Research on Optimized Clearing Model of Trans-provincial Power Transaction Based on Deepening Design

Xiaojun Cao 1*, Dan Zeng 1, Peng Ji 2, Wenyuan Huang 1 and Shizhen Wang 3
1 China Electric Power Research Institute (Nanjing), Nanjing, Jiangsu, 210003, China
2 Beijing Power Exchange Center, Beijing, 100031, China
3 College of Electrical Engineering and Control Science, Nanjing TECH University, Nanjing, 211816, China
*caoxiaojun@epri.sgcc.com.cn

Abstract. With the gradual deepening of power market reform, the top-level design of the market has been basically completed. According to the requirement of "Deepening Design Of National Unified Power Market", the ultimate goal of the power market in China is to establish a national unified operation mechanism of power market, so as to break down inter-provincial barriers, and finally realize the optimize configuration of power resources in a wider range. In this paper, based on the simplified model of national power grid, an optimal clearing model of the unified national power market with the province as the agent is established, and the validity of the proposed model based on practical scenario is verified.

1. Introduction
In 2018, the Beijing power exchange center took the lead in formulating the "Deepening Design Of National Unified Power Market", in which the whole market form, the whole power space and the whole system structure of the national unified power market system were designed.

Focusing on the goal of deepening the construction of the national unified power market, at the present stage, China is establishing a power market with both the inter-provincial and intra provincial levels to achieve the optimal allocation of power resources in a wider range on the basis of ensuring the stable and sufficient supply of the provincial power grid. Among them, the inter-provincial power trading mode design, especially the inter-provincial power market clearing link design is one of the important links of the power market construction.

However, a detailed scheme of two-level power market is lacked. At present, the PJM model of the United States[1] and the model of the European power market[2] are the representatives of the international power market model. Considering the actual demand of optimal allocation of resources between provinces[3][4], the domestic research on power market clearing model mainly draws lessons from Nordic power market construction ideas. Generally, dynamic partition pricing[6], sensitivity fuzzy clustering partition[7] and other methods are used to solve the problem of inter-provincial transmission congestion. At the same time, considering the differences of resource endowment among provinces, a clearing model of spot market based on flexible block trading is proposed[5].

With the expansion of market participants, power generation enterprises[8][9], renewable energy[10], power users[11], active distribution network[12], micro-grid[13][14], energy storage[15] and so on all participate in the market transaction and find the best bidding scheme under their respective market mode. At the same time, market operation modes serving different operation scenarios such as frequency
modulation [15], peak shaving [16], and clean energy consumption [9-11] are proposed. However, the current research focuses on market members or specific market operation scenarios, cannot make a preliminary exploration of the power market mechanism in China from the overall point of view. This paper takes "Deepening Design Of National Unified Power Market" as the instruction takes the province as the agent and carries on the purchase and sale power transaction in the inter-provincial field.

This paper starts with the design of market trading operation mode, establishes a unified national power market transaction model, considering the direct participation of power generation and load resources in the province to purchase power across provinces and regions with the balance of load supply and demand, so as to achieve the maximum social welfare in the overall scope. Finally, the rationality of the model is verified by an example, and the influence of tie line constraints on clearing transactions between provinces is analysed.

2. Trading structure of trans-provincial power market
In the mature stage of power market development, the power generation and load resources take the province as the agent to participate in the declaration of the inter-provincial market, and realize the optimal allocation of energy resources in the whole country. The specific market structure is shown in Figure 1.

![Figure 1. Construction and geometrical dimensions of specimens](image)

In Figure 1, the provincial power exchange center first organizes the market members within the province to bid and pre-clearing, and sends the purchase and sale curve to the national power exchange center after the provincial security check. After receiving the declaration curve of the purchasing and selling province, the national power exchange center takes the transmission capacity of the inter-provincial tie line calculated by the national power dispatching center as the constraint, optimizes the clearing of the inter-provincial power transaction with the maximum social welfare as the goal, and returns the clearing result through the security check to the provincial power exchange center, and the inter-provincial transaction ends.

3. Bidding method of market members
At present, the bidding methods of power market in various countries are different, the PJM bidding is based on the cost of segment bidding; the European power market has designed simply hourly orders, complex orders, block orders and so on. China is facing the contradiction between the serious regional transaction barriers and prominent demand of resource allocation in a large scale as Europe do, so we cantake the European power market bidding method as an example. On the other hand, considering that China's power market construction is still in the initial stage, market members' understanding of the power market still needs to be strengthened, so it is suggested that the market bidding should be carried out step by step. Therefore, this paper takes the European power market bidding as the reference, selects three representative bidding methods: simply hourly order, block order and flexible hourly order.
3.1. Simply hourly order
The simply hourly order is one of the most flexible bidding methods, and it is also the only way for the load side to participate in the market. Each market member provides bidding price, power and period. Market members consider the ramp constraints, and the coupling of bidding time is not needed in the clearing stage. simply hourly order is widely used in all kinds of thermal power units, which is the most widely used.

3.2. Block order
Block order allows many kinds of quantity-price combination bidding, including regular block order, movable block order, link block order and so on. Block order follows the principle of "all deal or all no deal ", that is, the bidding rate of bidding is 0-1 variable. This kind of bidding method is applicable to the places such as Jiangsu, Zhejiang, Fujian and so on which have nuclear power or super large thermal power units.

3.3. Flexible hourly order
Flexible hourly order requires market members to declare the amount of quantity and price with no specified period. The specific clearing period of this bidding is determined by the unified optimization of the clearing model. This kind of bidding is suitable for areas with more flexible generators, such as Sichuan, where there are more hydropower units.

4. Optimized clearing model of trans-provincial market

4.1. Objective function
(1) Principle of objective function
According to the principle of market economy, the goal of commodity trading is to maximize social welfare, so the objective function of power bidding can be expressed as:

$$\text{Max}(B_D - C_G)$$

Where, $B_D$ is the profit from consumers; $C_G$ is the cost of generators. In terms of electricity price settlement, there are two ways of settlement including unified settlement according to marginal price and settlement according to the actual bidding of each unit.

(a) Unified settlement according to marginal price

$$F_M = \min \sum_{i=1}^{N} \sum_{t=1}^{T} \pi_{\text{SMP}}(t) P_i(t)$$

$$\pi_{\text{SMP}}(t) = \max \{\pi_i[P_i(t)], \cdots, \pi[N][P_N(t)]\}$$

Where, $F_M$ is the electricity purchase cost under the unified settlement of marginal price. T is the number of periods in the trading cycle, and the day-ahead market usually takes one or a half hours as a trading period; $P_i(t)$ is the bidding quantity of unit i in t period. when the t is expressed in hours, that is, the unit output; i is the unit serial number, N is the total number of units; $\pi_{\text{SMP}}$ is the system marginal price; and $\pi_i[P_i(t)]$ is the bidding of unit i when its output is $P_i$.

(b) Settled according to actual bidding of each unit

$$F_B = \min \sum_{i=1}^{N} \sum_{t=1}^{T} \pi_i[P_i(t)] P_i(t)$$

Where, $F_B$ is the electricity purchase cost according to the actual bidding of each unit.

(2) Objective function of trans_provincial market in China
In China, the simply hourly order is only one way of demand side bidding; while there are three kinds of generation side bidding: simply hourly order, block order and flexible hourly order. Thus, the maximization of social benefits can be expressed as follows:

\[
\max_{\text{tot dem bo fho}} \quad w = u^{\text{demand}} - (c^{\text{sup}} + c^{\text{bo}} + c^{\text{fho}}) 
\]

Where, \( w^{\text{tot}} \) is the target social welfare, the optimization problem is maximum value of \( w \), \( u^{\text{demand}} \) is the total value of the load side, \( c^{\text{sup}} \) is the total value of the simply hourly order of the power supply side, \( c^{\text{bo}} \) is the total value of the power supply side block order, and \( c^{\text{fho}} \) is the total value of the flexible hourly order of the power supply side. The \( u^{\text{demand}} \), \( c^{\text{sup}} \), \( c^{\text{bo}} \), \( c^{\text{fho}} \) are shown as follows:

\[
u^{\text{demand}} = \sum_{a \in A} \sum_{b \in B} \sum_{t \in T} \left[ p_{a}^{s} \cdot Q_{a}^{s} \cdot X_{a}^{s} \right] 
\]

\[
c^{\text{sup}} = \sum_{a \in A} \sum_{b \in B} \sum_{t \in T} \left[ p_{a}^{s} \cdot Q_{a}^{s} \cdot X_{a}^{s} \right] 
\]

\[
c^{\text{bo}} = \sum_{a \in A} \sum_{b \in B} \sum_{t \in T} \left[ p_{a}^{b} \cdot Q_{a}^{b} \cdot X_{a}^{b} \right] 
\]

\[
c^{\text{fho}} = \sum_{a \in A} \sum_{f \in F} \sum_{t \in T} \left[ p_{a}^{f} \cdot Q_{a}^{f} \cdot u_{a}^{f} \right] 
\]

Where, \( p_{a}^{s} \), \( p_{a}^{b} \), \( p_{a}^{f} \) are respectively the price of load side simply hourly order, generation side simply hourly order, block order and flexible hourly order, \( Q_{a}^{s} \), \( Q_{a}^{b} \), \( Q_{a}^{f} \), \( Q_{a}^{fho} \) are respectively the power of load side simply hourly order, generation side simply hourly order, block order and flexible hourly order. \( X_{a}^{s} \), \( X_{a}^{b} \), \( X_{a}^{f} \), \( u_{a}^{f} \) are the bidding rate under different bidding method. Among them, \( X_{a}^{bo} \) and \( u_{a}^{f} \) are 0-1 variable because of their character.

4.2. Constraints of trans-provincial clearing model

(1) The constraints imposed by the first type of order are as follows:

\[
X_{a}^{b} \leq 1, \quad \forall t \in T 
\]

\[
X_{a}^{f} \leq 1, \quad \forall t \in T 
\]

\[
\sum_{t \in T} u_{a}^{f} \leq 1 \quad \forall fho \in FHO 
\]

Among them, a day is divided into \( t \) time periods and the granularity of time is 1 hour in this paper, formula (10) and formula (11) restrict the bidding rate of both power generation side and load side must not be greater than 1; formula (12) restricts the total bidding rate of flexible hourly order must not be greater than 1, the bidding period of flexible hourly order is subject to clearing system allocation, but the sum of bidding rate of each bidding time must not be greater than 1, that is, order in the same flexible hour can not repeated.

It should be noted that the constraints of orders is not only the above three formulas. It is stipulated in the definition of the decision variable, the bidding rate of block order and flexible hourly order (\( X_{a}^{bo} \) and \( u_{a}^{f} \)) is 0 or 1 because of theirs character.

(2) The power balance constraint is as follows:

\[
Q_{t}^{d} = \sum_{a \in A} \sum_{b \in B} \left[ Q_{a}^{b} \cdot X_{a}^{b} \right] 
\]
\[ Q_s^t = \sum_{a=1}^{b} \sum_{t=1}^{2} [Q_s^{a,b} \cdot X_s^{a,b}] + \sum_{a=1}^{b} \sum_{t=1}^{2} [Q_s^{a,b} \cdot X_s^{a,b}] + \]
\[ \sum_{a=1}^{b} \sum_{t=1}^{2} [Q_s^{a,b} \cdot u_s^{a,b}] \quad (14) \]
\[ P_{t,a}^{l} = \sum_{b=1}^{2} \sum_{t=1}^{2} [Q_s^{a,b} \cdot X_s^{a,b}] + \sum_{t=1}^{2} [Q_s^{a,b} \cdot X_s^{a,b}] + \sum_{t=1}^{2} [Q_s^{a,b} \cdot X_s^{a,b}] + \]
\[ \sum_{t=1}^{2} [Q_s^{a,b} \cdot X_s^{a,b}] \quad (15) \]
\[ e_{t,a}^{l} = \sum_{a=1}^{A} \sum_{t=1}^{2} [P_{t,a}^{l} \cdot PTDF_{t,a}^{a,b}] \quad (16) \]
\[ Q_s^t = Q_s^0, \forall t \in T \quad (17) \]

Where, \( Q_s^t \) is the sum of all the bidding electricity on the power generation side at time \( t \), \( Q_s^0 \) is the sum of all the bidding electricity on the load side at time \( t \). \( Q_s^{a,b} \), \( Q_s^{a,b} \) and \( Q_s^{a,b} \) are respectively declared electricity of simply hourly order, block order, flexible hourly order in generation side and \( Q_s^{a,b} \) is declared electricity of simply hourly order in load side. \( X_s^{a,b} \), \( X_s^{a,b} \) and \( u_s^{a,b} \) are respectively bidding rate of simply hourly order, block order, flexible hourly order in generation side and \( X_s^{a,b} \) is bidding rate of simply hourly order in load side. \( P_{t,a}^{l} \) is net injection of power in area \( a \) at time \( t \). \( e_{t,a}^{l} \) is the power from area \( a \) to area \( a_0 \) at time \( t \). Formula (17) indicates that the sum of all the bidding quantity on the generation side for all the time of the unified market is equal to the sum of all the bidding quantity on the load side, that is, the power balance is reached.

(3) The tie line capacity constraints are as follows:
\[ e_{t,a}^{l} \leq L_{t,a}^{\max} \quad (18) \]
\[ e_{t,a}^{l} \geq L_{t,a}^{\min} \quad (19) \]

Where, \( L_{t,a}^{\max} \) and \( L_{t,a}^{\min} \) represent the maximum and minimum limit values of transmission channels between area \( a \) and area \( a_0 \), respectively. However, in practical cases, it is not necessary to set a lower limit in most cases.

5. Example analysis

In this paper, a practical national grid structure is used for example analysis including the upper and lower limits of the real tie line transmission capacity, and the sensitivity factor. Considering that there is no block order or flexible hourly order in the current power market environment, so the above two are not considered in the example. In this paper, we assume that the market members conduct the day-ahead quantity-price curve every 1h. The purchasing provinces include Hebei, Shanghai, Jiangsu, Zhejiang, Hunan, Henan, Jiangxi, Liaoning and Shaanxi. Electricity selling provinces are Beijing, Tianjin, Tang, Shaanxi, Shandong, Anhui, Fujian, Hubei, Sichuan, Chongqing, Heilongjiang, Jilin, Gansu, Qinghai, Ningxia and Xinjiang.

Considering that the quantity-price bidding is not implemented in power purchasing provinces in the recent stage, the total electricity is divided into 24 declared power points according to the typical curve division. For power selling provinces, the quantity-price bidding curve is 8-stage of one day.

5.1. Optimized results

The result of bidding on both sides of the power generation and consumption and the actual transmission of power in the trans-provincial tie lines are calculated with specific optimization software. The bidding rates are shown in Table 1 and Table 2.
Table 1 Bidding rate of load side

| Time slot | Hebei | Shanghai | Zhejiang | Jiangxi | Liaoning |
|-----------|-------|----------|----------|---------|----------|
| 0         | 1     |          | 0.74883  |         |          |
| 1         | 1     |          | 0.70455  | 1       |          |
| 2         | 1     |          | 0.17941  | 1       | 1        |
| 3         | 1     |          | 0.58535  | 1       | 1        |
| 4         | 1     |          | 0.15957  | 1       | 1        |
| 5         | 1     |          |          | 0.62086 |          |
| 6         | 1     | 1        | 0.04950  | 1       | 1        |
| 7         |       |          | 0.99436  |         | 1        |
| 8         |       |          | 0.94356  |         | 1        |
| 9         |       |          | 0.96178  |         | 1        |
| 10        |       |          | 0.95045  |         | 1        |
| 11        |       |          | 0.13613  |         | 1        |
| 12        |       |          | 0.15141  |         | 1        |
| 13        |       |          | 0.92244  |         | 1        |
| 14        |       |          | 0.91474  |         | 1        |
| 15        | 1     |          | 0.94222  |         | 1        |
| 16        | 1     | 1        | 0.01010  |         | 1        |
| 17        | 1     |          | 0.95340  |         | 1        |
| 18        | 1     |          | 0.97243  |         | 1        |
| 19        | 1     |          | 0.93060  |         | 1        |
| 20        | 1     |          | 0.91094  |         | 1        |
| 21        |       |          | 0.93395  |         | 1        |
| 22        |       |          | 0.96778  |         | 1        |
| 23        |       |          | 0.41085  |         | 1        |

Table 2 Bidding rate of power generation

| Time slot | Shanxi | Shandong | Anhui | Fujian | Hebei | Shichuan | Chongqing | Gan| Qinghai | Ningxia | Xinjiang |
|-----------|--------|----------|-------|--------|-------|----------|-----------|    |         |         |          |
| 0         | 1      | 1        | 1     | 0.09453| 1     | 0.80209  | 1         | 1 | 1        | 1        | 1        |
| 1         | 0.03169| 1        | 1     | 0.09453| 1     | 1        | 1         | 1 | 1        | 1        | 1        |
| 2         | 0.01445| 1        | 1     | 0.09453| 1     | 1        | 1         | 1 | 1        | 1        | 1        |
| 3         | 0.14852| 1        | 1     | 0.12226| 1     | 1        | 1         | 1 | 1        | 1        | 1        |
| 4         | 0.23302| 1        | 1     | 0.12226| 1     | 1        | 1         | 1 | 1        | 1        | 1        |
| 5         | 0.18351| 1        | 1     | 0.12226| 1     | 1        | 1         | 1 | 1        | 1        | 1        |
| 6         | 1      | 1        | 1     | 0.07973| 1     | 0.41880  | 1         | 1 | 1        | 1        | 1        |
| 7         | 1      | 1        | 1     | 0.07973| 1     | 1        | 0.94177   | 1 | 1        | 1        | 1        |
| 8         | 1      | 1        | 1     | 0.07973| 1     | 1        | 0.94658   | 1 | 1        | 1        | 1        |
| 9         | 1      | 1        | 1     | 0.07026| 1     | 1        | 0.61328   | 1 | 1        | 1        | 1        |
| 10        | 1      | 1        | 1     | 0.07026| 1     | 1        | 0.61433   | 1 | 1        | 1        | 1        |
| 11        | 1      | 1        | 1     | 0.07026| 1     | 1        | 0.65691   | 1 | 1        | 1        | 1        |
| 12        | 1      | 1        | 1     | 0.07516| 1     | 1        | 0.83446   | 1 | 1        | 1        | 1        |
It can be seen from table 1 that Jiangsu, Hunan, Henan and Shanxi have not won the bid because of the low bidding price.

In table 2, the power generation side fails to win the bid or partially wins the bid. This is because the power demand of load side is lower than that of power generation side. In addition, some tie lines constraints the transmission power limit, and the generation side can not transmit freely to the load side, so there will be some provinces losing the bid.

5.2. Actual transmission of energy by tie lines

The actual transmission of energy in each tie line of this example is different in each time period, so it is difficult to present all of them in a single table. Therefore, table 3 intercepts representative time points and tie-lines as an example.

| Time   | Hebei—Shanxi | Henan—Shanxi | Zhejiang—Jiangsu | Hunan—Hubei | Henan—Hubei |
|--------|---------------|---------------|------------------|--------------|-------------|
| 2:00   | 169.72        | 1900          | -2636.01         | 1100         | 1402.27     |
| 11:00  | 126.54        | 1900          | -3462.90         | 1100         | 1604.20     |
| 20:00  | 111.08        | 1900          | -3812.11         | 1100         | 1645.71     |

It can be seen from table 3 that in the three typical time periods, both "Henan-Shanxi" and "Hunan-Hubei" tie lines have reached the limit value of transmission power, that is, tie line constraints have effectively affected the optimization clearance results and reduced the total social welfare, so the two lines can be given priority in the construction planning of HV transmission projects. At the same time, the actual transmission power of the "Zhejiang-Jiangsu" tie line in the peak period of power consumption is also close to the limit value of the tie line. As the power consumption of economic development continues to increase, the tie line can also be considered as the second echelon of the transmission line construction planning.

5.3. Comparative scenario analysis

Considering that the transaction between the buyer and the seller can not be reached due to the blocking of some tie lines, and the actual transmission power of "Henan Shanxi" and "Hunan Hubei" lines has reached the limit value of 1900MW and 1100MW respectively. In the calculation example of this section, the two lines will be expanded twice, expanding by 20% and 40% respectively, and other tie lines will remain unchanged.

From the aspects of total social welfare, situation of bidding, total power transaction and actual transmission power of tie line, the expansion of 20% and 40% on the basic example and specific tie line is compared.
It can be known that with the expansion of the "Henan-Shanxi" and "Hunan-Hubei" tie lines, the total social welfare has improved significantly. Therefore, it can be concluded that increase the transmission line whose transmission power is already at the limit value of tie line can improve the total social welfare value.

The calculation results of total energy trading of basic examples, 20% expansion of specific lines and 40% expansion of specific lines are shown in table 5. Each line represents the transaction electricity of each time period within a day. The results are shown in table 5.

Table 4 Actual transmission power of typical tie lines

|                      | Basic example | 20% expansion of specific lines | 40% expansion of specific lines |
|----------------------|---------------|---------------------------------|---------------------------------|
| Total social welfare | 25484725.39   | 27214373.56                     | 28761788.34                     |

Table 5 Electricity in a day different scenarios (MW·h)

| Time | Basic example | 20% expansion of specific lines | 20% expansion of specific lines |
|------|---------------|---------------------------------|---------------------------------|
| 0    | 7674.528966   | 8374.750927                     | 8895.185716                     |
| 1    | 7808.443001   | 8355.698955                     | 8836.393059                     |
| 2    | 7757.421646   | 8238.11575                      | 8718.809854                     |
| 3    | 6471.905781   | 6952.599885                     | 7433.293989                     |
| 4    | 6618.885866   | 7099.57997                      | 7580.274075                     |
| 5    | 6534.759649   | 7229.430476                     | 7727.25416                      |
| 6    | 8777.149442   | 9249.816244                     | 9730.510348                     |
| 7    | 8615.986322   | 9318.779593                     | 9848.094659                     |
| 8    | 8618.699065   | 9165.978896                     | 9885.089327                     |
| 9    | 9418.463917   | 10012.84229                     | 10714.38064                     |
| 10   | 9419.141803   | 9974.641862                     | 10693.75533                     |
| 11   | 9446.427365   | 10165.64654                     | 10655.58798                     |
| 12   | 9009.185951   | 9721.64582                      | 10202.33992                     |
| 13   | 9162.036565   | 9662.853164                     | 10143.54727                     |
| 14   | 8982.116814   | 9478.666066                     | 10141.85513                     |
| 15   | 9502.349518   | 10032.02648                     | 10747.63473                     |
| 16   | 9500.955356   | 10220.19507                     | 10749.64409                     |
| 17   | 9501.610073   | 10066.8551                     | 10785.96869                     |
| 18   | 10224.00593   | 10847.09537                    | 11532.65859                     |
| 19   | 10226.96431   | 10758.87086                    | 11412.89901                     |
| 20   | 10228.44353   | 10760.35008                    | 11343.31572                     |
| 21   | 9368.485108   | 9887.461752                    | 10586.13115                     |
| 22   | 9366.450651   | 9981.619754                    | 10653.27554                     |
| 23   | 9453.439852   | 10108.49461                    | 10579.78444                     |
With the expansion of the tie lines of "Henan-Shanxi" and "Hunan-Hubei", the bidding rates of Shanxi, Hubei, Chongqing and Qinghai, which are the power-selling provinces, have increased. It can be seen that through the expansion and reconstruction of the lines whose actual transmission energy is already in the limit value of tie line, the bidding rate of the generation side can be increased, and the energy that could not be sold due to "road congestion" can be sold through the tie line after expansion.

Table 6 20:00 Actual transmission power of typical tie-line

| Scenarios    | Hebei-Shanxi | Henan-Shanxi | Zhejiang-Jiangsu | Hunan-Hubei | Henan-Hubei |
|--------------|--------------|--------------|------------------|-------------|-------------|
| Basic example| 111.08       | 1900         | -3812.11         | 1100        | 1645.71     |
| expansion 20%| 163.48       | 2280         | -3912            | 1320        | 1955.3      |
| expansion 40%| 216.7        | 2660         | -4000            | 1540        | 2190.9      |

6. Conclusion
To support national unified power market construction, this paper designs a clearing mechanism of inter-provincial market transaction and carries on the model verification through the case design. Conclusions are as follows.

(1) The inter-provincial market trading mechanism, which takes the province as the agent, simplifies the influence of the provincial market on the inter-provincial transaction, thus solves the problem that the provincial market mechanism is not unified at the present stage, and is beneficial to the development of inter-provincial power transaction in the early stage of reform;

(2) The main constraint affecting the transaction is the trans-provincial tie line constraint. In order to maximize the efficiency of resource allocation, the calculation of available transmission capacity between provinces is very important.

In addition, it can be predicted that market members can directly participate in trans-provincial market transaction with a further liberalization of the power market, in which case the accuracy of the available transmission capacity calculation will be the key factor affecting the interests of inter-provincial transaction members.

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