A Unified Framework for Defining and Measuring Flexibility in Power System

Optimization and Equilibrium in Energy Economics Workshop

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Outline

• **WHY** do we need a framework for flexibility?
• **WHAT** is flexibility?
• **HOW** to measure flexibility?
• Applications
Motivation

• New England power system faces an increasing level of uncertainty as more renewable resources are integrated
  – 700 MW wind plants
  – 1200 MW solar (including behind-meter solar panels)

• This requires the system to have the ability to react to the rapid change of the system condition within an acceptable time frame and cost threshold

• The notion of flexibility recently has been drawing significant attention
Flexibility Literature Review

• Use additional reserve to provide flexibility
  – Leite da Silva, et. al. (2010), NREL (2010),

• Ramping products
  – MISO, CAISO

• Definition
  – Lannoye, et al. (2013): the ability of a system to deploy its resources to respond to changes in the demand not served by variable generation
  – Capasso, et al. (2005), Bresesti, et al. (2003): the attribute of the transmission system to keep up a desired standard of reliability at reasonable operation costs, when generation scenarios changes.

• Indices
  – Insufficient ramping resource expectation (IRRE), Lannoye, et al. (2013)
  – A flexibility index based on generator’s ramping capability and generating capacity, Ma, et al. (2013)
  – Balancing reserve, Menemenlis et al. (2011)
Need for a Unified Framework for Flexibility

- There are many flexibility measures provided for different aspects of flexibility using various approaches
- There is a lack of a general framework that encompasses different concepts and techniques
- A unified flexibility framework
  - Allow flexibility to be explicitly considered in the system design
  - Allow quantitatively compare across different options to increase the system flexibility
What is Flexibility

- Flexibility is the ability of a system to respond to a range of uncertain future states by taking an alternative course of action within acceptable cost threshold and time window.

- Four key elements
  - Time
  - Action
  - Uncertainty
  - Cost

- Serve as a basis for constructing measures of flexibility
Time

• Indicate how fast the system reacts to a disturbance and restore the system to its normal state.

• Seconds, minutes, hours, days, months, and years

• A system might have sufficient capacity to cope with demand growth in a year, but not enough capability to adapt to hourly load fluctuations.
Action

- The corrective actions that can be taken within the response time window:
  - AGC
  - Economic dispatch
  - Voltage control
  - Unit commitment
  - Interchange scheduling
  - Short-term outage coordination
  - Long-term outage coordination
  - Transmission and generation investment
  - 4 sec
  - 5 min
  - 1 hr
  - days
  - months
  - years
Uncertainty

• The lack of complete information of the future system state

• Component failure, load forecast errors, renewable generation variability

• The magnitude of uncertainty determines how much flexibility a system requires to handle uncertainty
  – A system that is flexible with respect to loss of one element (N-1 contingencies) may not be flexible for loss of two elements (N-2 contingencies)
Cost

• The response cost depends on the corrective action.

• Cost threshold
  – Some corrective actions become uneconomical, and will not be considered.

• Minimize response cost
  – The most economic corrective actions are sought in response to uncertainty
Illustrative Example of the Four-Element Framework


• Response time: one year

• Action: generation expansion, unit commitment and economic dispatch

• Uncertainty: load level, load profile, and renewable generation

• Cost: minimize the sum of dispatch, commitment and investment cost
How to Measure Flexibility

• Given a response time window, a response cost threshold, and a target variation range, a flexibility index is defined as follows:

\[
F = \frac{\text{The largest variation range of uncertainty the system can accommodate}}{\text{The target variation range of uncertainty the system aim to accommodate}}
\]

• The magnitude of the target range reflects decision makers’ risk preference

• Does system has enough flexibility to cover the targeted uncertainty?

• Quantify the system’s safety margin
Variation Range Maximization

\[
\max_{u^{LB}, u^{UB}, a(\cdot)} \| u^{UB} - u^{LB} \|
\]

Maximize the size of the variation range of uncertainty

\[
s.t. \quad Aa(u) + Bu \leq b \quad \forall u \in [u^{LB}, u^{UB}]
\]

The system’s reaction to uncertainty via corrective actions

\[
c^T a(u) \leq \bar{C} \quad \forall u \in [u^{LB}, u^{UB}]
\]

The budget for corrective actions

\[
[u^{LB}, u^{UB}] \subseteq [u^{LB, target}, u^{UB, target}]
\]

The lower and upper bounds of the variation range

The lower and upper bounds of the target variation range

The corrective actions responding to uncertainty

The response cost threshold
Not a Standard Robust Optimization Problem

• A standard robust optimization problem:

\[
\min_{a(.)} \left( \max_{u \in [u^{LB,*}, u^{UB,*}]} d^T a(u) \right)
\]

s.t. \( Aa(u) + Bu \leq b, \forall u \in [u^{LB,*}, u^{UB,*}] \)

– Given an uncertainty set, how to design the system to accommodate the worst case?
– The uncertainty set is pre-determined

• The variation range maximization problem:

\[
\max_{u^{LB}, u^{UB}, a(.)} \| u^{UB} - u^{LB} \|
\]

s.t. \( Aa(u) + Bu \leq b, \forall u \in [u^{LB}, u^{UB}] \)
\( c^T a(u) \leq \overline{C}, \forall u \in [u^{LB}, u^{UB}] \)

– Given the system’s capability, what is the largest uncertainty set it can accommodate?
– The uncertainty set is to be determined
Solution Methodology 1: Affine Policy

- Assume the corrective action linearly responds to uncertainty
  \[ a(u) = l + Lu \]

- Reformulate the variation range maximization problem
  \[
  \max_{u_{LB}, u_{UB}} e^T (u_{UB} - u_{LB}) \\
  \text{s.t. } A(l + Lu) + Bu \leq b, \forall u \in [u_{LB}, u_{UB}] \\
  c^T (l + Lu) \leq \bar{C}, \forall u \in [u_{LB}, u_{UB}] 
  \]

- Using the strong duality theory, the problem becomes
  - Linear program if the coefficients of the affine policy are pre-specified
  - Bilinear program otherwise
Solution Methodology 2: Benders Decomposition

• Variable substitution for $u \in [u_{LB}, u_{UB}]$

$$u = z \cdot u_{LB} + (1 - z) \cdot u_{UB}, \forall z \in [0,1]$$

• Two-stage robust optimization

$$\max_{u_{LB}, u_{UB}, a(.)} \|u_{UB} - u_{LB}\|$$

s.t.

$$Aa(z) + B(z \cdot u_{LB} + (1 - z) \cdot u_{UB}) \leq b, \forall z \in [0,1]$$

$$c^T a(z) \leq \bar{C}, \quad \forall z \in [0,1]$$

$$[u_{LB}, u_{UB}] \subseteq [u_{LB,target}, u_{UB,target}]$$

• Benders decomposition can be used to solve the robust optimization problem
Real-Time System Flexibility

- Response time window: 15 min
- Corrective action: dispatch of conventional units
- Cost: response cost threshold
- Uncertainty: wind output uncertainty

- ISO New England system
  - 2816 buses
  - 150 online conventional generators
  - 6 wind generators
    (artificially scaled up to 2479 MW in total)
**Formulation**

\[
\max_{d_{UB}, d_{LB}, p(.)} \sum_{n=\text{RAND}} (d_{n,T} - d_{n,T}^L) \\
\text{s.t. } \sum_{j=\text{conv}} p_{j,T}(d) + \sum_{n=\text{rand}} d_{n,T} = 0, \quad \forall d \in [d_{LB}, d_{UB}]
\]

Maximize the total net load variation range

\[
\sum_{n} SF_{n,l} \times (p_{j(n),T}(d) + d_{n,T}) \leq F_{l}^{\text{max}}, \quad \forall l = TL, \quad \forall d \in [d_{LB}, d_{UB}]
\]

Energy balance

\[
p_{j,0} - \Delta_{jn}^{d} \times T \leq p_{j,T}(d) \leq p_{j,0} + \Delta_{j}^{up} \times T, \quad \forall j = \text{conv} \quad \forall d \in [d_{LB}, d_{UB}]
\]

Transmission constraint

\[
p_{j,T} \leq p_{j,T}(d) \leq p_{j,T}^{\text{max}}, \quad \forall j = \text{conv}, \quad \forall d \in [d_{LB}, d_{UB}]
\]

Ramping capability

\[
\sum_{j=\text{CCU}} c_{j} \times p_{j,T}(d) \leq \bar{C}_{T}, \quad \forall d \in [d_{LB}, d_{UB}]
\]

Capacity constraint

\[
P_{j,T} \quad \text{Output of generator } j
\]

Dispatch cost budget

\[
\text{d} \quad \text{Net load uncertainty} = \text{load} - \text{wind output}
\]

\[
P_{j,T} \quad \text{Output of generator } j
\]

\[
SF_{n,l} \quad \text{Shift factor}
\]

\[
c_{j} \quad \text{Dispatch cost}
\]

\[
\Delta_{j} \quad \text{Ramp rate}
\]
Impact of Uncertainty

- The risk tolerance level can be quantified by the target variation range
  - Pessimistic target range
  - Optimistic target range

- The degree of flexibility depends on decision makers’ risk tolerance level
Impact of Cost

- Two levels of cost threshold
  - High: $10 Million
  - Low: 1.01×dispatch cost of meeting the forecasted net load
- The smaller the cost threshold, the narrower the largest variation range.
- Downward ramping capability is less affected by the cost limit than the upward ramping capability.
Application 1: Zonal Ramping Requirements

• A situation Awareness tool
  – By visualizing the flexibility metrics, operators can easily spot the flexibility shortage events in advance

• Real-time look-ahead application
  – Imposing zonal ramping requirements to prevent flexibility shortages

• Upward ramping requirement
  at a zone \( z \)
  \[
  \sum_{n \in N_z} \max \left( d_{n,UB,target}^{UB} - d_{n,UB}^{UB}, 0 \right)
  \]

• Downward ramping requirement
  at a zone \( z \)
  \[
  \sum_{n \in N_z} \max \left( d_{n,LB}^{LB} - d_{n,LB,target}^{LB}, 0 \right)
  \]

• This is a research project.
Example: ISO New England System

- Zonal ramping requirements

  - The system can prepare sufficient ramping capability at where it is needed to avoid possible flexibility shortage in the future.

  - Northeast Massachusetts (NEMA)/Boston
  - Southwest Connecticut (SWCT)
  - The rest of Connecticut
Effect of Zonal Ramping Requirements

- System is repositioned under the zonal ramping requirements
- Several downward/upward flexibility shortage events are eliminated
- Effectively deter early flexibility deficit
- Provide additional time for operators to solve flexibility issues
Application 2: Additional Unit Commitment

• Deterministic unit commitment is to meet the forecasted load.

• The deterministic commitment schedule may be highly suboptimal or infeasible when the actual system conditions significantly differ from the forecast.

• Which is the next most flexible offline unit that can be turned on to provide additional flexibility to respond to uncertainties?

• This is a research project. The potential application is the reserve adequacy assessment.
Example: Five-Bus System

- $20/MWh
  - Ramp = 10MW
  - [180~400]MW
  - Brighton

- $25/MWh
  - Ramp = 20MW
  - [10~150]MW
  - Alta

- $30/MWh
  - Ramp = 10MW
  - [50~350]MW
  - Park City

- $60/MWh
  - Ramp = 4MW
  - [50~300]MW
  - Solitude 1

- $140/MWh
  - Ramp = 2MW
  - [10~300]MW
  - Solitude 2

- $50/MWh
  - Ramp = 2MW
  - [100~300]MW
  - Sundance

- Load D
- Load B
- Load C
The upper bound of the largest range becomes flat after hour 8 due to the lack of upward ramping capability.
Sundance Commitment Result

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Remove the flexibility shortage events at Hours 8, 9, 12, 17, 20
Solitude 2 Commitment Result

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Complete remove all the flexibility shortage events
Further Analysis

- Solitude 2 is more flexible than Sundance although their ramp rates are both 2MW/MIN.
- The transmission congestion on lines AD and CD limits Sundance’s ability of sending electricity to load B and C.

Diagram:
- Nodes: Brighton, Alta, Park City, Sundance, Solitude 1, Solitude 2, Load B, Load C, Load D.
- Connections: E to A, A to B, B to C, C to D, D to Sundance, Sundance to Load D, Load D to Solitude 1, Solitude 1 to Solitude 2, Solitude 2 to Load C, Load C to Load B.
Application 3: Do-Not-Exceed Limit Wind Dispatch

• Different from conventional generators, wind resources are
  – Low operating cost
    • Negative marginal cost
  – Variable
    • Increased level of uncertainty in the real-time operation
  – Non-dispatchable
    • Wind generation can be only curtailed when reliability issues arise

• How to design a dispatch framework that uses system’s flexibility to better utilize the low cost wind resources while recognizing their variability?
DNE Limit

• The dispatch instruction for a conventional generator is a *desired dispatch point (DDP)*

• The dispatch instruction for a wind generator is a *dispatch range (DNE Limit)*

• The DNE limit is the maximum amount of wind generation that the system can accommodate without causing any reliability issues.

• Benefits of DNE limit:
  – Provide a dispatch guideline for wind resources
  – Ensure reliable system operation
  – Allow low cost wind resources to provide as much energy as possible

• DNE limit will be in production in the 1st quarter of 2016.
System Response under Wind Over-generation

Conventional:
- Receive DDPs
- Follow DDPs

AGC:
- Receive DDPs
- Provide frequency control
  - Regulation upper limit
  - Regulation lower limit

Wind:
- Receive DNE limits
- Actual output
  - DNE
  - Forecast
    - 0
DNE Limit Formulation

• Maximize the total DNE limit

• Subject To:
  – System is able to maintain energy balance under any wind output variations by AGC control
  – The flow on every transmission line remains within its limit under any realization of uncertain wind output by adopting AGC control
  – The AGC control must be subject to the corresponding physical limits
  – The output variation of a wind generator should be within its physical limits
DNE Limit Example

- ISO New England system
  - 6 wind generators with total capacity of 250 MW
  - 1~3 AGC units with regulation capability of 20~140 MW
Summary

- Propose a uniform framework for flexibility
- Propose a flexibility index under the uniform framework
- Compute the flexibility index using robust optimization techniques
- Zonal ramping requirement application
- Unit commitment application
- DNE limit application
Questions