Johns Hopkins Stochastic Multi-stage Integrated Network Expansion (JHSMINE) Version 1

Qingyu Xu, Benjamin F. Hobbs

July 2017

1 Introduction

In this document, the basic JHSMINE formulation will be shown. This whole formulation is a result of model development across multiple articles/reports. This is thus a combination of works of researchers from Hobbs group. The original formulation with two-stage stochastic programming was from [1]. Then in [2], this formulation was at the first time applied to WECC with DC OPF model enhancement. Details of a subsequent application that includes linearized unit commitment constraints [3] are in [4].

[1], A. H. van der Weijde, B. F. Hobbs, "The economics of planning electricity transmission to accommodate renewables: Using two-stage optimisation to evaluate flexibility and the cost of disregarding uncertainty," Energy Economics, vol. 34, no. 6, pp. 2089-2101, 2012.

[2] F. D. Munoz, B. F. Hobbs, J. L. Ho, S. Kasina, "An Engineering-economic approach to transmission planning under market and regulatory uncertainties: WECC case study," IEEE Transactions on Power Systems, col. 29, no. 1, pp. 307-317, 2014.

[3] S. Kasina, S. Wogrin and B. Hobbs, "Approximations to unit comment in planning models," INFORMS Annual Meeting, Minneapolis, 2013.

[4] J. Ho, B. F. Hobbs, P. Donohoo-Vallett, Q. Xu et al., "Planning transmission for uncertainty: Applications and lessons for the western interconnection," WECC, Salt Lake City, UT, 2016.

2 Formulation

2.1 Set

2.1.1 Root Set

- B: Bus set. Index: b, i
- G: Generation type set. Index: g
- H: Model stage set. Index: h
- J: State set. Index: j
- L: Line set. Index: l
- P: Period set. Index: t
- $Path$: Path set. Index: u
- RP: REC trading path set. Index: p
- S: Scenario set. Index: s

2.1.2 Subset

- B_C: Conventional hub set
- B_E: Existing buse set
- B_W: Renewable energy hub set
- G_D: Generation types to be dispatched
- G_P: Generation types modeled as parameters
- G_E: Existing generation types
- G_I: Generation types to be invested
- G_R: Renewable generation types
- L_{EXA}: Existing AC Lines
- L_{EXD}: Existing DC lines
- L_{CFB}: First stage backbone reinforcement candidate lines
- L_{CSB}: Second stage backbone reinforcement candidate lines
- L_{CBR}: First stage renewable access candidate lines
- L_{CWR}: Second stage renewable access candidate lines
- L_{EQ}: Equivalent lines
- L_H: Unidirectional fictitious hub lines, connecting conventional hubs to the grid

2.2 Parameters

2.2.1 Universal Parameters

- $A_{l,h}$: Stage availability of candidate line l, for first-stage candidates, 1 for year 10 and 20; for second-stage candidates, 1 for only year 20
- ACP_j^h: Alternate compliance payment (ACP) rate, Million\$/GWh
- B_l: Susceptance of line l, GW
- CX_l: Capital cost of line, Million\$
- EM_g: Emission rate, ton/MMBTU
- $\overline{F_l}$: Line thermal capacity, GW
- FOM_g: Fixed O&M cost Million\$/(GW year)
- FOR_g: Forced outage rate
- HW_t: Hour-weight of t
- $HR_{g,b}$: Heat rate of generation g on bus b, GW \$/MMBTU
- $IRPS_j$: Instate RPS requirement
- M_l: Large positive number for AC candidate line l, GW
- POR_g: Planed Outage Rate
- $PW_{b,j}$: Population allocation weight per bus to each state
- $\overline{R_u}$: Existing Path rating, GW

- $\overline{RX_l}$: Expansion of path rating with candidate line l, non-zero for backbone reinforcement
- V_h: Number of years for stage h
- $VOLL$: Value of load loss, Million\$/GWh
- $VOM_{g,b}$: Variable O&M cost Million\$/GWh
- $W_{b,g,t}$: Hourly capacity factors for wind, solar and hydro, 1 for other techs
- $Y^0_{b,g}$: Existing Capacity, GW
- $\overline{YMax_{b,g}}$: Maximum resource potential at bus under investment, GW
- $YR^h_{b_g}$: Cumulative forced retirement of generation capacity in stage h
- δ: Discount Rate
- $\Phi_{l,b}$ Element of line-node incidence matrix, 1 for to-bus, -1 for from-bus, otherwise 0
- $\Psi_{u,l}$ Element of path-line incidence matrix, 1 for to-bus, -1 for from-bus, otherwise 0
- $\Omega_{p,j}$: Element of REC trading path-state incidence matrix, binary

2.2.2 Scenario Specific Parameters

- p_s: Probability of scenario s
- $CTax_s$: Carbon tax per scenario, \$/ton
- $CY^h_{b,g,s}$: Capital cost of generation, Million\$/GW
- $D^h_{b,t,s}$: Forecasted demand, GW
- $FP^h_{b,g,s,t}$: Fuel price of generation g on bus b, Million \$/MMBTU
- $MC^h_{b,g,s,t}$: Generation marginal cost, Million\$/GW
- $RPS^h_{j,s}$: Renewable obligation of state j,%
- $WRPS_s$: Region-wise RPS renewable obligation, %

2.2.3 Calculating $MC^h_{g,s,t}$

$$MC^h_{g,s,t} = FP^h_{b,g,s,t}HR_{g,b} + CTax_s HR_{g,b} EM_g + VOM_{g,b} \tag{1}$$

2.3 Decision Variables

2.3.1 Investment Decision Variables

- x^{CFB}_l: Backbone reinforcement first stage decision, binary, defined on L_{CFB}
- $x^{CSB}_{l,s}$: Backbone reinforcement recourse decision, binary, defined on L_{CSB}
- x^{CFR}_l: Renewable access first stage investment decision, continuous 0-1, defined on L_{CFR}
- $x^{CSR}_{l,s}$: Renewable access investment recourse decision, continuous 0-1, defined on L_{CSR}
- $y_{b,g}$: Generation expansion anticipation, GW, positive, defined on $B_C \cup B_W, G_I$
- $y_{b,g,s}$: Generation expansion recourse anticipation, GW, positive, defined on $B_C \cup B_W, G_I$

2.3.2 Operation Decision Variables

- $f^h_{l,t,s}$: Power flow, GW, unrestricted
- $k^h_{b,g,t,s}$: Generation, GW, positive
- $n^h_{j,s}$: Noncompliance of renewable target, GWh, positive
- $q^h_{s,p}$: Renewable energy credit trading, GWh, positive
- $r^h_{b,t,s}$: Load curtailment, positive
- $\theta^h_{b,t,s}$: Phase angle, unrestricted
- $\phi^h_{b,t,s}$: Load uplift, GW

2.4 Objection Function

$$I^0_s = \sum_{l \in L_{CFB} \cup L_{CFR}} CX_l x_l + \sum_{g \in G_I} CY^0_{b,g,s} y_{b,g} \tag{2}$$

$$I^1_s = \sum_{l \in L_{CSB} \cup L_{CSR}} CX_l x_{l,s} + \sum_{g \in G_I} CY^1_{b,g,s} y_{b,g,s} \tag{3}$$

$$OC^h_s = \sum_{v=1}^{V_h} \left(\frac{1}{1+\delta}\right)^{v-1} 8760 \sum_{t \in P} \sum_{g \in G} MC^h_{g,s,t} HW_t k^h_{b,g,t,s} \tag{4}$$

$$OP^h_s = \sum_{v=1}^{V_h} \left(\frac{1}{1+\delta}\right)^{v-1} \left[\sum_{b \in B} 8760 VOLL HW_t (r^h_{b,t,s} + \phi^h_{b,t,s}) + \sum_{j \in J} ACP^h_{j,s} n^h_{j,s} \right] \tag{5}$$

$$OM^1_s = \sum_{b,g} FOM_g \left[Y^0_{b,g} - YR^1_{b,g} + y_{b,g} \right] \tag{6}$$

$$OM^2_s = \sum_{b,g} FOM_g \left[Y^0_{b,g} - YR^2_{b,g} + y_{b,g} + y_{b,g,s} \right] \tag{7}$$

$$O^h_s = OC^h_s + OP^h_s + OM^h_s \tag{8}$$

$$min \quad I^0 + \sum_{s \in S} p_s \left[\left(\frac{1}{1+\delta}\right)^{V_1} (I^1_s + O^1_s) + \left(\frac{1}{1+\delta}\right)^{V_1+V_2} O^2_s \right] \tag{9}$$

2.5 Constraints

2.5.1 RPS Constraint

Region-wise RPS:

$$\sum_{j \in J} \sum_{g \in G_R, t, b} 8760 HW_t PW_{b,j} k^h_{b,g,t,s} + n^h_{j,s} \geq WRPS_s \sum_{j \in J} \sum_{i,t} 8760 HW_t PW_{b,j} \left[D^h_{b,t,s} - r^h_{b,t,s} + \phi^h_{lo,b,t,s} \right] \quad \forall s, h \tag{10}$$

State-wise RPS:

$$\sum_{g \in G_R, t, b} 8760 HW_t PW_{b,j} k^h_{b,g,t,s} - \sum_p \left[\Omega_{p,j} q^h_{s,p} \right] + n^h_{j,s} \geq RPS^h_{j,s} \sum_{i,t} 8760 HW_t PW_{b,j} \left[D^h_{b,t,s} - r^h_{b,t,s} + \phi^h_{lo,b,t,s} \right] \quad \forall s, h, j \tag{11}$$

In-State RPS:

$$\sum_{g \in G_R, t, b} 8760 HW_t PW_{b,j} k^h_{b,g,t,s} - \sum_p \left[\Omega^{>0}_{p,j} q^h_{s,p} \right] + n^h_{j,s} \geq RPS^h_{j,s} IRPS_j \sum_{i,t} 8760 HW_t PW_{b,j} \left[D^h_{b,t,s} - r^h_{b,t,s} + \phi^h_{lo,b,t,s} \right] \quad \forall s, h, j \tag{12}$$

2.5.2 Transmission Constraint: KCL Component

Kirchhoff's Current Law:

$$\sum_{g} k^h_{b,g,t,s} + r^h_{b,t,s} + \sum_{l} \Phi_{l,b} f^h_{l,t,s} - \phi^h_{lo,b,t,s} - D^h_{b,t,s} = 0 \quad \forall b,t,s,h \tag{13}$$

Path Ratings:

$$|\sum_{l} \Psi_{u,l} f^h_{l,t,s}| \leq \left[\overline{R_u} + \sum_{l} A_{h,l} \overline{RX_l}(x_l + x_{l,s})\right] \quad \forall s,h,u,t \tag{14}$$

Load Curtailment Limits:

$$r^h_{b,t,s} \leq D^h_{b,t,s} \quad \forall b,t,s,h \tag{15}$$

Thermal Limits for Existing AC & DC lines:

$$|f^h_{l,t,s}| \leq \overline{F_l} \quad \forall l \in L_{EXA} \cup L_{EXD}, t, s, h \tag{16}$$

Thermal Limits for Candidate Lines:

$$|f^h_{l,t,s}| \leq \overline{F_l} A_{h,l}(x_l + x_{l,s}) \quad \forall l,t,s,h \tag{17}$$

Hub Line Flow Non-negativity:

$$f^h_{l,t,s} \geq 0 \quad \forall l \in L_H, t, s, h \tag{18}$$

Equivalent Line Thermal Capacity (For Pipe and Bubble formulation):

$$|f^h_{l,t,s}| \leq \frac{\pi}{6}|B_l| \quad \forall l \in L_{EQ} \tag{19}$$

2.5.3 Transmission Constraint: KVL Component

Swing Bus:

$$\theta^h_{'1',t,s} = 0 \quad \forall t,s,h \tag{20}$$

Kirchhoff's Voltage Law for Existing AC lines and Equivalent lines:

$$B_l \sum_{b} -1\Phi_{l,b}\theta^h_{b,t,s} = f^h_{l,t,s} \quad \forall l \in L_{EXA} \cup L_{EQ} \tag{21}$$

Kirchhoff's Voltage Law for First Stage Backbone Candidates:

$$|B_l \sum_{b} -1\Phi_{l,b}\theta^h_{b,t,s} - f^h_{l,t,s}| \leq M_l(1 - x_l) \quad \forall l \in L_{CFB}, t, s, h \tag{22}$$

Kirchhoff's Voltage Law for Second Stage Backbone Candidates:

$$|B_l \sum_{b} -1\Phi_{l,b}\theta^2_{b,t,s} - f^2_{l,t,s}| \leq M_l(1 - x_{l,s}) \quad \forall l \in L_{CSB}, t, s \tag{23}$$

Phase Angle Difference Limit:

$$|\sum_{b} \Phi_{l,b}\theta^h_{b,t,s}| \leq \frac{\pi}{6} \quad \forall l \in L_{EQ}, t, s, h \tag{24}$$

2.5.4 Generation Constraints

Generation Investment Potential:

$$y_{b,g} + y_{b,g,s} \leq \overline{YMAX_{b,g}} \quad \forall b,g,s \tag{25}$$

Invested Generation Limit Year 10:

$$k^1_{b,g,t,s} \leq (1 - POR_g)(1 - FOR_g)W_{b,g,t}y_{b,g} \quad \forall b \in B_W \cup B_C, g \in G_I, t, s \tag{26}$$

Invested Generation Limit Year 20:

$$k^2_{b,g,t,s} \leq (1 - POR_g)(1 - FOR_g)W_{b,g,t}\left(y_{b,g} + y_{b,g,s}\right) \quad \forall b \in B_W \cup B_C, g \in G_I, t, s \tag{27}$$

Existing Parameterized Generation:

$$k^h_{b,g,t,s} = (1 - POR_g)(1 - FOR_g)W_{b,g,t}(Y^0_{b,g} - YR^h_{b,g}) \quad \forall b, g \in G_P, t, s, h \tag{28}$$

Existing Dispatchable Generation:

$$k^h_{b,g,t,s} \leq (1 - POR_g)(1 - FOR_g)W_{b,g,t}(Y^0_{b,g} - YR^h_{b,g}) \quad \forall b, g \in G_D \cap G_E, t, s, h \tag{29}$$