Review on Stochastic Methods Applied to Power System Operations with Renewable Energy

Zhi Zhou, Audun Botterud, Cong Liu

Center for Energy, Environmental, and Economic Systems Analysis (CEEESA)
Energy Systems Division

Argonne National Laboratory
DOE Wind Power Program

Outline

- **Overview**

- **Addressing Uncertainty and Variability with Operating Reserves**
  - Probabilistic evaluation of reserves with renewable energy
  - Operating reserves in integration studies and industry
  - Stochastic scheduling formulations with implicit reserves

- **Stochastic Programming Formulations of the Unit Commitment Problem**
  - Stochastic programming based UC formulations
  - Uncertainty modeling
  - Modeling tools and solution algorithms
  - Test systems and performance comparison metrics

- **Other Unit Commitment Formulations under Uncertainty**

- **Industrial Applications**

- **Conclusion and Future Directions**

Outline

- **Overview**

- **Addressing Uncertainty and Variability with Operating Reserves**
  - Probabilistic evaluation of reserves with renewable energy
  - Operating reserves in integration studies and industry
  - Stochastic scheduling formulations with implicit reserves

- **Stochastic Programming Formulations of the Unit Commitment Problem**
  - Stochastic programming based UC formulations
  - Uncertainty modeling
  - Modeling tools and solution algorithms
  - Test systems and performance comparison metrics

- **Other Unit Commitment Formulations under Uncertainty**

- **Industrial Applications**

- **Conclusion and Future Directions**

Literature Review Overview

- Focus on
  - Power system operations with renewable energy
  - Stochastic UC and ED methods from day-ahead scheduling to real-time operations.
  - Operating reserve strategies based on probabilistic methods
  - Uncertainty modeling and representation for operation scheduling
  - Case studies and industry adoption

- Overview statistics of papers

Category	**UC/ED**	**Operating Reserve**	**Uncertainty Modeling**
Total	119	48	24

Outline

- Overview

- **Addressing Uncertainty and Variability with Operating Reserves**
  - Probabilistic evaluation of reserves with renewable energy
  - Operating reserves in integration studies and industry
  - Stochastic scheduling formulations with implicit reserves

- **Stochastic Programming Formulations of the Unit Commitment Problem**
  - Stochastic programming based UC formulations
  - Uncertainty modeling
  - Modeling tools and solution algorithms
  - Test systems and performance comparison metrics

- **Other Unit Commitment Formulations under Uncertainty**

- **Industrial Applications**

- **Conclusion and Future Directions**

Summary – Operating Reserve Requirement Estimation and Acquirement

- **Thermal Systems**
  - Probabilistic estimates of LOLP
    - Based on load forecasting error and forced outage rate
    - Reserves in UC to meet reliability constraints
    - Update risk index based on UC and schedule reserve to meet constraints
    - Integrate outage distribution into UC formulation to meet LOLP constraints.
  - Reserves in UC to minimize total system cost
    - Include reserve scheduling cost in the objective function
  - Ensure that all selected contingencies can be met in UC

- **Thermal Systems with Renewables**
  - Meet probabilistic reliability target assuming Normal distribution for renewable forecast error
  - Reserves in UC to minimize total system cost, including expected load shedding
  - Reserve evaluation based on probabilistic wind power forecasts
  - Operating reserve demand curves
  - New reserve products

- **Stochastic scheduling with implicit reserves**
  - Bouffard et al. 2005, 2009; Morales et al. 2009; Papavasiliou et al. 2011

Summary - Probabilistic reserve estimates for thermal systems

Application	Method	Reference
Probabilistic reserve estimates for thermal systems	Probabilistic estimates of LOLP	Anstine et al. (1963) [28] Garver (1966) [29]
	Reserves in UC to meet reliability constraints	Dillon et al. (1978) [30] Gooi et al. (1999) [31] Chattopadhyay and Baldick (2002) [32] Bouffard and Galiana (2004) [33] Ahmadi-Khatir et al. (2013) [36]
	Reserves in UC to minimize total system cost, including expected load shedding	Ortega-Vazquez and Kirschen (2007) [34]
	Ensure that all selected contingencies can be met in UC	Wang et al. (2009) [35]

Summary - Probabilistic reserve estimates with renewable energy

Application	Method	Reference
Probabilistic reserve estimates with renewable energy	Meet probabilistic reliability target assuming Normal distribution for renewable energy forecast error	Söder 1993 [17] Doherty and O’Malley 2005 [37] Makarov et al. 2008 2009 [38] [39]
	Reserves in UC to minimize total system cost, including expected load shedding	Ortega-Vazquez et al. 2009 [40]
	Reserve evaluation based on probabilistic wind power forecasts	Matos Bessa 2011 [41] Zhou and Botterud 2014 [42]
	Operating reserve demand curves	ERCOT 2013b [48] Zhou and Botterud 2014 [42]
	New reserve products	Wang, Hobbs 2014, 2015 [49] [50]
	Reserves in integration studies and industry developments	Ackerman et al. 2007 [43] Ela et al. 2011 [44] Holttinen et al. 2013 [45] Enernex 2010 [24] GE Energy 2010 [25] Lew et al. 2013 [26] Mills et al. 2013 [46] ERCOT 2013a [47] ERCOT 2013b [48] Ellison et al. 2012 [56] Ela et al. 2014 [15]

Outline

- Overview

- Addressing Uncertainty and Variability with Operating Reserves
  - Probabilistic evaluation of reserves with renewable energy
  - Operating reserves in integration studies and industry
  - Stochastic scheduling formulations with implicit reserves

- **Stochastic Programming Formulations of the Unit Commitment Problem**
  - Stochastic programming based UC formulations
  - Uncertainty modeling
  - Modeling tools and solution algorithms
  - Test systems and performance comparison metrics

- Other Unit Commitment Formulations under Uncertainty

- Industrial Applications

- Conclusion and Future Directions

Stochastic Programming Formulations

- A general stochastic programming formulation

$$\min\left\{\mathrm{C(u)} + \mathrm{E}_{\zeta\in\mathrm{H}}(\mathrm{F}(\mathrm{u}', \mathrm{g}, \zeta) | \mathrm{Au} \le b_u, u \in U, W^{\zeta} g^{\zeta} \le b_g^{\zeta}, \mathrm{u}' = \mathrm{u}, \forall\, \zeta \in \mathrm{H}\right\}$$

- A specific UC formulation with uncertainty from wind power

$$\mathrm{Min} \sum_{\mathrm{s}} \mathrm{prob_s} \cdot \left\{\sum_{\mathrm{t,i}} \left[\mathrm{FC^s_{t,i}} + \mathrm{C(RNS^s_t)} + \mathrm{C(ENS^s_t)}\right]\right\} + \sum_{\mathrm{t,i}} \mathrm{SC_{t,i}}$$

$$\sum_{\mathrm{i}} \mathrm{gen^s_{thermal,i,t}} + \mathrm{gen^s_{renewable,t}} = \mathrm{load_t} - \mathrm{ENS^s_t}, \qquad \forall\, \mathrm{t, s}$$

$$\sum_{i} r^{s}_{thermal,i,t} \ge \alpha_{\mathrm{sr}} \left(OR_{reg,t} + OR^{s}_{renewable,t}\right) - RNS^{s}_{t}, \qquad \forall\, t, s$$

Summary - Stochastic UC formulations

- **Extension from traditional UC formulation**
  - Minimizing expected operating cost (over all scenarios with associated probabilities)
  - Combination of stochastic UC and operating reserve constraints
  - Risk indices associated to different events
  - Emissions

- **Other Variations**
  - Rolling basis decision making
  - Sub-hourly dispatch constraints

- **Hybrid formulations**
  - Stochastic optimization and interval optimization combined
  - Stochastic optimization and robust optimization

Summary - Probabilistic wind power forecasting

- **General Problem**

$$f_p\left(p_{t+k} \middle| X = x_{t+k|t}\right) = \frac{f_{P,X}(p_{t+k}, x_{t+k|t})}{f_X(x_{t+k|t})}$$

- **Methods based on Input**
  - NWP point forecasts based
  - Power output point forecasts based
  - NWP ensembles based

- **Performance Metrics**
  - Calibration
  - Sharpness
  - Skill Score

- **Uncertainty Representation**
  - Scenario tree/bundles
  - Scenario set generated by Monte Carlo Simulation
  - Scenario screening/selection

References - Stochastic UC formulations

Applications	Specification	References
Extension from traditional UC formulation	Minimizing expected operating cost	Papavasiliou and Oren, (2013a) [64]
	Combination of stochastic UC and operating reserve constraints	Kalantari, et. al. (2013) [65] Ruiz, et. al. (2008) [72], (2009a) [62], (2009b) [73], (2010) [63] Zhou, et. al. (2013) [74]
	Risk indices associated to different events	Li, et. al. (2007) [61] Zhang, et. al. (2014) [66] Wu, et. al. (2008) [67]
	Emissions	Wu, et. al. (2007) [60]
Multi-stage decision making	Rolling basis decision making	Meibom, et. al. (2008) [75] Tuohy, et. al. (2008) [76], (2009) [77], Ela, et. al. (2010) [78]
Hybrid formulations	Stochastic optimization and interval optimization combined	Dvorkin, et. al. (2015) [80]
	Stochastic optimization and robust optimization	Zhao and Guan, (2013) [138]
Uncertainty Representation	Scenario tree/bundles	Li, et. al. (2007) [61] Takriti, et. al. (1996) [57], (2000) [59] Wu, et. al. (2007) [60], (2008) [67], Shiina and Birge, (2004) [69] Nowak, et. al. (2000) [122] Meibom, et. al. (2007) [131], (2010) [75], (2011) [130] Pappala, et, al. (2009) [126] Tuohy, et. al. (2008) [76] Ela, et. al. (2010) [78] Sturt and Strbac, (2011) [70]
	Scenario set	Ruiz, et. al. (2008) [72], (2009a) [62], (2009b) [73], (2010) [63] Papavasiliou and Oren, (2013b) [119] Nowak, et. al. (2005) [121] Carøe, et. al. (1998) [58], (1997) [117] Wang, et. al. (2008) [120] Huang, et. al. (2014) [124] Wu and Shahidehpour (2014), [81] Kalantari, et. al. (2013) [65] Dvorkin, et. al. (2015) [80] Wang, et. al. (2013) [79] Constantinescu, et. al. (2011) [116]
	Scenario screening/selection	Papavasiliou and Oren, (2013a) [64] Feng, et. al. (2013) [71]

Reference - Probabilistic wind power forecasting

Input data	References
NWP point forecasts based	Bremnes (2004) [82], (2006) [84] Lange (2005) [83] Jeon and Taylor, (2012) [85] Kou, et. al. (2013) [86] Messner, et. al. (2014) [87]
Power output point forecasts based	Nielsen (2006) [88] Pinson (2006) [89], (2012) [95] Bludszuweit (2008) [90] Juban, et. al. (2007) [91] Møller, et. al. (2008) [92] Carpinone, et. al. (2010) [93] Bessa, et. al. (2012) [94] Sideratos and Hatziargyriou, (2012) [96] Haque, et. al. (2014) [97] Wan, et. al. (2014) [98] Li, et. al. (2015) [99]
NWP ensembles based	Nielsen, et. al. (2006) [100], (2007) [101], Pinson and Madsen, (2009) [102] Möller, et. al. (2013) [103]

Summary - Solution methods for stochastic UC

- Extensive Form with Commercial Solver
  - Cplex/Gurobi
  - Others
    - FICO Xpress
    - CBC

- Decomposition Based Methods
  - By scenarios
  - By generation unit
  - By stage/time period

- Others
  - Heuristic-based: PSO

Reference - Solution methods for stochastic UC

Methods	Specification	References
Extensive Form with Commercial Solver	Cplex	Kalantari, et. al. (2013) [65] Zhang, et. al. (2014) [66] Ruiz, et. al. (2008) [72], (2009) [73] Dvorkin, et. al. (2015) [80] Zhao, et. al. (2013) [115].
	CBC	Constantinescu, et. al. (2011) [116]
	FICO Xpress	Sturt and Strbac, (2012) [70]
Decomposition Based	By scenarios	Carøe, et. al. (1998) [58], (1997) [117] Wu, et. al. (2008) [67], (2012) [118] Papavasiliou and Oren, (2013a) [64], (2013b) [119] Wang, et. al. (2013) [79] Wang, et. al. (2008) [120] Nowak, et. al. (2005) [121] Goez, et. al. (2008) [125]
	By generation unit	Shiina and Birge, (2004) [69] Nowak and Römisch, (2000) [122] Huang, et. al. (2014) [124]
	By stage/time period	Takriti, et. al. (1996) [57] Schneider, et. al. (2013) [123]
Others	Particle swarm optimization	Pappala et. al (2009) [126]

Summary – Test systems

- **Various IEEE test systems**
  - IEEE Reliability Test System
  - IEEE 118-bus system

- **Real world systems**
  - WECC-240 system
  - Reduce CAISO system
  - CAISO interconnection with the WECC
  - Eastern Interconnection
  - National-wide power systems or utility companies

Summary - Cost performance of stochastic UC methods

- **Economic metrics**
  - Expected cost savings
  - Committed conventional generation capacity and operating reserve
  - Renewable energy utilization
  - Number of startups from thermal units

- **Reliability metrics**
  - unserved energy and reserve

- **Examples**

Metrics	Cost Saving	References
Operating cost saving	0.82% to 1.22%	Ruiz, et. al. (2009) [62]
	1% to 1.8%	Ruiz, et. al. (2010) [63]
	1.93% to 2.77%	Papavasiliou and Oren, (2013a) [64]
	5.4%	Papavasiliou and Oren, (2013b [119])
	1.6%	Gröwe, et, al. (1995) [127]
	0.39% to 1.18%	Takriti, et. al. (1996) [57]
	4%	Takriti, et. al. (2000) [59]
	1.26%	Wang, et. al. (2008) [120]
	2.8% to 3.8%	Pappala, et. al. (2009) [126]
	0.6%	Tuohy, et. al. (2008) [76]
	1%	Constantinescu, et. al. (2011) [116]

Outline

- Overview

- Addressing Uncertainty and Variability with Operating Reserves
  - Probabilistic evaluation of reserves with renewable energy
  - Operating reserves in integration studies and industry
  - Stochastic scheduling formulations with implicit reserves

- Stochastic Programming Formulations of the Unit Commitment Problem
  - Stochastic programming based UC formulations
  - Uncertainty modeling
  - Modeling tools and solution algorithms
  - Test systems and performance comparison metrics

- **Other Unit Commitment Formulations under Uncertainty**

- Industrial Applications

- Conclusion and Future Directions

Other Unit Commitment Formulations under Uncertainty

- Robust optimization based UC

$$\min_{\boldsymbol{x}}\left(\boldsymbol{c}^T\boldsymbol{x} + \max_{\boldsymbol{d}\in D}\ \min_{\boldsymbol{y}\in\Omega(\boldsymbol{x},\boldsymbol{d})} \boldsymbol{b}^T\boldsymbol{y}\right)$$

$$s.t.\ \boldsymbol{F}\boldsymbol{x} \le \boldsymbol{f}, \boldsymbol{x}\ is\ binary$$

$$\Omega(\boldsymbol{x},\boldsymbol{d}) = \{\boldsymbol{H}\boldsymbol{y}(\boldsymbol{d}) \le \boldsymbol{h}(\boldsymbol{d}), \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{y}(\boldsymbol{d}) \le \boldsymbol{g}, \boldsymbol{I}_u\boldsymbol{y}(\boldsymbol{d}) = \boldsymbol{d}\}$$

- Formulations
  - First introduce robust optimization into UC model with wind power (Zhang and Guan 2009)
  - Variations:
    - Include n-k contingency into uncertainty set
    - Multi-stage robust UC
    - Consider nonparametric correlations between nodal demands
    - Stochastic robust model, Accommodate multiple uncertainty sets
    - Robust UC with demand response
    - Consider non-anticipativity constraints in the dispatch process
    - Minimax regret model

- Solution Methods
  - Column and constraint generation
  - Benders decomposition and outer approximation

Reference – Robust Optimization based Unit Commitment Formulation Under Uncertainty

Application	Specification	Reference
Robust optimization based UC	First introduce robust optimization into UC model with wind power	Zhang and Guan 2009 [146] Jiang et al. 2013 [148]
	Include n-k contingency into uncertainty set	Street et al. (2011) [147] Xiong and Jirutitijaroen (2012) [149] Wang, et. al. (2013) [153] Matos Bessa (2011) [41]
	Multi-stage robust UC	Zhao et al. (2013) [152]
	Combined stochastic and robust UC formulation	Zhao and Guan (2013) [139]
	Consider nonparametric correlations between nodal demands	Moreira et al. (2014) [158]
	Stochastic robust model, Accommodate multiple uncertainty sets	An and Zeng (2015) [159] Liu et al. (2015) [163]
	Robust UC with demand response	Zhao et al. (2013) [152] Liu and Tomsovic (2015) [162]
	Consider non-anticipativity constraints in the dispatch process	Lorca and Sun (2014) [160] Lorca et al. (2014) [161]
	Minimax regret model	Jiang et al. (2013) [164]
	Column and constraint generation	Zhao and Zeng (2012) [150] An and Zeng (2015) [159] Lee et al. (2014) [156] Liu et al. (2015) [163]
	Benders decomposition and outer approximation	Bertsimas et al. (2013) [151] Zhao and Guan (2013) [140] Moreira et al. (2014) [158] Zhao et al. (2013) [152]
	Column generation, Dynamically include critical transmission line constraints	Lee et al. (2014) [156]
	Different method to construct uncertainty sets	Guan and Wang (2014) [154]

Other Unit Commitment Formulations under Uncertainty

- **Chance constrained Based UC**

$$\min_{x,y} \boldsymbol{c}^T\boldsymbol{x} + \boldsymbol{b}^T\boldsymbol{y} + \boldsymbol{E}\big(\boldsymbol{P}(\boldsymbol{x},\boldsymbol{y},\boldsymbol{\xi})\big)$$

$$\begin{aligned} s.t. \quad & \boldsymbol{Fx} \le \boldsymbol{f}, \boldsymbol{x}\ is\ binary \\ & \boldsymbol{Hy} \le \boldsymbol{h} \\ & \boldsymbol{Ax} + \boldsymbol{By} \le \boldsymbol{g} \\ & \boldsymbol{I}_u\boldsymbol{y}(\boldsymbol{d}) = \boldsymbol{d} \\ & \Pr(G(\boldsymbol{x},\boldsymbol{y},\boldsymbol{\xi} \le \boldsymbol{0}) \ge \boldsymbol{1} - \boldsymbol{\epsilon} \end{aligned}$$

- **Other Miscellaneous UC Formulation with Uncertainty**
  - Stochastic dynamic programming
  - Fuzzy constraints/objective function

- **Summary**

Application	Specification	Reference
Chance Constrained based UC	First introduce wind into chanced constrained UC model	Ozturk (2003) [142] Ozturk et al. (2004) [143]
	Combined sample average approximation (SAA) algorithm	Wang et al. (2012) [144]
	alpha-quantile measure to determine the confidence level	Pozo et al. (2013) [145]
Other Miscellaneous UC Formulation with Uncertainty	fuzzy set	Hosseini, et. al. (2007) [165] Venkatesh et al. (2008) [166]
	Stochastic dynamic programming	Hargreaves and Hobbs (2012) [134] Schneider et. al. (2013) [124]

Outline

- **Overview**

- **Addressing Uncertainty and Variability with Operating Reserves**
  - Probabilistic evaluation of reserves with renewable energy
  - Operating reserves in integration studies and industry
  - Stochastic scheduling formulations with implicit reserves

- **Stochastic Programming Formulations of the Unit Commitment Problem**
  - Stochastic programming based UC formulations
  - Uncertainty modeling
  - Modeling tools and solution algorithms
  - Test systems and performance comparison metrics

- **Other Unit Commitment Formulations under Uncertainty**

- **Industrial Applications**

- **Conclusion and Future Directions**

Industrial applications

- **MISO**
  - Overcome Computational Challenges on Large Scale SCUC Problems
  - A Probabilistic Optimization Reliability Assessment Commitment Framework
  - Operational and Practical Considerations for Stochastic Unit Commitment Solutions
  - Applying Robust Optimization to MISO Look-ahead Unit Commitment

- **ISO-NE**
  - Study of Two-Stage Robust Unit Commitment
  - Wind Dispatch Using Do-Not-Exceed Limit

- **ERCOT**
  - Optimizing Wind Generation in ERCOT Nodal Market

Outline

- Overview
- Addressing Uncertainty and Variability with Operating Reserves
  - Probabilistic evaluation of reserves with renewable energy
  - Operating reserves in integration studies and industry
  - Stochastic scheduling formulations with implicit reserves
- Stochastic Programming Formulations of the Unit Commitment Problem
  - Stochastic programming based UC formulations
  - Uncertainty modeling
  - Modeling tools and solution algorithms
  - Performance comparison metrics
- Other Unit Commitment Formulations under Uncertainty
- Industrial Applications
- **Conclusion and Future Directions**

Conclusion and Future Directions

- **Conclusions**
  - The ***stochastic UC problem*** has received most of the attention among researchers, but new approaches for ***probabilistic estimates of operating reserves*** have also been proposed to account for the stochastic nature of transmission and generation outages.

  - The main focus in the literature on stochastic scheduling and dispatch is on ***cost savings*** and ***reliability impacts***. There is also increasing attention to ***market implications***.

  - Most of the studies report ***operating cost savings*** from using stochastic formulations, especially if potential savings on penalties for load or reserve curtailment are considered.

  - There is no ***standard framework*** and ***metrics*** to compare the pros and cons of different operational strategies.

  - ***Industry adaptation*** of probabilistic methods for operational decisions is still limited, but there is increasing interest in the topic.

Conclusion and Future Directions

- Directions
  - More ***systematic testing*** and ***comparison*** of different operational strategies, accounting for a larger set of the real-world issues, constraints, and potential future regulatory policies in power system and electricity market operations.
  - A closer investigation of the ***interaction between explicit operating reserve requirements*** imposed by traditional reserve constraints ***and the implicit reserves*** provided by stochastic scheduling and dispatch formulations.
  - Further investigation of the ***potential implications for pricing and market incentives*** under stochastic UC and ED, with the goal of providing efficient signals for operations and investments for all market participants.
  - Further refinements of methods for ***probabilistic forecasting, scenario generation and reduction***, as critical inputs to stochastic methods for power system operations.
  - ***Testing on real-world and large-scale systems***. More utility companies and ISOs should get involved to validate the performance of stochastic methods. Industry feedback and suggestions for improvements in research grade tools and algorithms will contribute to pave the way forward to more economic and reliable power systems with large share of renewables.

Q & A


danke
謝謝
ngiyabonga
teşekkür ederim
спасибо
dank je
thank you
gracias
tapadh leat
bedankt
hvala
dziękuje
mochchakkeram
go raibh maith agat
sukriya
kop khun krap
obrigado
grazie
arigato
takk
dakujem
мерси
terima kasih
감사합니다
merci