Improving Peak-load Pricing Method for Provincial Transmission and Distribution Network Considering Power Backflow

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Abstract. In view of the power backflow phenomenon in provincial transmission and distribution network caused by the fact that more and more new energy power is connected to the power grid, a provincial network voltage level pricing method considering power backflow is proposed. For exactly describing the complex power transmission relationships among various voltage levels in consideration of power backflow, a new power transmission model is proposed. And the balance parameters of the whole transmission and distribution network are gained based on the transmission data. The problems in cost sharing caused by power backflow are analysed and an improving peak-load pricing method solving the problems is proposed. Conceptions of source point transmission and distribution cost (SPTDC) and load point transmission and distribution cost (LPTDC) are defined. Through calculating the LPTDC in each voltage level, the cost apportionment is accomplished. The case study of a certain provincial power network is carried out and the effectiveness of this pricing method is proved. The results show that this method can recover all the transmission and distribution cost of the network and can authentically reflect the influence of power backflow on the transmission and distribution price.

1. Introduction
Chinese electric power system is undertaking a systematic reform at present, and one core part of this reform is the power transmission and distribution price. According to the general thinking that ‘hold the middle and liberalize both ends’, the transmission and distribution price should be set by government to strengthen the supervision of the authority on the transmission-distribution part. The approved price should ensure that the electric power enterprises recycle all the transmission and distribution cost and gain a reasonable profit. The official documents have made provisions for the regulation mode and the accounting method of permitted income, but the sharing method of the permitted income is not concretely regulated and the power backflow phenomenon is not considered.

Common power transmission and distribution pricing methods can be divided into two categories: the accounting cost method [¹] and the marginal cost method [²-⁴]. For the cost allocation process, the main sharing methods include DC power method, power flow tracing method [⁵-⁸] and peak-load pricing method [⁹]. The former two are all based on the usage degree of user nodes to the transmission and distribution network to share the cost. For their calculating objects are the branches and nodes, the
result is precise but the process is too complex to be applied in large power grid. The peak-load pricing method shares cost according to the usage degree of each voltage level users to the transmission and distribution network during peak-load period of system, it ignores the differences of the usage degree of users in one voltage level to the network and apportions the cost by voltage levels rather than nodes, therefore can be used in large power grid and reflects the differences of power supply cost to different voltage levels. Paper [10] gains the balance parameters of the power grid based on the power balance model and load data and then shares the cost according to the incremental load during peak load period. Paper [11] introduces the fundamentals and algorithm model of the peak-load pricing method and considers the situation where data is incomplete.

With the development of the wind power, photovoltaic power and distributed generation, more and more new energy is connected to the power system, which makes the calculation of the transmission and distribution cost more complex. New energy is usually connected to low voltage levels and therefore there is a phenomenon of power backflow in provincial power system. Power backflow is a situation where electric power is transformed from low voltage level to high voltage level. Current transmission and distribution pricing methods consider that the power only flows from high to low voltage level and therefore the users of high voltage grade don’t use the transmission and distribution devices of low voltage grade and don’t need to pay for the cost of low voltage level. However, the power backflow phenomenon will make the load of high voltage level use the transmission and distribution devices of low voltage level on a certain degree and therefore complicate the cost apportionment process. The study on the transmission and distribution pricing method considering power backflow is deficient at present.

Based on the above background, this paper proposes a pricing method for provincial transmission and distribution power grid considering power backflow. It can be used for the government regulators to calculate the transmission and distribution price for the provincial power grid with power backflow. The method takes the permitted income from government accounting as the total cost to be apportioned, and then shares the cost based on an improving peak-load pricing method which considers the power backflow. Conceptions of source point transmission and distribution cost (SPTDC) and load point transmission and distribution cost (LPTDC) are defined, and for one voltage level, the SPTDC and LPTDC can be calculated based on the usage degree of this voltage level to the transmission and distribution network. Finally, the transmission and distribution prices for each voltage level can be calculated according to the LPTDCs. The price for 500kV is trans-provincial tariff and the other prices are used in province. This method fully considers the power transmission relationships among all voltage levels and shares the total cost reasonably and fairly. The results of calculation example show that this method can recycle the total cost completely and help the power companies make ends meet.

2. Improving peak-load transmission and distribution pricing method

2.1 Total transmission and distribution cost
The calculation of transmission and distribution price mainly includes two processes: the accounting of the total transmission and distribution cost and the cost apportion. According to Transmission and distribution pricing method for provincial power grid (trial version) released by the state council, the permitted income includes the permitted cost, permitted profit and tax. This paper takes the permitted income as the total cost to be apportioned and the concrete accounting process of the permitted income can be referred to Transmission and distribution pricing method for provincial power grid.

2.2 Power transmission model for the whole power grid
This paper apportions the transmission and distribution cost in voltage levels. The first thing is to establish the power transmission model in consideration of power backflow, which is the base of sharing in voltage levels.
Power backflow is the situation where a lot of new energy be connected to the low voltage power system and be supplied to the high voltage users though the low voltage transmission and distribution network. Actually the transmission and distribution power grid is originally complex in China. The power transmission in China follows the general principle from high to low voltage level, and it exists cross-level transmission. For example, the 220kV voltage level in China usually supplies to the 110kV voltage level and 35 kV voltage level. When the phenomenon of power backflow is considered, the power transmission relationship can be more complex, each voltage level is supplied by several other voltage levels and supplies to several other voltage levels.

For all the electric energy transformed into one voltage level will use the transmission and distribution network of this level together and then supply to the load of this and other voltage levels, these energies should share the transmission and distribution cost of this voltage level together, and their differences in the usage degree of this voltage level can be ignored. As a result, this paper establishes the following power transmission model in voltage levels. The paper supposes the voltage levels from high to low were 500kV, 220kV, 110 kV, 35 kV, 10 kV, 380/220V and be recorded as \( i = 1,2,3,4,5,6 \). For any voltage level \( i \), one supply point \( a_i \) and one load point \( b_i \) are defined. All the power supply load of the voltage level \( i \) (\( S_i \), including the generation output of voltage level \( i \) and the power gained from all the other voltage levels) is connected to point \( a_i \), and then \( S_i \) is transformed to \( b_i \) through the transmission and distribution lines of voltage level \( i \), finally the power transformed to \( b_i \) supplies for the load of voltage level \( i \) and all the other voltage levels. The model is shown in figure 1:

![Figure 1. The power transmission model for voltage level \( i \).](image)

In the figure 1, \( S_{DT}^{i} \) represents the power supplied from voltage level \( l \) to voltage level \( i \); \( P_{DT}^{i} \) represents the power that voltage level \( i \) gained from voltage level \( l \); \( G_i \) represents the generation output of voltage level \( i \); \( S_i \) represents the power supply load of voltage level \( i \); \( D_i \) represents the load of voltage level \( i \); \( S_{DP}^{i} \) represents the power supplied from voltage level \( i \) to voltage level \( p \). This power transmission model also satisfies the following power balance equations:
Here, $\eta_{\text{Loss}}$, $\eta_{\text{Loss T}}$ represent the line loss rate and transformer loss rate of voltage level $i$ respectively; $\delta_{i,l}$ represents the proportion of power supply load that voltage level $i$ gained from voltage level $l$ to the total power supply load of voltage level $l$; $\text{LossL}^i$, $\text{LossT}^i$ represent the line loss load and transformer loss load of voltage level $i$ respectively. The generation output $G$ and the load $D$ of each voltage level are known quantities, and the power supply proportions $\delta$ among all voltage levels are known quantities, the balance parameters of the whole transmission and distribution network can be gained through adjusting the $\eta_{\text{Loss}}$ and $\eta_{\text{Loss T}}$ to make the system balanced.

2.3 Transmission and distribution cost apportion method

2.3.1 The problems of cost sharing when considering the power backflow. The peak-load pricing method shares the cost among voltage levels based on the running state of the system during peak-load period. It calculates the transmission and distribution cost of users in each voltage level according to the source and transmission route of the power. Because of the fact that there is no power backflow phenomenon in traditional transmission and distribution grid and the power only be transformed from high voltage level to low voltage level, the traditional peak-load pricing method shares the cost in voltage levels one by one. Specifically, the traditional method calculates the transmission and distribution cost of the highest voltage level first, and then calculates the costs of lower voltage levels one by one according to the costs of higher voltage levels and the power receiving proportions from higher voltage levels. This method actually shares the cost along the direction of power transmission.

However, when the power backflow is considered, the electricity is no longer transformed in a constant direction, but be transformed mutually among various voltage levels. Therefore, the level-by-level calculating method is inadequate. According to the thinking of cost conduction, this paper proposes the conceptions of source point transmission and distribution cost (SPTDC) and load point transmission and distribution cost (LPTDC). The source point and load point correspond the $a_i$ and $b_i$ ($i=1,2,..,6$) in power transmission model in figure 1. They are all virtual nodes and represent the power input point and output point of voltage level $i$. The point transmission and distribution cost (PTDC) means the transmission and distribution cost of all power transmitted to this point. And because the PTDC of one point can be expressed by the PTDCs of other points which exist direct transmission and distribution relationship with that point, the PTDCs can be calculated through building simultaneous equations. And the transmission and distribution price in voltage levels can be gained from LPTDCs. This method avoids the limitations caused by allocation along the direction of power transmission, and it can be used in transmission and distribution network with complex power transfer relationship.

This sharing method includes three steps: first, the total cost should be apportioned to the lines and transformers of all voltage levels according to the proportions of initial asset values of each voltage
level lines and transformers to the total initial asset value. Then, the usage degrees of each voltage level to each transmission unit (including transformer and voltage level) $\alpha_i$ and $\beta$ can be calculated according to the transmission power data $P_{Di}$ and $S_{Di}$ among voltage levels during peak-load period. And finally, the LPTDC of each voltage level can be calculated according to the $\alpha_i$ and $\beta$, the purpose of this step is to reappportion the total cost from lines and transformers to the users of each voltage level and gain the transmission and distribution price in voltage classes.

2.3.2 Cost sharing to the line and transformer of each voltage level. This paper takes the approved permitted income as the total cost to be apportioned in each voltage levels. Because of the fact that only the asset of lines and transformers can be aggregated in voltage levels in provincial common transmission and distribution network and the proportion of other fixed asset that can’t be aggregated is not large, this paper only apportions the total cost to the lines and transformers of each voltage level. And the basis is the proportions of initial asset values of each voltage level lines and transformers to the total initial asset value. The permitted incomes of line and transformer in each voltage level are shown in equation (2):

$$
C^i_k = I \cdot \frac{A^k_i}{A}
$$

$$
C^k_i = I \cdot \frac{A^i_k}{A}
$$

Here, $A$ represents the total fixed asset of lines and transformers in provincial common transmission and distribution network; $A^k_i$ represents the fixed asset of lines in voltage level $k$; $A^i_k$ represents the fixed asset of transformers in voltage level $k$; $I$ represents the total approved permitted income.

2.3.3 Usage degree of each voltage level to each transmission and distribution unit. For transporting power to voltage level $i$ ($i=1,2,\ldots,6$), voltage level $k$ $(k=1,2,\ldots,6, k\neq i)$ must use the transmission and distribution network of voltage level $k$ and the transformers between voltage level $i$ and $k$, and the usage degree of this part of power to the transformer ($\alpha^{k/i}$) is related to the proportion of this part of power to the total transferring power of this transformer during peak-load period. And the usage degree of this part of power to the transmission and distribution network of voltage level $k$ ($\beta^{k/i}$) is related to the proportion of this part of power to the total power supply load of voltage level $k$ during peak-load period. The equations for $\alpha^{k/i}$ and $\beta^{k/i}$ are as following:

$$
\alpha^{k/i} = \begin{cases}
\frac{S_{Di}^{k/i}}{S_{Di}} & k < i, \\
\frac{\sum_{j=k}^{i} S_{Di}^{j/i} + \sum_{m<k} S_{Di}^{m/k}}{S_{Di}} & k > i, \
\end{cases}
$$

Here, $S_{Di}^{k/i}$ represents the power supplied from voltage level $k$ to voltage level $i$ during peak-load period. When $k<i$, $\alpha^{k/i}$ means the proportion of power transferred from voltage level $k$ to level $i$ to the total transformer capacity of voltage level $k$, when $k>i$, $\alpha^{k/i}$ means the proportion of power transferred from voltage level $k$ to level $i$ to the total transformer capacity of voltage level $i$. 

Here, $S_{DIP}^{k/i}$ represents the power supplied from voltage level $k$ to voltage level $i$ during peak-load period; $S_i^k$ represents the power supply load of voltage level $i$ during peak-load period; $D_p^k$ represents the load of voltage level $i$ during peak-load period. When $k \neq i$, $\beta^{k/i}$ means the proportion of power supplied by voltage level $k$ to voltage level $i$ to the total supply power of voltage level $k$, when $k = i$, $\beta^{k/i}$ means the electricity sale rate of voltage level $k$. 

2.3.4 Reapportionment. Through the above two processes, the total cost has been apportioned to the lines and transformers of each voltage level, and then it should be reapportioned to the users of each voltage level to gain the final transmission and distribution price. In the model in chapter 2.2, the transmission and distribution price of voltage level $i$ equates to the price in load point $b_i$. For the reapportionment, the LPTDC of each voltage level should be calculated and the transmission and distribution price of each voltage level can be gained from LPTDC. LPTDC means the total transmission and distribution cost of all electrical energy transmitted to the load point. According to the power transmission model in chapter 2.2, the point transmission and distribution cost of $b_i$ is equal to the sum of the point transmission and distribution cost of the same voltage level source point $a_i$ and the transmission and distribution cost of the lines in voltage level $i$, and the point transmission and distribution cost of source point $a_i$ is equal to the sum of partial point cost of all the load point $b_j$ that supply to $a_i$ and the partial cost of the corresponding transformer:

\[
\begin{align*}
E(b') &= E(a') + C_i^T \\
E(a') &= \sum_{k=1}^{6} (\beta^{k/i} \cdot E(b^k) + \alpha^{k/i} \cdot C_T^k) \quad i = 1, 2, \ldots, 6 \\
C_T^k &= \begin{cases} 
C_i^k & : k < i \\
C_i^k & : k > i
\end{cases} \\
&= \begin{pmatrix} 
C_i^k \\
C_i^k
\end{pmatrix}, \quad k, i = 1, 2, \ldots, 6
\end{align*}
\]

(5)

Here, $E(a')$ represents the source point transmission and distribution cost of voltage level $i$; $E(b')$ represents the load point transmission and distribution cost of voltage level $i$.

Because the cost of each voltage level includes the partial costs of other voltage levels, the LPTDC of each voltage level can be expressed in matrix form:

\[
\begin{pmatrix} 
E(b^1) \\
E(b^2) \\
E(b^3) \\
E(b^4) \\
E(b^5) \\
E(b^6)
\end{pmatrix} = \begin{pmatrix} 
0 & \beta^{2/1} & \beta^{3/1} & \beta^{4/1} & \beta^{5/1} & \beta^{6/1} \\
\beta^{2/2} & 0 & \beta^{3/2} & \beta^{4/2} & \beta^{5/2} & \beta^{6/2} \\
\beta^{2/3} & \beta^{3/3} & 0 & \beta^{4/3} & \beta^{5/3} & \beta^{6/3} \\
\beta^{2/4} & \beta^{3/4} & \beta^{4/4} & 0 & \beta^{5/4} & \beta^{6/4} \\
\beta^{2/5} & \beta^{3/5} & \beta^{4/5} & \beta^{5/5} & 0 & \beta^{6/5} \\
\beta^{2/6} & \beta^{3/6} & \beta^{4/6} & \beta^{5/6} & \beta^{6/6} & 0
\end{pmatrix} \begin{pmatrix} 
E(b^1) \\
E(b^2) \\
E(b^3) \\
E(b^4) \\
E(b^5) \\
E(b^6)
\end{pmatrix} + \begin{pmatrix} 
B^1 \\
B^2 \\
B^3 \\
B^4 \\
B^5 \\
B^6
\end{pmatrix}
\]

(7)

And the equation can be simplified as following:
Here, $B' = C_k^l + \sum_{h<i} C_h^l \cdot \alpha_{hi}^k + \sum_{m<i} C_m^l \cdot \alpha_{mi}^k$, $B'$ is the sum of the line cost of voltage level $i$ and the partial cost of transformers that supply to voltage level $i$. $B'$ means the transmission and distribution cost of voltage level $i$.

The transmission and distribution price of voltage level $i$ equates the LPTDC of voltage level $i$ divides the corresponding user load $D'_i$:

$$\rho' = \frac{B' \cdot E(b')}{D'_i}$$

Here, $\rho'$ represents the transmission and distribution price of voltage level $i$.

### 3. Case study

This paper takes one provincial transmission and distribution grid as example to calculate the transmission and distribution price according to the network running data in one year. For there is a lack of data in the power measurement, this paper takes the annual transmission and distribution electricity data to calculate the price.

For showing the effect of power backflow phenomenon on transmission and distribution price, this paper uses two methods to calculate the price. The first method is the improving peak-load pricing method as introduced above, considering the power backflow and calculating the prices through point transmission and distribution cost. The second method ignores the power backflow and considers that the power is only transported from high voltage level to low voltage level. The second method takes the net power supply ($P_{\text{net}}^{k<h} - P_{\text{net}}^{h<k}$) as the practical data and use the traditional peak-load pricing method to share the total cost.

The permitted income of each voltage level line and transformer $C_k^l$ and $C_k^t$ are gained from equation (2) and shown in table 1. The annual electricity supply and consumption of each voltage level are shown in table 2. The annual transmission electricity of each voltage level are gained through the power transmission model in 2.2 and shown in table 3. It can be seen from the data in table 3 that this provincial power grid does exist power backflow phenomenon.

#### Table 1. The allowed income of line and transformation in voltage level.

| Voltage level $k$ (kV) | 500 | 220 | 110 | 35 | 10 |
|------------------------|-----|-----|-----|----|----|
| $A_l^k$ (million ¥)    | 431.80 | 7951.83 | 10542.22 | 8171.35 | 35374.27 |
| $A_t^k$ (million ¥)    | 2373.58 | 5937.34 | 7933.31 | 43.80 | 0 |
| $C_l^k$ (million ¥)    | 956 | 17605 | 23340 | 18091 | 78317 |
| $C_t^k$ (million ¥)    | 5255 | 13145 | 17564 | 96.97 | 0 |

#### Table 2. Annual electricity supply and consumption in voltage level.

| Voltage level $k$ (kV) | 500 | 220 | 110 | 35 | 10 |
|------------------------|-----|-----|-----|----|----|
| $G^k$ (MWh)            | 8054.9 | 6299.1 | 1158.9 | 262.9 | 422.2 |
| $D^k$ (MWh)            | 2027.7 | 970.4 | 2652.4 | 1319.5 | 8205.1 |
Table 3. Annual transmission of electricity among different voltage levels.

| Supply voltage level \( h \) (kV) | \( p_{bi}^{h/k} \) (MWh) | 500 | 220 | 110 | 35 | 10 |
|----------------------------------|--------------------------|-----|-----|-----|----|----|
| 500                             | 0                        | 0   | 0   | 0   | 0  | 0  |
| 220                             | 2577.3                   | 0   | 104202 | 2441 | 8722 |
| 110                             | 0                        | 3928.47 | 0   | 20202 | 64424 |
| 35                              | 0                        | 107.02 | 966.97 | 0   | 10133 |
| 10                              | 0                        | 310.02 | 390.25 | 0   | 0  |

Firstly, the transmission and distribution price is calculated considering power backflow. According to the cost sharing method above, the usage degrees of each voltage level to transmission and distribution unit \( \alpha_{i/bi}^{h/k} \) and \( \beta_{i/bi}^{h/k} \) can be calculated based on the transmission electricity data in table 2 and 3, and then the point transmission and distribution costs can be gained based on the \( \alpha_{i/bi}^{h/k} \) and \( \beta_{i/bi}^{h/k} \). The point transmission and distribution cost of each load point is shown in table 4:

Table 4. The transmission and distribution cost of bi.

| Voltage level \( i \) (kV) | 500 | 220 | 110 | 35 | 10 |
|-----------------------------|-----|-----|-----|----|----|
| \( B' \) (million ¥)        | 976 | 2313 | 3506 | 2249 | 9253 |
| \( E(b') \) (million ¥)     | 1045 | 3393 | 6484 | 3454 | 14568 |

According to the LPTDCs, the transmission and distribution price of each voltage level can be calculated, as shown in table 5:

Table 5. Power transmission and distribution price of each voltage level considering power backflow.

| Voltage level \( i \) (kV) | 500 | 220 | 110 | 35 | 10 | Recycled cost (billion ¥) |
|----------------------------|-----|-----|-----|----|----|---------------------------|
| \( p_{ri}^{i} \) (¥/kWh)   | 0.0126 | 0.0264 | 0.0559 | 0.1407 | 0.1760 | 1829.7 |

Then, the transmission and distribution price is calculated without considering power backflow. The net power supply is taken as the practical transmission data. The price of each voltage level is shown in table 6:

Table 6. Power transmission and distribution price of each voltage level neglecting power backflow.

| Voltage level \( i \) (kV) | 500 | 220 | 110 | 35 | 10 | Recycled cost (billion ¥) |
|----------------------------|-----|-----|-----|----|----|---------------------------|
| \( p_{ri}^{i} \) (¥/kWh)   | 0.0119 | 0.0247 | 0.0544 | 0.1430 | 0.1765 | 1829.7 |

It can be seen from table 5 that the total cost recycled through the improving peak-load pricing method is 182.97 billion yuan which is equal to the total permitted income in table 1. It means that this pricing method can recycle all the transmission and distribution cost effectively and it can be applied in the transmission and distribution grid existing power backflow phenomenon. What’s more, it can be seen in table 5 that there are obvious differences among the prices different voltage levels. Generally, the transmission and distribution price increases gradually with the decline of voltage level. This corresponds to the difference of the usage degree of transmission and distribution network among different voltage levels. Therefore, this pricing method can reflect the difference of power supply cost in different voltage levels effectively.

It can be seen from table 5 and table 6 that there are differences in the price considering power backflow and the price without. Concretely, the prices of high voltage levels are higher and the prices of low voltage levels are lower when considering the power backflow. It is because when the power
backflow is considered, the load of high voltage level will not only use the transmission and
distribution network of high voltage level, but also the network of low voltage level, which leads to
the increase of the price in high voltage level and the decline of the price in low voltage level.
Therefore, this pricing method can reflect the usage degree of users in each voltage level to the whole
transmission and distribution network more authentically.

4. Conclusion
This paper considers the power backflow phenomenon caused by the connection of new energy and
proposes a voltage level pricing method for provincial transmission and distribution network.
Considering the applicability, the method takes the permitted income regulated in power reform
documents as the total cost to be apportioned, and shares the cost in voltage levels to ensure it can be
used in large transmission and distribution network. This paper proposes the conception of point
transmission and distribution cost according to the cost conduction thinking, and shares the total cost
through calculating the point transmission and distribution cost of each load point. According to the
results of case study, this method can recycle all the transmission and distribution cost effectively
and reflect the usage degree of users in each voltage level to the whole transmission and distribution
network authentically.

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