Generation Expansion Planning Based on Multi-area Reliability Exponential Analytic Model and Emission Control

Lin Cheng

Tsinghua Univ.

Generation Expansion Planning

- **Considerations** requirements of power demands, installation capacities, loss of load probability (LOLP) levels, locations, and environmental limitations for emission controls
- **Methods**:
  - exponential analytic model: the influences of installed capacity of each area and transfer capability of the flowgate lines on the generation system reliability of every single area;
  - investment cost, O&M cost in objective function
  - flowgate transmission limitations and emission control are used as constraints

Optimization Framework

- **Considerations:**
  - Environmental constraints;
  - Reliability requirement;
  - Locations;
  - Load demand level;
  - Coordination between generation installation and transmission upgrade

Environmental Pollution in GEP

- China's power industry
  - Power demand level
  - Investment
  - Low efficiency in power generation

- Air pollution is inevitably caused by coal units, not only sulphur-dioxide (SO_2) and nitrogen-oxide (NO_x), but also large amount of greenhouse gases.

- Sulphur-dioxide emission owing to environmental constraints in China is 12 million tons annually, actual emission in 2006 is 25.9 million tons and sulphur-dioxide emission from fuel electric plant only has exceeded environmental capacity.

Coordination

- The problem of coordination becomes more difficult under power market deregulation. Generation expansion planning involves decisions on location and capacity of new generation, which may lead to adding or relieving congestion in transmission lines, so transmission expansion may be executed due to generation expansion planning (GEP)
- After transmission expansion, GEP should re-adjust to maximize investment revenues

Methods

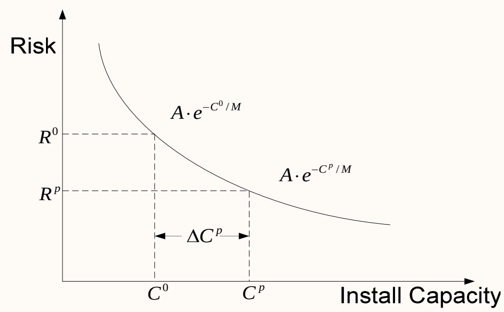
- A combined relationship between reliability and generation & transmission coordination is illustrated through the exponential analytic model of multi-area system
- Coordination is solved by the exponential analytic model
- Environmental constraints are expressed as emission limits in each area.

Generation Reliability

■Relationship between *reliability* and *capacity*

$$R = A \cdot e^{-C/M}$$

■Parameter solution



$$\ln \frac{R^p}{R^0} = M \cdot \Delta C_p$$

Multi-Area Generation Reliability

- Suppose that transfer capabilities in interfaces are abundant enough with no transmission constraints, reliability levels of all areas are generation-dominant problems. (*n* areas, *m* tie lines system)

$$\begin{cases} \boldsymbol{R} = diag(R_1^0, R_2^0, \ldots, R_n^0) \cdot [e^{-\boldsymbol{D_1} \cdot \boldsymbol{\Delta C}}, e^{-\boldsymbol{D_2} \cdot \boldsymbol{\Delta C}} \cdots e^{-\boldsymbol{D_n} \cdot \boldsymbol{\Delta C}}]^T \\ \boldsymbol{R} = [R_1, R_2, \ldots\ldots R_n]^T; \\ \boldsymbol{R^0} = [R_1^0, R_2^0, \ldots\ldots R_n^0]^T; \\ \boldsymbol{\Delta C} = [\Delta C_1, \Delta C_2, \ldots\ldots \Delta C_n]^T \end{cases}$$

$$\boldsymbol{D}_{n \times n} = \begin{bmatrix} d_{11} \cdots d_{1j} \cdots d_{1n} \\ \vdots \quad \vdots \quad \vdots \quad \vdots \\ d_{i1} \cdots d_{ij} \cdots d_{in} \\ \vdots \quad \vdots \quad \vdots \quad \vdots \\ d_{n1} \cdots d_{nj} \cdots d_{nn} \end{bmatrix}$$

- The element d_{ij} means the influence factor of generation installed capacity change in area *j* on the reliability level of area *i*, R_i^0 means reliability level of area *i* at the base case, C_i means installed capacity change in area *i*.

Multi-Area Generation Reliability

- Suppose that there are abundant total generation installed capacity and transmission constraints influence power interchange, then reliability levels of all areas become transmission-dominant problems.

$$
\begin{cases}
\boldsymbol{R} = diag(R_1^0, R_2^0, \ldots, R_n^0)\cdot[e^{-T_1\cdot \Delta Tie}, e^{-T_2\cdot \Delta Tie} \cdots e^{-T_n\cdot \Delta Tie}]^T \\
\boldsymbol{R} = [R_1, R_2, \ldots\ldots R_n]^T; \\
\boldsymbol{R^0} = [R_1^0, R_2^0, \ldots\ldots R_n^0]^T; \\
\boldsymbol{\Delta Tie} = [\Delta Tie_1, \Delta Tie_2, \ldots\ldots \Delta Tie_m]^T
\end{cases}
\qquad
\boldsymbol{T}_{n\times m} = \begin{bmatrix} t_{11}\cdots t_{1j}\cdots t_{1m} \\ \vdots \quad \vdots \quad \vdots \\ t_{i1}\cdots t_{ij}\cdots t_{im} \\ \vdots \quad \vdots \quad \vdots \\ t_{n1}\cdots t_{nj}\cdots t_{nm} \end{bmatrix}
$$

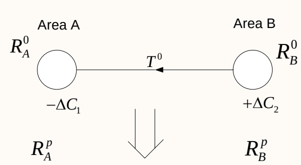
- The element t_{ij} means the influence factor of transmission capacity change in interface j on the reliability level of area i, Tie_j means transmission capacity change in interface j

Multi-Area Generation Reliability

- ***n* areas, *m* tie lines system**

$$
\begin{bmatrix} \ln\dfrac{R_1}{R_1^0} \\ \ln\dfrac{R_2}{R_2^0} \\ \vdots \\ \ln\dfrac{R_n}{R_n^0} \end{bmatrix}
= [\boldsymbol{D}|\boldsymbol{T}]\begin{bmatrix} \boldsymbol{\Delta C} \\ \boldsymbol{\Delta Tie} \end{bmatrix}
= \begin{bmatrix} d_{11}\cdots d_{1j}\cdots d_{1n} & t_{11}\cdots t_{1j}\cdots t_{1m} \\ \vdots \ \ddots \ \vdots \ \ddots \ \vdots & \vdots \ \ddots \ \vdots \ \ddots \ \vdots \\ d_{i1}\cdots d_{ij}\cdots d_{in} & t_{i1}\cdots t_{ij}\cdots t_{im} \\ \vdots \ \ddots \ \vdots \ \ddots \ \vdots & \vdots \ \ddots \ \vdots \ \ddots \ \vdots \\ d_{n1}\cdots d_{nj}\cdots d_{nn} & t_{n1}\cdots t_{nj}\cdots t_{nm} \end{bmatrix}
\cdot \begin{bmatrix} \Delta C_1 \\ \Delta C_2 \\ \vdots \\ \Delta C_n \\ \Delta Tie_1 \\ \Delta Tie_2 \\ \vdots \\ \Delta Tie_m \end{bmatrix}
$$

- **Sample**



$$
\begin{bmatrix} \ln\dfrac{R_A^p}{R_A^0} \\ \ln\dfrac{R_B^p}{R_B^0} \end{bmatrix}
= \begin{bmatrix} d_{11} & d_{12} & t_{11} \\ d_{21} & d_{22} & t_{21} \end{bmatrix} \cdot \begin{bmatrix} \Delta C_1 \\ \Delta C_2 \\ \Delta Tie_1 \end{bmatrix}
$$

清華大学 Tsinghua University

Optimization Model

- **Cost-Benefit Function**
- **Transmission Constraints of Flowgate**
- **Environmental Constraints**
- **Insufficient Transmission Capacity Expansion**

清華大学 Tsinghua University

Cost-Benefit Function

- Cost of Generation and Transmission Upgrade

$$C_{Inv} = \sum_{(i,j)} c_{ij} \cdot n_{ij} + \sum_{k} c_k \cdot n_k$$

c_{ij}: the cost of a transmission line in the *i*, *j* branch where n_{ij} lines were added;

c_k: the installation cost of a candidate generation node *k* where n_k generators were added.

- Operation and Maintenance Costs

$$C_{O\&M} = \sum_{u} (f_u + o_u) \cdot g_u$$

u: generating unit *u*;

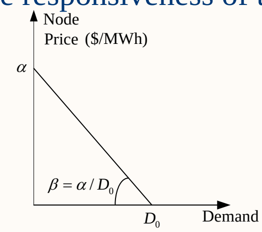
f_u: fuel cost for each unit of power output from the generating unit *u*;

o_u: O&M cost for each unit of power output from the generating unit *u*;

g_u: generation output of unit *u*

Consumer Benefit

- An affine inverse demand function is assumed. The curve shows a general form of a demand function that is used in this paper and indicates the price responsiveness of the consumers:



- Through the integration of demand function, the consumer benefit can be calculated

$$B = \alpha_v D_v - \frac{1}{2}\beta_v D_v^2$$

Transmission Constraints of Flowgate

- For a change in real power transaction between areas, say by $t_{k,l}$, the change in transmission line quantity is p_{ij}. In case of generation expansion, suppose load point demand increment is L_l, corresponding generation point output increases G_k, i.e., $t_{k,l} = L_l = G_k$.

$$PTDF_{ij-k,l} = \frac{\Delta p_{ij}}{\Delta t_{k,l}} = \frac{\Delta p_{ij}}{\Delta G_k} = PTDF_{ij-k}$$

- Total power flows through the flowgate *f* must be less than the maximum value

$$\sum_{ij \in f} \left(\sum_k PTDF_{ij-k} * G_k \right) \le C_f$$

Tsinghua University

Environmental Constraints

- For each region *r* of existing or new added generation installation, an upper bound for pollutant emission is imposed

$$K \cdot \sum_{s=1}^{S} h_{s,a} \sum_{u \in \Theta(r,s)} g_u \le H_{r,a} \quad a = 1, 2, 3$$

a: emission pollutant type (*a* =1 for sulphur-dioxide, *a* =2 for nitrogen-oxide, and *a* =3 for carbon-dioxide);

s: type of generation unit;

K: the number of hours within the interval;

: units set of type belonging to region ;

$h_{s,a}$ $\Theta(r,s)$: pollutant emission level for a unit of type ;

$H_{r,a}$: upper bound on pollutant emission within region during interval.

Tsinghua University

Two Models

- Constant Capacity Model: only generation expansion cost is included in investment function

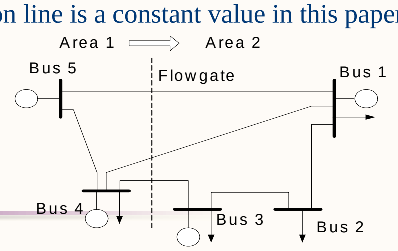
$$\begin{aligned} Min \quad & B - \sum_k c_k \cdot n_k - C_{O\&M} \\ s.t. \quad & \boldsymbol{R} = diag(R_1^0, R_2^0, \ldots, R_n^0) \cdot [e^{-D_1 \cdot \Delta C}, e^{-D_2 \cdot \Delta C} \cdots e^{-D_n \cdot \Delta C}]^T \\ & R_r \le R^{thres} \quad r = 1, 2, \ldots n \\ & \sum_{ij \in f} (\sum_k PTDF_{ij-k} * G_k) \le C_f \\ & K \cdot \sum_{s=1}^{S} h_{s,a} \sum_{u \in \Theta(r,s)} g_u \le H_{r,a} \quad a = 1, 2, 3 \end{aligned}$$

- Combined Model: generation shortage and insufficient transmission capacity

$$\begin{aligned} Min \quad & B - C_{Inv} - C_{O\&M} \\ s.t. \quad & \boldsymbol{R} = diag(R_1^0, R_2^0, \ldots, R_n^0) \cdot \\ & [e^{-\boldsymbol{D_1} \cdot \boldsymbol{\Delta C} + \boldsymbol{T_1} \cdot \boldsymbol{\Delta Tie}}, e^{-D_2 \cdot \Delta C + \boldsymbol{T_2} \cdot \boldsymbol{\Delta Tie}} \cdots e^{-D_n \cdot \Delta C + \boldsymbol{T_n} \cdot \boldsymbol{\Delta Tie}}]^T \\ & R_r \le R^{thres} \quad r = 1, 2, \ldots n \\ & \sum_{ij \in f} (\sum_k PTDF_{ij-k} * G_k) \le C_f \\ & K \cdot \sum_{s=1}^{S} h_{s,a} \sum_{u \in \Theta(r,s)} g_u \le H_{r,a} \quad a = 1, 2, 3 \end{aligned}$$

Five-Bus System

- In this system, the flows on lines 5-1, 4-1, and 4-3 have been selected as the lines that constitute a transmission flowgate.
- The total flow over these three lines is limited to 300 MW, there are no flow constraints on single lines;
- The capital cost per hour of adding extra capacity is assumed to be $25 per MW at each node;
- The operating costs are given in Table ;
- Coefficients of pollutant emissions are given in Table ;
- Cost of transmission line is a constant value in this paper.



System Parameters

TABLE I
Generator Data

Generator	Capacity(MW)	O&M Cost($/MWh)
Bus 1	200	30
Bus 3	520	25
Bus 4	600	10
Bus 5	210	15

TABLE II
Coefficients and Upper bounds for Pollutant Emission

Pollutant	Coefficients (g/MWh)			Bounds (*10^3kg/yr)		
	Coal	Oil	Gas	Bus 1	Bus 3	Bus 4
SO_2	5.84	14.30	0	50	50	50
NO_X	2.93	2.49	0.03	25	19	20
CO_2	890	753	448	15000	12000	12000

Constant Capacity Model

$$D_{2\times2}=\begin{bmatrix}2.92231 & 0.00000\\ 1.12802 & 1.13469\end{bmatrix}\times10^{-2}$$

- Area 2 is a sink area in current state, so installed capacity in area 2 does not improve the reliability level in area 1, then $d_{12}=0$;
- Within the range of transmission capacity of the flowgate, increment of installed capacity in both areas will improve the reliability level in sink area;
- due to $d_{22}>d_{21}$, installation in area 2 may be slightly more effective to improve the reliability level in sink area.

Constant Capacity Model

- Case 1: reliability threshold of area 2 is 2.4 hrs/yr;
- Case 2: reliability threshold of area 2 is 24 hrs/yr;
- Case 3: 2.4 hrs/yr reliability threshold constrained capacity model with environmental constraints;
- Case 4: 24 hrs/yr reliability threshold constrained capacity model with environmental constraints

Optimization Results

Case	Expansion (MW)				Profit($)
	Bus 1	Bus 3	Bus 4	Bus 5	
Case 1	0	498	89	0	36,785
Case 2	0	294	90	0	46,950
Case 3	279	221	87	0	35,360
Case 4	73	221	90	0	46,585

清華大學 Tsinghua University

Combined Model

$$I_{2\times 3} = \begin{bmatrix} 2.92231 & 0.00000 & 0.00000 \\ 1.12802 & 1.13469 & 0.45101 \end{bmatrix} \times 10^{-2}$$

- capacity increment in flowgate will lead to improvement in reliability level of sink area;
- Suppose area 1 have sufficient installed capacity, so its reliability level doesn't change with flowgate capacity.

清華大學 Tsinghua University

Combined Model

- Case 5: 2.4 hrs/yr reliability threshold combined model with environmental constraints;
- Case 6: 24 hrs/yr reliability threshold combined model with environmental constraints

Optimization Results

Case	Expansion (MW)			Profit($)
	Bus 4	Bus 5	Transmission	
Case 5	154	291	355	47,754
Case 6	154	146	210	53,556

Conclusions

- Multi-area generation reliability exponential analytic model takes the coupling influence between areas into account, and transmission capacity upgrade from the combined model has much influence on GEP.
- To make GEP more effective, environmental regulations from government requirement must be taken into account, test results show that emission control does limit output of some units, then GEP must be adjusted accordingly.
- Coordination between GEP and transmission upgrade is important in multi-area systems. Generation of lower cost can be transferred through newly built transmission lines to make the optimal GEP.

Thanks