Classification and Settlement Method for Congestion-related Imbalance Funds Based on Power Flow Tracing

Authors: Jing Zhaoxia, Li Wenxiao, Yi-fan Wang, Li Wenxiao

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Abstract

To reveal the formation mechanism of congestion-related imbalance funds under transmission network constraints and the inconsistency between settlement responsibility and physical causality, this paper constructs a classification identification and settlement mapping model for congestion-related imbalance funds based on power flow tracing theory. Through power decomposition, congestion costs are allocated to trading entities, and a settlement mapping matrix across market levels is established. Numerical examples demonstrate that the proposed method can effectively reduce the degree of cross-subsidization and significantly enhance the fairness and incentive compatibility of congestion cost allocation. The model exhibits a certain dependency on the integrity of system operation data and power flow observability, and it has not yet considered the impact of uncertainty factors and complex rules in actual markets. The proposed method can provide theoretical support for the refined settlement of congestion-related imbalance funds in regional and two-level spot markets.

Full Text

Preamble

Classification of Congestion-Related Imbalance Funds Based on Power Flow Tracing

(School of Electric Power, South China University of Technology, Guangzhou 510641, China) (Nanjing Branch of China Electric Power Research Institute Co., Ltd., Nanjing 210037, China)

摘要

To reveal the formation mechanism of congestion-related imbalance funds under transmission network constraints and address the inconsistency between settlement responsibility and physical causality, this paper constructs a classification, identification, and settlement mapping model for congestion-related imbalance funds based on power flow tracing theory. By utilizing power injection decomposition, congestion costs are allocated to specific market participants, and a cross-market hierarchical settlement mapping matrix is established.

Numerical examples demonstrate that the proposed method effectively reduces the degree of cross-subsidization and significantly enhances the fairness and incentive compatibility of congestion cost allocation. However, the model exhibits a certain level of dependence on the integrity of system operational data and power flow observability; furthermore, it does not yet account for the impact of uncertain factors or the complex rules of actual market environments. The methodology presented in this study provides theoretical support for the refined settlement of congestion-related imbalance funds in regional and two-tier spot markets.

关键词

Locational Marginal Price and Imbalance Settlement in Electricity Spot Markets

Classification Code: TP393

Abstract

In the context of modern electricity spot markets, the Locational Marginal Price (LMP) serves as a critical signal for reflecting the spatial value of electricity and managing network congestion. However, the practical implementation of LMP-based settlements frequently results in "imbalance funds" (also known as settlement surpluses or deficits). These funds arise from the inherent gap between the payments made by loads and the revenues received by generators, primarily due to network losses, congestion rents, and the non-convex nature of power system optimization. This paper analyzes the theoretical foundations of LMP and explores the mechanisms that generate imbalance funds. By examining the mathematical formulation of the economic dispatch problem, we categorize the components of these funds and discuss various allocation methods used to maintain financial neutrality within the market.

1. Introduction

The transition toward deregulated electricity markets has necessitated sophisticated pricing mechanisms that can account for physical grid constraints. Locational Marginal Pricing (LMP) has emerged as the industry standard for wholesale electricity markets, providing a transparent framework for managing transmission congestion and energy costs. Despite its efficiency in signaling economic value, the settlement process based on LMP is rarely revenue-neutral. The resulting imbalance funds represent a significant challenge for market operators, as they must be redistributed among market participants in a manner that is both equitable and preserves the incentive structures of the spot market.

2. Theoretical Framework of Locational Marginal Pricing

The LMP at a specific node is defined as the marginal cost of supplying the next increment of load at that node while satisfying all transmission constraints and operational limits. Mathematically, the LMP is derived from the shadow prices of the power balance and transmission constraint equations in an Optimal Power Flow (OPF) model.

The LMP at node i can generally be decomposed into three fundamental components: 1. **System Marginal Energy Price:** The cost of the marginal unit in the system. 2. **Marginal Loss Component:** The cost associated with incremental transmission losses. 3. **Marginal Congestion Component:** The cost reflecting the impact of transmission constraints on the delivery of power to that node.

3. Origins of Imbalance Funds

Imbalance funds in the electricity spot market are primarily driven by the following factors:

3.1 Transmission Congestion and Losses Under an LMP framework, loads typically pay the price at their respective nodes, while generators receive the price at their

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Wenxiao Li Zhaoxia Jing Yifan Wang (School of Electric Power Engineering, South China University of Technology, Guangzhou 510641, China) (Nanjing Branch,China Electric Power Research Institute Co., Ltd., Nanjing 210037, China)

Abstract

This study reveals the formation mechanism of congestion-related imbalance funds under transmission network constraints and addresses the inconsistency between settlement responsibility and physical causality. Based on flow tracing theory, a classification and settlement mapping model for congestion-related imbalance funds is developed. Through power flow decomposition, congestion costs are allocated to individual market participants, and a settlement mapping matrix across different market layers is established. Case studies demonstrate that the proposed method effectively reduces cross-subsidization and significantly improves the fairness and incentive compatibility of congestion cost allocation. The model relies on the completeness of system operational data and the observability of power flows, and does not yet account for uncertainties or the complexities of real-world market rules.

The proposed approach provides theoretical support 1for the refined settlement of congestion-related imbalance funds in regional and two-tier spot electricity markets.

Keywords

Congestion surplus Flow tracing Imbalance funds Electricity spot market

Locational marginal pricing

引言

Introduction

In recent years, as China' s power market reform continues to advance, regional power markets have formed a multi-level structure characterized by "provincial spot markets + inter-provincial transaction coordination." Under this market framework, the scale of inter-provincial power transactions has expanded continuously, leading to more frequent spatial allocation of electrical energy within regional grids. Consequently, the impact of transmission network constraints on market clearing results has become increasingly significant. To reflect the degree to which different market participants utilize transmission network resources, it is necessary to identify and classify congestion-related imbalance funds from the perspective of physical power flow. This provides essential support for refined settlement mechanisms in regional power markets. In highly marketized power systems, energy scheduling centers on market clearing results, where the scarcity of energy in both temporal and spatial dimensions is reflected through price signals. In inter-provincial and inter-regional power transactions, congestion issues caused by transmission network constraints have become increasingly prominent. The price spread revenue formed under nodal or zonal pricing mechanisms has become a vital component of the power market settlement system. This phenomenon has been subject to mature practical and theoretical summaries in the Nordic, U.S., and European single electricity markets, where its essence is regarded as the priced expression of spatial energy allocation efficiency under transmission capacity constraints [?]-[?]. However, under realistic constraints such as the coexistence of multiple time-scale markets and asymmetric settlement rules between generation and consumption sides, congestion-related revenues are not accurately returned to the corresponding responsible or beneficiary parties. Ultimately, this manifests at the settlement level as corresponding imbalance funds [?].

Without clear identification of causes and a reasonable allocation mechanism, these imbalance funds can easily weaken the effectiveness of price signals, affect the behavioral incentives of market participants, and even lead to imbalances of interests between regions and entities [?].

Some regional markets adopt a two-tier spot market architecture consisting of "inter-provincial + intra-provincial" levels. Given the large scale of inter-provincial power transmission, congestion on inter-provincial tie-lines is a routine operational feature [?]. Currently, the handling of inter-provincial congestion surplus is relatively crude, primarily allocated based on power delivery ratios or through negotiation, lacking a direct correspondence with physical power flows. In the Southern Regional Market, issues such as congestion management, transmission rights allocation, and congestion surplus distribution have become critical problems that need to be addressed [?].

This practical background constitutes the direct motivation for the research in this paper. Some regional markets adopt a two-tier spot market architecture consisting of "inter-provincial + intra-provincial" levels, where the large scale of inter-provincial power transmission makes tie-line congestion a routine operational characteristic [?].

Currently, the handling of inter-provincial congestion surplus is relatively crude, primarily allocated based on power delivery ratios or through negotiation, lacking a direct correspondence with physical power flows. In the Southern Regional Market, issues such as congestion management, transmission rights allocation, and congestion surplus distribution have become critical problems that need to be addressed [?]. Existing research generally analyzes the issue of imbalance funds from the perspectives of settlement mechanism design, pricing rules, and allocation principles. On one hand, some studies focus on the impact of imbalance pricing mechanisms on market efficiency and participant behavior, systematically analyzing the mechanisms by which different pricing and settlement schemes suppress speculative behavior and incentivize the fulfillment of balancing responsibilities; these studies often verify applicability in new power system scenarios through game theory models or simulation analysis [?]. On the other hand, related research starts from settlement processes and responsibility definition to perform systematic modeling and case verification of allocation or refund mechanisms for imbalance funds, emphasizing the importance of the "causer pays" principle and settlement operability [?]. While current research has sufficiently discussed the formation mechanisms and handling principles of imbalance funds, the analysis generally follows the main line of differences in settlement rules or price mechanisms, with limited further subdivision of the internal components of these funds. In particular, the imbalance funds implicitly formed by transmission congestion and spatial transmission differences are often lumped into system-level settlement surpluses or deficits, lacking targeted identification methods and independent settlement logic. To a certain extent, this weakens the consistency between congestion management, price signals, and settlement results, and is detrimental to interest coordination within regional and inter-provincial markets [?], [?].

From the perspective of power market theory, the congestion revenue corresponding to nodal price spreads is essentially the economic rent created by the transmission network acting as a "spatial converter."

The magnitude of this rent depends on the actual degree to which different power sources and loads occupy network resources. In an ideal nodal pricing market, such revenue can be naturally formed through congestion surpluses and used for transmission cost recovery or returned to market participants. However, under conditions of uniform price settlement or insufficient inter-market coordination, congestion revenue is difficult to manifest directly and explicitly, thus accumulating at the settlement level in the form of imbalance funds [?].

Power flow tracing methods provide an effective tool for characterizing the actual flow paths of electrical energy in the network. By decomposing line flows into the contribution shares of various generation or load entities, power flow tracing can truthfully reflect the impact of different entities on transmission resource occupancy and the formation of network congestion without relying on contract path assumptions.

In the early stages of power market development, power flow tracing was used for ex-ante pricing of transmission services to address the issue of transmission costs not being included in energy prices [?]. As power markets matured and deregulation progressed, these methods were applied to transmission congestion pricing, integrating generator fixed costs, line loss costs, and transmission congestion costs into electricity prices [?]. In the current environment of increasing penetration of renewable energy and distributed generation, power flow tracing supports Transmission System Operator and Distribution System Operator (TSO-DSO) coordination to resolve congestion issues based on demand response mechanisms. These methods can be used to calculate demand response prices, providing decision support for system operators [?].

In inter-provincial and inter-regional markets, the relationship between actual energy transmission paths and contract paths is weak [?]. Currently, European cross-border markets utilize power flow tracing methods to determine the allocation of congestion-related costs [?].

Based on the aforementioned research status, this paper focuses on the problem of imbalance funds caused by transmission congestion within the power market settlement system and proposes a classification and settlement method for congestion-related imbalance funds based on power flow tracing. First, the paper outlines the formation paths of congestion-related imbalance funds from the perspective of settlement mechanisms. Second, power flow tracing is utilized to identify the contribution of different market participants to congestion formation, achieving a categorized characterization of these funds. Finally, a corresponding settlement and allocation mechanism is constructed to ensure that congestion-related revenues or costs can be more accurately returned to the responsible or beneficiary parties, providing a theoretical basis and methodology for improving regional and inter-provincial power market settlement systems.

Analysis of the Formation Mechanism and Settlement Mechanism of Congestion-related Imbalance Funds

Institutional Basis for Congestion Surplus in Centralized Power Markets

In centralized markets, there is a deviation between the market value represented by the congestion surplus and the value flow of the final settlement. Under a unified clearing model, transmission network constraints are not ex-post correction factors but participate directly in the market clearing process as endogenous constraints. When transmission lines or key cross-sections reach their capacity limits, the system must satisfy security requirements by adjusting the generation output of different nodes or regions, thereby creating spatial differences in energy supply and demand.

At the price formation level, centralized markets typically reflect these spatial differences through nodal or zonal pricing. The price differences between different nodes or regions essentially reflect the marginal value of energy at different spatial locations under given network constraints. However, at the settlement level, for reasons such as reducing market complexity, balancing policy objectives, or linking with medium- and long-term (MLT) contracts, the actual settlement price system often simplifies spatial price signals to varying degrees. Examples include the use of uniform feed-in tariffs, uniform consumer-side prices, or contract price settlements. In regional markets encompassing multiple provinces, this deviation between clearing and settlement is particularly typical.

In the inter-provincial power delivery segment, some MLT contract volumes are primarily settled based on contract prices. However, during actual dispatch and operation, when inter-provincial tie-lines become congested, the dispatching agency must adjust the generation output of each province to satisfy security constraints, resulting in significant spatial price spreads at the nodal level. Nevertheless, the congestion surplus corresponding to these price spreads belongs neither directly to the generation side nor to the consumer side; instead, it accumulates in the settlement accounts of the dispatching agency or trading center. For a single province within a regional market, a congestion allocation mechanism "decoupled" from MLT transactions can be established to promote the separate settlement of congestion fees [?]. However, at the regional market level, there is still a lack of refined methods corresponding to physical power flows for handling the congestion surplus of inter-provincial MLT contracts. This institutional contradiction is precisely the typical institutional root cause of congestion-related imbalance funds.

It is evident that settlement methods in centralized power markets cannot fully reflect the energy value behind the congestion surplus. On one hand, market clearing results explicitly reflect transmission congestion and its impact on spatial energy allocation; on the other hand, the settlement process fails to perform clearing entirely according to the spatial price signals from the clearing level.

This discrepancy between clearing and settlement lays the foundation for the subsequent generation of various settlement imbalances [?].

2.2 集中式电力市场中产生阻塞盈余的制度基础

From the perspective of power market economics, the nodal or zonal price differentials formed under transmission congestion constraints reflect the restrictive role of the transmission network, as a scarce resource, on the spatial flow of electrical energy [?]. The economic implication of these price differentials is the marginal cost or marginal benefit generated by the conversion of electrical energy between different spatial locations. In an ideal nodal pricing market, this spatial value can be naturally externalized in the form of congestion surplus, with its use and ownership clearly defined within market rules. However, in actual operation, the settlement price system may not fully adopt nodal or zonal prices—for instance, when policy-driven variables are added to consumer-side settlement prices. When spatial signals in the price are unified or partially unified, the spatial value represented by the congestion surplus is not directly reflected in the settlement results between generation and demand sides.

This settlement imbalance does not originate from forecasting errors or performance deviations of market participants; rather, it is caused by the lack of explicit settlement of the spatial value of electricity under transmission congestion conditions. At the system level, such imbalances are typically aggregated in a centralized manner, manifesting as settlement surpluses or deficits. Given that its formation mechanism is highly correlated with transmission congestion and possesses distinct spatial attributes, this paper defines it as congestion-related imbalance funds.

In summary, congestion-related imbalance funds are not an additionally introduced cost or revenue. Instead, they represent an institutional residue generated by the simplified processing of clearing results under specific settlement rules within a centralized market.

2.3 潮流追踪方法的应用环境

Regarding congestion-related settlement surpluses, various allocation and mitigation methods have been established in current market rules and practices. Common approaches include allocation based on the proportion of regional net energy consumption, allocation based on contracted energy volume, and calculations derived from price differentials and power flow across critical sections [?], [?]. These methods possess a degree of feasibility in rule-making and practical operation, contributing to the achievement of settlement balance at an aggregate level.

The aforementioned methods generally rely on several implicit assumptions during their design. First, they assume that the spatial transmission of electrical energy is aggregatable; that is, the impact of energy from the same region or the same type of market entity on the transmission network is treated as equivalent output. Second, they assume a stable correspondence between the formation of line congestion and the scale of net energy consumption in each region. In scenarios where the network structure is relatively simple and the power flow distribution is relatively uniform, these assumptions can be considered approximately valid to a certain extent.

However, with the expansion of cross-regional power transmission, the increasing complexity of power grid structures, and the continuous enrichment of market trading products, actual power flow distributions often exhibit highly non-uniform characteristics. Even if different market entities are located in the same price zone or hold the same contracted energy volume, their degree of utilization of critical lines and bottleneck sections may differ significantly. In this context, allocation methods based on aggregated metrics struggle to accurately reflect the true physical process of congestion formation, and both their scope of application and explanatory power are subject to certain limitations.

From the perspective of formation mechanisms, the generation and magnitude of congestion-related imbalance funds ultimately depend on the power flow status of specific transmission lines and sections. When a particular line reaches or approaches its capacity limit, the system must adjust the output structure of different nodes or regions, thereby triggering spatial price differences and forming corresponding settlement surpluses. Consequently, congestion-related imbalance funds have a clear physical basis, and their economic outcomes can be traced back to the actual flow paths of electrical energy within the network. Therefore, the processing of congestion-related imbalance funds can be transformed into a technical problem: under the premise of not altering the centralized market clearing results, the established power flows are reasonably decomposed to characterize the contribution of different market entities to the utilization of the transmission network. Power flow tracing methods can be employed to resolve this issue [**?**].

Classification Method for Congestion-Related Imbalance Funds Based on Power Flow Tracing

3.1 不平衡资金分类与物理原理的一致性需求

Congestion-related imbalance funds originate from the incomplete explicit settlement of the spatial value of electricity under transmission network constraints. The scale and distribution of these funds are closely related to the power flow status of specific lines and interfaces. Therefore, the classification of congestion-related imbalance funds should be based objectively on the actual operational power flow of the system, rather than relying on contractual path assumptions or regional aggregate indicators.

From a technical perspective, a reasonable classification method should satisfy at least the following requirements: (1) the classification results must reflect the actual utilization of transmission network resources by different market participants, particularly their degree of usage regarding constrained lines and critical interfaces; (2) the classification process should be based on the established clearing results of the centralized market, without altering the system's power output structure or flow distribution; and (3) the classification method must possess clear physical meaning and interpretability, avoiding the direct equivalence of economic outcomes with physical contributions.

Consequently, the problem of classifying congestion-related imbalance funds can be formulated as follows: given the system topology, nodal power injections, and line flows, how can line flows be rationally decomposed into the contribution shares of different market participants to identify the power flows directly associated with the formation of congestion?

3.2 阻塞类不平衡资金结算的制度约束条件

Compared to addressing unbalanced funds at the pricing level, power flow tracing methods rely solely on nodal injection power and line power flows under established clearing results. The output of these methods reflects the actual spatial flow of electricity within the transmission network. Therefore, it is essential to distinguish between the classification principles of unbalanced funds and their settlement methods. Settlement methods at the economic level center on price signals and capital flows; conversely, fund classification based on physical principles centers on power flows and the utilization of network resources. In this sense, the only rational way for physical classification results to enter the settlement system is as explanatory supplementary information for existing economic settlement outcomes, rather than as decision variables that alter those outcomes.

In centralized electricity markets, congestion-related unbalanced funds are typically the result of uniform clearing and settlement mechanisms. Their processing is subject to various institutional constraints, including but not limited to: requirements for settlement closure, requirements for the seriousness of contract execution, and constraints on the rational participation of market entities. Collectively, these constraints dictate that any new technical method attempting to intervene in the processing of congestion-related unbalanced funds must not undermine existing market clearing results or contractual settlement relationships. Specifically, the settlement mapping of congestion-related unbalanced funds should satisfy at least the following conditions:

1. It must not alter the established settlement scope of medium-to-long-term contracts or spot markets.
2. It must not introduce new price signals or implicit incentive mechanisms.
3. It must not cause market entities to face unpredictable financial risks.

These conditions constitute the institutional boundaries for transitioning from physical classification to settlement mapping.

3.3 潮流追踪方法的基本原理

Power flow tracing methods are a class of power flow decomposition techniques based on nodal power balance relationships. These methods aim to characterize the actual flow paths of electrical energy within a transmission network based on established power flow calculation results. The core concept involves representing line power flows as a linear superposition of power injected at various nodes. By normalizing the nodal power balance equations, a distribution coefficient matrix from nodes to lines can be constructed, allowing the power flow of any given line to be decomposed into the sum of contributions from the power injected at each node. This decomposition depends solely on the system topology and the direction of power flow, without involving price signals or economic assumptions.

(1) Generation-side Power Flow Tracing Model

Consider a power system consisting of a set of nodes N and a set of lines L. Under steady-state operating conditions, each node satisfies the power balance constraint:

Pi inj = å Pij , “i Î N j:(i , j)ÎL

This formula expresses the equivalent form of Kirchhoff' s Current Law at the power level; specifically, the power injected into any given node must equal the sum of all line power flows leaving that node. This principle serves as the physical foundation for power flow tracing. In this context, P_i^{inj} represents the active power injection at node i (where generation is positive and load is negative), and P_{ij} represents the active power flow on line (i, j).

The term P_{ij} denotes the active power flow directed from node i to node j. Let G be the set of generation nodes within the system. For any generation node $g \in G$ with an injection power of P_g, we define $a_{g,ij}$ as the contribution coefficient of generation node g to the power flow on line (i, j). Consequently, we have:

Pij = å a g ,ij Pg , ” (i , j) Î L

g ,ij

= 1, 0 £ a g ,ij £ 1

The power flow on each transmission line can be "decomposed" into the sum of contributions from individual generating units. The contribution coefficient α reflects the proportion of a specific generating unit' s contribution to the power flow of a given line. Furthermore, a normalization constraint ensures that the sum of contribution coefficients from all generating nodes to a specific line equals exactly 1. This ensures that the line flow is fully allocated among all generating nodes without any "omissions" or "double counting."

In practical implementation, these contribution coefficients are obtained by constructing a nodal power distribution matrix. By representing the power grid topology as a directed graph, the incident power at each node is allocated according to the direction of power flow and propagated downstream layer by layer. This process determines the proportion of each generating node’ s contribution to the flow on different lines. In the numerical examples provided, the contribution coefficients are calculated using the Proportional Sharing method to construct the nodal power distribution matrix.

The fundamental premise of the Proportional Sharing method is the assumption that power flowing into a node is mixed proportionally before flowing out. That is, in the power flow exiting node i, the share of power originating from each inflow path is directly proportional to the magnitude of that inflow:

a g ,ij =

Pi , j Pi , j

, if Pi , j ^{3} e

where P_{gen} represents the total power generation of the system, and ϵ is a numerical truncation threshold used to filter out minor power flows.

(2) Identification of Constrained Lines and Congestion-Related Energy In the clearing results of a centralized market, let $L_c \in L$ denote the set of constrained lines where the line flow has reached or is approaching its capacity limit. The determination of congested lines is conducted using a line loading rate threshold:

$$(i,j) \in L_c \iff P_{i,j} \geq \eta \cdot P_{i,j}^{\max}$$

where $P_{i,j}^{\max}$ is the transmission capacity limit of the line, and η is the congestion determination coefficient. When the ratio of the actual power flow of a line to its capacity limit exceeds the threshold η (e.g., 95%), the line is considered to be in a congested or near-congested state. This serves as the bridge connecting power flow tracing results with congestion identification. Furthermore, congestion can be verified by the locational marginal price (LMP) difference between the two terminal nodes of the line; these two determination methods provide mutual validation. Based on the power flow tracing results, the congestion-related power of generation node g across the set of congested lines can be defined as:

Pgcon = å a g ,ij Pij (i , j)ÎLc

This metric characterizes the actual occupancy of constrained transmission resources by generation node g; a higher value indicates that the generation node contributes more significantly to congestion. In scenarios involving multiple transaction components, the congestion-related power for transaction component c during time period t is further expressed as:

Pc ,t = å Fkc,t (i , j)ÎLct

When a generation node corresponds to multiple transaction contracts, it is necessary to further "decompose" the congestion contribution of that node among the individual contracts. This decomposition is achieved through the contract execution ratio. In this context, $F_{k,c,t}$ represents the actual power flow contribution of transaction component c to line k during time period t.

The contribution of component c to the actual power flow of line k during period t is determined by the combination of the contribution coefficient a and the contract execution ratio, expressed as: $F_{k,c,t} = \text{line\_contrib}(g_c, k)_t \times ...$

exectc Pgcon

The matrix `line_{contrib}` serves as the core output of the power flow tracing process, representing the contribution of each generation node to the power flow of every transmission line. Here, gc denotes the generation node corresponding to contract c, and $exect_{c,t}$ represents the actual execution volume of transaction component c during time period t.

Furthermore, $P_{gcon,t}$ represents the actual power output of the node during time period t. This identification process does not alter the clearing results; rather, it analyzes the established power flow state to provide a physical basis for the subsequent classified settlement of congestion-related imbalance funds. (3) Calculation of Actual Transaction Execution and Allocation of Congestion Responsibility: The actual execution volume of transaction component c during time period t is constrained by three factors: the expected execution volume, the generator output, and the demand at the load node. It is determined by taking the minimum of these three values:

exectc = min Qtc , Pgcon ,t ´ b , d n c ,t ´ g

The equation above represents the physical feasibility constraints for contract execution: the actual execution volume must not exceed the expected contract volume, the actual available output of the generator, or the actual demand of the load node. Taking the minimum value ensures that these three conditions are satisfied simultaneously. Here, Q_{tc} is the expected contract execution volume for period t (determined by the daily contract volume and the period allocation coefficient), β is the generation utilization coefficient, γ is the load matching coefficient, and d_{nload} is the actual load of load node nc during period t. Furthermore, for trading components related to medium- and long-term contracts, a minimum output coefficient can be designed to ensure the execution rate of these contracts. For a congested line $k \in L_c$, its unit congestion cost is determined by the electricity prices on both sides of the line.

Based on the above analysis, this paper proposes a classification framework for congestion-related imbalance funds based on power flow tracing. The basic process is illustrated in Figure 1

:

(1) Using the centralized market clearing results as input, obtain the nodal

Figure 1

Figure 1: Figure 1

power injections and line power flows; (2) perform generation-side tracing of the system power flow to calculate the contribution coefficients of each generating entity to the line flows; (3) identify the set of congested lines and determine the congestion-related power for each generating entity accordingly; (4) classify and label the congestion-related imbalance funds based on the proportion of congestion-related power; (5) provide a reference for the further allocation or refund of congestion-related imbalance funds while maintaining the current settlement rules.

The core advantage of this framework lies in its ability to link the economic performance of congestion-related imbalance funds with the actual spatial flow of electrical energy. It does so without making any hypothetical modifications to the price formation mechanism or market clearing logic, thereby avoiding confusion between economic implications and physical realities.

4.1 算例基本参数

The design of the case study is based on the IEEE 30-bus system, as illustrated in Figure 2 [FIGURE:2]. This system features numerous inter-regional tie-lines and exhibits significant structural differences in power sources across regions. For instance, Region A has a high proportion of hydropower and renewable energy, whereas Region C serves as a load center with substantial power demand, maintaining a consistently high volume of inter-provincial power transactions. Under this operational pattern, critical transmission corridors are prone to power flow constraints during periods of high load or peak renewable generation, leading to nodal price differentials and congestion surpluses between regions. Hydropower units are installed at buses 11 and 13. Regarding the settlement process, the case study employs a multi-market settlement framework. A minimum output constraint of 50% is imposed on hydropower units to simulate priority generation scenarios. Spot market settlement is divided into two stages: day-ahead and real-time. The relationship between the day-ahead and real-time stages is defined as follows:

Day-ahead load is a fixed given value, while real-time load is generated based on a normal distribution using the specified variance for each load bus relative to the day-ahead load. Transmission costs are incorporated into the system and are reflected in the locational marginal prices.

30 节点系统被分为 A、B、C 三个区域。结算目标为当各区域间联络线发生

When congestion occurs, the contribution of each regional node to the congestion of cross-regional tie lines is calculated to achieve a final allocation of the congestion surplus.

30 节点系统分区简图

There are three primary medium-to-long-term power transmission contracts, all of which involve transmitting electricity from Region A, which possesses surplus generation capacity, to Regions B and C. These contracts are detailed in Table 1 :

Price (Yuan

(MWh)

/MWh)

The total daily energy volume for the three contracts is 1900 MWh. Contract 1 involves a hydroelectric unit in Area A (Node 11) supplying power to a load node in Area B (Node 21), with a daily volume of 800 MWh and a contract price of 280 yuan/MWh. Contract 2 consists of a thermal power unit in Area A (Node 1) supplying power to a load node in Area C (Node 24), with a daily volume of 600 MWh and a contract price of 420 yuan/MWh. Contract 3 involves a hydroelectric unit in Area A (Node 13) supplying power to a load node in Area B (Node 15), with a daily volume of 500 MWh and a contract price of 260 yuan/MWh.

To verify the applicability of the proposed method under different operating conditions, the numerical study incorporates a peak-day operation scenario characterized by the following features: during the eight daytime hours (09:00–16:00), the load factor increases to 1.08, while it remains at 0.95 during all other periods. The distribution of contract execution is aligned with load variations, with the contract execution ratio set at 6.5% per hour during peak periods and 3% per hour during off-peak periods. This scenario effectively simulates typical operating conditions where transmission line congestion is exacerbated during peak load periods.

4.2 算例结果

Market Clearing and Contract Execution Results

Based on the MATLAB platform, the CPLEX solver was utilized to perform the optimal clearing of the 24-hour spot market.

The clearing model aims to minimize the total system power generation cost. The constraint set includes nodal power balance constraints, unit output upper and lower limit constraints, unit ramp rate constraints, and transmission line capacity constraints. The clearing results demonstrate that solutions were successfully obtained for all 24 periods, ensuring stable system operation.

Due to their relatively low marginal costs (150 RMB/MWh and 180 RMB/MWh), certain units maintain high output levels across all periods, fulfilling the system’ s base load requirements. During peak load periods (09:00-16:00), the output of thermal power units increases significantly. Notably, the

Figure 4

Figure 2: Figure 4

Figure 5

Figure 3: Figure 5

output of the thermal unit at Node 5 (with a bid price of 400 RMB/MWh) rises from 13 MW during off-peak hours to approximately 112 MW during peak hours, thereby performing the primary peak-shaving task.

The summary of contract execution is shown in

. The total daily execution volume for the three contracts is 1838.5 MWh, with an overall execution rate of 96.8%, all of which exceed the 90% compliance threshold. Specifically, Contract 2 achieved the highest execution rate at 98.7%, while Contract 1 and Contract 3 reached 95.5% and 96.4%, respectively.

It can be observed that during off-peak load periods (01:00–08:00 and 17:00–24:00), the execution volumes for each contract remained stable and close to their planned values, with execution rates consistently maintained above 95%. During peak load periods (09:00–16:00), some fluctuations in execution rates occurred due to system dispatch requirements; however, the overall performance remained at a high level. Contract 2 exhibited the most stable performance, with its execution rate reaching 99.8% during several periods, attributed to the sufficient generation capacity at generation node 1.

(2) Locational Marginal Price Analysis

Locational Marginal Price (LMP) reflects the marginal value of electrical energy at each node and serves as a critical indicator for identifying transmission line congestion.

illustrates the distribution of LMPs across all nodes during a typical time period.

As observed from the Locational Marginal Price (LMP) distribution, the system exhibits significant regional price disparities. In Area A, the LMPs at generation nodes are relatively low; specifically, the LMPs at Node 11 and Node 13, where hydropower units are located, remain around 150 RMB/MWh and 180 RMB/MWh, respectively, reflecting the marginal value of low-cost power generation resources. Conversely, the LMPs at load nodes in Area B and Area C are markedly higher. During peak hours (09:00–16:00), the LMPs at the terminal nodes of Area C (such as Nodes 25, 26, and 30) can reach 455–465 RMB/MWh. This creates a price spread of approximately 300 RMB/MWh relative to the generation nodes in Area A.

The fundamental cause of this price spread lies in the transmission congestion of inter-regional tie lines. When Region A transmits power to Regions B and C,

Figure 6

Figure 4: Figure 6

the power flow on key tie lines approaches their maximum capacity limits. This prevents low-cost electricity from being fully transmitted to load centers, forcing the system to dispatch high-cost units to meet demand. Consequently, spatial price differences emerge. This price spread serves as the economic source of congestion surplus and forms the physical basis for the generation of congestion-related unbalanced funds.

3. Line Flow and Congestion Analysis

Line flow analysis is critical for identifying the congestion status of the system.

illustrates the temporal variations in power flow across the inter-regional tie lines.

The simulation results indicate that line L16 (connecting nodes 12-13) remains in a congested state across all time periods, with power flow reaching -122.4 MW (where the negative value denotes a flow direction from node 13 to node 12). This line serves as a critical corridor for exporting hydropower from Area A to Area B. Similarly, line L13 (connecting nodes 9-11) operates at full capacity, with power flow maintained at approximately -102 MW.

The congestion on these two lines directly restricts the transmission capacity of low-cost hydropower from Area A to Area B. During peak hours (09:00–16:00), inter-regional transmission demand increases significantly, causing additional lines to approach their thermal capacity limits.

The power flow on line L41 (nodes 6-28) increases from approximately 20 MW during off-peak periods to approximately 77 MW during peak periods. Similarly, the power flow on line L9 (nodes 6-7) shifts from approximately -5 MW to approximately -97 MW. Both trends reflect the increased transmission pressure on the system under high-load conditions.

The core objective of this work is to utilize power flow tracing methods to identify the contribution of various contracts to congested lines, thereby enabling the classified settlement of congestion-related unbalanced funds. Based on a power flow tracing algorithm employing the proportional sharing principle, we calculate the contribution share of each contract to the power flow of every transmission line during each time interval.

The total amount is 68,073.37 yuan, with Contract 1 accounting for 29,376.92 yuan (43.2%), Contract 2 accounting for 20,195.89 yuan (29.7%), and Contract 3 accounting for 18,500.56 yuan (27.2%).

Blocking Responsibility (Elements)

In the context of system performance analysis and concurrency control, "blocking responsibility" refers to the identification and attribution of delays within a multi-threaded or distributed environment. When a process or thread enters a blocked state, it is critical to determine the root cause—the "responsible element" —that prevents the task from proceeding. This analysis is essential for optimizing throughput and reducing latency in complex software architectures.

Definition and Scope

Blocking responsibility elements represent the specific resources, locks, or dependencies that trigger a synchronization wait. In modern high-concurrency systems, blocking is rarely the result of a single isolated factor; rather, it often emerges from a chain of dependencies. Identifying the primary responsibility element involves tracing the execution flow to distinguish between "active waiting" (busy-waiting) and "passive waiting" (suspended by the scheduler).

Key Components of Blocking Responsibility

The analysis of blocking responsibility typically focuses on several core elements:

- **Resource Contention:** This occurs when multiple threads compete for a finite resource, such as CPU cycles, memory bandwidth, or I/O ports. The responsibility lies with the resource allocator or the high-demand process.
- **Synchronization Primitives:** The most common source of blocking involves mutexes, semaphores, and condition variables. Here, the responsibility is attributed to the thread currently holding the lock (the "holder") rather than the thread waiting for it (the "waiter").
- **External Dependencies:** In distributed systems, blocking responsibility often shifts to external service calls, database queries, or network latency. These are categorized as remote blocking elements.
- **System-Level Constraints:** This includes kernel-level interventions such as page faults, context switching overhead, or interrupt handling, where the operating system itself becomes the responsible entity.

Analytical Methodology

To accurately assign blocking responsibility, systems employ various diagnostic techniques. Call-stack analysis allows developers to see where a thread was interrupted, while wait-graph analysis helps identify deadlocks or circular dependencies. By quantifying the "blocking time" associated with each element, developers can prioritize optimizations that yield the greatest impact on overall system performance.

In conclusion, understanding blocking responsibility elements is fundamental to transitioning from reactive troubleshooting to proactive performance engineering. By isolating the specific elements that cause stalls, engineers can implement more efficient locking strategies, improve resource scheduling, and enhance the scalability of deep learning frameworks and large-scale computing systems.

Percentage (%)

Daily Execution Volume (MWh)

As indicated by the results of the congestion responsibility allocation, Contract 1 bears the largest proportion of congestion responsibility. This outcome is consistent with its physical characteristics: the generation node 11 for Contract 1 is situated at a core location within Area A. Consequently, supplying power to node 21 in Area B requires transmission through several critical tie-lines—specifically the congested lines L16 and L13—resulting in the highest contribution to system congestion. Although Contract 3 has the smallest daily execution volume (482 MWh), it still bears a corresponding share of congestion responsibility because its generation node 13 must also utilize the congested line L16 to supply power to Area B.

The congestion responsibility is highly correlated with system load levels. During peak hours (09:00-16:00), the total congestion responsibility increases significantly as rising loads lead to more frequent line congestion. Conversely, during off-peak periods (01:00-08:00 and 22:00-24:00), the congestion responsibility remains relatively low. These temporal characteristics verify that the power flow tracing method can accurately capture the dynamic process of congestion formation.

Medium- and long-term contracts typically specify a nominal transmission path (the contract path). However, during actual operation, electrical energy is distributed and flows through the network according to Kirchhoff' s laws. Consequently, the actual transmission path often deviates from the contract path. presents the results of the path analysis for each contract.

Average Path Overlap

Average Path Deviation (APD)

The results of the path analysis indicate significant discrepancies between the actual power transmission paths and the contracted paths for all three transactions. Contract 2 exhibited the highest path deviation at 90.5%, implying that over 90% of the actual transmission lines utilized were outside the scope of the contractually agreed path. Contracts 1 and 3 also showed substantial deviations of 80.9% and 86.3%, respectively. These findings demonstrate that in complex network structures, traditional congestion cost allocation methods based on contract paths have clear limitations, as they fail to accurately reflect the physical flow of electricity.

In contrast, the power flow tracing-based method proposed in this paper can accurately identify the actual transmission paths of electrical energy within the network, thereby enabling a more rational allocation of congestion responsibility. Rather than relying on contract path assumptions, this approach is based on physical power flow calculation results, providing clear physical significance and interpretability.

Focusing on the issue of congestion-related imbalance funds caused by transmission congestion in centralized electricity markets, this paper constructs a classification and analysis framework based on power flow tracing, starting from the formation mechanism and physical essence of these funds. The findings are subsequently verified through numerical examples.

The mechanism underlying the generation of congestion-related imbalance funds is the spatial value deviation between clearing results and settlement criteria. Specifically, within an institutional context where unified clearing and simplified settlement coexist, the spatial marginal value reflected by nodal price differentials is not fully and explicitly settled. Consequently, the economic rent corresponding to transmission congestion is deposited as imbalance funds in the form of a systemic surplus. These funds possess a clear physical foundation, and their scale is directly correlated with the power flow status of constrained transmission lines.

Power flow tracing methods establish an interpretable mapping between congestion rents and physical power flows. Without altering established market clearing results, these methods decompose line flows from the generation side to identify the actual share of constrained transmission resources occupied by different market participants. This allows for a quantitative characterization of power flows related to congestion. Furthermore, this approach maintains a clear boundary between physical decomposition and economic settlement, ensuring that economic outcomes do not interfere with physical causality.

The numerical examples presented in this paper demonstrate that the allocation of congestion responsibility is not simply a function of contract energy volume. Instead, it is primarily determined by the degree to which a specific transaction contributes to the power flow on critical bottleneck lines. This responsibility exhibits significant dynamic characteristics over time, correlating strongly with system load levels and the operational status of line constraints. These findings validate the physical consistency and temporal traceability of the proposed method.

In complex network structures, the actual physical path of power flow differs significantly from the paths stipulated in bilateral contracts. Relying solely on contractual paths to assign congestion responsibility fails to accurately reflect the true utilization of transmission resources. The power flow tracing method effectively overcomes this limitation, enhancing both the objectivity and the interpretability of the classification of congestion-related imbalance funds.

In summary, this paper establishes a classification and analysis framework for congestion-related imbalance funds based on the principle of physical mechanism consistency. By utilizing the power flow tracing method, it is possible to provide a physically consistent classification and explanation of congestion-related funds while maintaining the existing market-clearing results. This approach enhances the rationality of settlement responsibility allocation. The proposed method offers significant reference value for regional electricity markets characterized by large-scale inter-provincial transactions, a high proportion of medium- and long-term contracts, and prominent transmission corridor constraints. Furthermore, it provides technical support for the refined management of imbalance funds and the optimization of settlement mechanisms within regional electricity markets.

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Development Strategy for China’ s High-End Scientific Instruments Toward 2035

Abstract

High-end scientific instruments serve as the “multipliers” of scientific research and the “cornerstones” of industrial development. They represent a strategic high ground in international scientific and technological competition. This paper systematically analyzes the current development status and challenges of high-end scientific instruments in China, identifying key gaps in original innovation, core components, and market competitiveness. By benchmarking against global leaders and considering the evolving landscape of scientific research, we propose a development strategy for China’ s high-end scientific instruments toward 2035. This strategy emphasizes a “dual-track” approach: achieving self-reliance in core technologies while fostering a robust innovation ecosystem. We outline priority areas including advanced microscopy, high-resolution mass spectrometry, and quantum-based measurement systems. Finally, policy recommendations are provided to strengthen the synergy between industry, academia, and research institutes, optimize the talent cultivation system, and improve the evaluation mechanism for instrument development.

1. Introduction

Scientific instruments are the fundamental tools for human exploration of the unknown and the primary drivers of technological progress. In the current era of rapid scientific evolution, high-end scientific instruments have become indispensable for breakthroughs in frontier fields such as quantum information, life sciences, and deep-space exploration. For a major scientific power, the ability to independently develop and manufacture high-end instruments is a critical indicator of national strength and technological sovereignty.

Historically, China has made significant progress in the instrument industry. However, compared to the world’ s leading levels, there remains a prominent structural contradiction: while the scale of the industry is large, the high-end market is heavily dependent on imports. This “bottleneck” (chokehold) problem not only limits the autonomy of China’ s scientific research but also poses potential risks to national security and industrial stability. Therefore, formulating a long-term development strategy toward 2035 is of paramount importance.

2. Current Status and Gap Analysis

2.1 Global Development Trends The global scientific instrument market is currently characterized by high concentration and rapid technological iteration. Leading multinational corporations maintain their dominant positions

Figure 3

Figure 5: Figure 3

Figure 7

Figure 6: Figure 7

through continuous R&D investment and aggressive mergers and acquisitions. Key trends include: - **Intelligence and Automation:** The integration of artificial intelligence (AI) and machine learning (ML) is transforming instruments from simple measurement tools into intelligent systems capable of autonomous data analysis and experimental optimization. - **Extreme Precision

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Figures

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