Research on Method of Cross-Provincial Transmission Pricing and Benefit Estimating Based on Power Tracing

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Abstract. The fair and reasonable method of cross-provincial transmission pricing can give the price and economic signal for the each trader. The models of cross-provincial transmission pricing and evaluation are based on power tracing is proposed in this paper. In the cross-provincial transmission pricing model the load is allocated no transmission cost when the load bus is as the same with the originate bus of one branch. And the cross-provincial transmission benefit is evaluated accurately by consumers’ surplus through the relation between generation and load based up-stream tracing. And the power use of cross-provincial transmission grid for each trader is considered in this model.

1. Introduction
In order to promote the large-scale optimization of resources, countries around the world have strengthened interconnection and transmission between regions. In the United States the interconnection of the regional markets has strengthened and cross-regional power transactions carried on extensively. In Australia the construction of inter-regional interconnected power grids has increased and the states are more closely connected. In the EU a unified power market has been built and cross-border power transactions have conducted. In China UHV long-distance and large-scale power transmission is vigorously developing. Under this circumstance, it is necessary to establish a fair inter-provincial transmission pricing method and a reasonable benefit evaluation method and to provide effective reference and guide transactions for all parties to the transmission transaction from price signals and economic incentives.

From the existing research, the research on trans-provincial transmission is mostly concentrated on the cost allocation method in transmission pricing [1-4]. The parties involved in the transmission often can only judge the economics of the transmission transaction from the single power supplying generator price and single power receiving user price. When the trans-provincial transmission network is more and more complicated, there will be multiple power supplying generators for one power receiving user. Similarly, there are multiple power receiving users for one power supplying generator. In this case, the single price level will be difficult to reflect. The comprehensive benefits of the power generators and the users.
2. Cross-provincial Transmission Pricing

2.1. Fundamental
There are two main problems to be solved in cross-provincial transmission pricing: one is how to allocate the cross-provincial transmission cost to the power generators and the consumers. The other problem is how to allocate the total transmission cost of generators to each one and how to allocate the total transmission cost of users to each one.

In the first question, the allocating ratio of transmission cost between generator and customer is greatly influenced by the tendency of the national policy and the negotiation between the power generator and the customer. Therefore, the allocating ratio of transmission cost between generator and customer is determined through the foreign experience and the actual situation of China’s policy in this paper.

In the second question, the trans-provincial transmission costs are all fixed costs. The direct and effective indicator for the fixed cost of different users or power suppliers is the degree of use of the line by the power users or the power generators. The acceptable physical quantity is the passing power of the power users or the power generators on the line. The power flow tracing method [5-7] is based on the principle of proportional distribution shown in Figure 1. The power source where the power flow on one line comes from is determined by upstream tracing, and the load where the power flow on one line goes to is determined by downstream tracing. So the extent to which the line is used by the power users or the power generators, based on which the ration of cost allocated to each users of generators is quantified.

\[
\begin{align*}
  f_i &= f_i \frac{f_3}{f_5 + f_4} + f_i \frac{f_4}{f_5 + f_4} \\
  f_2 &= f_2 \frac{f_3}{f_5 + f_4} + f_2 \frac{f_4}{f_5 + f_4}
\end{align*}
\]

Figure 1. Allocation according to the ratio.

2.2. Pricing model
Based on the power flow tracing method, power generator’s price and power user’s price is determined by the following five steps.

At first, the allocating ratio of transmission cost between generator and customer is determined. In some countries, the transmission cost is usually allocated to both the generator and the customer. The main reason is that the power generator and the power consumer are both users of the transmission network, so they should be treated fairly when they share the transmission costs. The ratio of transmission cost allocation between generator and customer in some countries in Europe is shown in Table 1 [8]. The ratios are different in different countries, but basically the proportion of power generation is less than the proportion of electricity users. In addition, there are some countries, all of the transmission cost are allocated to the electricity consumers. At present, China’s power generators do not share the cost of cross-provinces transmission. In the future, with the continuous advancement of China’s electricity price reform and power market reform, the power generation party will share a certain proportion of cross-provincial transmission costs. And this ratio will negotiated by generators, customers and governments.
Table 1. Allocating Ratio of Transmission Cost between Generation and Customer.

| country       | generators | consumers | country       | generators | consumers |
|---------------|------------|-----------|---------------|------------|-----------|
| Austria       | 20%        | 80%       | Ireland       | 25%        | 75%       |
| Belgium       | 9%         | 91%       | Norway        | 34%        | 66%       |
| Denmark       | 4%         | 96%       | Portugal      | 7%         | 93%       |
| Finland       | 15%        | 85%       | Romania       | 18%        | 82%       |
| France        | 2%         | 98%       | Spain         | 13%        | 87%       |
| the United Kingdom | 27%   | 73%       | Sweden        | 25%        | 75%       |

Secondly, the power flow on the each cross-provincial line caused by the power source at each bus is determined by upstream tracing. And the total power flow caused by one power source is the sum of the power flow on all cross-provincial lines caused by this source. It is calculated as follows.

\[ P'_{Gk} = \sum_{i,j} \frac{P_{ij}}{P_i} [A_u]_{Gk} P_{ud} \]  \hspace{1cm} (1)

\[ P = \sum_{j \in L_i} P_i + P_{\alpha_0} (i = 1, 2, ..., n) \]  \hspace{1cm} (2)

\[ [A_u]_{ij} = \begin{cases} 1 & (i = j) \\ \frac{P_{ij}}{P_i} & (j \in L_i) \\ 0 & (\text{others}) \end{cases} \]  \hspace{1cm} (3)

Where, the total power flow contribution of the generator Gk to the transmission network is P'Gk, the power flow on the line ij where i is the starting bus and j is the ending bus is Pij, the total power of the bus i is Pi, the active power injected by generator Gk is PGk, the upstream tracing matrix [1-4] is Au, and all the line which injects power to bus I forms the set Li-.

Thirdly, the power flow on the each cross-provincial line going to the power load at each bus is determined by downstream tracing. And the total power flow going to one power load is the sum of the power flow on all cross-provincial lines going to this load. The load bus is the accesses bus of the trans-provincial transmission network for the provincial grid in China's power grid. It is calculated as follows.

\[ P'_{Lk} = \sum_{i,j} \frac{P_{ij}}{P_j} [A_d]_{Lk} P_{id} \]  \hspace{1cm} (4)

\[ [A_d]_{ij} = \begin{cases} 1 & (i = j) \\ \frac{P_{ij}}{P_j} & (j \in L_i) \\ 0 & (\text{others}) \end{cases} \]  \hspace{1cm} (5)

Where, the total power flow contribution of the load Lk to the transmission network is P'Lk, the active power consumed by the load Lk is PLk, the downstream tracing matrix [5-7] is Ad.

Fourthly, according to the power flow caused by the generator at one bus in the transmission network, the total transmission cost shared by the all power generators is allocated to every generator at each network bus. And according to the power flow going to the load at one bus in the transmission network, the total transmission cost shared by the all loads is allocated to every load at each network bus. The transmission cost will be allocated to the load both at starting bus and at ending bus of one
If the power on a line AB flows from A to B and both bus A and bus B are connected to the load, the loads at starting bus A and at ending bus B will share a certain proportion of the transmission cost. As for fair, whoever pays for the use of transmission. And the load at starting bus A does not use the transmission function of the line at this moment, so the load at starting bus A end should not share the transmission cost of the line. Therefore the proportion of cost allocated to the load at the start of the line is needed to be adjusted. The adjustment method is as follows. If the bus k of the load Lk is the same as the starting bus i of the line ij, the proportion of the cost allocated to the bus k is 0. The the proportion of the cost allocation is calculated as follows.

$$C_{Gi} = \frac{P_{Gi}}{\sum_{k=1}^{nG} P_{Gk}}$$  \hspace{1cm} (6)$$

$$C_{Lk} = \frac{P_{Lk}}{\sum_{i=1}^{nL} P_{Lk}(k \neq i)}$$  \hspace{1cm} (7)

Where, the total number of power supplies and load buses in the network are $n_G$ and $n_L$ respectively.

Fifthly, the electricity price of each bus is calculated according to the power generation or consumption of each bus and the transmission cost allocated to this bus. It is calculated as follows.

$$T_{Gi} = \frac{C_{Gi}}{Q_{Gk}}$$  \hspace{1cm} (8)$$

$$T_{Lk} = \frac{C_{Lk}}{Q_{Lk}}$$  \hspace{1cm} (9)$$

Where, the power prices of the power supplier and load buses in the network are $T_{Gi}$ and $T_{Lk}$ respectively, the power quantity of the power supplier and load buses in the network are $Q_{Gk}$ and $Q_{Lk}$ respectively.

3. Benefit Estimation on Cross-provincial Transmission

The cross-provincial transmission benefit estimation uses consumer surplus as the main indicator, reflecting the benefits of the electricity consumers or users. The consumer surplus is the difference between the benchmark price of the coal-fired generators in the receiving area and the power receiving price if power send to this receiving area. If the consumer surplus in a certain place is positive, it means that it is cheaper to accept cross-provincial power transmission than to purchase electricity from a local coal-fired power plant. From the economic point of view, the local purchaser accepts cross-provincial power transmission. The consumer surplus is calculated as follows.

$$W = T_1 - T_2$$  \hspace{1cm} (10)$$

Where, the consumer surplus is WL, the benchmark price of the coal-fired generators in the receiving area is T1, and the power receiving price if power send to this receiving area is T2. However, as for the power receiving provinces, the power sending suppliers are not clear. Maybe the power sending suppliers come from power plants in many other provinces. In this case, the real power receiving price is calculated as follows. At first, the power suppliers who send power to this provincial power grid and the corresponding power flow are determined by upstream tracing. The power sending price is the weighted average price of each power supplier. And then receiving price is the sum of the power sending price and the transmission price. The calculation is as follows.
\[
T_3 = \sum_k P_{Gk'-Lk}^T T_{Gk'} + T_{Lk}
\]

(11)

Where, the real power receiving price is \(T_3\), the power flow from power supplier \(G_k'\) to the load \(L_k\) is determined by the upstream tracing method and the price of the power source \(G_k\) is \(T'_{Gk'}\).

4. Example Analysis
At present, the construction of inter-provincial power grids has strengthened in China. In the future, AC transmission networks will form between East area, Central China, North China, Northeast China, Northwest China and other provinces. The example is cross-provincial transmission networks such as North China. The cross-provincial power grid is as the 16-bus power grid shown in Figure 2. The power generation, load capacity, and generation price of each bus are shown in Table 2. The power flow on each line is as shown in Table 3. The total annual transmission cost of this cross-provincial power grid is 277 million yuan. Considering the current reality in China, the cross-provincial transmission costs are still allocated to the power consumers here. According to the above pricing and benefit estimation model, the transmission costs allocated to each bus and the price of each bus are determined as shown in Table 3.

![Figure 2. 16-bus grid.](image)

**Table 2. Generation and Load and Generation Price of Each Bus.**

| bus | G(MW) | L(MW) | generation price (yuan/MWh) | bus | G(MW) | L(MW) | generation price (yuan/MWh) |
|-----|-------|-------|----------------------------|-----|-------|-------|----------------------------|
| 1   | 25    |       | 19                         | 9   | 39    | 16    | 311                        |
| 2   | 30    |       | 34                         | 10  | 73    | 11    | 37                         |
| 3   | 73    | 311   | 11                         | 11  | 32    | 12    | 3                          |
| 4   | 32    | 394   | 12                         | 12  | 37    | 13    | 12                         |
| 5   | 37    | 436   | 14                         | 14  | 39    | 15    | 33                         |
| 6   | 39    | 116   | 16                         | 16  | 58    | 118   | 35                         |
| 7   | 118   | 436   | 311                        | 17  | 58    | 436   | 16                         |

Figure 2. 16-bus grid.
Table 3. Power Flow of Each Line.

| starting bus | ending bus | power(MW) | starting bus | ending bus | power(MW) |
|--------------|------------|-----------|--------------|------------|-----------|
| 1            | 6          | 23        | 8            | 7          | 31        |
| 2            | 1          | 78        | 8            | 14         | 82        |
| 2            | 5          | 36        | 9            | 8          | 57        |
| 3            | 16         | 18        | 9            | 13         | 41        |
| 3            | 4          | 89        | 10           | 9          | 60        |
| 4            | 5          | 113       | 10           | 12         | 29        |
| 4            | 11         | 86        | 11           | 10         | 123       |
| 5            | 6          | 55        | 12           | 13         | 72        |
| 5            | 9          | 57        | 13           | 14         | 77        |
| 6            | 7          | 86        | 14           | 15         | 126       |

Table 4. Transmission Cost and Price of Each Bus.

| bus | transmission cost allocated to each bus (million yuan) | transmission price (yuan/MWh) | bus | transmission cost allocated to each bus (million yuan) | transmission price (yuan/MWh) |
|-----|-------------------------------------------------------|-------------------------------|-----|-------------------------------------------------------|-------------------------------|
| 1   | 11.1                                                  | 74                            | 10  | 17.6                                                  | 86                            |
| 2   | 11.5                                                  | 64                            | 12  | 3.2                                                   | 179                           |
| 5   | 13.6                                                  | 61                            | 13  | 10.4                                                  | 144                           |
| 6   | 43.2                                                  | 62                            | 14  | 22                                                    | 111                           |
| 7   | 70.9                                                  | 100                           | 15  | 62.6                                                  | 83                            |
| 9   | 10.6                                                  | 93                            | sum/average | 277           | 83                            |

From the results, the load center is higher in the use of the grid and transmission price at this bus is higher. If power plant and load both at the same bus, the load can offset by the generator and the use of load at this bus is less. And the price at this bus is low even if the load is high, such as bus 6. The provinces with positive consumer surplus in North China are A and B provinces. The consumer surplus is 4.9 yuan/MWh and 4.8 yuan/MWh respectively. The two provinces have higher enthusiasm for receiving electricity outside the province. The cross-provincial transmission price of province A is 74 yuan / MWh, and that of province B is 62 yuan / MWh. Although the cross-provincial transmission price of province A is higher than that of province B, the power receiving price in province A is lower than that in province B. So the benefit of power sending to province A is better.

5. Conclusion
A model of cross-provincial transmission pricing and benefit evaluation is proposed in this paper based on the power tracing method. The cost allocated to the users of cross-provincial transmission grid according to the power flow caused by the uses. Based on the improved downstream tracing method, the load no longer share the transmission cost of the line where the load is at the starting bus. So it is fairer to the load. Based on the upstream tracing method, the corresponding relationship of the load and the power supplier establishes. The consumer surplus is determined by this relationship can estimate the benefits of the cross-provincial transmission more reasonably. The example of transmission price and benefit of inter-provincial power grids in North China and other places shows the effectiveness of the method. And the transmission price and benefit provide effective price and economic incentive signals to all parties.
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