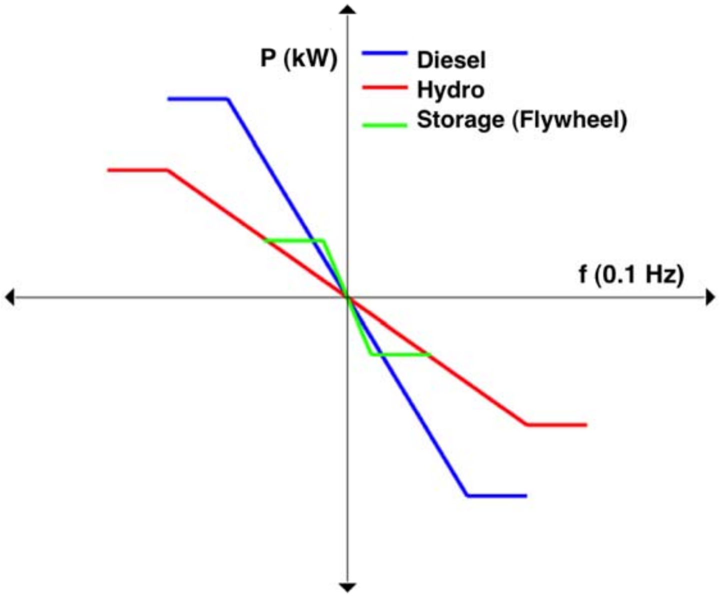
Droop

- ***Hydro***

$$G_H = \frac{1}{\sigma_H} = \left(e_h + D - \frac{k_q T_q}{T_f} + \frac{k_q T_q}{r_h T_w} - \frac{k_w}{r_h}\right)$$

- ***Diesel***

$$G_D = \frac{1}{\sigma_D} = \left(D + \frac{c K_D a}{\gamma}\right)$$



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Design of Control Gain

❖ **Power Model of Island's Grid**

$$P_{G_C}[K+1] = AP_{G_C}[K] + B\omega_{G_C}^{ref}[K] + W\left(P_W[K+1] - P_W[K]\right)$$

Control Input

❖ *Tracking Wind Variations*

$$\omega_{G_C}^{ref}[K] = -B^{-1}W\left(P_W[K] - P_W[K-1]\right)$$

❖ *Full-State Feedback Gain*

$$\omega_{G_C}^{ref}[K] = -(k)(P_G[K])$$

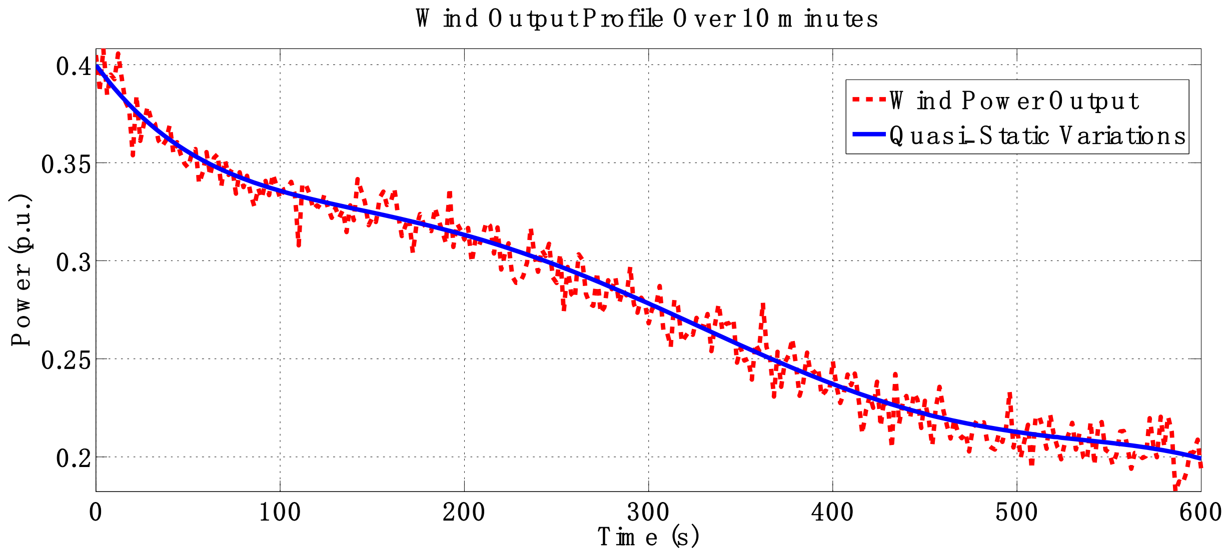
❖ *Tracking with a Stable System*

$$P_G[K+1] = AP_G[K] + B_{Stab}\,\omega_{G_{C1}}^{ref}[K] + B_{Track}\,\omega_{G_{C2}}^{ref}[K] + W\left(P_W[K+1] - P_W[K]\right)$$

Sustainable Intra-Dispatch Power Balancing

Rate of Energy Produced=*Rate of Energy Consumed*

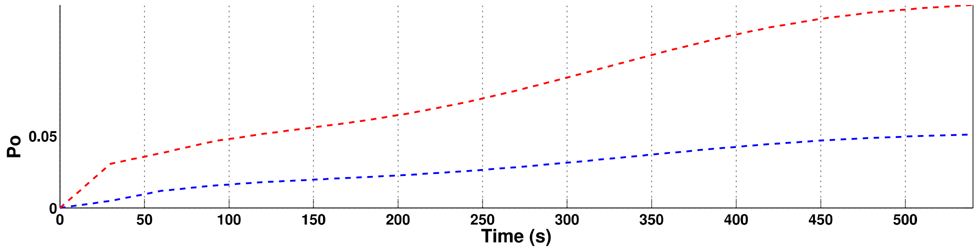
\+ *Rate of Wind Energy Lost*



Align Time-Scales of Generation Resources with

Time-Scale of Power Imbalances

Flores: Balancing Quasi-Static Wind Variations



Balancing Flores Island

- *Steady-State Droop subjected to Network Constraints*
- *Generator respond to Quasi-Stationary Wind Variations*
- *Feedback Response to Sustained Deviations*
- *Set Points Updated 30-seconds*
- *Error/Residual Imbalance picked-up by AGC/Slack*

Location-based Challenges

- *Electric Wires Transport of Energy between Nodes*
- *Power Transferred (Voltage Angle, Impedances)*
- *Enough Generation Capacity - Power Delivery*

Azores: Intra-Dispatch Demand Response

Classification of Loads:

- *Motor Load or Resistive Load*
- *Utility of Load – Commercial/Industrial/Residential*
- *Size (Large-Sustained variations, Small-Fluctuations)*
- *Time Scale or Rate of Response to Imbalances*
- *Willingness to Participate*

Azores: Intra-Dispatch Demand Response

Flores-*Variable Speed Drives*

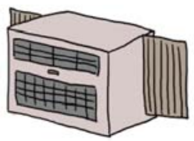
❖*Refrigeration Load (42% of Residential Consumption)*

1.5^{o} Celsius Rise in Freezer- 30 minutes Power Deficit

❖*Candidate for Short-Term Power Balancing*

❖*Can Handle Fast On/Off Switching Cycle*

S. Miguel-*Commercial & Industrial Loads*



❖*Shopping Mall – Air Conditioners (VSD)*

❖*Cement Factory- Motor Load for Crushing/Grinding/Sieving/Mixing of Raw Material (Variable Speed Drive or Direct Control)*

❖*Grocery Store- Refrigeration (VSD)*

❖*Hotel's Laundry Load- Washer Dryer (VSD)*

Questions ???