FERC 2018 Software Conference

# Frequency-Optimized Security-Constrained Economic Dispatch (fSCED)

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# Outline

- Motivations/disclaimers
- Technical set-up
- fSCED model
- Conclusions

Disclaimer: Our comments today represent only the authors' opinions and do not necessarily represent the opinions of the Federal Energy Regulatory Commission or any Commission members

# Introduction

- fSCED is a form of a security-constrained economic dispatch (SCED) model that incorporates frequency management into the optimization
- Same set of resources is optimized as under normal SCED (dispatchable generators, load, devices, etc.)
- Except that we now add system frequency to the dispatchable variables, and model its interaction with device inertia
- fSCED might be useful in markets/optimizations such as:
  - Dispatch of regulation resources
  - Clearing of 5-min real-time markets
  - Clearing of some future intermediate market (more frequent than 5 mins)

# Origins

- fSCED conceived from mentoring new employees on questions like:

  What *really* physically happens when SCED cannot find a feasible solution that satisfies the nodal power balance constraint?

- Well, what really happens?
  - First, something happens within the SCED model
  - But ultimately, something different happens in the physical system
  - (We’ll come back to the details in a couple slides)

- This raises the question: If the physical behavior isn’t too difficult to model, why not just model it within SCED?
- Also motivated in part by the related existential question:

  What would we want markets look like if computers/data were perfect?

- Overall, this seemed like a model that should exist, at least for research purposes (although many practical issues to be resolved)

# Disclaimers

- We present fSCED as a *potentially* useful or interesting model, but…
- We take no position on when/if it would make sense to incorporate into actual operations (likely not right away)
- Exactly where fSCED might be best incorporated needs additional research
- While we compare fSCED to the current SCED model for purposes of *explanation*, this is not to criticize SCED (its imperfections might be perfectly appropriate; more complexity might be overkill)
- Also, SCED in operations typically converts reserves to energy instead of having the frequency effects we discuss here; for explanation purposes only, we're assuming a more naive SCED

# Disclaimers

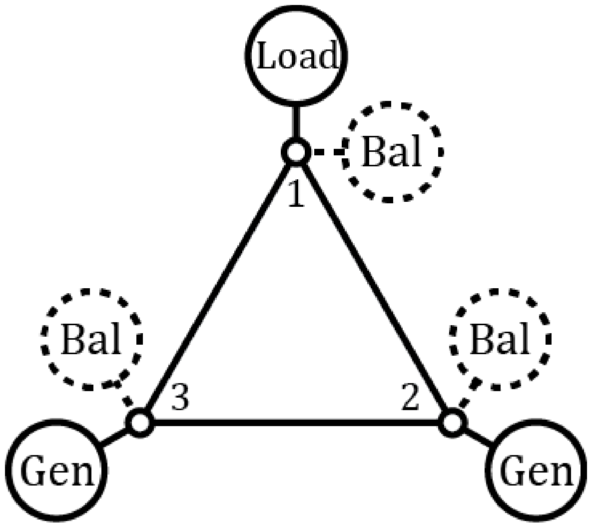
- Many factors affect the potential utility of pursuing fSCED in the future, including but not limited to:
  - Competing priorities
  - How fast computers/algorithms get
  - System "size" and system inertia (affects timescales of frequency change)
  - Quality of system data (device inertia in particular)
- Also, there is a scope problem
  - Pure fSCED requires dispatch of all devices in a synchronized interconnection
  - Obviously, this is not typically the case in ISOs
  - However, future research might determine that the fSCED concept (or a variation thereof) could be used to better optimize resources in some situations

# What Happens In the SCED Model When No Power-Balanced Feasible Solution Exists?

Approximate explanation:

1) The model determines, after furiously searching for feasible solutions, that none exist
2) With no feasible solution available, the model carefully moves into the infeasible realm, *selectively* relaxing nodal power balance constraints
3) Any incremental relaxation of a nodal power balance constraint is considered to have a cost equal to an administratively specified constraint relaxation penalty price.

   (Basically, we code into the model an unlimited well of make-believe balancing power at each node, available at a high penalty price.)
4) Considering the constraint relaxation penalty price, the model optimizes the amounts and locations of constraint relaxations



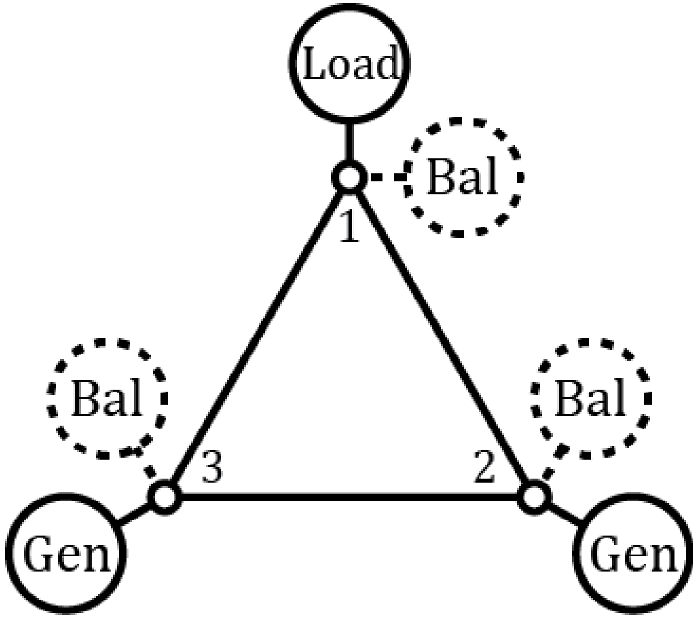
# Reality Check

- There are not really (in the physical world) infinite wells of balancing power available at every node
- Some physical nodes *do* indeed have the ability to tap into balancing energy
- …from changes in kinetic energy of spinning inertial masses
- But, such balancing energy is a direct function of system frequency, so it:
  - Isn’t unlimited (very limited band of acceptable frequencies surrounding 60 Hz)
  - Isn’t independently dispatchable nodally

# SCED vs. fSCED Conceptual Models (system level)

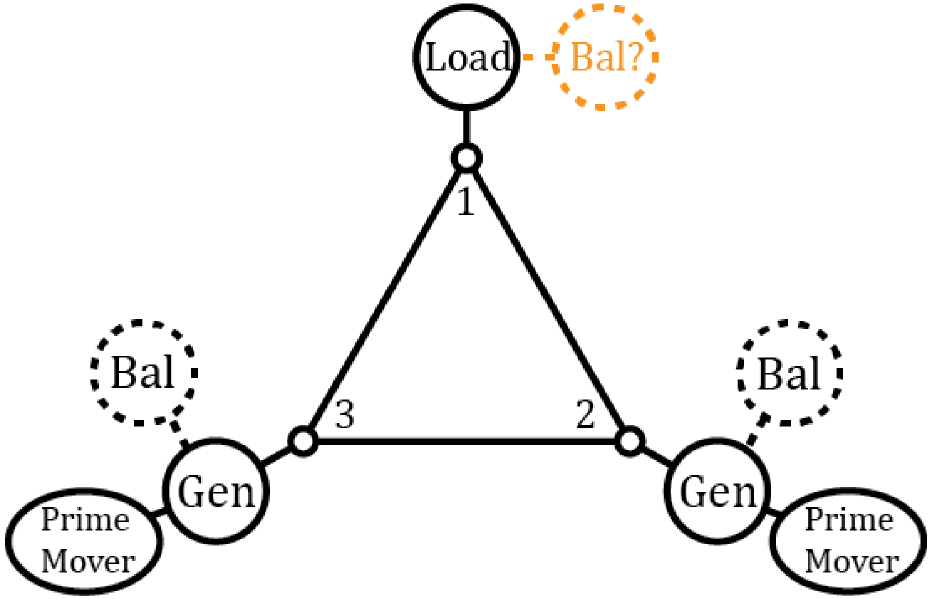
## SCED

- Make-believe energy balancing at nodes
- Unlimited balancing (at a high price/MWh)
- Balancing independently dispatchable at each node
- Ignores frequency (not in model at all)
- Modeling assumptions cause inaccurate transmission flow calculations




## fSCED (aka "reality")

- Real inertial balancing *behind* gens/loads
- Device inertial balancing modeled as function of frequency (not independently dispatchable)
- Balancing limited and valued by how it affects frequency (frequency supply curve)
- Accurate transmission flow calculations

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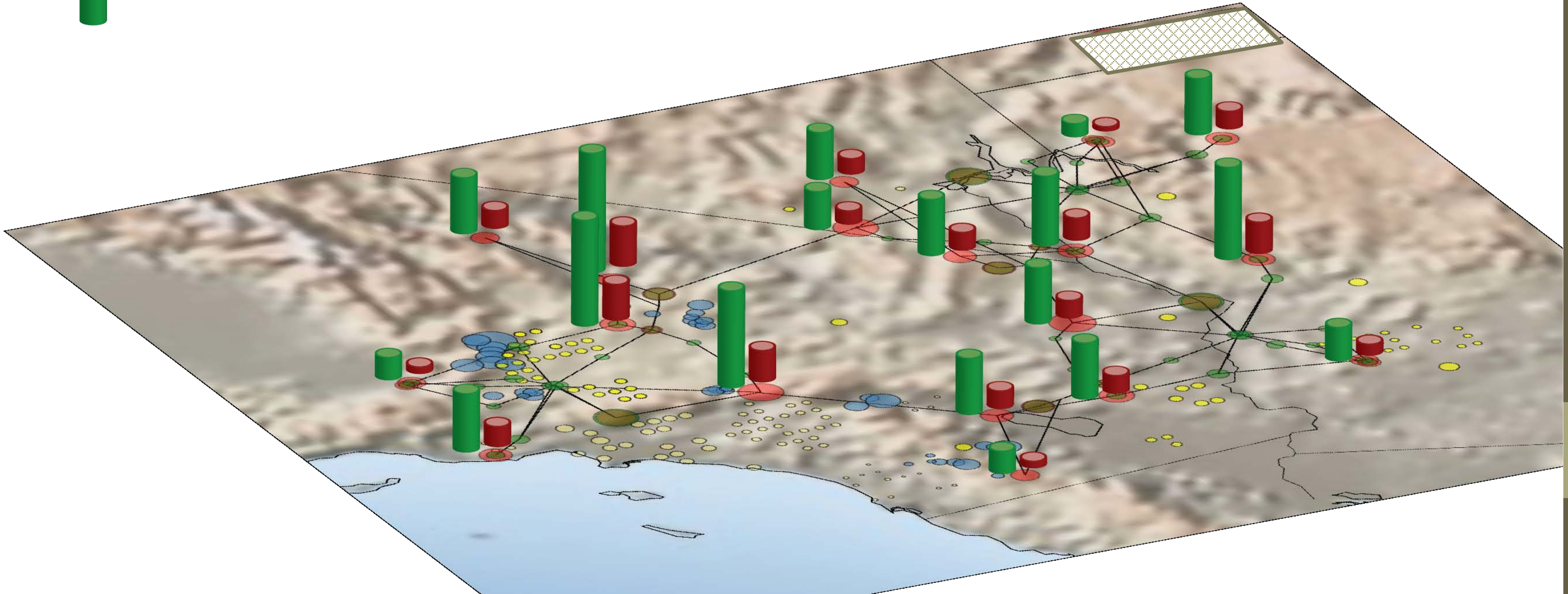
# Inertial Balancing Power in fSCED: Small frequency change

Balancing power injection

Inertia

- Across nodes, balancing power is proportional to inertia
- As magnitude of frequency change varies, balancing power scales by the same factor

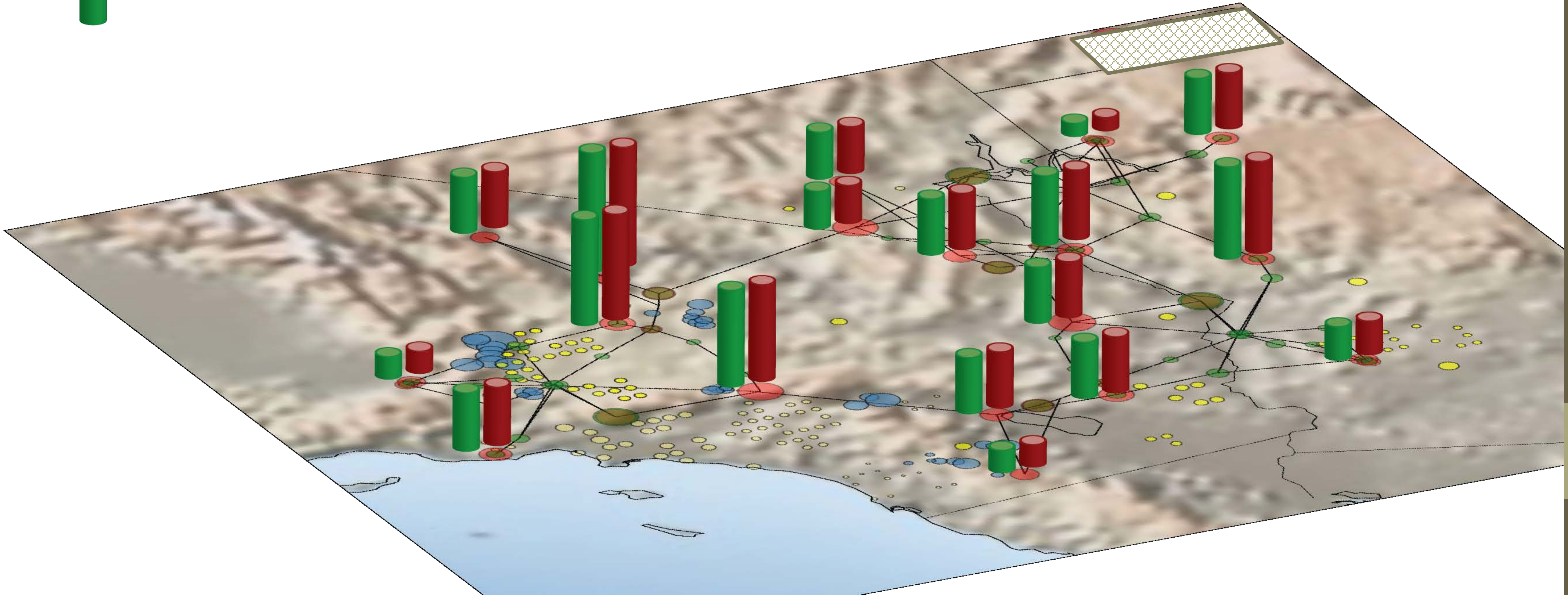


# Inertial Balancing Power in fSCED: Medium frequency change

Balancing power injection

Inertia

- Across nodes, balancing power is proportional to inertia
- As magnitude of frequency change varies, balancing power scales by the same factor

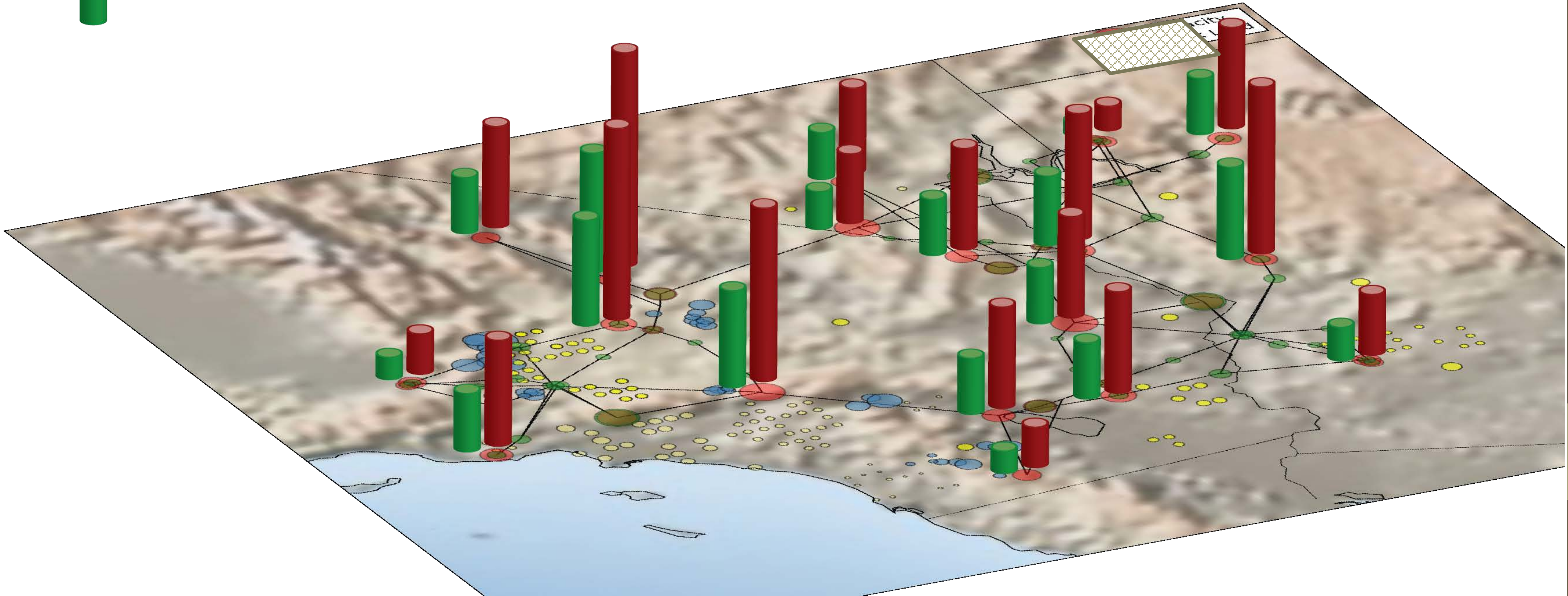


# Inertial Balancing Power in fSCED: Large frequency change

- Across nodes, balancing power is proportional to inertia
- As magnitude of frequency change varies, balancing power scales by the same factor

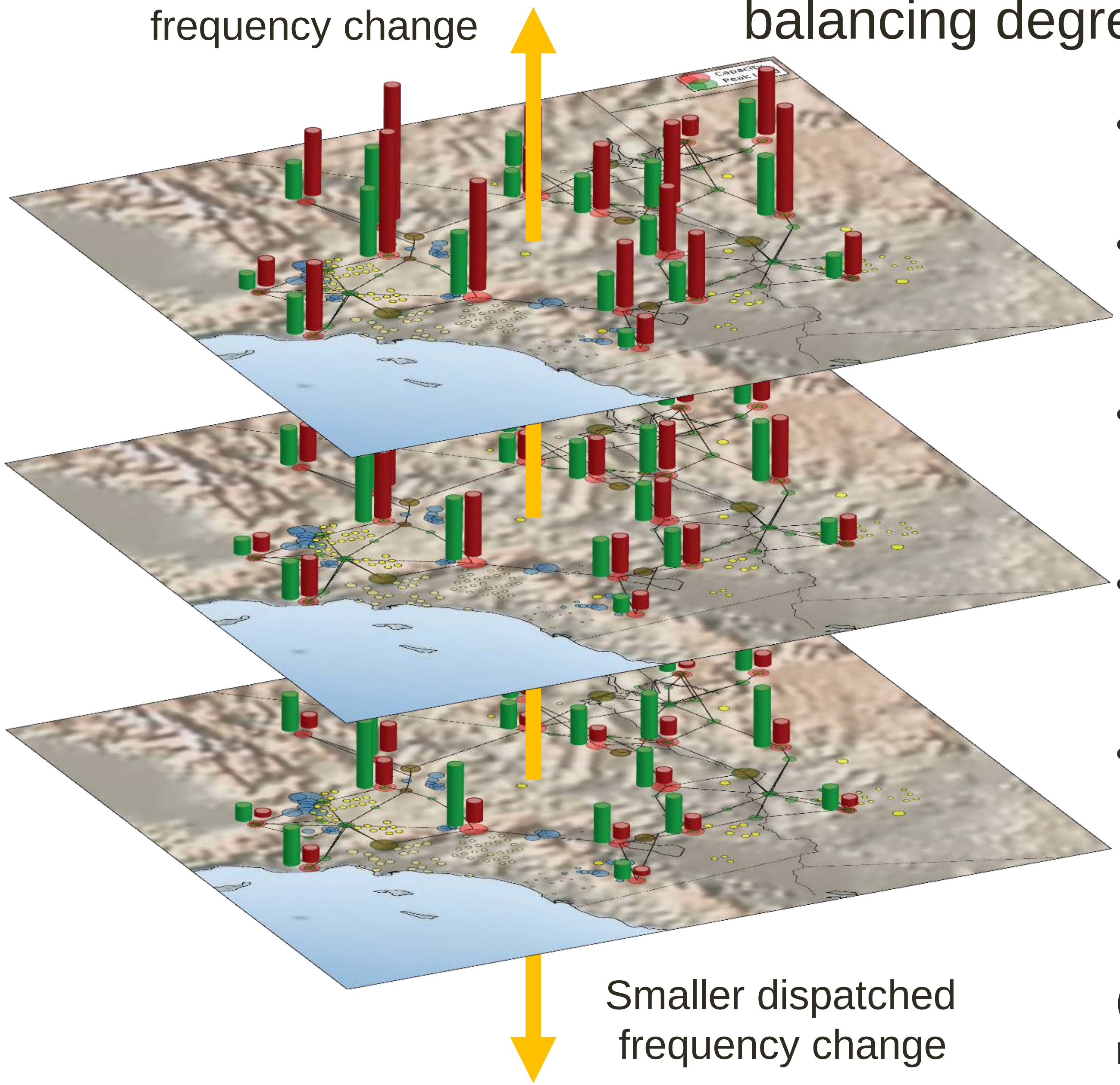
Balancing power injection

Inertia



# Magnitude of frequency change is the *only* inertial balancing degree of freedom in a real system

Larger dispatched frequency change



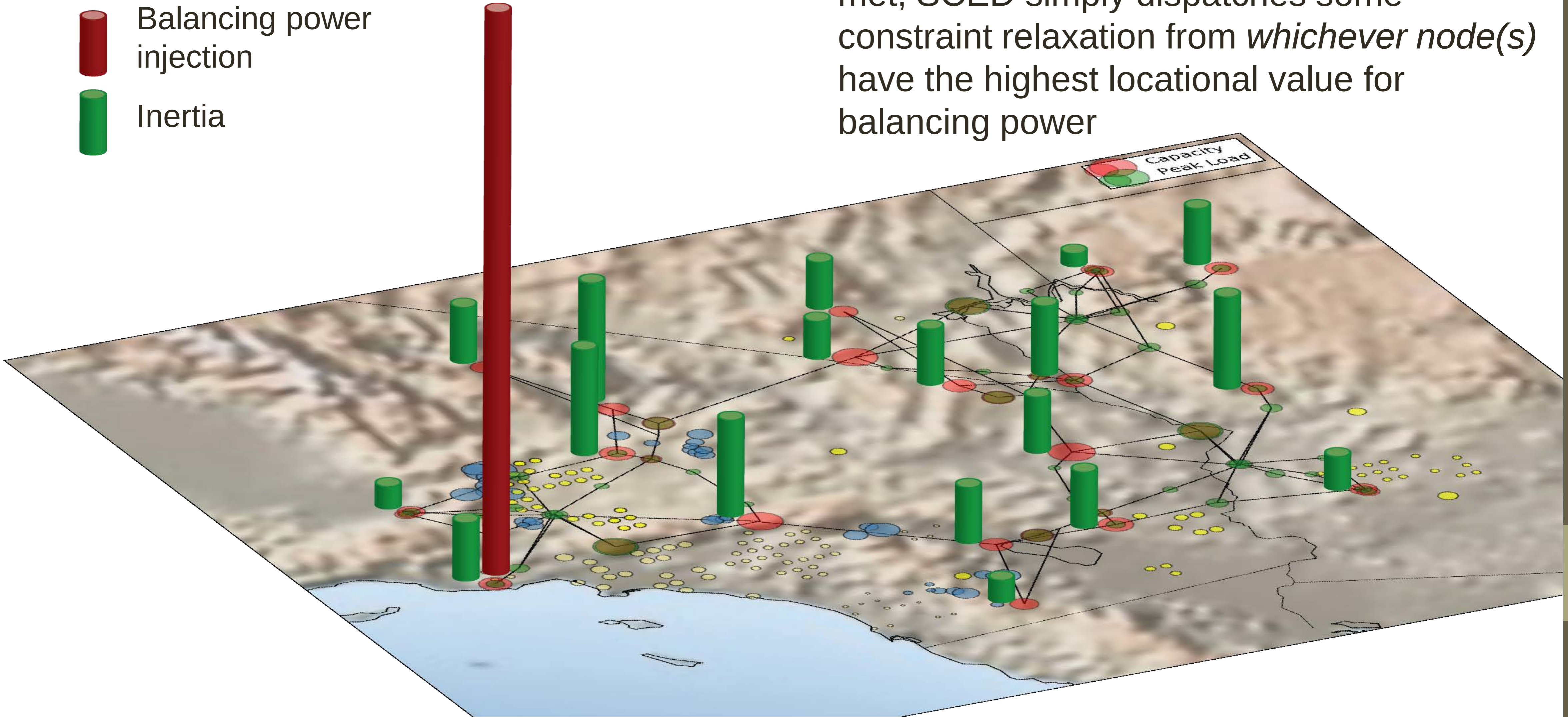
Smaller dispatched frequency change

- If the system dispatch a certain frequency change…
- …that defines a vector of injections of inertial balancing power roughly proportional to the magnitude of frequency change
- Conversely (but equivalently), if the system decides it needs a certain amount of balancing power…
- …it can only get that amount by dialing frequency such that the *sum* of the inertial balancing power injections match the need
- However, it *cannot* control independently which nodes provide how much inertial balancing power (those proportions are fixed by the locational distribution of inertia)

(Not shown here, but "injections" can be negative, if a frequency *increase* is dispatched)

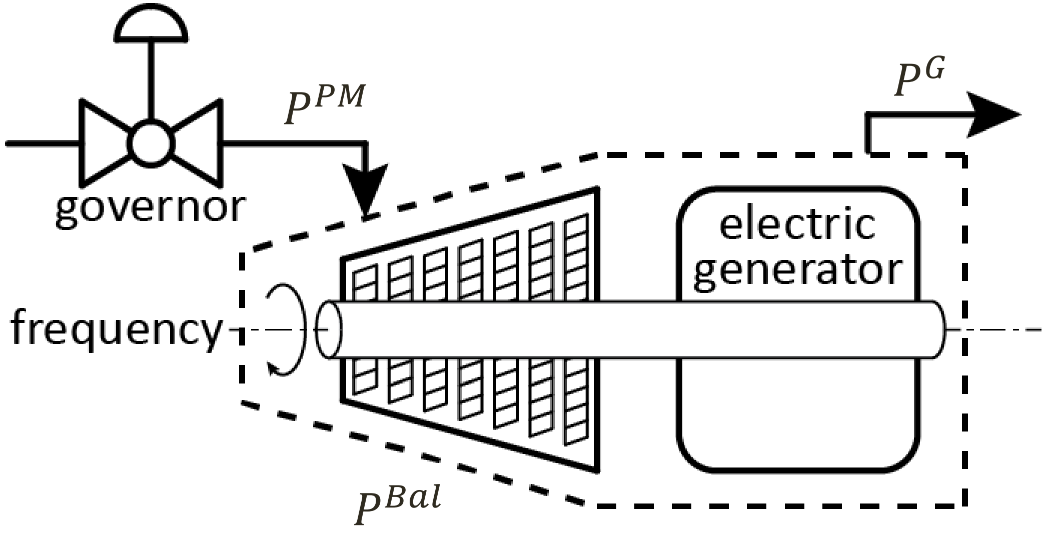
# Balancing Power in SCED

- SCED has *no such limit* on where phantom balancing power can be dispatched from
- When power balance constraints can't be met, SCED simply dispatches some constraint relaxation from *whichever node(s)* have the highest locational value for balancing power



# fSCED Conceptual Device Power Balance Model

- Model applies only to inertial generators
- Shown is a steam turbine, but concepts apply to other gen types (CT, wind, hydro, etc.)
- Power from prime mover drives the electric generator (and the prime mover itself)
- Prime mover's mechanical power ($P^{PM}$, in MW) is converted into two things:
  1) Generated electric power ($P^G$)
  2) Balancing power ($P^{Bal}$) from change in rotational kinetic energy ($\Delta KE$) of the combined prime mover and generator
  3) Also some generator and frictional losses (ignore for now)
- Min/max constraints on $P^{PM}$ and $P^G$
- Ramp rate constraint on $P^{PM}$ only




$$P^{PM} = P^{Bal} + P^G \qquad P^{Bal} = \frac{\Delta KE}{3600 \cdot T}$$

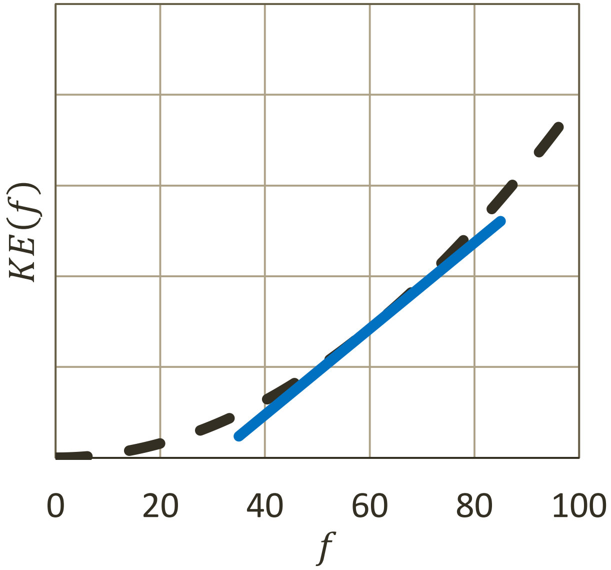
$$P^{PM} = \frac{\Delta KE}{3600 \cdot T} + P^G$$

where $T$ is the period length in hours (such that $3600 \cdot T$ is the period length in seconds)

# Physics Model of Kinetic Energy in a Rotating Mass

- Kinetic Energy ($KE$, in Joules or J) is given by: $KE = \frac{1}{2} I (2\pi f)^2$

  where $I$ is inertia (in kg·m$^2$) of the spinning mass and $f$ is frequency (in cycles/s or Hz)
- $KE(f)$ is a nonlinear function of $f$
- But it is *nearly* linear in the neighborhood of 60 Hz defining the feasible operating space
- Linearize using a first order Taylor series expansion about $f \approx 60$ Hz
- Using that approximation, we can also approximate the *difference* in $KE$ for any two frequencies near 60


First order Taylor series expansion

$$f(x) \approx f(a) + \frac{f'(a)}{1!}(x - a)$$

$$KE' = 4\pi^2 I f$$

$$KE(f) \approx (2\pi^2 I 60^2) + 4\pi^2 I 60 \cdot (f - 60)$$

$$KE \approx I(-7.11E4 + 2.37E3 f) \text{ [Joules]}$$

$$\Delta KE \approx I(2.37E3)(f - f_{previous}) \text{ [Joules]}$$

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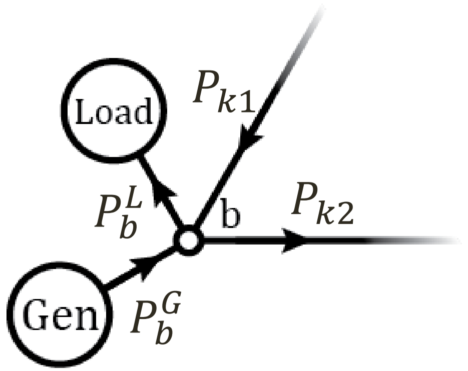
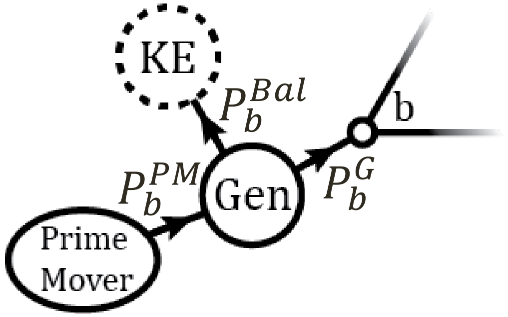
# Unique fSCED Constraints

- Nodal (bus) power balance constraint
  - Constraint equation is same as in normal SCED
  - However, this constraint is *not* allowed to be relaxed in fSCED
  - …because the system stress previously modeled in SCED as power balance relaxation is now modeled as frequency changes




$$P_b^G - P_b^L + \sum_{k \in TX_b^{end}} P_k - \sum_{k \in TX_b^{start}} P_k = 0$$

- Device power balance constraint
  - Completely new constraint
  - Combines math from previous two slides
  - For the same reasons as discussed above, the device power balance constraint is not allowed to be relaxed




$$P_b^{PM} - P_b^{Bal} - P_b^G = 0$$

$$P_b^{PM} - \frac{I_b(6.58E{-}7)\left(f - f_{previous}\right)}{T} - P_b^G = 0$$

# Unique fSCED Objective Function Terms (and related constraints)

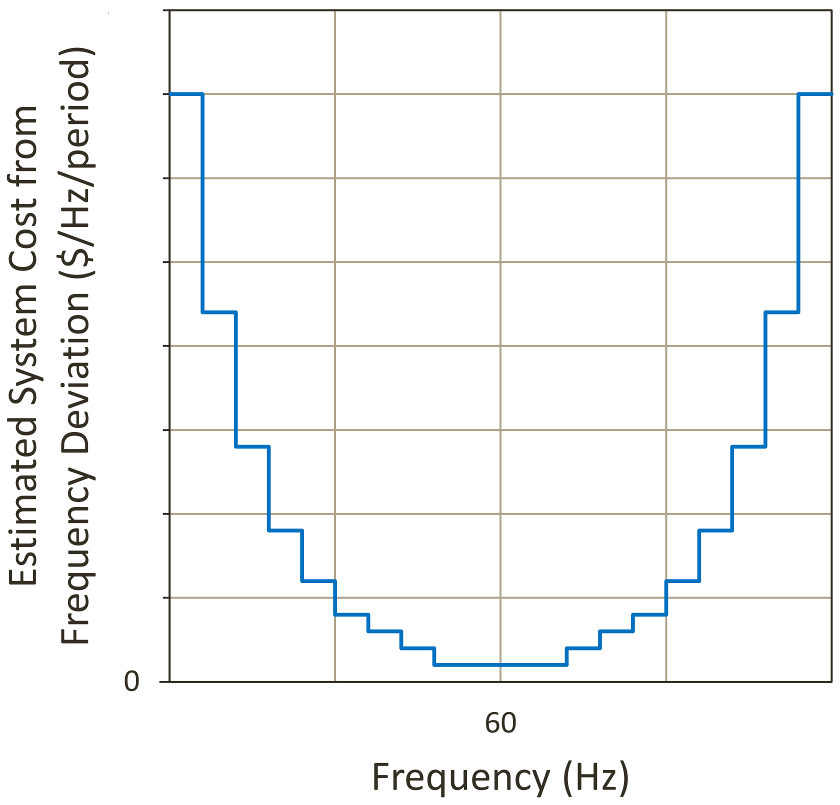
- Frequency deviation supply curve
  - Estimated cost to system of deviating from nominal frequency (mainly due to system risk)
  - Tiered structure, similar to imbalance penalties or transmission constraint demand curves
  - Frequency deviation supply cost is calculated by summing over the steps ($s$) of the step functions of up and down deviations

$$C^f = \sum_s \left(c_s^+ \cdot f_s^{dev+}\right) + \sum_s \left(c_s^- \cdot f_s^{dev-}\right)$$

  - Where the variables ($f, f_s^{dev+}, f_s^{dev-}$) are defined/constrained as:

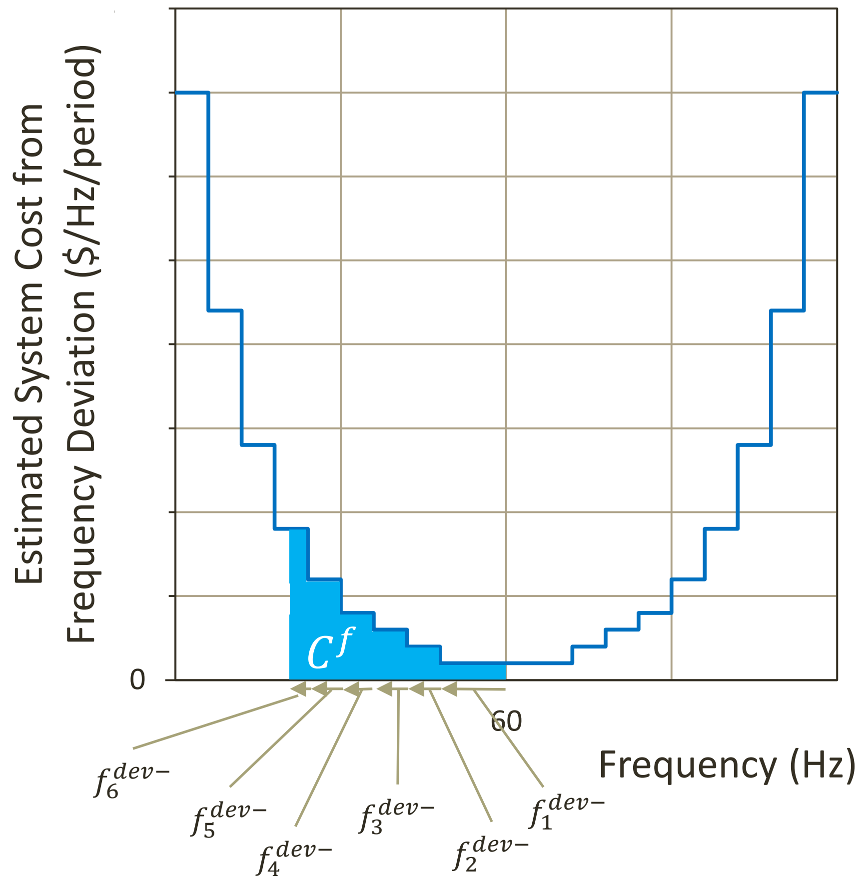
$$f = 60 + \sum_s f_s^{dev+} - \sum_s f_s^{dev-} \qquad f_s^{dev+}, f_s^{dev-} \in [0, f_s^W]$$

and $f_s^W$ is the width of the steps on the step function



# Frequency Deviation Supply Curve Examples

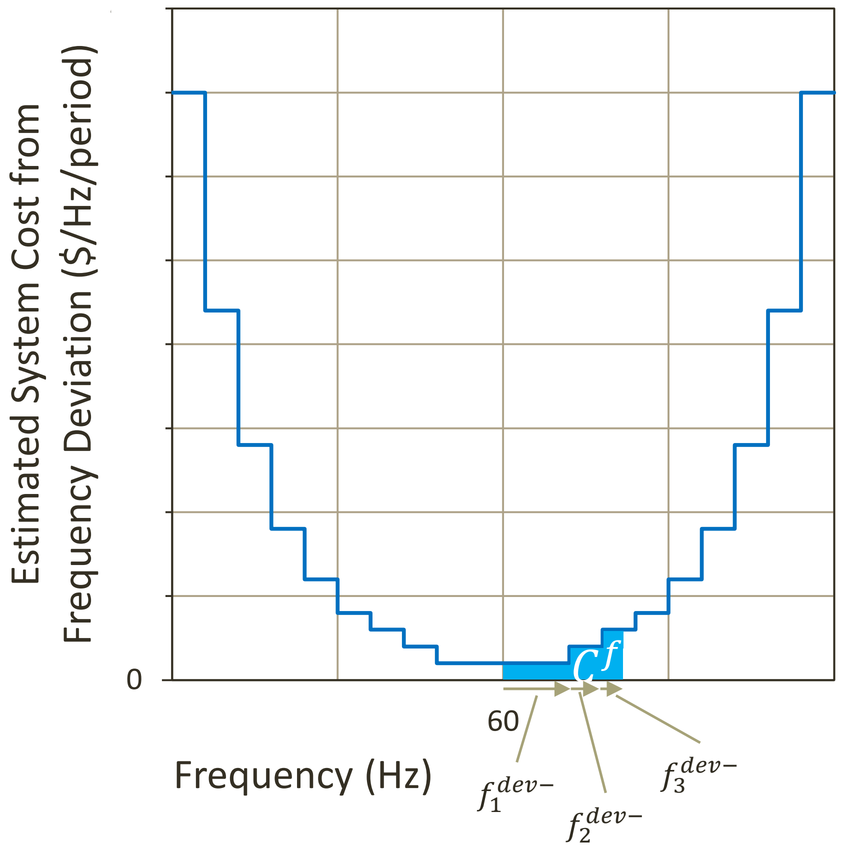
Example 1: Supplying negative frequency deviation




$$f = 60 - f_1^{dev-} - f_2^{dev-} - f_3^{dev-} - f_4^{dev-} - f_5^{dev-} - f_6^{dev-}$$

$$C^f = c_1^- \cdot f_1^{dev-} + c_2^- \cdot f_2^{dev-} + c_3^- \cdot f_3^{dev-} + c_4^- \cdot f_4^{dev-} + c_5^- \cdot f_5^{dev-} + c_6^- \cdot f_6^{dev-}$$

Example 2: Supplying positive frequency deviation




$$f = 60 + f_1^{dev+} + f_2^{dev+} + f_3^{dev+}$$

$$C^f = c_1^+ \cdot f_1^{dev+} + c_2^+ \cdot f_2^{dev+} + c_3^+ \cdot f_3^{dev+}$$

# fSCED Optimization Model: Variables

| Symbol | Description | Units |
|---|---|---|
| $P_b^G$ | Electric power dispatched from the generator at bus $b$ | MW |
| $P_b^{PM}$ | Mechanical power dispatched from generator prime mover at bus $b$ | MW |
| $P_k$ | Electrical power flowing on line $k$, defined to be positive in the direction from specified start bus $i$ to end bus $j$ | MW |
| $\theta_b$ | Voltage phase angle at bus $b$ | Radians |
| $f$ | System frequency | Hz |
| $f_s^{dev+}$, $f_s^{dev-}$ | Amount of frequency deviation (up and down) from nominal, as dispatched within frequency deviation step $s$ (shown in step function on slides 18-19) | Hz |

# fSCED Optimization Model: Data/Parameters

| Symbol | Description | Units |
|---|---|---|
| $T$ | Length of market period | h |
| $c_b$ | Marginal cost of generator at bus $b$ | \$/MWh |
| $c_s^+, c_s^-$ | Marginal cost of frequency deviations in up and down directions, for step $s$ | \$/Hz |
| $P_b^L$ | Forecasted load at bus $b$ | MW |
| $P_B$ | System power base = 100 MW | MW |
| $B_k$ | Electrical susceptance of line $k$ | p.u. |
| $\tau_k$ | Transformer turns ratio of line $k$ | - |
| $I_b$ | Moment of inertia of generator at bus $b$ | kg·m$^2$ |
| $K$ | Kinetic energy constant = 6.58E-7<br>(Calculated as (2.37E3-s$^{-1}$)/((3600-s/h)(1E6-J/MJ)). See slides 15-17.) | h/s |

# fSCED Optimization Model: Data/Parameters

| Symbol | Description | Units |
|---|---|---|
| $R_b^{up}, R_b^{down}$ | Ramp rate limits in up and down directions | MW/h |
| $f_{previous}$ | Frequency in previous period | Hz |
| $P_{b,previous}^{PM}$ | Mechanical power dispatched from generator prime mover at bus $b$ in previous period | MW |
| $P_k^{lim}$ | Thermal transmission limit on line $k$ | MW |
| $P_b^{PMmin}, P_b^{PMmax}$ | Economic minimum and maximum operating limits of prime mover at bus $b$ | MW |
| $P_b^{Gmax}$ | Economic maximum operating limit of electric generator at bus $b$ | MW |
| $f_s^W$ | Step width of frequency deviation supply curve step $s$ | Hz |
| $b \in B$ | Set of nodes or buses | - |
| $s \in S$ | Set of steps for frequency deviation supply curve step function | - |
| $k \in TX$ | Set of transmission lines | - |

# fSCED Optimization Model

(new components in red)

frequency deviation cost (slides 18, 19)

Minimize production cost: $\phi = T \cdot \sum_b (c_b \cdot P_b^G) + \sum_s (c_s^+ \cdot f_s^{dev+}) + \sum_s (c_s^- \cdot f_s^{dev-})$

Subject to constraints:

(1) Nodal power balance

$$P_b^G - P_b^L + \sum_{k \in TX_b^{end}} P_k - \sum_{k \in TX_b^{start}} P_k = 0 \qquad \forall\, b \in B$$

(2) Transmission flow

$$P_t = P_B \left(\frac{B_k}{\tau_k}\right)(\theta_i - \theta_j) \qquad \forall\, k \in TX \text{ with endpoints } i \text{ (start) and } j \text{ (end)}$$

(3) Device power balance (slides 15, 16, 17)

$$P_b^{PM} - \frac{I_b \cdot K}{T}(f - f_{previous}) - P_b^G = 0 \qquad \forall\, b \in B$$

(4) Ramp rate limits (slide 15)

$$-R_b^{down} \le \frac{P_b^{PM} - P_{b,previous}^{PM}}{T} \le R_b^{up} \qquad \forall\, b \in B$$

(5) Frequency (slides 18, 19)

$$f = 60 + \sum_s f_s^{dev+} - \sum_s f_s^{dev-}$$

(5) Variable bounds

$$P_k \in [-P_k^{lim}, P_k^{lim}], \quad P_b^{PM} \in [P_b^{PMmin}, P_b^{PMmax}], \quad P_b^G \in [0, P_b^{Gmax}],$$

$$f \ge 0, \quad f_s^{relax+}, f_s^{relax-} \in [0, f_s^W]$$

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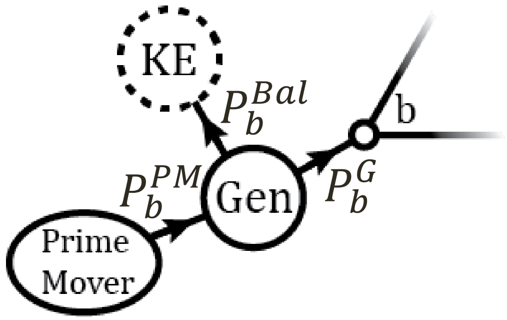
# Dispatch Under fSCED: Slightly Weirder Than Under SCED

- There are three pieces of data related to a generator's performance: $P^G$, $P^{PM}$, and/or $P^{Bal}$
- Like under SCED, we could send out only the desired *electrical* power output ($P^G$) as a dispatch instruction
- That would work perfectly *if* everyone followed their dispatch instructions and there were no contingencies or deviations from load forecasts
- But if any events that affect frequency occur, then $P^G$ instructions could imply ambiguous or infeasible prime mover outputs; it would break down at the exact moment fSCED is designed for: system stress
- Instead, we need to dispatch generators with prime movers according to their *prime mover* power output ($P^{PM}$)
- This is different than shaft power, so hard to meter
- But we can dispatch to the sum of $P^{Bal}$ and $P^G$, each of which should be easy to meter (may need to consider losses)



# Conclusions and Final Thoughts

- fSCED offers a way to manage system frequency thorough an accurate optimization
- Possible uses in applications relevant to system economics, reliability and/or resilience, including:
  - Optimizing automatic generation control (AGC) dispatch for regulating resources
  - Finding feasible solutions to 5-min market where today none exist
- Many practical considerations/hurdles
  - Other priorities, technical requirements, “scope” problem
- Dispatch under fSCED would need to be different for resources with prime movers

# Questions/Discussion

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