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Inter-Provincial Electricity Spot Market Model for China

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***Abstract*—A new round of electricity market reform has been carried out in China since 2015. Due to the spatial mismatch of electricity supply and demand in China, inter-provincial electricity market will occupy an important position in the electricity market system in China. The experience of European unified electricity market provides inspirations for the construction of the national electricity market in China. In this paper, European unified electricity market is introduced, including the day-ahead market coupling mechanism and corresponding market clearing algorithm. The enlightenment of European experience to China is analyzed, from mechanism design to technique implementations. Then, an inter-provincial electricity spot market model is proposed for the national unified electricity market in China, and the market clearing algorithm is designed. Based on the proposed model, energy flow and cash flow of the national market are analyzed. Case study based on a 19-bus system shows the effectiveness of the proposed model.**

Keywords—electricity market, market coupling, European experience, inter-provincial trading, day-ahead

I. Introduction

A new round of power industry reform in China has been carried out since the leading policy document, *Several Opinions of the CPC Central Committee and the State Council on Further Deepening the Reform of the Electric Power System* – also known as Policy No. 9 – is launched in March, 2015. This reform plan seeks to restore the commodity attributes of the electricity, optimize the allocation of power resources through market mechanisms, promote the accommodation of renewable energy (RE), provide scientific and reasonable guidance for the power system planning, and ensure the security and reliability of the power system operation.

As the spatial distribution characteristics of electricity demand and supply in China [1], large scale and long distance electricity transmission is necessary. Since the *Renewable Energy Law* was issued by the Chinese government in 2006， there has been rapid growth in the investment for wind power generation and photovoltaic generation specially in the northwest region of China, which is rich in wind and solar energy. However, the RE generators are faced with serious curtailment challenges in recent years [2]. One reason is that, due to the intermittency and uncertainty of RE [3], there is inadequate generation capacity to provide peaking service in RE-abundant areas. Meanwhile, the northwest region of China has large capacity of RE, however the power demand in northwest region is low. On the contrary, the power demand of eastern region is high with low RE capacity. Therefore the power generated from RE in northwest region must be transmitted to eastern region to decrease the curtailment. Thus, the utilization of RE generation should be enhanced from provincial and trans-regional levels [4]. It is necessary to accelerate the establishment of an open competitive national unified electricity market in China.

The history and experience of the European internal electricity market have certain reference significance for the construction of the national unified electricity market in China with the provincial power market as the starting point. Since the late 1980s, Europe has begun to promote the integration of the electricity and natural gas industries, aiming to reduce Europe's overall energy dependence on the outside world through the open integration of internal energy markets, promote the diversification of energy supply among member states, and ensure the safe, sustainable and affordable energy supply in Europe. In response to this goal, in recent years, Europe has continued to promote the deepening of power market reforms in member states, improve the market transactions and power grid operation rules, strengthen the merger of Power Exchanges (PXs) and the integration of power markets in member states, promote transnational energy cooperation and deepen the construction of a unified power market [5].

The construction of European unified electricity market has undergone a multi-phase process from single country markets to cross-border regional markets, from medium-to-long-term and short-term contract transactions to day-ahead and intra-day transactions. At present, European internal electricity market, which is characterized mainly by day-ahead market integration, has covered 23 countries, and a wide range of resources optimization allocation of electric power market transaction platform is initially formed [6]. The construction of a unified electricity market makes the market more competitive and the allocation of resources more efficient. It can achieve complementary advantages of resource more effectively among member states, protect the security of power supply and better adapt to the demand of large-scale consumption of clean energy.

The major contributions of this paper are as follows:

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1) The mechanism and algorithm of European unified electricity market are summarized, including the basic principle and main process of Market Coupling, EUPHEMIA model and the model implementation. Then, the enlightenment of European experience to China is analyzed from the perspective of mechanism design and technical implementation.

2) Considering the national conditions and provincial electricity spot market construction situation in China, inter-provincial electricity spot market model for the national unified electricity market is proposed and the market clearing algorithm is designed. Based on the proposed model, the energy flow and cash flow of the national market transactions are analyzed.

II. European Electricity Market Coupling Model

A. European Day-Ahead Market Coupling Mechanism

The cross-border joint clearing in day-ahead electricity market of European countries is realized through Market Coupling (MC). Market Coupling is a way to integrate different electricity markets into one coupled market. In the coupled market, the marches between demand and supply are no longer limited to the local territorial scope. On the contrary, in a market coupling approach, energy transactions can involve sellers and buyers from different areas as long as the electricity network constraints are satisfied [7]. The main benefit of the Market Coupling approach falls in improving the market liquidity along with the beneficial side effect of reducing electricity price volatility. Market coupling also benefits market participants. Physical transmission rights are no longer necessary for cross-border transactions. Participants only need to submit the orders to their local Power Exchanges and the orders can be matched with other orders in all the coupling market provided the electricity network constraints are satisfied.

The current market coupling process is as follows:

1) Based on the maximum transmission capacity of the tie-line and the results of the previous explicit auctions (based on the cross-border transmission plans notified by market participants), the TSO of each country calculates the available transmission capacity (ATC) for each bidding area and submits it to the market coupling system.

2) Each market member should submit their bidding prices to their local power trading institutions within a unified time, and each power trading institution will submit the summarized orders to the market coupling system.

3) The market coupling system is operated by the rotating power trading institution. Unified optimization and clearing are performed according to the ATC and the submitted orders. The matched volume, the clearing price and the "commercial flow" of each bidding area are calculated. Each market member should formulate a cross-border trading plan based on the clearing results and submit it to the relevant TSO.

4) The market transaction information is collected and released by PXs.

B. Clearing Algorithm

The coupling day-ahead market clearing in Europe is mainly based on the Price Coupling of Regions (PCR) project. EUPHEMIA (Pan-European Hybrid Electricity Market Integration Algorithm) is the algorithm that was developed to solve the problem associated with the coupling of the day-ahead power markets in the PCR project [8]. EUPHEMIA matches energy demand and supply for all the periods of a single day at once while taking into account the market and network constraints. The objective of EUPHEMIA is to maximize the social welfare, i.e. the total market value of the day-ahead auction expressed as a function of the consumer surplus, the supplier surplus, and the congestion rent including tariff rates on interconnectors if they are present. EUPHEMIA returns market clearing prices, matched volumes, and the net position of each bidding area as well as the flow through interconnectors.

The input of EUPHEMIA is divided into three categories: bidding data, topology data and network data. Among them, the bidding data mainly includes Aggregated Hourly Orders, Complex Orders, Block Orders, Merit Orders, PUN Orders and other different types of bidding information. The supply and demand curve can be formed as stepwise, piecewise linear or mixed model. The topology data mainly refers to the node information of the physical power grid and the upper and lower price limits of each bidding area; the network data mainly includes various constraints of the physical power grid, such as the net output position ramping constraints, tie-line capacity constraints, tie-line commercial revenue constraints, transmission line ramping constraints, balance constraints, network loss constraints, etc.

Before the market coupling, several bidding areas are managed by an exchange. After the market coupling, these bidding areas still exist, and all bidding areas are cleared at the same time. The clearing price of each bidding area may be different, which must meet the upper and lower price limits of each bidding area.

When forming the supply and demand curve, both the stepwise model and the piecewise linear model are used. This is because the models used by the various exchanges were different. In order to avoid causing additional burden to market participants, these models are retained after the market coupling.

Bidding areas can exchange energy between them in an ATC model, a flow based model or a hybrid model (combination of the previous two models).

III. Enlightenment of European Experience to China

Although there are some differences of reality factors between China and Europe, like energy industry structure and resource distribution, the construction experience of European unified electricity market has shed some light on China. In combination with the background of power market reform in China, the mechanism design and technical implementation are analyzed in this section.

A. Unified National Power Market Mechanism for China

From the perspective of the market structure, it is a reasonable choice to build a unified national power market in a “unified market, two-level operation” mode. The EU market coupling model provides a way for China's provincial power market evolving into the national market.

Considering China's national conditions and development path, the coordinated operation of the national and provincial market should coordinate the inter-provincial and intra-provincial transactions in accordance with the "unified market, two-level operation" market model. The so-called "unified market" refers to the establishment of a unified national power market, with a unified market framework, operating platform, core rules, and coordinated operation to promote the optimal allocation of energy resources across the country.

Under the framework of a unified market, the national and provincial trading platforms operate separately, with division of labor and collaboration and different focuses, but are also closely integrated. Under the coordinated operation mode of the national and provincial markets, the national market is mainly positioned to optimize the allocation of energy resources in a wider range, promote clean energy accommodation, and implement the national energy strategy. The function of the provincial market is optimizing the resource allocation in the province, based on the implementation of inter-provincial allocation results, to ensure the balance of power and energy in the province and maintain the safe and stable operation of the power grid.

The national day-ahead market determines the cross-province and cross-region schedule based on the bidding of supply and demand of each province. The provincial day-ahead market clearing takes the results of the national market as a boundary condition to ensure the implementation of the tie-line schedule. In the national market clearing, inter-provincial and inter-regional transmission costs need to be considered.

As the boundary condition for the market clearing of various provinces, the inter-provincial and inter-regional schedule obtained by the national market clearing needs to be physically executed. However, the winning bids of the market participants in the national market are only of settlement significance, and physical execution is not required. The national market is cleared based on the method of centralized optimization and marginal clearing. The day-ahead market clearing in the province is based on security-constrained unit commitment (SCUC), minimizing the province electricity purchase cost while ensuring cross-province and cross-region electricity transactions. At the same time in day-ahead settlement the nodal electricity price is obtained.

B. Technical Implementation

The enlightenments of the technical implementation of European model are as follows.

1) The basic principle of the national market is technology neutrality, that is, specific technology should not be considered in the market clearing. However, different bidding types can be designed for different types of generating units. Once cleared, all units face the same price. Subsidies are generally handled outside the spot market.

2) When integrating different provincial and regional markets, the network model can be simplified as a simple topology model like ATC or a more accurate power flow model, which is related to the stability margin and coupling degree of the power grid.

3) There are many different situations in which the supply and demand curves intersect. The market rules need to clearly specify the methods for determining the price and amount of liquidation in different situations.

4) The bidding curves in the early market were stepwise, and now many markets have seen more complex linear bidding curves that reflect the characteristics of supply and demand more accurately.

5) In addition to the hourly bidding, there are various varieties such as packaged bidding, mutually exclusive bidding and related bidding. Different market participants can choose the appropriate trading variety according to their resources. For example, for a hydropower unit that is regulated on a daily basis, the amount of electricity that can be generated in a day is fixed, and the generation time is relatively flexible, then the flexible hourly bid form can be used. In the design of the market mechanism, it is also possible to continuously innovate and design new varieties according to the specific conditions of market participants.

IV. Inter-Provincial Electricity Spot Market Model

Based on the design of national unified electricity spot market, the inter-provincial day-ahead market adopts the method of centralized optimization and marginal clearing. In order to achieve the national day-ahead clearing mechanism, it is necessary to establish a national unified electricity spot market inter-provincial price coupling model, taking the maximum social welfare as the optimization objective, while considering power transmission costs and tie-line power constraints. The model proposed in [9][10] is adopted in this paper. For easy understanding, the key formula is presented as follows.

A. Model Assumptions

Considering a multi-region power system with both AC and DC tie-lines, to simulate the power flow between regions, following assumptions are given:

- Each regional system is reduced to a virtual node, which is used to calculate the power flow on the AC tie-line;
- The transmission power of the DC tie-line is independently adjustable within its power capacity.

The simplification performed in Hypothesis 1 is widely used in the literature about multi-regional market, and is also implemented in practice. For example, the simplified general grid model is used in the European day-ahead market coupling. The rationality of Hypothesis 1 is that, compared with the inter-regional power grid, the intraregional power grid is usually more closely connected electrically, so the internal system structure can be ignored when calculating the inter-regional power flow. According to Hypothesis 1, the inter-regional power flow is only determined by the terminal condition of tie-line. Hypothesis 2 is achievable, because the transmission power of the DC link can be controlled by adjusting the firing angle of the converter, the arc extinction angle and the tap setting of the transformer. Under this assumption, the transmission power on the DC tie-line can be used as the decision variable for tie-line scheduling optimization.

B. Objective Function

The inter-temporal constraints are not considered, so the electricity market is cleared for each time interval separately. For each time period, the objective function of the proposed model is minimizing the total operating cost of the system, including the power generation cost and tie-line transmission cost as follows.

$$\min_{\mathrm{P}^{\mathrm{G}},\mathrm{P}^{tl(\mathrm{dc})}} \sum_{a,i} c_{a,i}(p_{a,i}^{\mathrm{G}}) + \sum_{k} \pi_k p_k^{tl} \tag{1}$$

where $c_{a,i}(\bullet)$ and $p_{a,i}^{\mathrm{G}}$ are the generation offer function and real power output of unit i in regional system a, respectively. p_k^{tl} is the power flow on tie-line k, and π_k is the corresponding transmission tariff.

C. Constraints

Tie-line flows and phase angles of virtual nodes are denoted by P^{tl} and θ, respectively. For distinction, the power flows on the AC and DC tie-lines are specified as $\mathrm{P}^{tl(\mathrm{ac})}$ and $\mathrm{P}^{tl(\mathrm{dc})}$, which are both part of P^{tl}. In addition, network parameters are defined. Let W denote the region-tieline incidence matrix, while $\mathbf{W}^{\mathrm{dc}}$ 和 $\mathbf{W}^{\mathrm{ac}}$ are the incidence matrices corresponding to DC and AC interconnectors, respectively. **y** is the AC interconnector admittance vector.

For the reduced inter-regional network, as shown in Fig. 1, the net export of each region is defined as,

$$p_a^{nex} = 1^T \mathrm{P}_a^{\mathrm{G}} - 1^T \mathrm{P}_a^{\mathrm{D}}, \forall a \tag{2}$$

where $\mathrm{P}_a^{\mathrm{G}}$ and $\mathrm{P}_a^{\mathrm{D}}$ are the generation power and demand load of each region.

Denote the vector of p_a^{nex} as $\mathbf{P}^{nex}$, then the power flow equation of inter-regional AC network can be formulated as,

$$\mathrm{Y}^{\mathrm{ac}}\theta = \mathrm{P}^{nex} - \mathrm{W}^{\mathrm{dc}}\mathrm{P}^{tl(\mathrm{dc})} \tag{3}$$

$$\mathrm{P}^{tl(\mathrm{ac})} = \mathrm{diag}(\mathrm{y})\mathrm{W}^{\mathrm{ac}}\theta \tag{4}$$

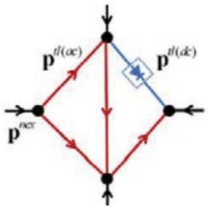

Fig. 1. Reduced inter-regional system

Constraint (3) expresses the regional power balance, where Y^{ac} is the nodal admittance matrix of the reduced inter-regional AC network, which can be formulated as $\mathrm{Y}^{\mathrm{ac}} = \mathrm{W}^{\mathrm{ac}}\mathrm{diag}(\mathrm{y})(\mathrm{W}^{\mathrm{ac}})^T$. Equation (4) is the power flow representation of the AC interconnectors.

Bounds on the generation outputs and interconnector flows are modeled as follows,

$$\underline{\mathrm{P}}_a^{\mathrm{G}} \le \mathrm{P}_a^{\mathrm{G}} \le \overline{\mathrm{P}}_a^{\mathrm{G}}, \forall a \tag{5}$$

$$-\overline{\mathrm{P}}^{tl(\mathrm{dc})} \le \mathrm{P}^{tl(\mathrm{dc})} \le \overline{\mathrm{P}}^{tl(\mathrm{dc})} \tag{6}$$

$$-\overline{\mathrm{P}}^{tl(\mathrm{ac})} \le \mathrm{P}^{tl(\mathrm{ac})} \le \overline{\mathrm{P}}^{tl(\mathrm{ac})} \tag{7}$$

D. Algorithm Process

The proposed model for inter-provincial electricity spot market is a linear programming model, which can be efficiently solved using the commercial solver CPLEX. The algorithm flowchart of this model is shown in Fig. 2.

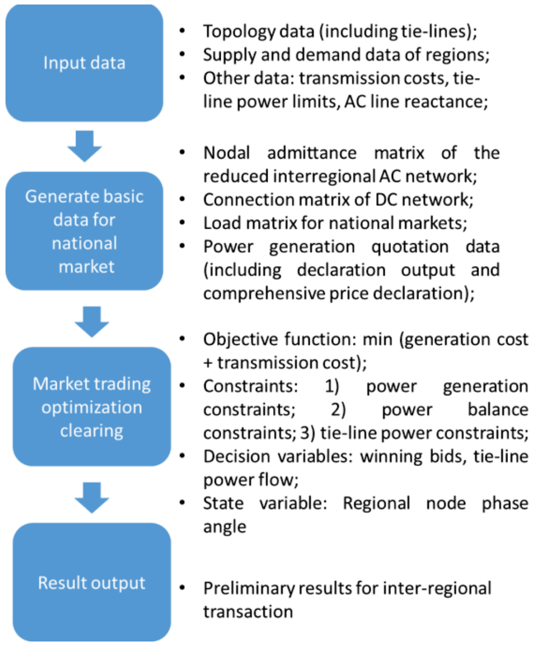

Fig. 2. Algorithm flowchart of the proposed model

V. Case Study

In this case study, the testing environment is Thinkpad T440p, 2.40 GHZ with 8 cores. The program is developed using MATLAB R2013b. The optimization solver is CPLEX 12.4.

A. Basic Data

A 19-bus network shown as Fig. 3 is created to simulate the topology for the national market.

The model parameters include topology, transmission tariff, tie-line power limit, AC line reactance (per unit value), load profile, installed capacity and bidding parameters of each region, etc. The transmission tariff is modified based on the "Inter-Provincial and Inter-regional Special Project Transmission Tariff" which has been implemented in China [11]. The power limit of the AC/DC tie-line is shown in Fig. 4. The load profile of each region is based on the typical load profiles of provincial power grids" 0. Based on the total thermal power installed data of each province in 2019, according to the IEEE-118 standard system, each region is set to contain 54 units, and the minimum technical output of thermal power units is considered. The installed capacity of thermal power units in each region is shown in Fig. 5.

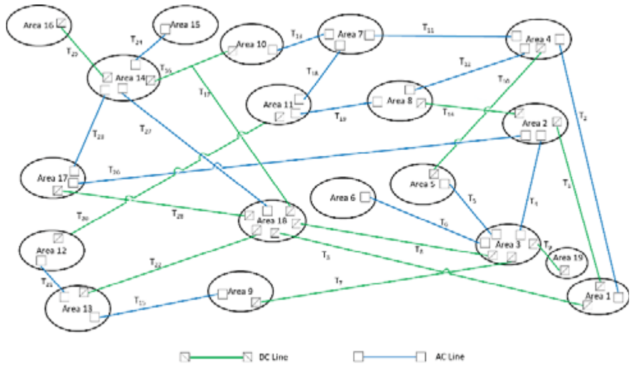

Fig. 3. The topology of the 19-bus system

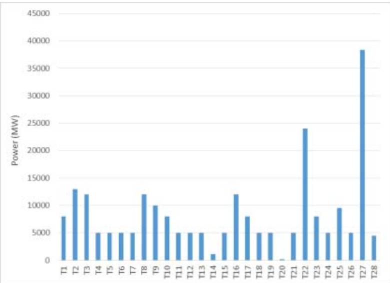

Fig. 4. Tie-line power limit

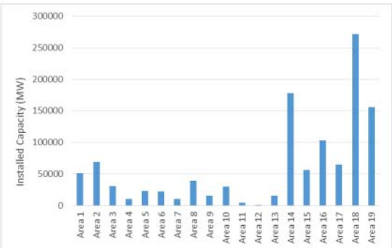

Fig. 5. Installed capacity of thermal power units in each region

The thermal power units in each region bid in the form of an hourly bid with five price segments., The offers of 54 units are based on the feed-in-tariff (FIT) of coal-fired power units of various provinces nationwide released on July 1, 2017. The wind power generation profile of each region is based on the typical wind power generation profiles of provincial power grids with zero offer. The offered power and prices of photovoltaic power generation in each region is simulated in the same way. The offered power and prices of hydropower in each region are based on the installed capacity, generation capacity and FIT of hydropower units in each province in June 2019.

B. Results

According to the model proposed in this paper, the inter-regional market clearing for each time interval is conducted. The inter-regional trading quantity in a day is shown in Fig. 6.

The transmission power of the tie-lines between regions during 24 hours is shown in Fig. 7. Taking several tie-lines as examples, the transmission power is shown in Fig. 8.

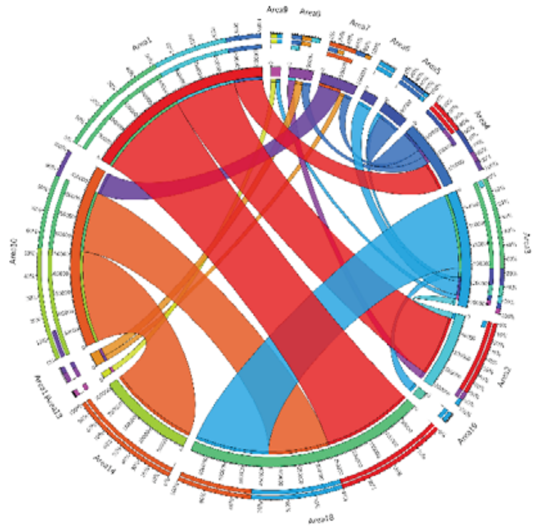

Fig. 6. Inter-regional trading quantity(MWh)

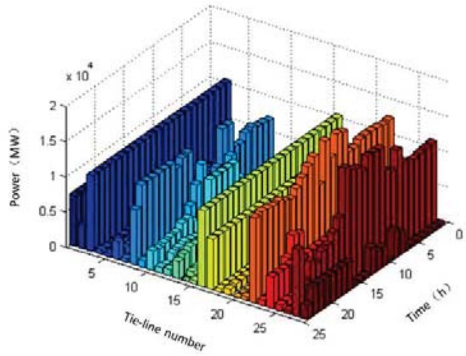

Fig. 7. Transmission power of tie-lines between regions

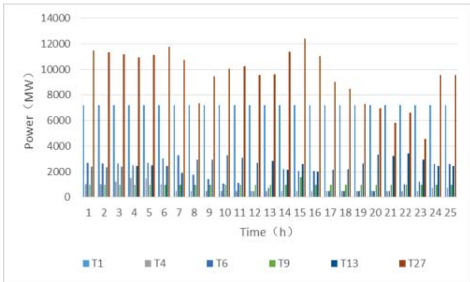

Fig. 8. Transmission power of several tie-lines

The electricity price in each region during 24 hours is shown in Fig. 9. Taking Area 1 as an example, the electricity price during 24 hours is shown in Fig. 10.

The energy flow and cash flow of each region participating in the national unified electricity market on a settlement date are shown in Fig. 11. The results can be used to calculate the local power generation income, electricity expense of local users, net transmission power income of tie-lines, and transmission cost shared by tie-lines participating in inter-regional transaction of each region, so as to conduct financial analysis from the perspective of the national dispatch center, as shown in Table I.

The inter-provincial transaction revenue (only regions with positive revenue) is shown in Fig. 12.

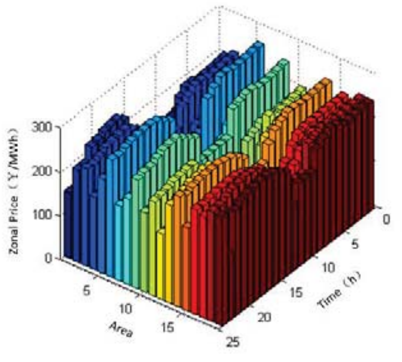

Fig. 9. Zonal price during 24 hours

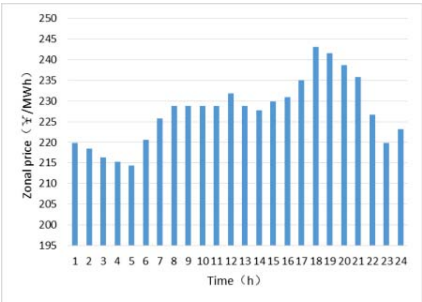

Fig. 10. Electricity price of Area 1

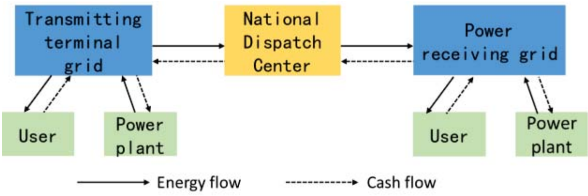

Fig. 11. Schematic diagram of energy flow and cash flow in the national unified electricity market

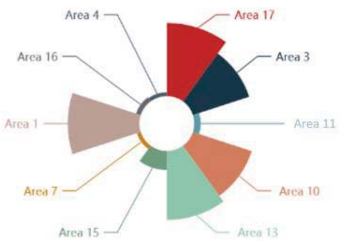

Fig. 12. Illustration of inter-provincial transaction revenue (only regions with positive revenue)

TABLE I. FINANCIAL ANALYSIS AT THE NATIONAL DISPATCH LEVEL

	Congestion revenue (million yuan)	**Transmission revenue (million yuan)**
National Dispatch Center	109.52	67.17

VI. CONCLUSION

Due to the spatial mismatch of electricity supply and demand in China, a nationwide electricity market is necessary. Considering the national conditions and provincial electricity spot market construction situation in China, the experience of European unified electricity market can provide inspirations for the construction of national electricity market in China. In this paper, the mechanism and algorithm of European unified electricity market are summarized, including the basic principle of Market Coupling and the implementation of Euphemia. Then the enlightenments of European experience to China are analyzed from the perspective of mechanism design and technical implementation. The main design idea for the unified national electricity market in China is studied. Considering all types of energy and breaking down interprovincial barriers, the inter-provincial electricity spot market model for China is proposed. Case study based on the 19-bus system is carried out, in which energy flow and cash flow of the national market transactions are analyzed. The effectiveness of the proposed model is validated. Hopefully, it may provide some inspirations to the construction of the unified national electricity market in China from the technical perspective.

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