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A COMPREHENSIVE REVIEW ON TRANSMISSION LOSS ALLOCATION-RESTRUCTURED POWER SYSTEMS

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ABSTRACT:

Restructuring of electricity supply industry introduced the concept of deregulation. The introduction to various transmission losses and charge allocation systems is discussed in this study. Starting with an overview, the basic elements of the power system (structure, model and operation) are described to give an introduction for better understanding of deregulation concept. After thorough literature, based on research area this paper presents traditional based, conventional tracing and computational Intelligence for allocating losses charges are classified based on their guiding principles and formulation approaches. Transaction-based approaches provide simplicity and convenience of implementation in real-world issues. Conventional tracing techniques offer accurate results, but they still rely on certain concepts to make tracing easier. The adaptability of computational intelligence techniques has increased their standing relative to other techniques.
Index Terms---Power System Elements, Losses Charge Allocation Methods, MW-mile method, TGLDF method.

1. INTRODUCTION:

In a deregulated environment, participants collaborate to create a competitive electricity market, in contrast to vertically integrated systems. Restructuring of market has divided the main roles of a single monopoly entity to separate parties, which have such key participants as generation companies , transmission company , distribution company, retailers and end-users [1].The collaboration of all the parties results in an unbundled electrical market that satisfies the needs and demands of each participant while maintaining a "two-way" power trade that benefits of all parties. As a result, a number of GENCOs will be allowed to sell the generated power to end users as their purchasers [2], [3]. This electricity is transferred via the transmission and distribution system. There is another entity that plays an important role: the Independent System Operator (ISO). The ISO is in charge of coordinating, supervising, and monitoring the system for safe, dependable, and effective market functioning rather than owning a transmission system like TRANSCO. As a result, it guarantees the safe operation and control of the deregulated system's whole transmission grid. In exchange, the TRANSCO and ISO charge the market players transmission fees in order to recoup their operating costs.

Numerous studies have been undertaken in an effort to produce non-discriminatory policies as a means of solving the issue. According to a report, the postage stamp, contract path, and distance-based MW-mile methods are the three embedded approaches that take into account the real network utilisation of a transaction [4]. Those techniques are based on transaction between point of injection and extraction of power in a transmission system. An summary of the restructured electricity market, fundamental elements of market operation, and the transmission charge idea are provided at the outset of the examination. Then, in chronological sequence, a brief description of each category of charge allocation method is offered, beginning with the transaction-based method followed by conventional electricity tracing and ended with computational intelligence approach.

2. OVERVIEW ON RESTRUCTURED POWER SYSTEM:

A power system with several market players organised and managed by a single market operator, whose role it is to operate the market while maintaining a secure and dependable system operation, is known as a "deregulated electricity market" or a "restructured power market." The vertically integrated system, which is built on a monopoly, is managed, operated, and controlled by one utility. The reformed system encourages a competitive energy market where each system member will have their own right to compete and make choices for better services. The restructured power system line diagram is as shown in the figure 1. The following three elements make up a restructured power system [1] which is discussed in brief:

- *System structure –* It outlines the various market entities and types. The five market participants are customers, retail companies (RETAILCO), distribution companies (DISCO), generation companies (GENCO), and transmission companies (TRANSCO). The lone body that functions independently as the market operator and is in charge of managing these participants is the independent system operator (ISO).
- *System model -* It outlines the process of buying and selling energy. In the first model, which is pool-based, each participant whether they are sellers or buyers submits their bids for the price and amount of energy to the pool, which serves as a centralised marketplace. With a set of agreements in a predetermined contract between them, the second form, known as a bilateral contract, encourages the freedom of choice among sellers and purchasers.
- *System operation –* It demonstrates how the various entities interact in a highly competitive market. GENCOs and ISO are the major players in the competitive market's operation. They have distinct goals set in accordance with the requirements of other participants and the system itself as they contribute to market operation. The ISO fights to preserve an effective market operation by assuring secure and stable electricity supply, but GENCOs' only goal is to make as much money as possible.

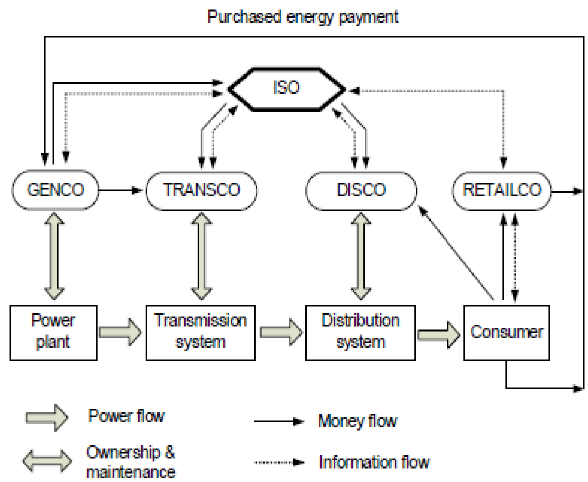

Figure 1: Restructured Power System with its key participants

3. VARIOUS LOSSES – CHARGE ALLOCATION METHODS:

If GENCOs receive money from their buyers for the sold energy, then TRANSCO should receive payment from other market participants on the basis that they have used its transmission services and facilities for energy transaction. This is done by allocating the cost to the participants in the form of transmission charges [1]. In general, the charges can have usage charge, congestion charge and losses charge. Based on these , the losses charge can be allocated by the following methods:

- Transaction based allocation
- Conventional electricity tracing
- Computational Intelligence

3.1 Transaction based allocation

Under this category, there are three methods. First one is postage-stamp method, second one is contract path method and third one is MW-mile method which is described in brief.

- *Postage stamp allocation* –This method assumes that the entire grid is used for the transaction and distributes the losses fee to participants only based on the amount of power that was transacted [1], [5]. It is therefore a pro-rata strategy. Additionally, it indicates that the network topology, power flow direction, operational state, transmission distance, and power injection and extraction points are disregarded.
- *Contract path method* – The assumption that the entire grid is used during transaction is not technically reliable. Hence, to improve the weakness of postage stamp method, allocation of losses charge to network users is limited to artificial path specified by a contract: the contract path method [1], [6]. The artificial path is a group of transmission lines connected between a pair of power producer and buyer, whereby it is created according to contract agreed between TRANSCO and both participants. Thus, it is called as contract path. Through this contract, the transacted power between producer and buyer is assumed to flow along the contract path.
- *MW-mile method* – There is no power flow analysis required in the previous two methods as the losses charge is based on: (1) magnitude of transacted power and; (2) assumption on transmission path used by participants. MW-mile is the first ever approach that pinpoints the precise transmission route taken by the power being traded. The transmission path used by participants is technically identified without biased assumptions. For every transaction '*t*' between a power producer and a buyer, the losses charge imposed on every line is calculated by the product of Megawatt loss, length of transmission line in miles and cost per unit loss and length agreed by both participants [7], [8].

3.2 Conventional electricity tracing

In this category, The Topological Generation and Load Distribution Factor (TGLDF), state graph theory, and superposition technique will be included. These methods are explained in the subsequent sections in this paper. The technical accuracy of the earlier transaction-based allocation algorithms has some limitations. As a result, a new stage in the development of technologies for allocating losses charges, known as electricity tracing, began. Bialek [9], [10], and Kirchens [11] were the first to propose the idea of tracing methods. Both of these pioneers were responsible for the majority of currently used tracing techniques, including participation matrix tracing algorithm [13], [14] and superposition based power tracing [12].

- *Topological generation and load distribution factor:*

Bialek first presented this methodology in 1996 [9], [10]. A set of nodes, directed links (transmission lines and transformers), and a set of sources and sinks are used to connect and define the network, which is considered to be topological in nature (generators and loads). This approach is founded on the so-called proportional sharing principle (PSP), which claims that "an outflow leaving a node comprises the same proportion of the inflows per total flows." The downstream algorithm is known as Topological Load Distribution Factor, and the upstream algorithm is known as Topological Generation Distribution Factor (TGDF) (TLDF). Gross demand and net generation are two ideas that must be taken into account while applying both methods. Gross demand means that the system losses are allocated to each load, while the net generation denotes the system losses are subtracted from each generator. Hence, the network is treated to be lossless during tracing process.

Contribution in gross line flow by all generators is:

$$P_{i-j}^{gross} = \sum_{k=1}^{N_g} D_{i-j,k}^{gross} \; P_{Gk} \qquad \ldots(1)$$

Contribution in gross load by all generators is:

$$P_{Di}^{gross} = \sum_{k=1}^{N_G} D_{Di,k}^{gross} \; P_{Gk} \qquad \ldots(2)$$

Where, the distribution factors and upstream matrix are determined as follows:

$$D_{i-j,k}^{gross} = \frac{|P_{i-j}|}{P_i}[A_u^{-1}]_{ik} \qquad \ldots (3)$$

$$D_{Di,k}^{gross} = \frac{P_{Di}}{P_i}[A_u^{-1}]_{ik} \qquad \ldots (4)$$

$$[A_u]_{ij} = \begin{cases} 1 & for\ i = j \\ -|P_{j-1}|/P_j & for\ j \in \alpha_i^u \\ 0 & otherwise \end{cases} \qquad \ldots(5)$$

The allocated losses to individual generators and loads can be determined by firstly conducting TLDF for tracing net generation contributions. After that, the contributions in gross demand (in TGDF) and net generation (in TLDF) are used to calculate the allocated losses by using the following equations (6) and (7) for individual generators and loads respectively

$$P_l^k = \sum P_{Di,k}^{gross} - P_{Gk}^{net} \qquad \ldots(6)$$

$$P_l^k = P_{Dk}^{gross} - \sum P_{Gi,k}^{net} \qquad \ldots (7)$$

- *State graph theory:*

The rival to Bialek's TGLDF is the one developed by Kirschen in [11],the graph theory. If Bialek's method requires transformation of power system into lossless condition, the one from Kirschen necessitates for simplification of power system to state graph. The simplified system consists of commons and links, having their specific definitions. A common is a set of contiguous buses supplied by the same set of generators, while the link is a set of branches that interconnect commons. Generator domain, a set of buses supplied by a sole generator, shall be firstly identified prior to determining commons and links.Figure. 2, states that the dotted lines indicate three commons connected by links as follows: common C1 (bus 1 and 4), common C2 (bus 2, 3 and 5) and common C3 (bus 6); link L1 (line 1-2, 1-5 and 4-5) and link L2 (line 2-6,3-6 and 5-6)

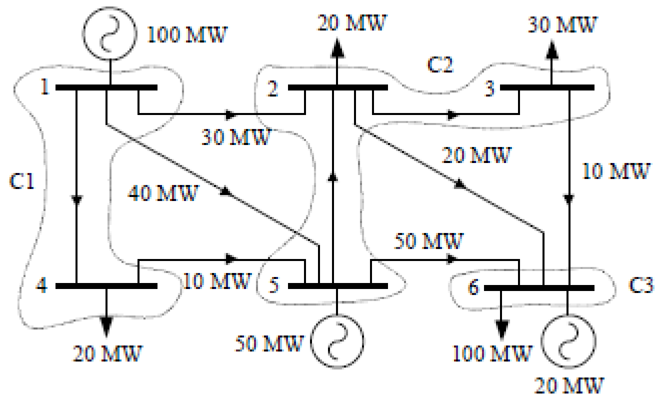

Figure 2: power system marked with commons

From these analysis, the same system can be represented in the form of a state graph as shown in Figure 3….

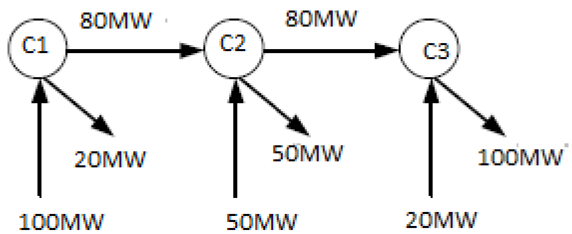

Figure 3:State graph for the 6 bus power system

The next stage is to trace the contribution of individual generators to line flows and loads recursively. This is done through the following equations:

$$C_{out,k}^{i} = \frac{\sum_j P_{jk}^{i}}{P_{in,k}} \qquad \ldots(8)$$

$$P_{jk}^{i} = C_{out,j}^{i} P_{jk} \qquad \ldots(9)$$

$$P_{in,k} = P_{GK} + \sum_j P_{jk} \qquad \ldots(10)$$

Equations (8), (9) and (10) represent the relative contribution, absolute contribution and total inflow respectively. The letter 'j' signifies a common that bring inflows to common 'k'.

- *Superposition technique:*

Bialek's tracing algorithm requires lossless power system and PSP assumption, while Kirschen's method requires complicated transformation of power system to state graph with recursive tracing process. Thus emerged a more sophisticated method developed by Teng [12], which can trace complex power without requiring modifications or assumptions as that of the previous tracing methods. This is called the superposition technique and it relies strictly on circuit theory. The tracing algorithm is based on four steps; (1) voltage tracing via basic Ohm's Law; (2) current tracing; (3) complex power tracing; and (4) losses tracing. The equivalent current source and load impedance are determined as follows

$$I_{Gk} = conj\left(\frac{P_{Gk} + jQ_{Gk}}{V_{Gk}}\right) \qquad \ldots(11)$$

$$Z_{Di} = \frac{|V_{Di}|^2}{P_{Di} - jQ_{Di}} \qquad \ldots(12)$$

The Z-bus matrix is formed by including the load impedance as:

$$\mathbf{Z} = \begin{bmatrix} Z_{11} & \cdots & Z_{1k} & \cdots & Z_{1N_{bus}} \\ \vdots & \ddots & \cdots & \cdots & \vdots \\ Z_{i1} & \cdots & Z_{ik} & \cdots & Z_{iN_{bus}} \\ \vdots & \cdots & \cdots & \ddots & \vdots \\ Z_{N_{bus}1} & \cdots & Z_{N_{bus}k} & \cdots & Z_{N_{bus}N_{bus}} \end{bmatrix} \quad \ldots (13)$$

After that, contribution of generators in bus voltages is traced according to Ohm's Law which is done as follows:

$$V_i^k = Z_{ik} I_{Gk} \quad \ldots(14)$$

Later, generator contributions in line and load currents are determined through the following equations:

$$I_{ij}^k = Y_{ij}\left(V_i^K - V_j^k\right) + j\frac{B}{2}V_i^k \quad \ldots(15)$$

$$I_{Di}^k = \frac{V_i^k}{Z_{Di}} \quad \ldots(16)$$

The next step is to calculate the complex powers of line flow and load contributed by individual generators using the following formulas once the contributed voltages and currents have been determined:

$$S_{ij}^k = V_i^k conj(I_{ij}^k) \quad \ldots (17)$$

$$S_{Di}^k = V_{Di} conj(I_{Di}^k) \quad \ldots (18)$$

Finally, the losses allocated to individual generators are performed as below:

$$S_{loss}^k = S_{ij}^k + S_{ji}^k \quad \ldots(19)$$

Thus, the method promotes effectiveness as both real and reactive powers can be traced simultaneously.

3.3 Computational intelligence based tracing

In this category, based on the computational intelligence techniques, it can have prediction-based and optimization- based approach, which is explained in brief as

- *Prediction based electricity tracing:*

The prediction based tracing model is illustrated in Figure 4. The core of this technology is what is known as an artificial neural network (ANN). It is possible to use additional function estimators, such as the Support Vector Machine (SVM). The concepts of [15], [16] - [19] and [20] - [22] were the first to formulate electricity tracing as a prediction or function estimation problem. Two sorts of data are employed in the training phase of their suggested model: input data and target data. The former can be gleaned from daily load profiles (real and reactive power) and planned real power generation, whereas the latter can be gleaned from standard tracing method results. This implies that electricity tracing using traditional techniques like TGLDF or superposition is required to obtain the target data prior to running the built predictive model.

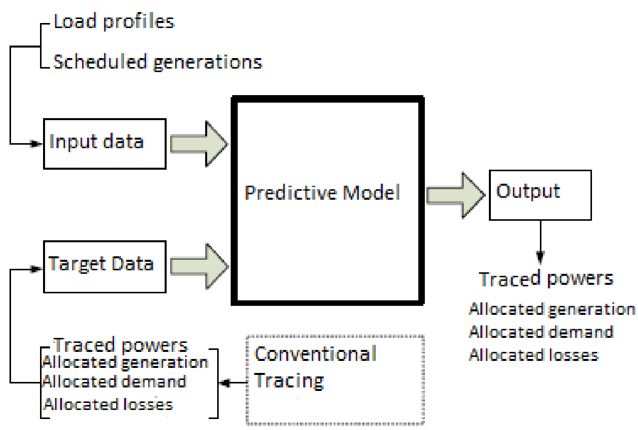

Figure 4: Prediction based tracing model

Essentially, the user of this approach doesn't need to perform any mathematical derivations. The output's uniqueness is, however, constrained by the reliance on traditional tracing techniques. The predictive model will therefore be trained and tested by feeding it input and target data. The trained model is then tested by using fresh input data to make a prediction (or estimation). Eventually, the participants' powers and losses were distributed (generators and loads) are produced as its output. The flow chart in Figure 5 provides an overview of this.

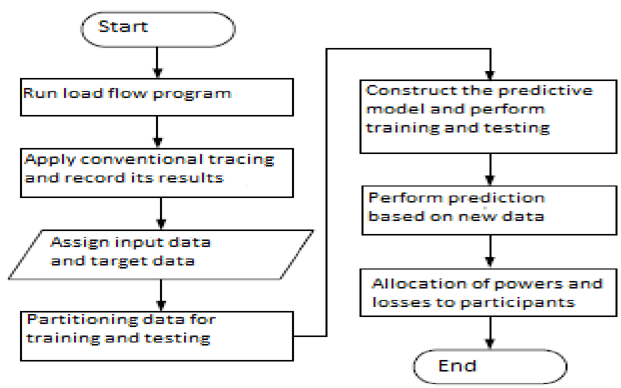

Figure 5: Algorithm for predicition based training

- *Optimization based tracing:*

The optimization-based method to electricity tracing is the most uncommon and unimaginable. Abhyankar originally shown the capability of optimization for tracing application in [23]. Its limitations for practical applications are an excess of constraints, equations, and difficult mathematical considerations. This is made worse by the method's mysterious approach because no algorithm or flowchart was given. Later, Hamid provided more clarification on the concept by formulating a straightforward problem utilising metaheuristic optimization techniques as Ant Colony Optimization (ACO) and Evolutionary Programming (EP) [24, 25]. The proposed problem formulation, with some adjustments, was generally modelled after that of Abhyankar [23]. Prior to applying an optimization technique, the following three components must be appropriately specified: decision variables, constraints and objective function .Decision variables are inserted in a huge matrix to represent a single member of the population in the optimization method. They are made up of contribution fractions (generators and loads) in line flow and losses. The flow constraint, source and sink constraints, and fraction limit restrictions are based on those of Abhyankar. Hamid developed an objective function that was based on the generation-demand balancing idea to indicate the suggested method's technical accuracy. In Figure 6, the proposed framework is displayed.

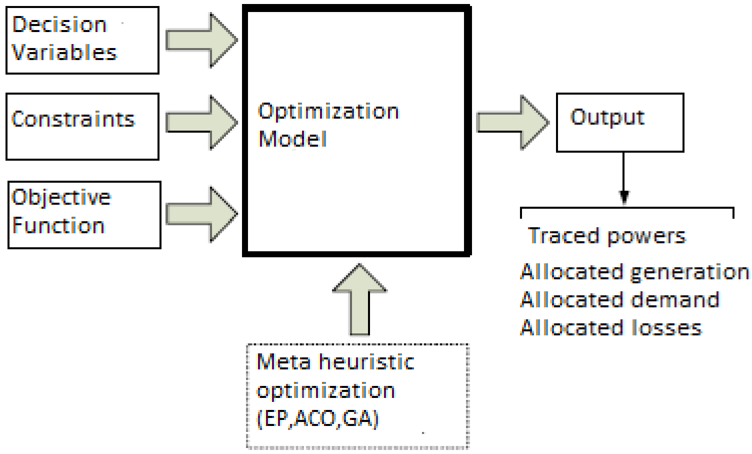

Figure 6:Optimization based tracing model

The following problem formulation is presented in the context of generation tracing, but it can also be modified for the purpose of load tracing.

Objective Function:

$$\min\left\{ f(\beta_{Di}^{k}, \beta_{loss,l}^{k}) = 1 - \sum_{i=1}^{N_D} \beta_{Di}^{k} - \sum_{l=1}^{N_L} \beta_{loss,l}^{k} \right\} \quad \text{...(20)}$$

Decision Variables:

$$\mathbf{S}_{\mathbf{GT}} = [\beta_1, \beta_2, \ldots, \beta_n, \ldots, \beta_N] \quad \text{...(21)}$$

Subject to constraints in [23]:

$$P_{fl} = \sum_{k=1}^{N_G} \beta_{fl}^{k} P_{Gk} \quad \text{...(22)}$$

$$P_{Di} = \sum_{k=1}^{N_G} \beta_{Di}^{k} P_{Gk} \quad \text{....(23)}$$

$$0 \le \beta \le 1, \quad \forall \beta \text{ in } \mathbf{S}_{GT} \quad \text{....(24)}$$

Finally, the allocated losses to individual generators and loads for *l*-th line are calculated via (25) and (26) respectively:

$$P_{loss,l}^{k} = \beta_{sl}^{k} P_{Gk} \left(1 - \frac{P_{rl}}{P_{sl}} \right) \quad \text{...(25)}$$

$$P_{loss,l}^{k} = \beta_{rl}^{k} P_{Dk} \left(\frac{P_{sl}}{P_{rl}} - 1 \right) \quad \text{...(26)}$$

The proposed algorithm using meta-heuristic optimization technique is illustrated in Figure 7. In the diagram, the algorithm performs optimization with the aim of minimizing fitness in (20) towards zero.

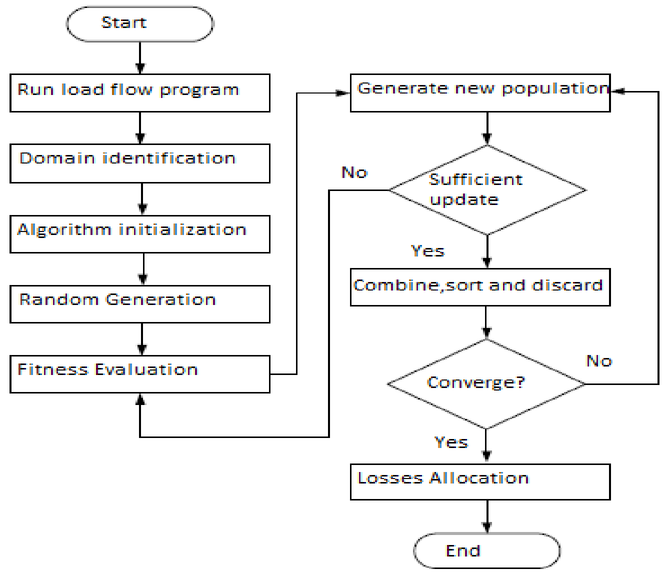

Figure 7: Optimization based tracing algorithm

From the reviews on losses charge issues in the deregulated power market are presented. It starts with conventional techniques of allocating loss of charges and their limitations in terms of how precise and dependable the scheme they provided. The reviews of electricity tracing applications are then given, and a comparison of their performance is summarize in the Table 1 and Table 2.

Table 1: Different types of losses charge allocation methods

Category	Method	Payment Method	Main principle
Transaction based	Postage stamp	Transacted power	Pro rata based principle
	Contract path	Transacted power	Allocation based on the chosen lines
	MW-mile	Transacted power	Distance based allocation
	ITL	Transacted power	Sensitivity Analysis
Conventional Tracing	Bialek's TGLDF	Contributed power	Proportional sharing
	Kirschen's graph theory	Contributed power	Commons, links and state graph
	Teng's superposition	Contributed power	Circuit theory
Computational Intelligence	Prediction	Contributed power	Predictive model
	Optimization	Contributed power	Optimization model

TABLE 2 : Different types of losses charge allocation methods with strength and weakness

Category	Method	Strength	Weakness
Transaction Based	Postage stamp	Easy and simple for implementation	Physical power system is not considered
	Contract path	Easy and simple for implementation	Assumption for the lines used in the contract
	MW-mile	Length of transmission lines is considered	Cost per length has to be agreed between seller and buyer
	ITL	Contribution in losses is considered	Negative participation among generators and loads
Conventional Tracing	Bialek's TGLDF	No negative participation among generators and loads	Require matrix inversion and lossless system
	Kirschen's graph theory	Power system is simplified to facilitate the tracing process	Same contribution for all generators of common
	Teng's superposition	Simultaneous real and reactive power tracing	Negative participation among generators and loads
Computational Intelligence	Prediction	Applicable at all possible system conditions	Require conventional methods for training vector
	Optimization	Applicable at all possible system conditions	Computational burden for larger systems

From the table it is observed that, after reviewing the prior techniques for allocating losses charges, Table 2 summarizes their advantages and disadvantages. According to the table, transaction-based techniques charge market players based on transacted power, which is the purchased power decided upon by the seller and the buyer. The other techniques, in contrast to this strategy, rely on precise utilization in powers and losses, which is the power given by individual participants taking into account physical network architecture, power flow direction, and other technical features of the system. Different approaches necessitate various problem formulation and solution assumptions. The majority of transaction-based methodologies are deficient in actual consideration because they overlook the system's true state; for example, load flow analysis only considers the transfer of power between two parties (seller and buyer). In practice, not all energies are directly supplied by a single generator and entirely absorbed by a single load. Therefore, it is necessary to calculate the percentage of individual system users' engagement. There is no doubt that electrical tracing is the only method that can meet this requirement. Table 2 demonstrates that no method is ideal and that each has its own advantages and disadvantages. As was previously said, transaction-based approaches did provide simplicity and convenience of implementation in real-world issues. But this is not the case. Conventional tracing techniques offer accurate results, but they still rely on certain concepts to make tracing easier. Additionally, several of them are incapable of producing any outcomes while the power system is at contingency. The adaptability of computational intelligence techniques has increased their standing relative to other techniques. The tracing data are accessible under all system-possible circumstances. However, the uniqueness of the findings produced by predictive models is constrained by their dependency on conventional tracing for a training vector, and the computing complexity of optimization models limits their use in real-world systems.

4. CONCLUSIONS

A survey on the essential elements of the deregulated electricity market and several systems for allocating losses charges was effectively carried out. This study seeks to give an overview of the deregulation of the energy industry and the reorganized power market to all researchers and new readers. They can utilize the research results offered in this paper as a guide for their future studies and as justification for the decision they will make on the most appropriate approaches to employ. Consequently, it is hoped that this survey will expand academics' involvement in the research on restructured power market.

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