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Market Oriented Transmission Expansion Planning

Xiaodi Wang[1*], Jinyue Yan

Future Energy Center, Malardalen University

ABSTRACT

The reform of electricity market in China has made the market participants more active, which has posed a series of challenges for the power system planning with high penetration of renewable energy. This paper proposed a price-driven bi-level model for transmission expansion planning. At the upper level, the investment cost and operation cost of the transmission system is comprehensively considered. While at the lower level, the market clearing model is established, i.e., energy market and reserve market. The local marginal prices are obtained to guide the expansion planning of the upper level. By integrating the market clearing model of the lower level using Karush-Kuhn-Tucker condition, a mixed-integer nonlinear programming problem is formulated, which is further solved by a Heuristic method. In the case study, a modified Garver-6 bus system is utilized to verify the validity of the proposed method.

Keywords: transmission expansion planning, optimization, electricity market, local marginal price.

1. INTRODUCTION

Transmission expansion planning (TEP) is an important research topic that plays a fundamental role in maintaining the security and reliability of power systems[1]. TEP usually solves the problem of how to expand the transmission network while satisfying the forecasted demand at minimum expansion and operational costs over a given planning horizon. Planning new transmission assets to integrate renewable energy sources (RES), however, has become increasingly difficult, because of the mid- and long-term uncertainties associated with the deployment of renewable generation, as well as the development of a more competitive electricity market [2].

Usually, the TEP problem in the electricity market environment can be modeled as a bi-level optimization problem with the upper level representing the system planner's decision making and the lower-level accounting for the market clearing problem [3]. A great deal of effort has been devoted to deal with various aspects related to this problem [4]-[5]. Ref [6]–[8] are some of the relevant examples of bilevel approaches for TEP. In [6], a bilevel approach was proposed to minimize costs associated with the transmission expansion plan while facilitating trades in the electricity market. In [7], the framework presented in [6] was extended by the inclusion of security constraints. In [8], the authors used a bilevel framework to model the efficiency benefit (benefit of accessing lower cost distant generation) and the competition benefit (benefit of improving competition among generators) associated with additional transmission capacity. In addition, trilevel models such as [9]–[10] were also presented to tackle the TEP problem. In [9], a trilevel model was developed to determine the transmission expansion plan while considering the equilibria associated with generation expansion and pool-based market clearing. In [10], a trilevel formulation was proposed to address the TEP problem under uncertainty in demand and in available generation capacity of existing generating units.

In general, the main objective of a TEP problem in deregulated power systems is to provide a nondiscriminatory and competitive environment for all stakeholders, while maintaining power system reliability with the growing capacity of the renewable energy. TEP affects the interests of market participants unequally and this should be considered in transmission planning.

Congestion cost, as a measurement to weight the competitiveness degree of an electricity market. As less transmission lines are congested, i.e., as constraints for dispatching the cheapest undispatched generation decrease, Locational Marginal Price (LMP) differences among buses and consequently congestion cost decreases and vice versa. From another viewpoint, maximizing the social welfare can be used as a proper criterion to encourage the competition between market players.

In this regard, this paper proposed a market-driven bi-level model for transmission expansion planning while considering the different penetration of renewable energy. At the upper level, the investment cost, operation cost and social welfare of the independent system operator (ISO) is comprehensively considered. While at the lower level, a market clearing model is formed. The LMP of the transmission network is obtained to guide the expansion planning of the upper level. By integrating the market clearing model of the lower level using Karush-Kuhn-Tucker condition, a mixed-integer nonlinear programming (MINLP) problem is formulated The MINLP problem is further solved using an improved differential evolution (IDE) method. A modified Garver-6 bus system is utilized to verify the validity of the proposed method.

2. BI-LEVEL MODEL FORMULATION

2.1 The upper-level model: minimize the cost of independent system operator

The objective function of ISO is to minimize the total expansion and expected operational costs over a given planning horizon as formulated below:

$$\min_{x^u} C^S(x^u) := C^E(x^u) + \sum_{j\in J} z_j \left(C_j^P\left(x^u, x_j^L\right) + C_j^U\left(x_j^L\right)\right) \quad (1)$$

Where C^E denote the expansion cost, C_j^P represents the market clearing results, and C_j^U means the system utility cost. System utility cost consists of the generators utility and load utility, which can be calculated as below:

$$C^E(x^u) = \left(\sum_{l\in L^e} \rho_l^e \sigma_l^e K_l^e + \sum_{l\in L^n} \rho_l^n \sigma_l^n K_l^n\right) \quad (2)$$

$$C_j^U\left(x_j^L\right) = -\sum_{t\in T}\sum_{g\in G} \lambda_{j,t,g}^{lmp} p_{j,t,g}^g + \sum_{t\in T}\sum_{d\in D}\left(-\alpha_m D_{j,t,m}^d + \frac{1}{2}\beta_m {D_{j,t,m}^d}^2\right) \quad (3)$$

S.t.

$$\sum_{l\in L^e} \rho_l^e \sigma_l^e K_l^e + \sum_{l\in L^n} \rho_l^n \sigma_l^n K_l^n \le I^{max} \quad (4)$$

$$\sigma_l^e + \sigma_l^n \le 1 \qquad \forall l \in L \quad (5)$$

where $x^u = \{\sigma_l^e, \sigma_l^n\}$ are the upper-level decision variables. σ_l^e, σ_l^n is binary variable to decide whether to build a new transmission line or to expand the existing transmission line; K_l^e, K_l^n is the capacity of the new transmission line and the expanded existing transmission line. L^e, L^n are the candidate set for newly built transmission lines and candidate transmission lines; I^{max} is the maximum investment cost; α_m, β_m is the coefficient of load's utility; $p_{j,t,g}^g$ is the dispatched generator output; $\lambda_{j,t,g}^{lmp}$ is the LMP.

2.2 The lower-level model: market clearing

The market clearing model can be understood as an economic dispatch problem, which can be expressed as below:

$$\min_{x^u} C_j^P\left(x_{j,t}^L\right) := \sum_{t\in T}\Big(\sum_{d\in D} c_{j,t}^D p_{j,t,d}^d + \sum_{g\in G} c_{j,t}^G p_{j,t,g}^g + \sum_{g\in G} c_{j,t}^{ru} r_{j,t,g}^{ru} + \sum_{g\in G} c_{j,t}^{rd} r_{j,t,g}^{rd}\Big) \quad (6)$$

where $x_{j,t}^L = \left\{D_{j,t,m}^0, p_{j,t,d}^d, p_{j,t,g}^g, r_{j,t,g}^{ru}, r_{j,t,g}^{rd}, f_{j,t,l}, \theta_{j,t,b}\right\}$ are the lower-level decision variables. $p_{j,d}^d$ is the renewable curtailment amount. $c_{j,t}^D, c_{j,t}^G, c_{j,t}^{ru}, c_{j,t}^{rd}$ refers to the unit cost of renewable energy curtailment, conventional generator output, and upper/lower reserve capacity provided by conventional generators.

The market clearing model submit to the following constraints:

2.2.1 generator constraints:

$$p_{j,t,g}^g + r_{j,t,g}^{ru} \le G_g^{max} \quad (7)$$

$$r_{j,t,g}^{rd} - p_{j,t,g}^g \le -G_g^{min} \quad (8)$$

$$r_{j,t,g}^{ru} \le R_g^{RU} \quad (9)$$

$$r_{j,t,g}^{rd} \le R_g^{RD} \quad (10)$$

$$p_{j,t,g}^g \ge 0, r_{j,t,g}^{ru} \ge 0, r_{j,t,g}^{rd} \ge 0 \quad (11)$$

where G_g^{max}, G_g^{min} are the minimum/maximum output of a generator; R_g^{RU}, R_g^{RD} are the minimum/maximum capacity to provide reserve service a generator.

2.2.2 renewable energy curtailment and load constraints:

$$0 \le p_{j,d}^d \le G_{j,t,d}^{re} \quad (12)$$

$$D_{j,t,b}^0 \le D_{j,t,b}^d \le D_{j,t,b}^{max} \quad (13)$$

where $G_{j,t,d}^{re}$ is the maximum output of a renewable energy device; $D_{j,t,b}^{max}, D_{j,t,b}^{0}$ is the upper/lower limit of the demand at bus b.

2.2.3 system operation constraint

1) Nodal balance constraint

$$G_{j,t,b}^{re} - p_{j,b}^{d} + p_{j,b}^{g} - \sum_{l|b\in o(l)} f_{j,t,l} + \sum_{l|b\in r(l)} f_{j,t,l} = D_{j,t,b}^{d} \tag{14}$$

2) Reserve constraint

$$\sum_{g\in G} r_{j,t,g}^{ru} \ge \phi^{G} \sum_{b\in B} G_{j,t,b}^{re} + \phi^{D} \sum_{b\in B} D_{j,t,b}^{d} \tag{15}$$

$$\sum_{g\in G} r_{j,t,g}^{rd} \ge \phi^{G} \sum_{b\in B} G_{j,t,b}^{re} + \phi^{D} \sum_{b\in B} D_{j,t,b}^{d} \tag{16}$$

where ϕ^{G}, ϕ^{D} are the reserve capacity coefficients.

3) Security constraint

$$\theta^{min} \le \theta_{j,t,b} \le \theta^{max} \tag{17}$$

$$-\sigma_{l}^{e} K_{l}^{e} \le f_{j,t,l} \le \sigma_{l}^{e} K_{l}^{e} \tag{18}$$

$$-(1-\sigma_{l}^{e})M_{l} \le f_{j,t,l} - B_{l}\big(\theta_{j,t,o(l)} - \theta_{j,t,r(l)}\big) \le (1-\sigma_{l}^{e})M_{l} \tag{19}$$

$$-K_{l}^{o} - \sigma_{l}^{n} K_{l}^{n} \le f_{j,t,l} \le K_{l}^{o} + \sigma_{l}^{n} K_{l}^{n} \tag{20}$$

$$f_{j,t,l} = B_{l}\big(\theta_{j,t,o(l)} - \theta_{j,t,r(l)}\big) \tag{21}$$

where $\theta_{j,t,b}$ is the node voltage; $f_{j,t,l}$ is the power flow; M_{l} is a big number.

The dual variables for the lower level constraints (7)-(21) are $\Big\{m_{j,t,g}^{G^+},\ m_{j,t,g}^{G^-},\ m_{j,t,g}^{RU},\ m_{j,t,g}^{RD},\ m_{j,t,g}^{g},\ m_{j,t,g}^{ru},\ m_{j,t,g}^{rd},\ m_{j,t,b}^{d},\ m_{j,t,b}^{D},\ m_{j,t,d}^{DD}, \lambda_{j,t}^{l},\ \lambda_{j,n}^{ru},\ \lambda_{j,n}^{rd}, \varepsilon_{j,t,b}^{L^-}, \varepsilon_{j,t,b}^{L^+},\ \mu_{j,t,l}^{f^-},\ \mu_{j,t,l}^{f^+},\ \psi_{j,t,l}^{f^-},\ \psi_{j,t,l}^{f^+},\ \psi_{j,t,l}^{L}\Big\}$, from which we can calculate the LMP of the system as

$$\lambda_{j,t,b}^{lmp} = \lambda_{j,t}^{l} + h\left(\mu_{j,t,l}^{f^-}, \mu_{j,t,l}^{f^+}, \psi_{j,t,l}^{f^-}, \psi_{j,t,l}^{f^+}, \psi_{j,t,l}^{L}\right) \tag{22}$$

3. SINGLE MODEL FORMULATION

The Lagrange function of the lower-level can be formulated as

$$L = \sum_{d\in D} c_{j,t}^{D} p_{j,t,d}^{d} + \sum_{g\in G} c_{j,t}^{G} p_{j,t,g}^{g} + m_{j,t,g}^{G^+}\big(p_{j,t,g}^{g} - G_{g}^{max}\big) + m_{j,t,g}^{G^-}\big(-p_{j,t,g}^{g} + G_{g}^{min}\big) - p_{j,t,g}^{g} m_{j,t,g}^{g} + m_{j,t,d}^{D}\big(p_{j,t,d}^{d} - G_{j,t,d}^{re}\big) - p_{j,t,d}^{d} m_{j,t,d}^{d} - \lambda_{j,t,b}^{lmp}\Big(G_{j,t,b}^{re} - p_{j,b}^{d} + p_{j,b}^{g} - \sum_{l|b\in o(l)} f_{j,t,l} + \sum_{l|b\in r(l)} f_{j,t,l} - D_{j,t,b}^{d}\Big) + \varepsilon_{j,t,l}^{L^+}\big(\theta_{j,t,b} - \theta^{max}\big) + \mu_{j,t,l}^{L^+}\big(f_{j,t,l} - B_{l}\big(\theta_{j,t,o(l)} - \theta_{j,t,r(l)}\big) - (1-\sigma_{l})M_{l}\big) + \mu_{j,t,l}^{L^-}\big(-f_{j,t,l} + B_{l}\big(\theta_{j,t,o(l)} - \theta_{j,t,r(l)}\big) - (1-\sigma_{l})M_{l}\big) + \mu_{j,t,l}^{f^+}\big(f_{j,t,l} - \sigma_{l}^{e} K_{l}^{e}\big) + \mu_{j,t,l}^{f^-}\big(-f_{j,t,l} - \sigma_{l}^{e} K_{l}^{e}\big) \tag{23}$$

Since the lower market clearing problem is an linear problem, in this regard, the bi-level problem of Eq.(1) can be formulated as a single level problem as

$$\begin{aligned}\min_{x^u} C^{S}(x^u) := \sum_{j\in J} w_j \Bigg(&\sum_{t\in T}\sum_{d\in D} c_{j,t}^{D} p_{j,t,d}^{d} \\ &+ \sum_{t\in T}\sum_{g\in G}\Big(c_{j,t}^{G} p_{j,t,g}^{g} + c_{j,t}^{ru} r_{j,t,g}^{ru} + c_{j,t}^{rd} r_{j,t,g}^{rd} - \big(\lambda_{j,t,g}^{lmp} p_{j,t,g}^{s} + \lambda_{j,t}^{ru} r_{j,t,g}^{ru} + \lambda_{j,t}^{rd} r_{j,t,g}^{rd}\big)\Big) \\ &+ \sum_{t\in T}\sum_{d\in D}\Big(-\alpha_m D_{j,t,m}^{0} + \frac{1}{2}\beta_m {D_{j,t,m}^{0}}^{2}\Big)\Bigg) \\ &+ \Bigg(\sum_{l\in L^e} \rho_{l}^{e} \sigma_{l}^{e} K_{l}^{e} + \sum_{l\in L^n} \rho_{l}^{n} \sigma_{l}^{n} K_{l}^{n}\Bigg)\end{aligned} \tag{24}$$

S.t.

Constraint (4)-(5), Constraint (7)-(21)

$$G_{j,t,b}^{re} - p_{j,b}^{b} + p_{j,b}^{g} - \sum_{l|b\in o(l)} f_{j,t,l} + \sum_{l|b\in r(l)} f_{j,t,l} = D_{j,t,b}^{d} \tag{25}$$

$$m_{j,t,d}^{DU} - m_{j,t,d}^{DD} - \lambda_{j,t,b}^{lmp} + \phi^{D}\lambda_{j,t,n}^{ru} + \lambda_{j,t,n}^{rd}\phi^{D} = 0 \tag{26}$$

$$c_{j,t}^{D} - \lambda_{j,t,d}^{lmp} + m_{j,t,d}^{D} - m_{j,t,d}^{d} = 0 \tag{27}$$

$$c_{j,t}^{G} + m_{j,t,g}^{G^+} - m_{j,t,g}^{G^-} - m_{j,t,g}^{g} = 0 \tag{28}$$

$$c_{j,t}^{ru} + m_{j,t,g}^{G^+} + m_{j,t,g}^{RU} - m_{j,t,g}^{ru} - \lambda_{j,t}^{ru} = 0 \tag{29}$$

$$c_{j,t}^{rd} + m_{j,t,g}^{G^-} + m_{j,t,g}^{RD} - m_{j,t,g}^{rd} - \lambda_{j,t}^{rd} = 0 \tag{30}$$

$$\mu_{j,t,l}^{L^+} - \mu_{j,t,l}^{L^-} + \mu_{j,t,l}^{f^+} - \mu_{j,t,l}^{f^-} + \lambda_{j,t,r(l)}^{l} - \lambda_{j,t,o(l)}^{l} = 0 \tag{31}$$

$$\psi_{j,t,l}^{L^+} - \psi_{j,t,l}^{L^-} + \psi_{j,t,l}^{L} + \lambda_{j,t,r(l)}^{l} - \lambda_{j,t,o(l)}^{l} = 0 \tag{32}$$

$$\varepsilon_{j,t,b}^{L^+} - \varepsilon_{j,t,b}^{L^-} + \sum_{l\in L^e|b\in r(l)}\big(\mu_{j,t,l}^{L^+} - \mu_{j,t,l}^{L^-}\big)B_l - \sum_{l\in L^e|b\in o(l)}\big(\mu_{j,t,l}^{L^+} - \mu_{j,t,l}^{L^-}\big)B_l + \sum_{l\in L^o|b\in r(l)} \psi_{j,t,l}^{L} B_l - \sum_{l\in L^o|b\in o(l)} \psi_{j,t,l}^{L} B_l = 0 \tag{33}$$

And other a series of compensatory relaxed constrains. The problem is solved by an improved differential evolution (IDE) algorithm in [11].

4. CASE STUDY

In this section, to show the effectiveness of the proposed approach, we test a modified Garver- 6-bus system to conduct numerical experiments, which includes six buses and seven transmission lines. We consider 2 coal plants (G1 =250 MW at bus1 and G2

G2=120 MW at bus 2), and 1 wind farm (WT=200 MW at bus 6). Here, the modified 6-bus system already have 5 existing transmission lines as well as 7 candidate transmission lines (denoted by red dotted lines). Specific settings for the 6-bus system are presented in Tables I.

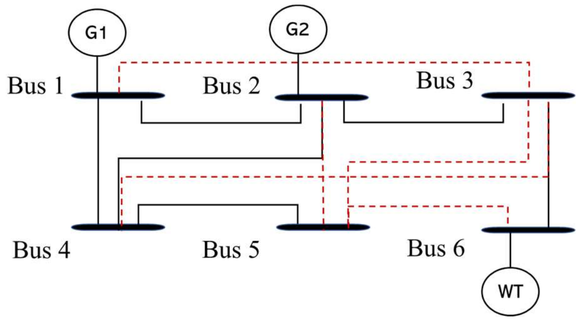

Fig 1 The modified Garver-6 system.

Table 1 The system parameters

index	branch	Line capacity (MW)	Exiting line	Candidate line
1	1-2	128	1	1
2	1-4	128	1	1
3	2-3	80	1	1
4	3-6	104	1	1
5	4-5	132	1	1
6	2-4	104	0	1
7	5-6	72	0	1
8	1-3	56	0	1
9	2-5	104	0	1
10	3-5	64	0	1
11	3-4	64	0	1
12	1-6	64	0	1

Besides genetic algorithm (GA) is adopted as comparison algorithm to compare the transmission expansion results of the IDE algorithm. The results are shown in Table 2 and Table 3.

Compared with GA method, the transmission line expansion of IDE method achieves better investment performance in term of the economy. Although the system operation cost of IDE method is higher than that of GA. IDE method has comprehensively considered the load demand utility and the market clearing result, which can promote market participants to participate in the electricity market. On the other hand, more system demand means that less renewable energy is required to be curtailed.

Table 2 Transmission expansion results

Method	Newly built line	Expansion line	Invest cost
GA	1-6、2-5、3-4	3-6	1150
IDE	5-6	1-4	625

Table 3 Daily operation results

	GA	IDE
Generatio (MWh)	1134.2	1445.3
Load (MWh)	1080	1421
Renewable curtailment (MWh)	54.2	24.3
System operation cost ($)	16413.3	19104.3
System utility	2639	3378

Table 4 Transmission expansion results with different renewable energy penetration

penetration	20%	40%	60%
Newly built line	2-4	1-6、3-4	1-6、2-5
Expansion line	1-4	1-4、3-6	1-4、3-6
Invest cost ($)	1160	1960	2480
Average LMP ($/MW)	20	18	24.28
Renewable energy Curtail rate	0%	8%	32.3%

The influence of different renewable energy penetrations on transmission planning results are also analyzed. Table 4 show that the transmission planning results under the renewable energy penetrations vary from 20% to 60%.

The growing renewable energy penetrations in the system, increase the demand to build new lines and expand existing lines in the transmission network, as well as the investment cost.

In addition, the renewable energy penetrations also have a significant impact on the LMP of the system. More renewable energy helps ISO choose more high-quality and economical conventional units to generate electricity (in the case of 40% renewable energy penetration). However, too much renewable energy can lead to line congestion (in the case of 60% renewable energy penetration), which results in unfairness among market participants.

5. CONCLUSION

This paper proposes a price-driven bi-level model for transmission expansion planning while considering the different penetration of renewable energy. The case study shows that compared with traditional GA method, the proposed method can:

1) achieve better investment cost while considering the system operation security;

2) achieve better social utility, which helps to motivate end-users consume more renewable energy;

3) achieve more fair market environment by avoiding line congestion.

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