Primary and Secondary Frequency Control
Reserves Adequacy in Grids with High
Penetration of Intermittent Generation

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The Electrical and Computer Engineering Department
The University of Texas at Austin

Student: Hector Chavez
Supervisor: Prof. Ross Baldick
OUTLINE

INTRODUCTION
   Generation-load balance and frequency control
   Frequency control and intermittent generation
   Work objective

ADEQUACY OF PRIMARY FREQUENCY CONTROL RESERVES:
   Current PFC adequacy criteria
   Identification and simulation of wind in ERCOT
   Results

ADEQUACY OF SECONDARY FREQUENCY CONTROL RESERVES:
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Frequency Control Characteristics

- Frequency control manages to keep power balance when scheduled power differs from actual load.

<table>
<thead>
<tr>
<th>Type</th>
<th>Handles</th>
<th>ERCOT Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary (PRC)</td>
<td>Sudden loss of generation (load)</td>
<td>Responsive Reserves</td>
</tr>
<tr>
<td>Secondary (SFC)</td>
<td>Net load* swings, RTM deviations</td>
<td>Regulation</td>
</tr>
<tr>
<td>Tertiary (TFC)</td>
<td>Reserve restoration after a contingency</td>
<td>Non-spinning reserves, RTM</td>
</tr>
</tbody>
</table>

* Net load = Load – Intermittent generation

This work only considers the adequacy of primary and secondary frequency control
The impact of Intermittent Generation on Frequency Control

- **Inertia**: the contribution of intermittent generation to system inertia is low to zero (power electronic devices, in principle, decouple spinning machines)

- **Governor capability**: intermittent generation has low to zero frequency response (cannot increase power output in response to a frequency drop)

- Net load swings: intermittent production is hard to forecast and dispatch.
Purpose of this work

- To establish frequency control adequacy for scenarios of large penetration of intermittent generation.
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The purpose of PFC

- To prevent system frequency from dropping and triggering under frequency relays (and shedding load) after large sudden loss of generation (NERC).
- In ERCOT: frequency system shall not drop below the ERCOT first load shedding level, 59.3Hz
ERCOT PRC Determination

- ERCOT PFC reserve determination: equal to the largest single possible generation loss in the system [1].

- It may not be adequate since it does not consider inertia and governor capability reductions.

- Need to determine what affects PFCR

Role of RTM in PFC Adequacy

- RTM defines generation dispatch, affecting the number of responsive units.

- Also, the DAM defines the number of on-line units that determines the inertia of the system (not considered in this work)
Governor

- No consideration in current markets on how fast units respond (ramp rate), but it does matter for PFC adequacy.

The analysis will be focused on how to include governor dynamic limitations in the RTM to assess PFC adequacy.

Loads?
Idea

❖ To prevent frequency from triggering UFR by dispatching generating units in a proper manner.

❖ Need to include the swing equation and governor dynamics in reserve determination.

❖ Current approaches are mathematically complex; need to simplify governor dynamics.
Idea (con’t)

❖ To find an algebraic expression between power loss, system inertia, governor ramp rates, and frequency nadir requirement to be included in the OPF formulation

\[
\sum_{j \in J} R_j \geq P_{LOSS} \\
R_j \leq 2r_j \left( \frac{M_H (f_s - f_{MIN}) - P_{LOSS}t_d}{P_{LOSS}} \right)
\]

\(R_j\) : Reserve from unit \(j\) (MW)
\(r_j\) : Unit \(j\) governor ramp rate (MW/s)
\(M_H\) : System inertia (MWs/Hz)
\(f_{MIN}\) : Minimum frequency allowed (Hz)
\(t_d\) : System governors dead time (s)
\(P_{LOSS}\) : Largest contingency (MW)

\(j \in J\), the set of all generators except generator \(k\), where \(k\) is the generator that trips.
Governor Ramp Rate-constrained OPF

\[
\begin{align*}
\min & \sum_{i \in G} (e_i(P_i) + s_i(R_i)) \quad \text{(Energy } e_i(P_i) \text{ and reserve } s_i(R_i) \text{ costs)} \\
\sum_{i \in G} P_i &= \sum_{i \in F} d_i \quad \text{(Power Balance)} \\
\sum_{i \in J} R_j &\geq P_{\text{LOSS}} \quad \text{(PFC adequacy 1)} \\
R_j &\leq 2r_j \left( \frac{M_H (-\Delta f_{\text{MIN}}) - P_{\text{LOSS}} t_d}{P_{\text{LOSS}}} \right), \quad j \in J \quad \text{(PFC adequacy 2)} \\
\sum_{i \in G} A_{il}^G P_i &\leq \sum_{i \in F} A_{il}^L d_i + \bar{L}_l, \quad l \in T \quad \text{(Transmission)} \\
0 &\leq R_j \leq \bar{R}_j, \quad j \in J \quad \text{(PFC reserve limit)} \\
P_i &\geq \underline{P}_i, \quad i \in G \quad \text{(Generator min. output)} \\
P_i + R_i &\leq \bar{P}_i, \quad i \in G \quad \text{(Generator max. output)}
\end{align*}
\]

All variables do not affect the linearity of the feasible set.
ERCOT Simulation

- Power flow case of ERCOT (1.2 GW wind, 34 GW load)
- Identification of ERCOT transient stability model using actual data of contingencies.
- The identified model is updated with transmission expansion (CREZ) and 14GW of wind output.
- Wind inertia and governor response is assumed to be null.
- Thermal units are switched off to integrate wind units so that total capacity stays roughly constant.
Identification Results

<table>
<thead>
<tr>
<th>Thermal Units</th>
<th>Thermal Capacity</th>
<th>Responsive Units</th>
<th>Responsive Capacity</th>
<th>Inertia (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>215</td>
<td>33983 MW</td>
<td>176</td>
<td>13761.8 MW</td>
<td>6.4s@34GW</td>
</tr>
</tbody>
</table>
ERCOT simulation

- The nadir-constrained OPF is ran (CPLEX) for different nadir requirements, and the trip of the unit STP2 (AEP Central Company, 1362 MW) is considered.
Simulated Frequency

- **Frequency (Hz)**
  - Unconstrained
    - $f_{\text{min}} = 59.15$
    - $f_{\text{min}} = 59.25$
    - $f_{\text{min}} = 59.35$
    - $f_{\text{min}} = 59.42$

- **UFR set point (Adequacy level)**
- **Time (s)**

**Mechanical power**

Unconstrained case is not adequate

Report
Dispatch results

### Table XI
ERCOT 14GW Wind Dispatch results

<table>
<thead>
<tr>
<th>$\Delta f_{\text{MIN}}$ (Hz)</th>
<th>$\Delta f_{\text{nad}}$ (Hz)</th>
<th>OPF Objective ($/5 \text{ min}$)</th>
<th>Energy Payment ($/5\text{min}$)</th>
<th>PFCR Price ($/\text{MW}$)</th>
<th>PFCR Payment ($/5\text{min}$)</th>
<th>Responsive Units (#)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(*)</td>
<td>59.066</td>
<td>-103,079</td>
<td>486,254</td>
<td>0</td>
<td>0</td>
<td>37</td>
</tr>
<tr>
<td>59.15</td>
<td>59.189</td>
<td>-102,874</td>
<td>499,738</td>
<td>2.58</td>
<td>3,521</td>
<td>52</td>
</tr>
<tr>
<td>59.25</td>
<td>59.277</td>
<td>-102,017</td>
<td>507,891</td>
<td>7.92</td>
<td>10,788</td>
<td>65</td>
</tr>
<tr>
<td>59.35</td>
<td>59.365</td>
<td>-100,425</td>
<td>513,926</td>
<td>10.05</td>
<td>13,699</td>
<td>89</td>
</tr>
<tr>
<td>59.42</td>
<td>59.425</td>
<td>-98,762</td>
<td>522,913</td>
<td>17.18</td>
<td>23,404</td>
<td>127</td>
</tr>
</tbody>
</table>

(*) : Unconstrained

Inertia reduces from 6.4s (34GW/1.2GW) to 4.8s (34GW/14GW) because of less thermal units online to integrate the wind (same total capacity).
Effects of the Nadir Constraint

- The nadir constraint distributes PFC burden amongst more units making the overall system faster.

- This prevents cheap units from being fully dispatched, causing a more expensive dispatch (similar to transmission limits)

- Wind units are assumed to have no frequency response. The situation may improve with synthetic inertia, but it is still necessary to include an *a priori* way to determine PFCR adequacy.
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SFC Purpose

- Prevent *net load swing* (RTM deviations, wind variability/ramps, load variability) from carrying the frequency *too far* from 60 Hz.

- Definition of *too far* in North America: compliance with NERC Control Performance Standards (CPS1, CPS2). ERCOT has a CPS2 waiver.
ERCOT CPS1

\[
CPS1 = 100 \left( 2 - \frac{\Delta f_{avg}^2}{\varepsilon^2} \right) \%
\]

\(\Delta f_{avg}\) is the 1-min average of 4 sec. sampled frequency

\(\varepsilon\) captures how well frequency has been controlled historically (\(\varepsilon = 30\)mHz for ERCOT, 18mHz in the EIS)

A CPS1 score over a rolling 12 month average should be at least 100\%. In other words, system frequency must be within the band 60\(\pm0.03\) Hz \textbf{most} of the time.
ERCOT Regulation Adequacy

- A GE study determines that additional regulation (MW) for incremental wind shall be 3 standard deviations of incremental variability due to wind.
- It neglects frequency dynamics and does not considers CPS1 as a Regulation performance standard.
- Need for a dynamic simulation to determine the adequacy of ERCOT method.

Analysis of Wind Generation Impact on ERCOT Ancillary Services Requirements
http://www.uwig.org/AttachA-ERCOT_A-S_Study_Exec_Sum.pdf
Simulation of ERCOT

ERCOT Frequency dynamics

The model will consider data of two actual contingencies to identify model parameters
Single Machine Model of ERCOT

\[ \frac{1 + sT_c}{1 + sT_a} P_{\text{cap}} \]

\[ P_m \]

\[ \frac{1}{sT_H} \]

\[ \Delta P \]

\[ \Delta f \]

Need for a linear model to run an identification algorithm

From Inertia Estimation

\[ \frac{1 + sT_c}{1 + sT_a} P_{\text{cap}} \]

\[ \frac{1}{sT_H} \]

\[ \Delta P \]

\[ \Delta f \]

Identification process for \( T_a, P_{\text{cap}}, \) and \( T_c \)

From Droop characteristic
Wind model

- Divided into two processes: wind noise and ramps
  - Wind Noise: represents 1-by-1 minute variability
  - Wind Ramps: represents significant ramp ups and ramp downs.
- The trend in statistical parameters of the processes for different wind capacities is examined to estimate the parameter for a larger capacity.
- The model is not meant to fully represent the underlying stochastic process associated to wind; rather, it tries to improve current scaling up approaches.
Wind Noise

Wind noise approximates to a Laplacian random walk

\[ W_t = W_{t-1} + X_t, \]
\[ X_t \sim \text{Laplace}(0, \lambda_L) \]

Normalized wind 1-by-1 min diff. process

Variation of the parameter \( \lambda_L \) with installed capacity
Simulation results

- Regulation procurement is adjusted according to the ERCOT method (the GE table), and a month is simulated.
Simulation results

Abnormal accumulation of samples around governor dead band

Regulation is not capable of maintaining frequency within the CPS1 band of 30mHz, so frequency reaches values for which governors are active.
Monthly CPS1 of 56% is not adequate.
Comments

- Regulation based on the GE table is not sufficient (according to the simulation), but ERCOT frequency has been adequate (according to reality).
Comments (con’t)

- Plausible reason: governor dead bands in ERCOT have been tightened unilaterally by some generators.

- A tighter dead band (16mHz) may maintain frequency within the CPS1 required band of 30mHz. (in the case of the simulation, governor dead bands were 36mHz)

- In such a case, an increment in net load variability would lead to an increment in governor deployments rather than a need for more regulation.

- This should affect the adequacy of PRC reserves.
Comments (con’t)

- However, the “headroom” of the system is generally larger that the sum of primary and secondary frequency control reserves (units partially dispatched not participation in the AS market contribute to the headroom). ERCOT requires all units to have governor in service (except nuclear and wind units).

- This reserves surplus may be enough to cover the reduction in PFC reserves due to more variability. In large penetrations scenarios, the headroom may no longer be enough.
Questions