Optimal Clearing Model of Centralized Market Considering Path Constraints

Zheng Zhao¹,a, Kening Chen¹, Yu Jiang², Xuwen Liu²
¹State Grid Energy Research Institute, Beijing, China
²State Grid JiangSu Electric Power Co., Ltd, Jiangsu, China
aE-mail: zhaozheng@sgeri.sgcc.com.cn

Abstract: China's electricity market is now still in the mode of "Unified market and two-tier operation" including provincial and inter-provincial market. The inter-provincial market is divided into the medium and long-term market and spot market. This study takes the inter provincial spot market as the research object, and proposes a unified optimization clearing algorithm for inter provincial spot market considering path constraints. The proposed method is able to handle AC-DC hybrid electricity network, and sort and determine the trading pairs using power flow tracing algorithm. The power market software PLEXOS and practical market data are used to simulate the proposed model, and the results show the accuracy and effectiveness.

1. Introduction

According to the document that the National Energy Administration (NEA) approving the pilot run of the Cross Regional Inter-Provincial (CRIP) spot market of surplus renewable energy power (GNHJ [2017] No. 46), the State Grid Corporation of China officially launched the CRIP spot market on August 18, 2017, and has been put into trial operation more than 3 years.

In 2019, the accumulated trading volume of CRIP market among provinces is 5.3 billion kWh. The average settlement price of generation side is 155.46 yuan / MWh, and the average price reduction on power consumption side is more than 200 yuan / MWh. Among them, 4.61 billion kWh of electricity was transmitted from the northwest, 340 million kWh from the northeast, 50 million kWh from North China and 300 million kWh from the southwest.

At present, the CRIP market is a bilateral market. The power resources on generation side are wind, solar, and hydro power, where the energy purchasing side are provincial power company, which acts on behalf of its power users and retailers to participate the CRIP market. In day-ahead market, the market sellers and purchasers submit the "power-price" bidding curve of each time interval (15 minutes) of the next day, and the market operator determine the clearing generation and ATC results by using a high-low matching method. The high-low matching clearing method is only applied on fixed trading paths, is not a globally optimal clearing algorithm on the whole network. [1-12]

However, as the deepening of China's power market reform, the CRIP market will face the following challenges. One is the diversification of market entities. In the power generation side, in addition to hydropower, wind power, and solar, thermal power, nuclear power and pumped storage energy can participate in the market in the future. On the power energy consumption side, in future, the power users and retailers will be able to participate in the market by themselves.

Secondly, the scope of the market continues to expand. With the promotion of the construction of the national unified market, a complete inter provincial market, including medium-to-long term inter
provincial and spot markets, is gradually formed. The number of provinces participating in the interprovincial spot market will continue to increase, and the provinces that do not participate in the interprovincial spot market, such as JingJinTang area, Fujian and so on, will be gradually included.

Thirdly, the market is becoming more and more complex. In order to improve the operation efficiency of the market, the interprovincial spot market and the regional peak regulation ancillary service market will be gradually integrated in the future. The CRIP market will be an AC - DC hybrid market in which the power flow directions on AC lines are not unidirectional.

Based on the above considerations, this study proposes a unified optimization clearing algorithm for interprovincial spot market considering path constraints, such as node power flow balance, line power flow constraints, line ramping constraints, trading path constraints, etc.

The main features of the model are as follows: first, it supports the solution of complex AC / DC hybrid network with uncertain power flow direction, adopts the unified clearing method, constructs the mathematical unified optimization equation, and does not set the fixed path. Secondly, it is compatible with the current fixed path trading mode, and develops the path constraint algorithm to support the clearing method on the fixed path at present. Thirdly, the power flow tracing algorithm is innovated and developed, which can solve the power flow path from sending province to receiving province, which is convenient for transaction matching and settlement.

2. Model
The topology of the proposed CRIP spot market is taking the provinces or price areas due to congestion in the province as the base node, and building cross regional AC / DC hybrid network. Under the conditions of transmission security constraints and price constraints, the participated power resources are uniformly and optimally allocated with the goal of maximizing the social welfare.

2.1. Optimization goal
The goal of the optimization is to maximizing the social welfare, where the Welfare = Purchasing cost – Generation cost – Transmission cost. The equation is shown as follows.

\[
\text{Welfare} = \sum_{i=1}^{n} \sum_{b=1}^{B} X_{i,b}^P P_{i,b}^P - \sum_{i=1}^{m} \sum_{b=1}^{B} X_{i,b}^G P_{i,b}^G - \sum_{k=1}^{l} X_k^T P_k^T
\]  

(1)

Where at a specific time interval, \( X_{i,b}^P \) is the clearing power output of purchaser \( i \) at band \( b \) of its bidding curve, and \( P_{i,b}^P \) is the corresponding price on band \( b \), and there is a total number of \( n \) purchasers. \( X_{i,b}^G \) is the clearing power output of generator \( i \) at band \( b \) of its bidding curve, and \( P_{i,b}^G \) is the corresponding price on band \( b \), and there is a total number of \( m \) generators. \( X_k^T \) is the clearing power output of line \( k \) and \( P_k^T \) is the wheeling charge of line \( k \).

In order to implement the power flow tracing method, the transmission clearing power output variable \( X_k^T \) is decomposed into multiple sub-variables, shown as the following equation.

\[
X_k^T = \sum_{i=1}^{n} \sum_{j=1}^{m} x(i,j,k)
\]  

(2)

In which, variable \( x(i,j,k) \) indicates the power energy transmits from generator \( i \), flows through transmission line \( k \) and finally reaches to purchaser \( j \).

2.2. Constraints
The node power injection constraint, the line flow constraint, transmission and ramping up and down constraints and path constraint are considered.

2.2.1. Node constraint
For a node \( d \), the injected power and output power should always be balanced.
\[
\sum_{d} \sum_{i=1}^{n} \sum_{j=1}^{m} x(i, j, k) = \sum_{d} \sum_{i=1}^{n} \sum_{j=1}^{m} x(i, j, k)
\]  

2.2.2. Line constraint
The clearing power on a specific line should be within its ATC limits.
\[
P_k^{\text{min}} \leq x(i, j, k) \leq P_k^{\text{max}}
\]  

2.2.3. Ramping constraint
The power ramping between two consecutive time intervals should be within the transmission line maximal adjusting capability.
\[
P_k^{\text{min}} \leq \sum_{i=1}^{n} \sum_{j=1}^{m} x(i, j, k)^{T+1} - x(i, j, k)^T \leq P_k^{\text{max}}
\]  

2.2.4. Path constraint
If there is a fixed trading path s between generator i and purchaser j and line k is part of the trading path, the variable \( x(i, j, k) \) will be included in the model and be computed. If not, the value of \( x(i, j, k) \) will be forced to zero.

3. Simulation Results
A case study is carried out by using a set of practical data on one operation day of CRIP spot market. The total power bidding by generators is 37.619 million kWh, while the total power bidding by purchasers is 620.965 million kWh. The electricity market simulation software PLEXOS is used to model the CRIP market. The schematic diagram of the model is as follows.

Figure 1 Diagram of Inter-provincial Spot Market

In the above diagram, the lines include both AC and DC lines. There are 33 bidding data from sending end and 16 bidding data from receiving end. A total of 47 lines was modeled, including parameters of loss rate, wheeling charge, power flow limits and etc. A unified optimizing clearance algorithm was applied by PLEXOS.

3.1. Case 1 – Compare actual results and simulated results
By setting the path constraint in the above proposed model, the comparison results are shown as the following tables.
Table 1 Comparison of day-ahead clearing power at sending and receiving provinces
(Unit: ten thousands kWh, cent/kWh)

| Provinces | Actual | Simulated |
|-----------|--------|-----------|
|           | Trading Volume | Price | Trading Volume | Price |
| Sending End | Jilin | 48.2 | 13.9 | 48.2 | 13.9 |
|           | Qinghai | 484.9 | 16.6 | 489.4 | 16.7 |
|           | Xinjiang | 234.8 | 14.0 | 237.3 | 14.0 |
|           | Gansu | 440.9 | 17.2 | 440.0 | 17.2 |
| Receiving End | Shanghai | 714.4 | 29.4 | 723.7 | 29.3 |
|           | Hebei | 41.0 | 22.3 | 41.0 | 22.3 |
|           | Henan | 317.5 | 24.3 | 322.7 | 24.2 |

Table 2 Comparison of day-ahead transmission trading volume
(Unit: ten thousands kWh)

| Transmission line | Actual | Simulated |
|-------------------|--------|-----------|
| Lingshao | 664.3 | 661 |
| Siyu | 189.9 | 185.5 |
| Erxiang | 114.9 | 127.1 |
| Yihua | 29.1 | 31.5 |
| Longzheng | 29.1 | 31.3 |

Table 3 Comparison of day-ahead trade volume on fixed paths
(Unit: ten thousands kWh)

| Seller | Buyer | Path | Actual | Simulated |
|--------|-------|------|--------|-----------|
| Gansu | Henan | Tianzhong | 176.5 | 177.3 |
| Gansu | Shanghai | Qishao->Linfeng(Yihua, Longzheng,Genan),Lingshao | 264.4 | 264.9 |
| Jilin | Hebei | Lugu | 48.2 | 48.1 |
| Qinghai | Shanghai | Lingshao | 484.9 | 489.6 |
| Xinjiang | Henan | Tianzhong | 169.4 | 173.8 |
| Xinjiang | Shanghai | Qishao->Linfeng(Yihua, Longzheng,Genan),Lingshao | 65.6 | 66.1 |

The results are basically consistent, which verifies that the unified clearing algorithm considering path constraints can achieve the optimization goal as the same as matching clearing method.

3.2. Case 2 – Compare different market clearing methods
In this case, the high-low matching clearing algorithm and proposed unified clearing method are compared. The comparison results are shown as following.

Table 4 Comparison of different clearing algorithms
(Unit: ten thousands kWh, cent/kWh)

| Provinces | Proposed clearing algorithm | Matching clearing method |
|-----------|----------------------------|--------------------------|
| Sending   | Jilin | 48.1 | 48.2 |
|           | Qinghai | 511.5 | 484.9 |
|           | Xinjiang | 325.1 | 234.8 |
|           | Gansu | 555.9 | 440.9 |
| Receiving | Shanghai | 927.6 | 714.4 |
|           | Hebei | 41.0 | 41.0 |
|           | Henan | 253.9 | 317.5 |
Zhejiang | 75.7 | 48.2 \\
Total   | 1298.2 | 1210

The unified optimization clearing algorithm optimizes the global variables, improves the transmission utilization rate, and further promotes the renewable energy consumption. Based on the unified clearing method, the trading volume was 13 million kWh; based on the fixed path matching clearing, the trading volume was 12.1 million kWh. It can be seen the unified clearing method was more effective than the fixed path matching clearing, and increase the trading volume by 900 thousand kWh.

4. Conclusions
In this research, it proposes a unified optimization clearing algorithm for inter provincial spot market considering path constraints. The proposed model supports the solution of complex AC / DC hybrid network with uncertain power flow direction and is compatible with the current fixed path trading mode. Moreover, the power flow tracing algorithm is innovated and developed, which can solve the power flow path from sending province to receiving province, which is convenient for transaction matching and settlement. Simulation shows the accuracy and effectiveness of the proposed method. The proposed method can be taken as reference for future inter-provincial market design to better promote the renewable energy and optimize the allocation of power resources in large-scale range.

Acknowledgments
This work is supported by a research program “Research on Electricity Market Interaction Mechanism of Centralized and Decentralized Decision-making in Energy Internet Background and Blockchain Based Distributed Transaction Support Technology” of State Grid Corporation of China (No. 5108201918043A0000).

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