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Enhancement of Generator Contribution Allocation Using Power Tracing Approaches in Deregulated Power Systems

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Transmission open access in deregulated power systems requires a transparent and physically consistent allocation of transmission usage among market participants. A persistent challenge is the accurate quantification of individual generator contributions to transmission line flows, particularly in meshed networks where loop flows and counterflows are present. Conventional power tracing–based allocation methods are attractive due to their conceptual simplicity; however, their capability to represent counterflow effects and generator responsibility remains limited. This paper presents a comparative methodological study of generator contribution allocation using three representative power tracing approaches: the Bialek proportional sharing method, the Extended Incidence Matrix (EIM) formulation, and the Generalized Generation Distribution Factor (GGDF) based sensitivity method. A unified analytical framework based on DC power flow is developed to ensure a consistent and fair comparison under a deregulated transmission open access environment. The proposed framework is evaluated on a standardized 6-bus test system under both normal operating conditions and counterflow scenarios. Simulation results show that proportional sharing–based and EIM approaches yield comparable and stable allocation results under normal conditions but assign only non-negative contributions. In contrast, the GGDF-based method is able to produce both positive and negative contribution values, explicitly capturing counterflow effects and identifying generators that relieve line loading. The main contribution of this study is to clarify the methodological behavior of different power tracing approaches and to enhance the interpretability of GGDF-based allocation for practical transmission usage assessment. The findings provide useful insights for the selection of appropriate allocation techniques in transmission pricing, congestion management, and market settlement applications.

Keywords: Power tracing, generator contribution allocation, transmission open access, deregulated power systems, GGDF.

1. INTRODUCTION

The deregulation and restructuring of electric power systems have fundamentally transformed the operational and economic framework of modern electricity networks. Under the Transmission Open Access (TOA) paradigm, generation, transmission, and consumption entities are unbundled, allowing multiple market participants to access shared transmission infrastructure in a non-discriminatory manner. Although this restructuring promotes competition and market efficiency, it also introduces significant challenges related to fair transmission usage allocation and cost responsibility determination among generators and loads [1], [2].

In deregulated electricity markets, transmission networks operate as common carriers supporting bilateral and multilateral power transactions. Consequently, transmission pricing and settlement mechanisms must accurately reflect the actual physical utilization of transmission assets. A fundamental requirement in this context is the ability to quantify how much each generator contributes to power flows on individual transmission lines. Such information is essential for equitable cost recovery, congestion management, and the prevention of cross-subsidization among market participants [3].

Assigning generator responsibility in meshed transmission networks is inherently complex. Due to the physical laws governing power flows, electrical power injected by a generator does not follow contractual paths but is distributed over multiple transmission corridors. Moreover, loop flows and counterflows may occur, whereby certain generator injections can reduce loading on congested lines. These phenomena further complicate the interpretation of transmission usage and challenge traditional allocation mechanisms [4].

To address these challenges, numerous transmission usage allocation approaches have been proposed. These approaches can generally be classified into sensitivity-based techniques, which rely on linearized relationships between injections and line flows, and power tracing–based techniques, which explicitly track the propagation of power from generators through the network to loads and transmission lines. Among these, power tracing approaches have attracted considerable attention due to their intuitive physical interpretation and suitability for TOA-based transmission pricing frameworks [5].

Despite their advantages, existing power tracing methods exhibit notable limitations. Classical proportional sharing approaches are computationally efficient and easy to implement, but they allocate only non-negative contributions and therefore fail to explicitly represent counterflow effects. Conversely, sensitivity-based formulations capable of capturing negative contributions may suffer from limited interpretability when directly applied to practical transmission pricing and settlement problems [6]. These limitations indicate the need for a clearer methodological understanding of how different tracing approaches allocate generator responsibility under diverse network conditions.

Recent developments in electricity market settlement further emphasize the importance of accurately linking physical power flows with financial transactions. Studies employing power flow tracing in settlement frameworks demonstrate that inappropriate interpretation of generator contributions can lead to distorted price signals and inefficient congestion revenue allocation [7]. This reinforces the necessity of robust and interpretable generator contribution allocation methods as a foundation for fair transmission usage pricing.

Motivated by these observations, this paper focuses on a methodological comparative evaluation of generator contribution allocation using representative power tracing approaches in deregulated power systems. Rather than proposing a new tracing algorithm, this study aims to clarify the methodological behavior of different tracing techniques and to improve the interpretability of sensitivity-based allocation results within a unified analytical framework.

Although numerous power tracing and sensitivity-based allocation methods have been reported in the literature, there is still a lack of a unified and clearly structured comparison that explains how different approaches assign generator responsibility in meshed transmission networks, particularly under loop flow and counterflow conditions. In addition, the practical interpretation of GGDF-based allocation results for transmission usage assessment remains insufficiently clarified.

Accordingly, this study aims to develop a unified DC power flow–based analytical framework for comparing representative generator contribution allocation methods. Specifically, the study systematically compares the Bialek proportional sharing method, the Extended Incidence Matrix (EIM) method, and the GGDF-based sensitivity approach in terms of their generator contribution allocation characteristics. Furthermore, this work investigates how each method allocates generator contributions under normal operating conditions as well as under counterflow scenarios. Another objective is to enhance the physical interpretation of GGDF-based allocation results with respect to generator responsibility and transmission usage. Ultimately, this study seeks to provide methodological insights that support the selection of appropriate allocation techniques for transmission pricing, congestion management, and settlement applications in deregulated power systems.

2. LITERATURE REVIEW

Early studies on transmission pricing emphasized the importance of aligning economic signals with physical power flows in order to ensure efficient network utilization and appropriate cost recovery [7], [8]. In deregulated electricity markets, inappropriate allocation of transmission usage may lead to cross-subsidization among generators and loads, thereby distorting investment signals and dispatch decisions.

Various transmission usage allocation schemes have been proposed, ranging from postage-stamp pricing to marginal and flow-based approaches. While simple pricing mechanisms are attractive due to their ease of implementation, they fail to reflect the actual utilization of transmission assets in meshed transmission networks [9]. Consequently, flow-based allocation methods, which explicitly account for network constraints and power flow physics, have gained increasing attention.

Power tracing techniques were developed to determine how electrical power injected by generators propagates through the network to loads and transmission lines. Among these, the proportional sharing principle represents one of the most widely adopted foundations. This principle assumes that power leaving a bus carries the same proportional composition as the power entering that bus. Based on this concept, Bialek proposed upstream and downstream tracing algorithms for allocating generator and load contributions to network flows [10], [11].

Proportional sharing–based methods offer intuitive physical interpretation and low computational burden, making them attractive for transmission pricing and congestion cost allocation under open access environments [12]. However, these methods inherently assign only non-negative contributions and therefore cannot explicitly represent counterflow effects, where certain generator injections reduce loading on specific transmission lines.

Graph-theoretic tracing approaches were introduced by Kirschen and co-authors, in which the network is decomposed into domains supplied by identical sets of generators [13], [14]. Although this method provides useful insight into generator–load relationships, it assumes uniform contribution within each domain and may exhibit limited accuracy in highly meshed networks with complex power flow patterns.

To overcome some limitations of proportional sharing, matrix-based tracing formulations have been proposed. The Extended Incidence Matrix (EIM) approach extends the conventional network incidence matrix to analytically represent generator-to-line and generator-to-load relationships [15]. This formulation enables direct computation of contribution factors using linear algebraic expressions derived from power flow solutions.

The EIM-based approach avoids explicit proportional sharing assumptions and offers a compact mathematical formulation suitable for analytical studies. Nevertheless, in practice, EIM-based allocation often produces results similar to classical proportional tracing when applied to linearized DC power flow models [16]. Moreover, like proportional sharing methods, its ability to explicitly capture counterflow effects remains limited.

Sensitivity-based allocation methods evaluate generator responsibility by analyzing how incremental changes in generator injections affect transmission line flows. Generalized Generation Distribution Factors (GGDFs) extend the conventional PTDF concept by directly linking generator injections to line flow variations [17]. Unlike proportional tracing and EIM-based approaches, GGDF-based formulations can yield both positive and negative contribution values, thereby capturing counterflow phenomena in meshed transmission networks.

Although GGDF-based methods offer improved physical consistency, several studies report that their results are often difficult to interpret for transmission pricing and cost allocation purposes, because raw sensitivity values do not directly translate into intuitive responsibility shares [18]. As a result, additional interpretation or normalization procedures are required for practical applications.

Recent research on electricity market settlement further highlights the importance of linking financial transactions with physical power flows. Transaction-based settlement frameworks employing power flow tracing demonstrate improved transparency in congestion surplus allocation and imbalance settlement [19]. These studies emphasize that inaccurate or poorly interpreted generator contribution allocation can lead to distorted market signals and inefficient congestion revenue distribution.

The increasing use of power tracing in settlement applications reinforces the need for allocation methods that are not only physically accurate but also methodologically interpretable. In particular, the ability to clearly explain the role of counterflows and generator responsibility is critical for regulatory acceptance and practical implementation in deregulated markets [20].

From the reviewed literature, it is evident that substantial progress has been made in the development of generator contribution allocation methods. Nevertheless, existing approaches still exhibit complementary strengths and limitations that motivate further methodological clarification and structured comparison. Proportional sharing approaches offer simplicity and intuitive interpretation, while matrix-based formulations provide analytical compactness. Sensitivity-based GGDF methods improve physical consistency by capturing counterflow effects.

However, the following research gaps remain:

1. Existing studies often investigate individual allocation methods in isolation, with limited unified comparative evaluation under a common analytical framework.
2. While GGDF-based formulations can represent counterflows, their practical interpretation for transmission usage allocation remains insufficiently clarified.
3. There is a lack of concise methodological studies that explicitly link tracing behavior to generator responsibility under transmission open access conditions.

This paper addresses these gaps by providing a unified comparative methodological analysis of representative power tracing approaches and by enhancing the interpretation of GGDF-based allocation results for practical transmission usage applications.

3. METHOD

This section presents the methodological framework used to evaluate generator contribution allocation in deregulated power systems. The methodology is structured into three main components: the DC power flow model, power tracing using proportional sharing and matrix-based formulations, and sensitivity-based allocation using the GGDF approach. This structure enables a consistent and transparent comparison among representative tracing methods.

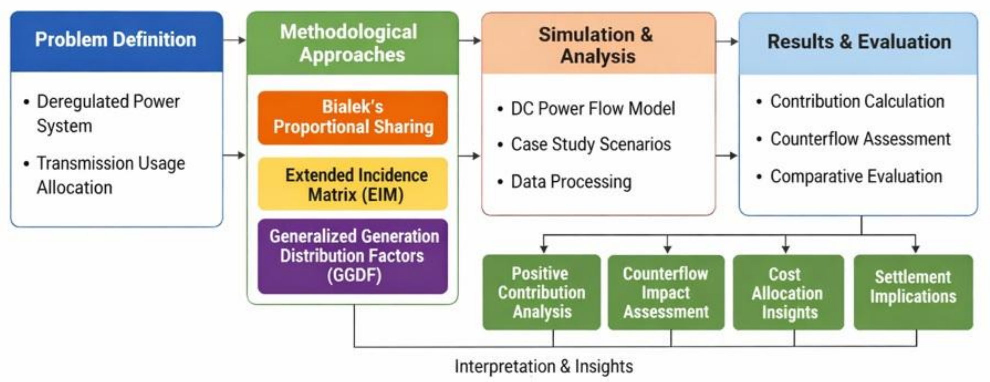


Figure 1. Overall methodological framework for generator contribution allocation using power tracing approaches

A. DC Power Flow Model

To ensure analytical transparency and computational efficiency, the proposed methodology is based on the DC power flow model, which is widely adopted in transmission pricing and allocation studies. The DC power flow assumes:

1. Bus Voltage Magnitudes are Fixed at 1.0 P.U.,
2. Line Resistances and Reactive Power Flows are Neglected,
3. Voltage Angle Differences are Small.

Under these assumptions, the active power flow on a transmission line connecting bus *i* and bus *j* is expressed as

$$P_{ij} = \frac{1}{X_{ij}}(\theta_i - \theta_j) \qquad (1)$$

where X_{ij} is the line reactance, and θ_i and θ_j are the voltage angles at buses *i* and *j*, respectively.
The nodal power balance equation at bus *i* is given by

$$P_i = \sum_{j\in\Omega_i} \frac{1}{X_{ij}}(\theta_i - \theta_j) \qquad (2)$$

where P_i represents the net active power injection at bus *i*, and Ω_i denotes the set of buses connected to bus *i*. Solving (2) for all buses yields the voltage angle vector, from which line flows are obtained using (1).

B. Power Tracing Based on Proportional Sharing (Bialek Method)

The proportional sharing principle assumes that power flowing out of a bus carries the same proportional composition as the power flowing into that bus. Based on this principle, the Bialek upstream tracing method is employed to determine generator contributions to transmission line flows.

Let P_{in} denote the total inflow to bus *i*, consisting of generator injections and incoming line flows. The fraction of power from generator *g* contributing to the outflow of bus *i* is defined as

$$\alpha_{ig} = \frac{P_{ig}}{P_{in}} \qquad (3)$$

where P_{ig} is the power contribution of generator *g* at bus *i*. The contribution of generator *g* to the flow on line *(i,j)* is then given by

$$P_{ij}^{(g)} = \alpha_{ig} \cdot P_{ij} \qquad (4)$$

By applying (3) – (4) recursively across the network, the contribution of each generator to every transmission line can be obtained. While this method is intuitive and computationally efficient, it allocates only non-negative contributions and does not explicitly represent counterflow effects.

C. Extended Incidence Matrix (EIM) Formulation

To provide an alternative analytical representation, the Extended Incidence Matrix (EIM) approach is adopted. This method extends the conventional network incidence matrix to incorporate generator and load injections.

Let A denote the node–branch incidence matrix of the network. The extended incidence matrix A_e is constructed by augmenting A with generator injection terms. The relationship between nodal injections and line flows can be expressed as

$$\mathbf{P}_l = B_l A_e \mathbf{P}_n \tag{5}$$

where $\mathbf{P}_l$ is the vector of line flows, B_l is the diagonal matrix of line susceptances, and $\mathbf{P}_n$ represents the vector of nodal power injections.

Generator contribution factors are obtained by decomposing $\mathbf{P}_n$ into individual generator components. The contribution of generator *g* to line *l* is then computed analytically as

$$P_l^{(g)} = \Gamma_{lg} \cdot P_g \tag{6}$$

where Γ_{lg} denotes the EIM-based allocation factor. Although the EIM formulation avoids explicit proportional sharing assumptions, its allocation results often resemble those of proportional tracing under linearized power flow conditions.

D. Sensitivity-Based Allocation Using GGDF

The Generalized Generation Distribution Factor (GGDF) approach evaluates generator contributions based on sensitivity analysis. GGDFs quantify the incremental impact of generator injections on line flows.

The GGDF of generator *g* on line *l* is defined as

$$\mathrm{GGDF}^{lg} = \frac{\partial P_l}{\partial P_g} \tag{7}$$

Using the DC power flow model, GGDFs can be derived from the system susceptance matrix and the network topology. The contribution of generator *g* to the flow on line *l* is then given by

$$P_l^{(g)} = \mathrm{GGDF}^{lg} \cdot P_g \tag{8}$$

Unlike proportional tracing methods, GGDF-based allocation can yield both positive and negative values, thereby explicitly capturing counterflow effects. However, raw GGDF values do not directly indicate generator responsibility shares, motivating the need for enhanced interpretation.

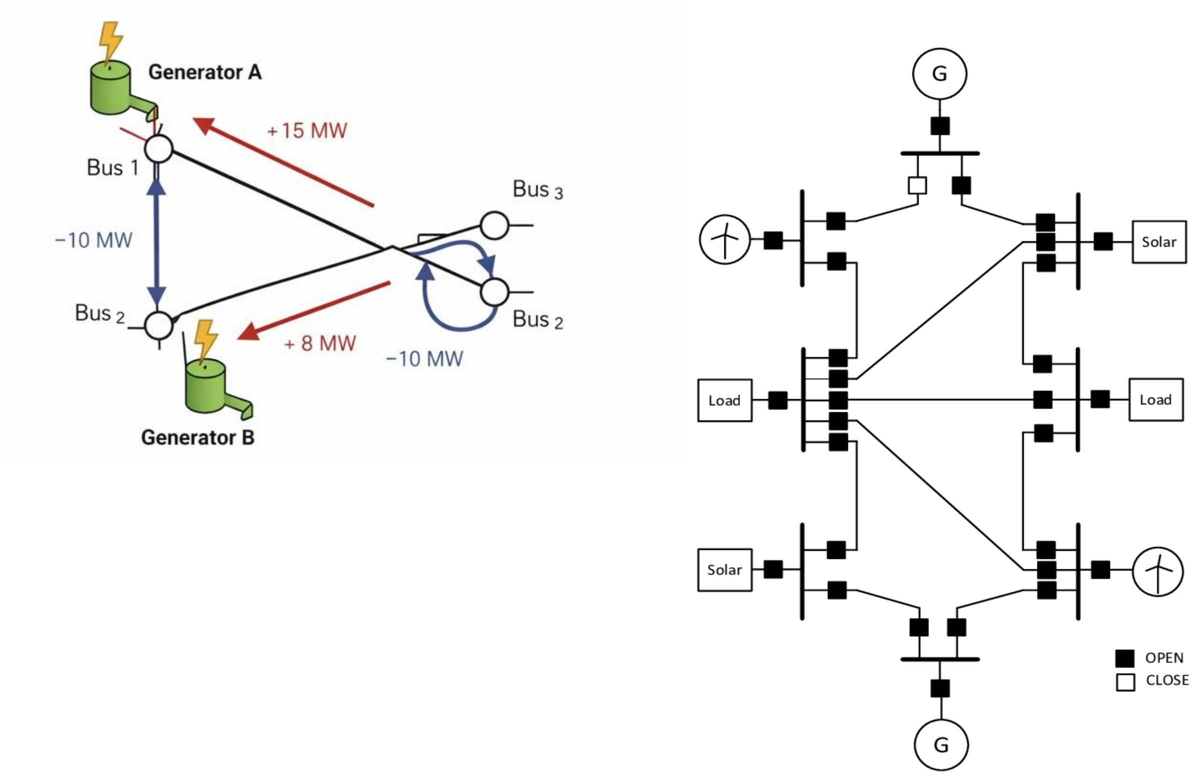


Figure 2. Conceptual illustration of generator contribution and counterflow in a meshed transmission network.

E. Interpretation of GGDF-Based Generator Responsibility

To improve the practical interpretability of GGDF-based results, generator responsibility is evaluated by examining the relative magnitude and sign of $P_l^{(g)}$across generators. Positive values indicate that a generator contributes to increasing the loading of a transmission line, while negative values represent counterflow contributions that relieve line loading.

For comparative analysis, the absolute contribution values are normalized with respect to total line flow magnitude, yielding a relative responsibility index:

$$R_{lg} = \frac{P_l^{(g)}}{\sum_g |P_l^{(g)}|} \qquad (9)$$

This normalized index facilitates consistent comparison between proportional tracing and sensitivity-based methods, while preserving the physical significance of counterflow effects.

F. Scope and Limitations of the Research Procedure

The proposed research procedure is designed to support a transparent and consistent methodological comparison of generator contribution allocation approaches rather than to provide a comprehensive operational assessment of large-scale power systems. Accordingly, several modeling assumptions and simplifications are adopted.

First, the study employs the DC power flow model, which neglects transmission losses, reactive power flows, and voltage magnitude variations. Although these simplifications limit the ability to represent detailed AC network phenomena, the DC model is widely accepted in transmission pricing, congestion analysis, and allocation studies because it preserves the dominant linear relationship between nodal power injections and line flows. This property makes it particularly suitable for isolating and comparing the fundamental allocation behavior of different tracing methods under identical conditions.

Second, the validation is performed using a standardized 6-bus test system. As discussed in Section IV.A, the use of a small benchmark system is motivated by the need for analytical transparency and ease of interpretation. The simplified network structure allows the effects of loop flows and counterflows on generator contribution allocation to be clearly identified without obscuring influences from large-scale network complexity.

Third, two operating scenarios are considered, namely a base case and a counterflow case. These scenarios are selected to represent typical and stressed operating conditions that are sufficient to reveal the essential differences between proportional sharing–based and sensitivity-based allocation methods. The objective is not to exhaustively enumerate all possible operating conditions, but to demonstrate the methodological characteristics of each approach under representative cases.

The extension of the proposed framework to AC power flow models, larger test systems (e.g., IEEE 30-bus or IEEE 118-bus), and a broader range of operating scenarios constitutes an important direction for future research.

4. RESULTS AND DISCUSSION

A. Test System and Simulation Setup

The proposed methodological comparison is validated using a standardized 6-bus test system, which is widely employed in transmission pricing and power flow tracing studies due to its simplicity and analytical transparency. The selection of a standardized 6-bus test system is motivated by the methodological nature of this study. The primary objective is not to evaluate large-scale computational performance, but to clearly illustrate and compare the fundamental allocation behavior of different power tracing approaches under identical operating conditions. A small and well-known test system provides high analytical transparency, allowing the impact of loop flows and counterflows on generator contribution allocation to be examined and interpreted without obscuring effects from network size or topological complexity.

Moreover, the adopted 6-bus system has been widely used in transmission pricing and power flow tracing studies as a benchmark for methodological validation and conceptual demonstration. The simplified structure enables direct verification of allocation results and facilitates clear comparison among proportional sharing–based, matrix-based, and sensitivity-based approaches.

Nevertheless, the authors acknowledge that practical implementation in real-world transmission networks involves larger and more complex systems, such as IEEE 30-bus or IEEE 118-bus test systems. The extension of the proposed comparative framework to large-scale networks is therefore identified as an important direction for future work.

Two operating scenarios are considered to highlight the characteristics of different power tracing approaches:

1. Base Case: Normal operating condition without significant loop flow effects.
2. Counterflow Case: Modified generation dispatch designed to introduce counterflow on selected transmission lines.

This setup enables a clear examination of generator contribution allocation behavior under both conventional and counterflow-dominated conditions.

B. Generator Contribution Allocation Results

Table I summarizes the generator contribution to a selected transmission line (Line L2–L4) under the base operating condition, as obtained using the Bialek proportional sharing method, the Extended Incidence Matrix (EIM) approach, and the GGDF-based formulation.

Table 1. Generator Contribution to Line L2–L4 (Base Case)

Generator	Bialek Method (%)	EIM Method (%)	GGDF Method (%)
G1	46.2	44.8	41.5
G2	33.5	35.1	36.8
G3	20.3	20.1	21.7

As shown in Table 1, all three methods produce comparable allocation results under the base case. The proportional sharing–based Bialek method and the EIM approach yield nearly identical contribution patterns, reflecting their similar treatment of power flow propagation under linear operating conditions. The GGDF-based results also exhibit consistency, with minor variations due to sensitivity-based allocation.

C. Impact of Counterflow on Generator Contribution

To further evaluate methodological differences, a counterflow scenario is introduced by increasing the output of Generator G3 while reducing the output of Generator G1. Table 2 presents the resulting generator contribution allocation to the same transmission line.

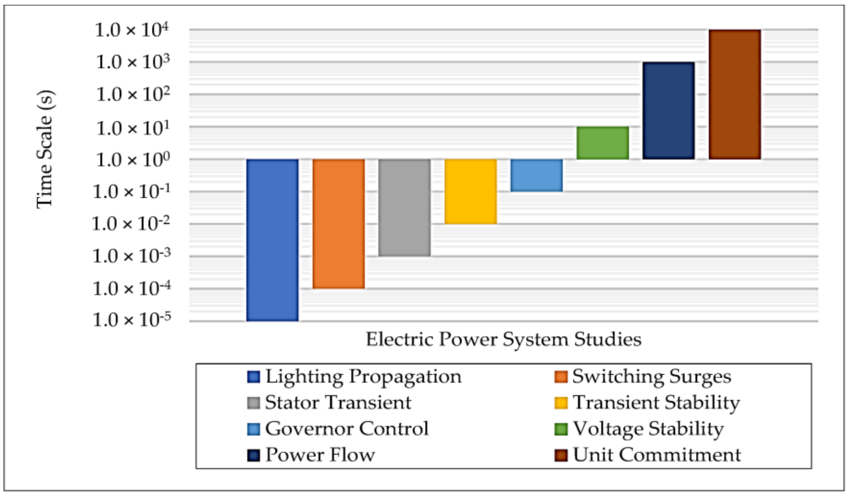
Table 2. Generator Contribution to Line L2–L4 (Counterflow Case)

Generator	Bialek Method (%)	EIM Method (%)	GGDF Method (%)
G1	39.4	38.7	28.6
G2	34.1	35.4	42.1
G3	26.5	25.9	–10.7

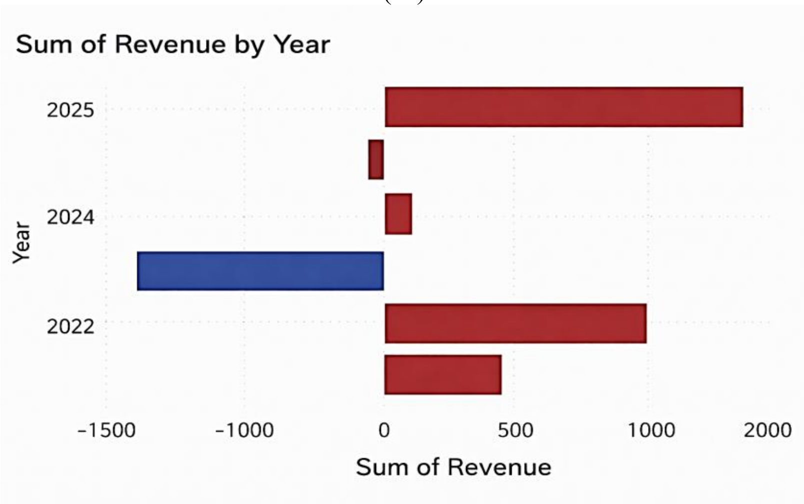
It is evident from Table 2 that the Bialek and EIM methods continue to allocate only positive contributions, even under counterflow conditions. In contrast, the GGDF-based method assigns a negative contribution to Generator G3, indicating that its injection reduces the loading on Line L2–L4. This negative contribution explicitly captures the counterflow effect, which cannot be represented by proportional sharing–based approaches.

D. Comparative Visualization of Allocation Results

To further clarify the impact of counterflow on generator contribution allocation, Fig. 3 presents a comparative visualization of generator contributions to the selected transmission line under the counterflow operating condition. The figure compares the allocation results obtained using proportional sharing–based methods (Bialek and Extended Incidence Matrix) and the GGDF-based sensitivity formulation using a consistent graphical representation.



(3a)



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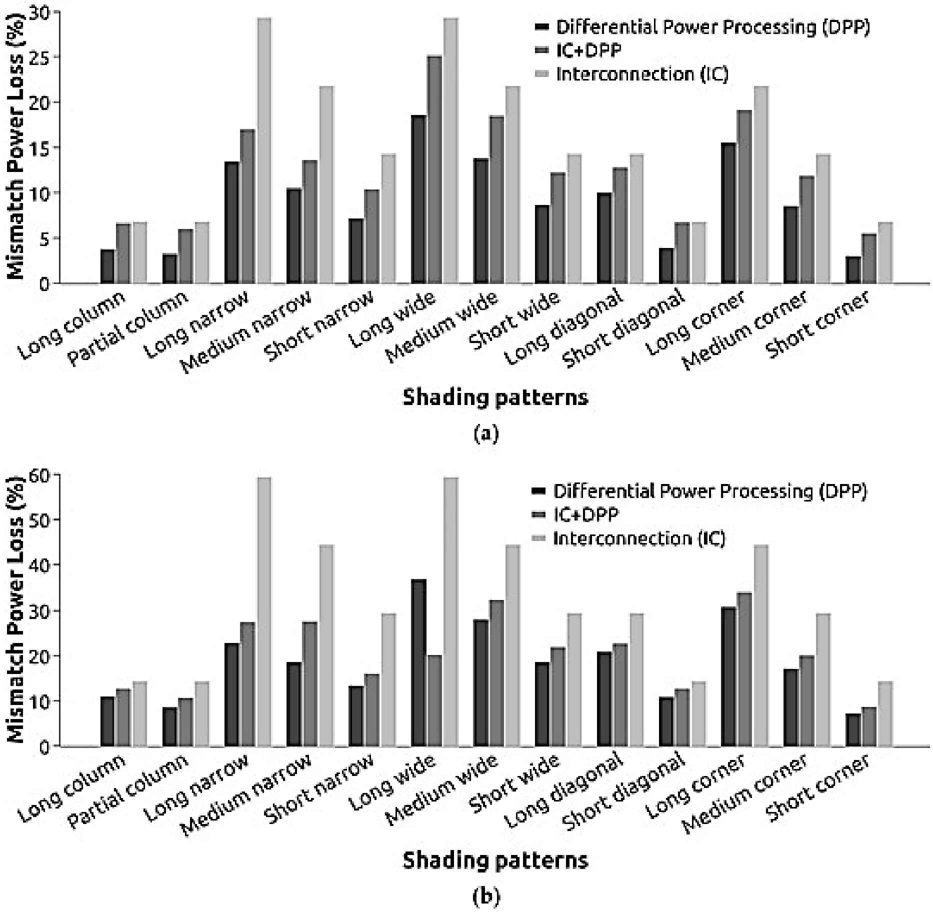

(3c)

Figure 3. Comparative visualization of generator contribution allocation under counterflow conditions using different power tracing methods

(a) Bialek proportional sharing method, (b) Extended Incidence Matrix (EIM) method, and (c) GGDF-based sensitivity method.

As shown in Fig. 3(a) and Fig. 3(b), the Bialek and EIM methods assign only positive contribution values to all generators, reflecting their inherent limitation in representing counterflow effects. In contrast, Fig. 3(c) shows that the GGDF-based formulation assigns a negative contribution to Generator G3, explicitly indicating that its power injection reduces the loading of Line L2–L4. This comparative visualization clearly highlights the fundamental methodological difference between proportional tracing approaches and sensitivity-based allocation methods, particularly in their ability to capture counterflow phenomena in meshed transmission networks.

The results demonstrate that methodological differences become significant under counterflow conditions, even when all methods are based on the same DC power flow solution. Proportional sharing and EIM approaches provide stable and intuitive allocation results; however, their inability to represent negative contributions may lead to an overestimation of generator responsibility on congested lines.

In contrast, the GGDF-based method offers a more physically consistent representation of generator responsibility by explicitly capturing counterflow effects. From a transmission usage and pricing perspective, this distinction is crucial. Generators that reduce line loading should not be penalized under transmission usage allocation schemes, and sensitivity-based formulations provide a mechanism to reflect this behavior.

Nevertheless, the GGDF-based approach requires careful interpretation, as raw sensitivity values may be counterintuitive to market participants. The normalized responsibility representation discussed in Section III facilitates meaningful comparison with proportional tracing results while preserving the physical significance of counterflows.

Overall, these findings confirm that no single tracing method is universally superior. Instead, the choice of allocation technique should depend on the intended application. Proportional sharing–based methods remain suitable for simplified pricing schemes, whereas GGDF-based formulations offer enhanced insight for congestion-aware transmission usage and settlement applications.

E. Practical Implications for Transmission Pricing and Market Settlement

The observed differences between proportional sharing–based and GGDF-based allocation methods have important practical implications for transmission pricing, economic incentives, and fairness among market participants. In proportional sharing and EIM-based approaches, all generators are assigned strictly non-negative contributions to transmission line flows. Consequently, generators are always interpreted as users of transmission capacity, regardless of whether their injections increase or relieve congestion. In practical pricing frameworks, this characteristic may lead to generators that actually reduce line loading being charged for transmission usage, thereby distorting economic signals.

In contrast, the GGDF-based formulation explicitly produces negative contribution values when a generator injection causes counterflow and reduces the loading of a transmission line. From a market perspective, this behavior is physically consistent and economically meaningful. Generators that alleviate congestion contribute positively to system security and operational efficiency and therefore should not be penalized in transmission usage allocation. Sensitivity-based allocation thus provides a mechanism to reflect the true impact of generator injections on network utilization.

These differences directly influence pricing signals. Under proportional sharing–based allocation, congestion-related charges are distributed only according to positive usage shares, potentially overestimating the responsibility of some generators and underestimating the beneficial role of others. As a result, investment and dispatch decisions may be biased, since generators do not receive proper economic incentives to locate or operate in a manner that mitigates congestion.

From the perspective of market fairness, GGDF-based allocation supports a more balanced treatment of market participants by distinguishing between generators that aggravate congestion and those that relieve it. However, the practical use of GGDF-based results requires careful interpretation, as raw sensitivity values may not be intuitive to system operators or market participants. The normalized responsibility index adopted in this study facilitates comparison with proportional tracing results while preserving the physical meaning of negative and positive contributions.

Overall, the results indicate that proportional sharing–based methods remain suitable for simplified and transparent pricing schemes where interpretability and computational simplicity are prioritized. Conversely, GGDF-based allocation is more appropriate for congestion-aware transmission pricing and settlement frameworks in which accurate representation of counterflow effects and economic efficiency are critical. The choice of allocation method should therefore be aligned with the specific objectives of the market design and regulatory framework.

5. CONCLUSION

This paper has presented a methodological comparison of generator contribution allocation using representative power tracing approaches in deregulated power systems. The study focused on three widely referenced methods namely the Bialek proportional sharing method, the Extended Incidence Matrix (EIM) formulation, and the Generalized Generation Distribution Factor (GGDF) based approach evaluated under a unified DC power flow framework. The results demonstrate that under normal operating conditions, proportional sharing based and matrix-based methods yield comparable and stable allocation outcomes. However, when counterflow conditions are introduced, significant methodological differences emerge. Proportional tracing and EIM approaches allocate only positive contributions, thereby failing to explicitly represent generator injections that relieve transmission line loading. In contrast, the GGDF-based formulation successfully captures both positive and negative contributions, providing a more physically consistent representation of generator responsibility in meshed networks. The comparative analysis further highlights that while GGDF-based allocation offers enhanced insight into counterflow effects, its practical application requires careful interpretation. The normalized responsibility representation adopted in this study facilitates meaningful comparison with proportional tracing results and improves the interpretability of sensitivity-based allocation outcomes for transmission usage assessment. Overall, the findings confirm that no single power tracing method is universally optimal for all transmission pricing and allocation applications. Proportional sharing–based approaches remain suitable for simplified and transparent allocation schemes, whereas GGDF-based formulations are more appropriate for congestion-aware transmission usage and settlement frameworks. The methodological insights provided in this paper support informed selection of allocation techniques under transmission open access environments. Future work may extend the proposed analysis to AC power flow models, incorporate transmission losses and reactive power effects, and investigate the implications of generator contribution allocation in large-scale networks and real-time market settlement mechanisms. From a regulatory and operational perspective, the results of this study suggest that the selection of a generator contribution allocation method should be aligned with the objectives of the Transmission Open Access (TOA) policy framework. For regulatory environments that prioritize transparency, simplicity, and ease of implementation, proportional sharing–based methods or EIM-based formulations remain appropriate due to their intuitive interpretation and stable allocation behavior. However, for TOA policies that emphasize congestion-aware pricing, economic efficiency, and accurate reflection of physical network usage, GGDF-based sensitivity allocation is more suitable, as it explicitly captures counterflow effects and distinguishes between generators that aggravate congestion and those that relieve it. Accordingly, regulators may consider adopting proportional tracing approaches for basic transmission usage charging, while employing GGDF-based allocation as a complementary tool for congestion-related pricing, settlement, and incentive design. System operators can use sensitivity-based allocation results to better identify congestion-relieving resources and to support operational and planning decisions. These recommendations provide practical guidance for integrating generator contribution allocation methods into TOA-based transmission pricing and settlement frameworks.

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