Comprehensive Evaluation for Cost Transmission Path of Frequency Regulation Ancillary Service at Different Stages in Electric Market

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Abstract. Ancillary services (AS) are indispensable parts of power products. Currently in China, it appears that the cost transmission path of ancillary services is not clear, and cost allocation mechanism fails to reveal fairness, which cannot meet the requirements of future market development. The paper constructs a comprehensive evaluation system for ancillary service cost-transmission paths. Taking frequency regulation as an example, the paper evaluates feasible cost cost-transmission paths. Finally, the paper chooses the optimal cost transmission path based on characteristics of market stage for frequency regulation.

1. Introduction
Currently generators are usually the ancillary service sellers, as well as the undertakers of most ancillary service costs. They should pay the Power Grid according to on-grid electricity proportion, which does not reflect causing blame or benefit of market members. The cost transmission process is not clear and justifiable. It is urgent to design the reasonable cost-allocation mechanism of ancillary services. Paper [1] mainly studies the ancillary service cost-allocation method for electricity directly buyers, amortizing ancillary service costs based on responsibilities of users and generators. Paper [2] and [3] study cost-allocation model of ancillary service incurred by accessed wind power. Paper [4] does research on cost-allocation method of peak load regulation based on cooperative game. The papers above did not think over the adaptability between electric market development stage and cost-allocation mechanism. This paper evaluates various cost-allocation methods of frequency regulation and selects the optimal cost transmission process at different development stages of electric market.

2. Comprehensive evaluation for cost transmission path of ancillary services

2.1. Establishment of Evaluation Index System
Comprehensive evaluation index system is constructed based on segment targets classified from the overall goal of comprehensive evaluation.

When designing the evaluation index system, it is necessary to consider the market members involved in cost transmission path and cost transmission’s applicability. In accordance with the screening principles of independence, quantifiability, and versatility, the paper will adopt as few indicators as possible while meeting the evaluation requirements. Ancillary service cost transmission
process includes cost allocation and recovery, so it is necessary to evaluate fairness and rationality of cost allocation, transparency of price transferring form, operation practicality, and benefit to the society. The paper extracts nine indicators from four dimensions. The integral evaluation index system is shown in Figure 1.

![Figure 1. Comprehensive evaluation index system for the cost transmission of ancillary services.](image)

All indicators’ calculation method is demonstrated in detail below.

2.1.1. Fairness. The index Fairness is used to assess whether the cost transmission mechanism is fair and justifiable. It refers to fair cost-allocation among all market participants, such as power generators, electric users, and electric-selling companies.

2.1.2. Scientificity. The index Scientificity is used to assess whether cost-allocation reflects the principle of responsibility or benefit. There are two individual indicators demonstrating the index Scientificity:

2.1.2.1. Not Allocation Ratio. The indicator measures if the cost allocation mechanism is too strict or too lenient. An overly strict allocation mechanism will cause most market participants to become apportioned objects, and an overly lenient allocation mechanism will make the proportion of apportioned objects too small. Not Allocation Ratio is calculated by this way:

\[
Z_k = \frac{n_k}{N_k}, \ k = 1,2,3
\]

\(Z_k\): Not Allocation Ratio of participant group \(k\);
\(n_k\): Quantity of members who do not need to join in allocation in the participant group \(k\);
\(N_k\): Member quantity of the participant group \(k\).

The participant group 1 consists of power generators. The participant group 2 consists of electric-selling companies. The participant group 3 consists of users.

2.1.2.2. Allocation Intensity. The other hand of Scientificity is reflected by not imposing excessive burdens on market participants. Define the indicator “Allocation Intensity” to measure the rigor level of cost allocation. Allocation Intensity refers to the proportion of the number of market participants whose allocating costs fall within a certain range to total number of market participants. Allocation Intensity is calculated by this way:

\[
Q_k = \frac{g_k}{N_k}, \ k = 1,2,3
\]
2.1.2.3. Effectiveness. The index Effectiveness is used to examine the improvement of power system’s operation level after new cost transmission mechanism being carried out. Because ancillary service cost transmission mechanism is designed to ensure safe, high-quality and economic operation in power system, and improve the management level for the Power Grid. Define “Improvement of Operational Management” as the next-level indicator of Effectiveness.

In order to measure the increase/decrease in demand of ancillary services, it is necessary to determine a benchmark value to be comparable, and the benchmark value must be able to represent the operational management level before the new cost transmission mechanism being carried out. Select the operational management level during the Two Rules¹ as the benchmark value. Improvement of Operational Management can be calculated by this way:

\[
K_i = \frac{Q_i}{B_i}, k = 1,2,3
\]

\(K_i\): Improvement of Operation Management Degree of the ancillary service type \(i\);
\(Q_i\): Demand of the ancillary service type \(i\);
\(B_i\): Benchmark value of the ancillary service type \(i\);

There are usually 4 types of ancillary services in China’s electricity market. So, \(i\) can be from 1 to 4.

2.1.2.4. Economic Benefit. The index Economic Benefit is used to measure the total social economic benefits bringing by new cost transmission method. Ancillary service cost transmission mechanism is designed to increase total social benefits and maximize benefits of power plants, electricity-selling companies and users. Thus, Economic Benefit’s quantitative indicators are drawn from the three aspects: power plant benefit, electricity-selling company benefit, and user benefit. Economic benefit can be calculated by this way:

\[
B_k = \sum_{j=1}^{N_k} b_{kj}, k = 1,2,3
\]

\(B_k\): Total economic benefit of the participant group \(k\);
\(b_{kj}\): Economic benefit of the individual member \(j\) in participant group \(k\);
\(N_k\): Member quantity in the participant group \(k\);

2.1.3. Weight Determination of Evaluation Indicators

There are several indicators in the index system for evaluating ancillary service cost transmission, which increases difficulty of determining the importance weight for each indicator. In addition, directly determining the importance weight through considering influence degree of each indicator, which often causes the incomplete consideration, or disagreement among decision makers.

2.1.3.1. Construct the Judgment Matrix. The quantification of two-two importance comparison in judgment matrix can apply the Nine-Level Scale. Then apply the Delphi method in scoring indicators at the secondary level. According to experts’ scoring result, construct the judgment matrix \(A\) for indicator B1, B2, B3, B4 in the secondary level:

¹ Power Plant Grid Operation Management Regulations and Grid-connected power plant auxiliary service management implementation rules
\[
A = \begin{bmatrix}
1.00 & 2.00 & 1.50 & 2.50 \\
0.50 & 1.00 & 0.67 & 0.83 \\
0.67 & 1.50 & 1.00 & 2.80 \\
0.40 & 1.20 & 0.36 & 1.00
\end{bmatrix}
\]

2.1.3.2. Calculate the Eigenvector of Matrix A. After mathematical calculation and normalization, the eigenvectors of matrix A can be obtained:
\[W=(0.3879, 0.1780, 0.2877, 0.1464)^T\]

2.1.3.3. Weight Consistency Test. The maximum characteristic root of matrix A can be calculated by this way:
\[
\lambda_{\text{max}} = \sum_{i=1}^{n} \frac{(AW)_i}{m W_i} = \frac{1.5414, 0.6857, 1.2232, 0.6179}{1}
\]
Because \(m\) is 4, \(\lambda_{\text{max}}\) is 4.0682.
The consistency indicator (CI) of matrix A is:
\[
CI = \frac{\lambda_{\text{max}} - m}{m - 1} = 0.0227
\]
The average random consistency indicator (RI) of matrix A can be obtained by looking up the “RI Table”; RI is 0.9. Therefore, the random consistency ratio (CR) equalled “CI/RI” is 0.0281, which is less than 0.1. This is to say, the judgment matrix A has a consistency and the secondary indicators’ weights are valid. Apply the method above to calculating weights of the third indicators. Consequently, weights of the indicators in evaluation index system at all levels are shown in Table 1.

| Target Layer (A) | Secondary Indicator (B) | Weight | Third Indicator (C)                        | Weight |
|------------------|-------------------------|--------|-------------------------------------------|--------|
| Cost transmission path | Fairness (B1)           | 0.3879 | Satisfaction of generations (C1)          | 0.1293 |
|                   |                         |        | Satisfaction of users (C2)                | 0.1293 |
|                   |                         |        | Satisfaction of electricity-selling companies (C3) | 0.1293 |
|                   | Scientists (B2)         | 0.1780 | Not allocation ratio (C4)                 | 0.0890 |
|                   |                         |        | Allocation Intensity (C5)                 | 0.0890 |
|                   | Effectiveness (B3)      | 0.2877 | Improvement of operational management (C6) | 0.2877 |
| Economic Benefit (B4) |                         | 0.1464 | Economic benefit of generations (C7)      | 0.0163 |
|                   |                         |        | Economic benefit of users (C8)            | 0.0163 |
|                   |                         |        | Economic benefit of electricity-selling companies (C9) | 0.0163 |

3. Feasible cost transmission path of frequency regulation
Generally, the cost transmission process of ancillary service includes three courses: cost allocation, cost recovery, and cost compensation, as is shown in Figure 2. Cost transmission paths are different in cost allocation entities (cost shoulders), while recovery entity and compensation entity are all determined.
There are six cost transmission paths: ① Path one is that cost is shared by all generations; ② Path two is that cost is shared by all users; ③ Path three is that generations bear more than 50% of the cost, and the remained is shared by users; ④ Path four is that users bear more than 50% of the cost, and the remained is shared by generations; ⑤ Path five is that generations and users are shared according to their “causing liability”; ⑥ Path six is that cost is borne by AS purchasers in bilateral transactions.

4. Evaluation of cost transmission path of frequency regulation
Ancillary service market (ASM) will be constantly changing, with the development of electric market. This paper divides ASM into three phases, namely early stage, transition stage and maturity stage.

4.1. Early Stage
Data is collected from AS providers, demanders, grid companies, and related experts based on the quantitative methods set by each indicator. Unavailable data can be scored by expert scoring. When raw data is collected, do standardized processing (dimensionless and consistent processing) with raw data. As for “forward” indicators (namely the larger, and better), its standardized methods are as (7): As for “not-forward” indicators (namely the smaller, and better), its standardized methods are as (8):

\[ U_i = \frac{x_i - x_{\text{min}}}{x_{\text{max}} - x_{\text{min}}} \times 40 + 60 \] (7)

\[ U_i = \frac{x_{\text{max}} - x_i}{x_{\text{max}} - x_{\text{min}}} \times 40 + 60 \] (8)

\( U_i \) is the processed data;
\( x_i \) is raw data;
\( x_{\text{max}} \) is the largest value among data sequence;
\( x_{\text{min}} \) is the smallest value among data sequence.

After standardized processing, indicator values are shown in Table 3.

| Third Indicator (C) | Path one | Path two | Path three | Path four | Path five | Path six |
|---------------------|----------|----------|------------|-----------|-----------|----------|
| C1                  | 100      | 60       | 80         | 70        | 90        | 100      |
| C2                  | 60       | 100      | 70         | 80        | 90        | 70       |
| C3                  | 100      | 90       | 100        | 90        | 100       | 100      |
| C4                  | 60       | 60       | 60         | 60        | 100       | 60       |
| C5                  | 99       | 99       | 98         | 98        | 98        | 98       |
| C6                  | 99       | 90       | 95         | 90        | 92        | 90       |
| C7                  | 100      | 82       | 73         | 73        | 64        | 60       |
| C8                  | 100      | 64       | 82         | 72        | 64        | 60       |
| C9                  | 93       | 80       | 87         | 60        | 93        | 100      |

Multiply indicator values by the corresponding weights to calculate comprehensive scores:

\[ S = \sum_{i=1}^{n} W_i S_i \] (9)
S is the comprehensive score; 
$W_i$ is the weight of indicator $i$; 
$S_i$ is the value of indicator $i$.

Six cost transmission paths are ranked in the order of the comprehensive scores as Path one, Path three, Path five, Path six, Path two, Path four. It can be seen from the above table that Path one has the highest score, followed by Path three, Path five, Path six, Path two, and Path four. Thus, Path one is more suitable for early stage of market.

4.2. Transition Stage
Under the transition stage, electric market will be more mature and technology will improve. The paper predicts indicator values and does standardized processing.

According to indicator values, weights and formula (9), six cost transmission paths are ranked in the order of the comprehensive scores as: Path three, Path five, Path four, Path one, Path two, Path six. It can be seen from the above table that Path three has the highest score, followed by Path five, Path four, Path one, Path two, and Path six. Thus, Path three (Generations bear more than 50% of frequency regulation cost, and the remained is shared by users) is more suitable for transition stage of market.

4.3. Maturity Stage
Under the maturity stage, trading modes of electricity and frequency regulation will change. The paper predicts indicator values and does standardized processing.

According to indicator values, weights and formula (9), six cost transmission paths are ranked in the order of the comprehensive scores as: Path six, Path five, Path two, Path three, Path four, Path one. It can be seen from the above table that Path six has the highest score, followed by Path five, Path two, Path three, Path four, and Path one. Thus, Path six is more suitable for maturity stage of market.

5. Conclusion
This paper constructs a comprehensive evaluation system for cost transmission paths of ancillary service, and evaluates cost transmission paths of frequency regulation under different stages of market. The results show that: Path one is more suitable for early stage of market; Path three is more suitable for transition stage of market; the decentralized purchase market, Path six is more suitable for maturity stage.

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