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ORIGINAL RESEARCH

Determining the optimal bid direction of a generation company using the gradient vector of the profit function in the network constraints of the electricity market

Mohammad Ebrahim Hajiabadi[1] | **Mahdi Samadi**[1] | **Mohammad Hassan Nikkhah**[2] | **Hossein Lotfi**[1] | **Li Li**[3]

[1]Department of Electrical and Computer Engineering, Hakim Sabzevari University, Sabzevar, Iran

[2]School of Engineering, RMIT University, Melbourne, Australia

[3]Faculty of Engineering and Information Technology, University of Technology Sydney, Sydney, Australia

Correspondence
Mohammad Ebrahim Hajiabadi, Department of Electrical and Computer Engineering, Hakim Sabzevari University, Sabzevar, Iran.
Email: me.hajiabadi@hsu.ac.ir

Abstract

One of the primary challenges faced by generation companies (GenCos), which operate multiple generation units within the electricity market, is the determination of the optimal bid price for these units to maximize profit. This paper proposes a novel approach to ascertain the optimal bid price direction for GenCos by leveraging the gradient vector of the profit function within the constraints of the electricity market. First, the Jacobian matrix of unit profits is computed using the electricity market structural decomposition method. This matrix highlights how the profit of generation units is affected by market input parameters, including the bid prices of the units. Then, the gradient vector of the GenCos' profit function and the optimal bid price direction are derived from the Jacobian matrix. The methodology is applied to a 24-bus IEEE network, with results validated against those from a simulation method to confirm the efficacy of the proposed approach. The simulation results show that the highest and lowest profit changes with a step increase of 0.1$/MWh are observed for GenCo 4 and GenCo 6 with values of 60.28 and 2.20 $/h, respectively. The proposed approach can be effective in the changes of bid direction of the units of a GenCo to achieve the highest possible profit.

1 | INTRODUCTION

1.1 | Motivation and aim

The strategy of adjusting the bid price of the units by the owner of each company emerges as a critical challenge for maximizing the profit of any generation company (GenCo). In the competitive electricity market, the allocation of generation hinges on the bids submitted, necessitating that each GenCo competes by proposing bids to secure market share. This competitive landscape offers GenCos opportunities to enhance their profit [1]. Consequently, each GenCo is motivated to strategically formulate its bids within the restructured power market to maximize its profit [2]. To maximize profits in a competitive market, GenCos are compelled to set their bids closely aligned with marginal production costs. The challenge for each GenCo lies in identifying the optimal bid price that navigates market constraints and forecasts to achieve the highest profit. On the other hand, given the electricity market's imperfect competition, GenCos attempt to increase its profit margins by setting prices above the marginal production cost [3]. Therefore, GenCos' strategy of proposing electricity prices becomes crucial for attaining greater profit. This paper aims to introduce a novel approach for optimizing electricity price proposals of GenCos, as illustrated through graphical representations in Figure 1.

1.2 | Literature review

According to the graphical literature review in Figure 1, the structural decomposition method has been used across various domains, including market power, collusion, congestion

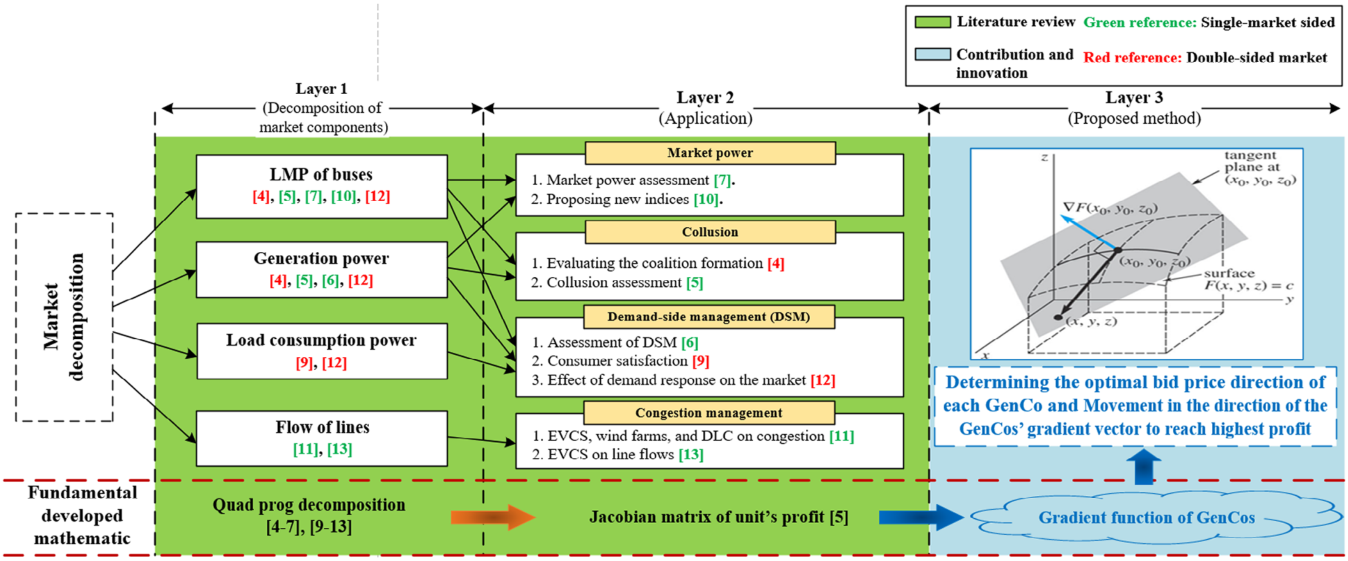

FIGURE 1 Graphical literature review of market decomposition and contribution of the proposed method.

management, and demand-side management in both single-sided and double-sided markets. Notably, to tackle potential collusion among market participants, a new index is proposed using the structural decomposition method, aiming to optimize social welfare in the double-sided market [4]. Also, a method is proposed to assess the collusion among generation units in a single-sided market by using the Jacobian matrix in [5], introducing two lemmas to calculate the factors influencing the profit of generation units. In [6], a methodology for evaluating the costs associated with the demand-side management program considering energy losses and line congestion is proposed, where the influence of such programs on cost variations is examined. The structural decomposition of the locational marginal price (LMP) of the buses is proposed in [7] to explore the potential for market power formation among GenCos in a single-sided market. Research in [8] employs structural decomposition to study the statistical dynamics of electricity prices under different network load conditions, uncovering a linear relationship between the LMP and the strategy of GenCos. An analytical method based on structural analysis to investigate customer satisfaction sensitivity to its contributing factors is investigated in [9], using the Lagrange function and the Kahn-Tucker condition to maximize social welfare in the double-sided market. A novel index to analyse the market power of generation units and GenCos based on their capacity to influence electricity prices is proposed in [10], dissecting the LMP into four main components to identify the impact of each factor on LMP variations. The contribution of electric vehicle charging stations, wind farms, and the direct load control program to line congestion changes under different load conditions is determined through structural analysis in [11], with the study also investigating the impact of each factor on the line congestion changes via several indices. The impact of the demand response program on the LMP, generation power, and responsive electricity consumption as market components is investigated in [12] through quadratic programming in a two-sided electricity market. In [13], the influence of electric vehicle charging stations on changes in the flow of network lines is analysed, proposing an index to quantify the station's impact on network congestion. Lastly, an analytical approach is proposed to evaluate collusion between GenCos and transmission companies, analysing factors affecting changes in congestion rent of lines and zones and introducing six indices to identify the contribution of each factor to these changes [14]. The exact role of energy resources and distributed generations in variations in congestion on network lines is determined using structural decomposition and an analytical method [15]. The Kahn–Tucker conditions in the Lagrange technique are used to precisely compute the effect of five factors on fluctuations in the power of network lines. The best places for wind farms and electric vehicle charging stations are initially identified by utilizing a potent structural decomposition technique to analyse the flow characteristics of grid lines. Each item added to the network is then given a transmission fixed cost [16].

In addition, significant research has been conducted in the area of GenCos' behaviour using learning algorithms. For example, an approach using the Q-learning algorithm is developed to model the behaviour of GenCos in [17], enabling GenCos to iteratively learn and adjust their strategy. In [18], the Q-learning algorithm is used to assess the bidding behaviour of GenCos, including adjustment of their sensitivity to price fluctuations through a correction factor. Also, under different market clearing scenarios, the strategic behaviour of GenCos based on the learning mechanism is modelled in [19]. The impact of learning on the behaviour of GenCos in the monopoly electricity market is investigated in [20], where the GenCo agents periodically adjust their price offer. In [21], the genetic algorithm is used to formulate a novel strategy to estimate GenCos' profit, with the instantaneous electricity price determined by a similarity function. Additionally, the Q-learning algorithm is applied to analytically examine the factors influencing the LMP of buses, aiming to evaluate GenCos' strategic behaviour [22].

Collusion among GenCos to increase profits leads to the formation of market power, which affects the market equilibrium point. In general, various factors influence the formation of market power. Market power refers to the capacity of participants in the electricity market to increase their profits by maintaining prices above competitive levels for a significant period of time. This phenomenon is indicative of a non-competitive market and can undermine economic efficiency [23]. Market power occurs when producers manipulate prices to their advantage using methods such as increasing supply or decreasing generation [23, 24]. For example, a study on the European electricity market shows that prices are significantly influenced by generation owners [25]. David and Wan provide an overview of market power, focusing on different equilibrium models and strategies for mitigating market power [26]. The long-term impact of generational ownership on market power is examined in [27], suggesting that a limited number of investors could lead to welfare reductions. A comprehensive method for assessing market power, based on the concept of centrality from social network analysis, is proposed in [28], along with several indices for developing market power criteria. In [29], the models of Bertrand, Cournot, Stackelberg, and supply function equilibrium are examined to analyse market power. One of the factors affecting the market power is transmission constraints. A market power analysis considering network constraints, fuel constraints, and weather pattern limitations is investigated in [30]. A new approach for market power analysis employing three indices based on network flow, minimum generation, and residual supplier is proposed in [31]. A quantitative and theoretical analysis for evaluating the impact of demand shifting on reducing market power by the production side is proposed in [32]. A Cournot-based model for detecting the presence of market power is used to evaluate the Korean [33] and Colombian [34] markets. A set of techniques (concentration ratios, the Herfindahl–Hirschman Index, the Lerner Index, the residual supply index, and the supply margin) are employed to assess the Singapore electricity market [35]. In [14], an analytical method is proposed to evaluate collusion between GenCos and transmission companies, introducing several indices to evaluate collusion and the impact of each factor on network congestion changes. In [36], a tool for future market data analysis is proposed to detect collusion among generating units. In this regard, all possible scenarios of collusion are considered, and the obtained statistics are used to train a learning algorithm. In [37], an algorithm based on reinforcement learning is proposed to evaluate market performance against collusion among users. The effect of multiple markets on collusive behaviour is investigated in [38], albeit without considering transfer restrictions in the strategy of GenCos. Market power in the electricity market with the integration of renewable energy sources is evaluated in [39], considering explicit and implicit collusion. The potential for collusion between the unreliable coordinator and electric vehicle charging stations is investigated in [40], which could harm others' profits and social welfare. In addition, a new blockchain-based framework for reliable coordination is used in this study. In [41], the possibility of collusion among GenCos using the game theory model is investigated, distinguishing between weak and strong types of collusion.

The goal of [42] is to thoroughly examine the strategies used to raise the proportion of renewable energy sources and the ways in which these resources engage in the power markets. In this context, a thorough examination of several topics is provided under separate parts, including policies that support renewable energy sources, electricity market structures, market development, ideal bidding strategies, and methods of renewable energy sources' collective involvement in the energy markets. In order to eliminate imbalances and participate in the day-ahead and balancing markets, including bilateral contracts, [43] provides a bi-level and multistage framework in which a renewable energy portfolio manager controls renewable energy sources combined with an energy storage system. The day-ahead and balancing market trading, as well as bilateral contracts, are the means by which an ideal bidding strategy for a wind energy portfolio manager that includes electric vehicle parking lots is suggested in [44]. This strategy takes into account line capacities and risk management in order to maximize profits.

Indeed, the structural decomposition method has been extensively applied in research covering market power, collusion evaluation, congestion management, and demand-side management, as shown in Layers 1 and 2 of the graphical literature in Figure 1. However, to date, there has not been a study that introduces an optimal bid pricing strategy for each GenCo in the electricity market based on the profit gradient of the GenCos to achieve the maximum profit.

1.3 | Contribution and paper organization

As highlighted in Layer 3 of the graphical literature in Figure 1, the main innovation of this paper is to propose an analytical method combined with structural decomposition to maximize the profit of each GenCo in the network by using the gradient vector of the profit function of GenCos. In other words, the proposed method identifies that the marginal units placed in each GenCo with the least changes in the bid price in the optimal direction will achieve the highest profit for their GenCo by considering the transmission constraints. Imagine that generation company g has n generation units. If this generation company is supposed to reach the maximum possible profit by increasing the specific bid price, the bid price of the generation units placed in it should act in the right direction and make optimal changes. In this regard, this paper uses the vector of profit gradient of generation companies to reach the maximum profit. In general, the strategy of moving in the optimal direction of the bid prices by GenCos using the gradient vector of GenCos' profits has not been studied so far. Therefore, the most important innovation of this paper is to examine the optimal changes in the bid price of the generation units of each GenCo to achieve the maximum profit.

The remaining paper is organized as follows: The basic formulation related to the problem is presented in Section 2. Then, the proposed formulas are presented in Section 3. Afterward, the results of the proposed formulas are presented in Section 4. Finally, the conclusion and summary of the paper are provided in Section 5. In the following, the formulation of the problem will be presented.

2 | PROBLEM FORMULATION

In this section, first, the basic formulas related to market structural decomposition are presented. Then, the Jacobian formulation of profit from generation units is defined to calculate the effect of factors on profit changes.

2.1 | Electricity market structural decomposition

First, the input data for the problem is provided, which includes the bid price of the units, the minimum and maximum capacity of the units, and the capacity of the network lines. Then, by implementing the market clearing program, the generation power of generation units, the LMP of buses, and the flow of network lines are calculated. The objective function of the problem in this study is the cost function of generation units [5], which is defined in (1):

$$\begin{aligned}
&\underset{P_G,P_L}{\text{Min}} \sum_{i=1}^{Ng} \left(a_i.Pg_i + \frac{1}{2} b_i.Pg_i^2 \right) \\
&M_G.P_G - M_L.\,P_L = P_D \;\; : \text{LMP} \\
&P_l - (\theta_a - \theta_b)\, x_{ab}^{-1} = 0 \quad \forall l \\
&P_G^{\text{Min}} \leq P_G \leq P_G^{\text{Max}} \,\&\, -P_L^{\text{Max}} \leq P_L \leq P_L^{\text{Max}}
\end{aligned} \tag{1}$$

where a_i and b_i are the coefficients of the problem's cost function. P_G, P_D and P_L are the vectors of generation power, load consumption, and power of network lines, respectively. M_G and M_L are the intersection matrices of bus and generation units and bus and network lines, respectively. By using the method in [5, 14], the factors affecting the changes in the LMP of buses and the generation power of the units are defined as follows:

$$\begin{bmatrix} dP_G \\ d\text{LMP} \end{bmatrix} = [L] \times \left[d\,a_{mrg} \quad dP_G^{\text{Min}} \quad dP_G^{\text{Max}} \quad dP_D \quad dP_L^{\text{Max}} \right]^T \tag{2}$$

where,

$$[L] = \begin{bmatrix} La_{Pg} & Lmn_{Pg} & Lmx_{Pg} & Ld_{Pg} & Ll_{Pg} \\ La_{\text{LMP}} & Lmn_{\text{LMP}} & Lmx_{\text{LMP}} & Ld_{\text{LMP}} & Ll_{\text{LMP}} \end{bmatrix} \tag{3}$$

The proof of this method is in [5].

The factors that make up the generation power of units and the LMP of buses are classified into five categories: marginal, expensive, cheap units, network load, and congested lines. Marginal units are units that influence the generation power of the units and the LMP of buses with their bid prices. Similarly, expensive units are the ones that affect the two factors mentioned with their minimal self-generation capacity, while cheap units are the units that affect the two factors mentioned with their maximum generation capacity. The focus of this paper is on marginal units to calculate the profit of GenCos because marginal units with the bid price affect the changes in the generation power of the units (La_{Pg}) and the LMP of the buses (La_{LMP}). La_{Pg} and La_{LMP} are two matrices affecting the generation power of the units and the LMP of buses. In fact, these two matrices are applied as input to the Jacobian matrix to calculate the impact of the influencing factors on the profit changes of units.

2.2 | Profit decomposition of generation units

In this section, the impact of the influencing factors on the profit changes of the units is determined. In general, the profit of unit i (i.e. revenue minus generation cost [45]) is calculated as (4).

$$\begin{aligned}
\text{Profit}_i = \text{Revenue}_i - \text{Cost}_i = (Pg_i.\text{LMP}_i) \\
- \left(a_i.Pg_i + \frac{1}{2} b_i.Pg_i^2 \right)
\end{aligned} \tag{4}$$

where LMP_i is the locational marginal price of the bus i. Equation (4), which expresses the profit [29] of each generation unit, can be rewritten as follows according to [5]:

$$\begin{aligned}
[\text{PR}] = \left([P_G] \odot [\text{LMP}] \right) \\
- \left([\hat{a}] \odot [P_G] + \frac{1}{2} [\hat{b}] \odot [P_G] \odot [P_G] \right)
\end{aligned} \tag{5}$$

which can be rewritten based on Hadamard multiplication as follows [5]:

$$\begin{aligned}
[\text{PR}] = (K\,.\,\text{Q}) \odot (W\,.\,\text{Q}) \\
- \left([\hat{a}] \odot (K\,.\,\text{Q}) + \frac{1}{2} [\hat{b}] \odot (K\,.\,\text{Q}) \odot (K\,.\,\text{Q}) \right)
\end{aligned} \tag{6}$$

where the matrices K and W and the vector Q are defined as follows:

$$K = \text{La}_{\text{Pg}},\; W = \text{La}_{\text{LMP}},\; Q = \left[a_{mrg}, P_G^{\text{Min}}, P_G^{\text{Max}}, P_D, P_L^{\text{Max}} \right]^T \tag{7}$$

As a result, as shown in Layer 2 of the graphical literature in Figure 1, the profit change rate (dPR) of the units is defined as follows using the Jacobian matrix [5].

$$[dPR]_{Ng\times 1} = \left[\underbrace{Sa}_{Ng\times Nmrg} \quad \underbrace{Smn}_{Ng\times Nmn} \quad \underbrace{Smx}_{Ng\times Nmx} \quad \underbrace{Sd}_{Ng\times Nb} \quad \underbrace{Sl}_{Ng\times Ncl}\right] \times \begin{bmatrix} d\,a_{mrg} \\ dP_G^{\mathrm{Min}} \\ dP_G^{\mathrm{Max}} \\ d\,P_D \\ dP_L^{\mathrm{Max}} \end{bmatrix} \tag{8}$$

where Sa, Smn, and Smx are the effective matrices of marginal, expensive, and cheap units on the profit changes of generation units, respectively. Sd and Sl are the effective matrices of network load and congested lines on profit changes of generation units. Therefore, the profit changes of each generation unit are affected by the five factors of marginal, expensive, and cheap units, network load, and congested lines [5], which are defined in (9).

$$\begin{aligned}\Delta Profit_i = &\sum_{j}^{Nmrg} Sa(i,j).da_j + \sum_{j}^{N\min} Smn(i,j).dPg_j^{\min} \\ &+ \sum_{j}^{N\max} Smx(i,j).dPg_j^{\max} + \sum_{n}^{Nb} Sd(i,n).dPd_n \\ &+ \sum_{l}^{Ncong} Sl(i,l).dP_l^{\max} \\ &(\forall i = 1, 2, \ldots, Ng)\end{aligned} \tag{9}$$

Therefore, by using the Jacobian method and the Hadamard multiplication, it is possible to calculate the impact of the influencing factors (marginal, expensive, cheap units, load consumption, and congested lines) on the profit changes of the generation units; the proof of this method is examined in [5]. These coefficients, which are obtained analytically, determine the contribution of each factor to the profit in a transparent, fast, and precise manner. Therefore, the proposed approach provides a powerful tool to specify the key factors affecting the profit of each unit. In the following, the formulation related to the optimal bid direction will be presented.

3 | FORMULATION OF GRADIENT VECTOR AND UNITS' OPTIMAL BID PRICE DIRECTION

In this section, a brief explanation of the gradient vector is provided first. Then, the gradient vector of GenCos' profit is presented as the proposed method of this paper, which has not been discussed in previous studies. Finally, the optimal bid price direction for each marginal unit placed in GenCos is determined using the gradient vector. In general, the gradient vector of a scalar function f that maps $R^n \to R$ where $x = (x_1, x_2, \ldots, x_n)$ is as follows [46]:

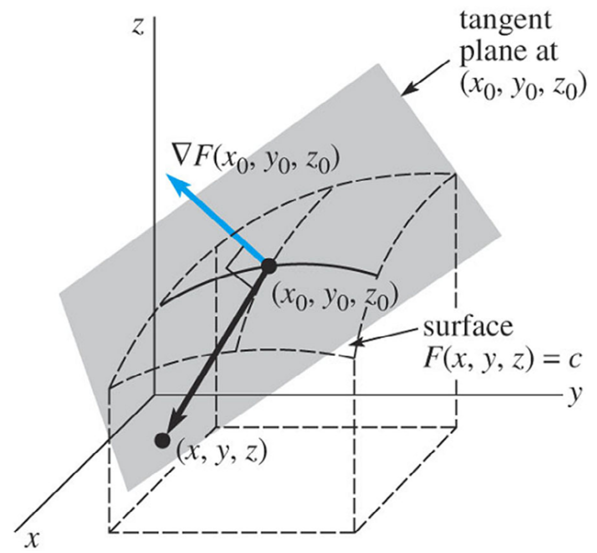

FIGURE 2 The gradient vector of the function f.

$$\nabla f(x) = \frac{\partial f(x)}{\partial x_1}\hat{x}_1 + \frac{\partial f(x)}{\partial x_2}\hat{x}_2 + \cdots + \frac{\partial f(x)}{\partial x_n}\hat{x}_n \tag{10}$$

For example, as shown in Figure 2, if f is a function of three variables (x, y, and z), its values can be visualized as a plane. In this context, moving in the direction of the function's gradient on this plane, with a certain value, results in the most changes. This leads us to a pivotal question: what is the rate of change in bid price per unit of GenCo to achieve maximum profit?

In other words, what precise adjustment ratio should a GenCo apply to the bid price of its units to maximize profits? Tackling this question necessitates a sophisticated mathematical model capable of incorporating all market constraints, a subject yet to be explored in existing research. Certainly, according to mathematical principles, moving in the direction of the gradient vector of a multivariable function yields the most significant enhancement in the function's value. Therefore, by determining the gradient vector of a GenCo's profit, one can determine the direction of movement for maximizing profit (the direction in this multidimensional context means the rate of change in the bid price for each of the GenCo's units).

The focal point in this paper is the gradient function of the GenCos' profit. Assuming the network comprises n GenCos, each GenCo can include marginal, expensive, and cheap units; marginal units affect the profit changes of GenCos by changing their bid price. In fact, moving along this surface means constant profit for Genco, and the axes of the graph are the bid prices of the units placed in that company. To achieve the maximum profit, it is imperative to move in the direction dictated by the gradient vector. The maximization of a GenCo's profit, attributed to the bid price offerings of marginal units at a given step, is a function influenced by the variable $Nmrg$, creating a definable surface within an *Nmrg*-dimensional space. Therefore, the gradient vector is used to maximize the profit of each GenCo. In essence, the methodology introduced herein specifies the extent to which the generation units of a GenCo should adjust their bid prices to secure maximum profit for their company. To determine the optimal bid price for the maximum profit of GenCo *g*, the following Lemma is proposed.

Lemma. *If GenCo* g *owns several generation units, including marginal units, the profit gradient of GenCo* g *is defined as follows:*

$$\nabla \text{Profit\_ G}_g = \sum_{i \in G_{m,g}} \left(\sum_{j \in G_g} Sa\,(j, i) \right) \hat{a}_i \tag{11}$$

Proof. The profit of the GenCo g ($Profit\_G_g$) resulting from adjustments in its bid price, particularly from those marginal units, is derived from aggregating the profits of all the generation units ($Profit\_u_j$) within it, influenced by the bid price changes of marginal units, as illustrated in (12):

$$\text{Profit\_G}_g\left(a_g\right) = \sum_{j \in G_g} \text{Profit\_u}_j\left(a_g\right),\; a_g = \left\{a_i | i \in G_{m,g}\right\} \tag{12}$$

where $Sa(j,i)$ is the effective coefficient of the marginal unit i located in the GenCo g on the profit changes of the generation unit j in that GenCo. Also, Sa is the matrix obtained from the Jacobian matrix.

where a_i is the bid price of marginal unit i, $G_{m,g}$ is the set of marginal units of GenCo g.

The gradient of GenCo g resulting from the bid price of marginal units is obtained as in (13):

$$\nabla \text{Profit\_ G}_g = \sum_{i \in G_{m,g}} \frac{\partial \text{Profit\_G}_g}{\partial a_i}\,\hat{a}_i \tag{13}$$

where

$$\frac{\partial \text{Profit\_G}_g}{\partial a_i} = \sum_{j \in G_g} \frac{\partial \text{Profit\_u}_j}{\partial a_i}, \quad \forall i \in G_{\text{m,g}} \tag{14}$$

According to (9), we have:

$$\frac{\partial \text{Profit\_u}_j}{\partial a_i} = Sa\,(j, i)\;\forall j \in G_g, \quad \forall i \in G_{\text{m,g}} \tag{15}$$

Therefore, Equation (11) is proved.

To this end, the changes in the bid price of the marginal unit i within the GenCo g and its movement direction to reach the maximum profit can be calculated by the proposed method.

The changes of optimal bid price direction (OBPD) of GenCo g (increase or decrease in price) per marginal unit placed in it and the specified movement step amount (K_g) are proposed as in (16). This approach is novel, as it incorporates the constraints of transmission, a factor not previously accounted for in earlier research. As a result, GenCo g needs to determine the direction and amount of changes in the price of its marginal units to maximize the profit, and the proposed method is designed to address this challenge effectively. In the following, the results of the proposed method will be presented.

$$\text{OBPD}\left(G_g\right) = K_g \times \frac{\nabla \text{Profit\_G}_g}{\left|\nabla \text{Profit\_G}_g\right|} = K_g \times \sum_{i \in G_{m,g}} \left(\frac{\sum_{j \in G_g} Sa\,(j, i)}{\sqrt{\sum_{i \in G_{m,g}} \left(\sum_{j \in G_g} Sa\,(j, i) \right)^2}} \right) . \hat{a}_i \tag{16}$$

To normalize the amount of changes in the bid price of marginal units in the appropriate direction, the profit gradient of the GenCo g is divided by its value. The value of the profit gradient of the GenCo g is defined as follows:

$$\left|\nabla \text{Profit\_G}_g\right| = \sqrt{\sum_{i \in G_{m,g}} \left(\sum_{j \in G_g} Sa\,(j, i) \right)^2} \tag{17}$$

In general, if GenCo g has n marginal units, the price change of that company's offer with a specific step (K_g) consists of an n-dimensional space that depends on the n marginal units in that GenCo. Therefore, the amount of change in the bid price of GenCo g caused by n marginal units is as follows:

$$K_g = \sqrt{\left(\text{bid}_{g,1}\right)^2 + \cdots + \left(\text{bid}_{g,i}\right)^2 + \cdots + \left(\text{bid}_{g,n}\right)^2} \tag{18}$$

where $\text{bid}_{g,i}$ is the bid price of unit i within GenCo g. For example, the sample space for the bid price of two GenCos with two and three marginal units are shown in Figure 3. In other words, the change modes of the bid price of two marginal units in Figure 3a with step K_g are on the circumference of a circle, but for another GenCo with three marginal units, they are on the surface of a sphere.

In the following, the results obtained from the proposed method will be presented.

4 | SIMULATION RESULTS

In this section, first, the information related to the implementation of the market-clearing program in the basic mode is provided. Then, the quantity and direction of the bid price change of the marginal units placed in the GenCos are examined by the gradient vector. Finally, the results obtained from the proposed gradient vector approach are compared those obtained

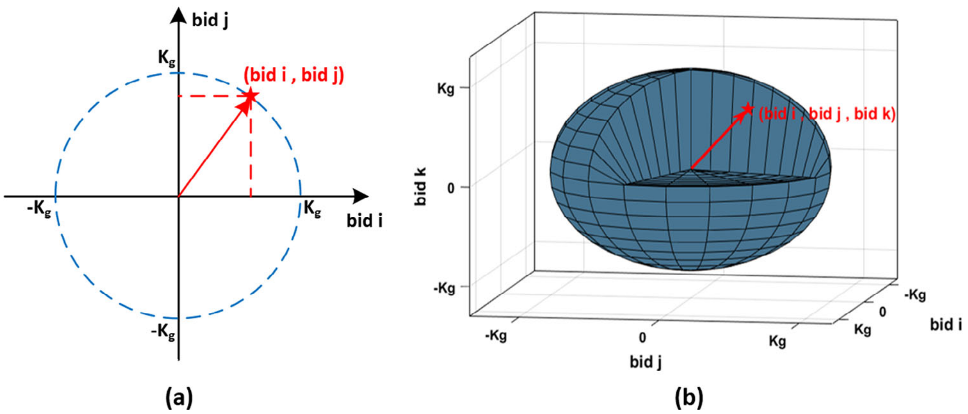

FIGURE 3 Bid direction for (a) two marginal units (b) three marginal units.

TABLE 1 Generation units located in each generation company (GenCo).

GenCo	1	2	3	4	5
Unit	27, 31–32	19, 21–23	18, 20, 24–25	15, 26, 30	13, 16
GenCo	6	7	8	9	–
Unit	7–12	14, 17	1–6	28–29	–

with the simulation method to validate the efficacy and accuracy of the gradient vector's application. The proposed method is implemented on the 24-bus network, and the results are analysed. The proposed method is implemented and executed in MATLAB software.

4.1 | Basic mode

In the basic mode, the market clearing program is executed with the bid price of generation units. After the implementation of the market-clearing program, the categorization of generation units into marginal, expensive, and cheap is established, and the result of the program's implementation of the program are specified. In general, there are 13 marginal units, five expensive units, and 14 cheap units in the network. In addition, the data related to the GenCos, the bus of each GenCo, and the bid price of each GenCo are available in [10]. Furthermore, the distribution of generation units across the various GenCos is presented in Table 1.

4.2 | The maximum profit of each GenCo using the gradient vector

The marginal units of each GenCo must change their bid price in such a way that ensures profit maximization for their respective GenCo. The profit of GenCos in the basic case according to (4) and the incremental profit of GenCos through the application of gradient vector are shown in Figure 4. The highest and lowest profits are related to GenCos 2 and 6, with values of 6143.1 and 29.6 \$/h, respectively. It is natural that the increase in the bid price of marginal units affects GenCos's profit. GenCo 4 and GenCo 6 obtained the highest and lowest profit changes due to the change in their bid prices, with values of 60.28 and 2.20 \$/h, respectively. In GenCo 4, unit 30, by increasing its bid price by 0.1 \$/MWh, has a significant effect on increasing the profit of its company, so that the bid price of unit 15 remains unchanged. In fact, the profit obtained for all GenCos is due to the gradient vector at its maximum value, and for changes in the bid price with other values, less profit is obtained for each GenCo. Therefore, the movement in the direction of the profit gradient vector for each GenCo, as advocated by the proposed method, determines both the direction and the optimal magnitude of the bid price change required for each marginal unit. Here, the bid price increase of each GenCo is equal to 0.1 \$/MWh ($K_g = 0.1$ \$/MWh).

The distribution of marginal units among the GenCos varies, with GenCos 2, 4, 5, and 7 possessing two marginal units each, GenCo 3 having three, GenCos 1 and 6 each with one, and GenCos 8 and 9 without any. The adjustments for optimal bid pricing for marginal units in GenCos 2, 4, 5, and 7 are detailed in Figure 5, showcasing the specific increments needed for maximizing profits. For example, for GenCo 2, units 19 and 23 require increases in their bid prices by 0.065 and 0.075 \$/MWh, respectively, to achieve optimal profits. In addition, GenCo 4 only needs to increase the bid price of marginal unit 30 by 0.1 \$/MWh to reach the highest possible profit with a step of 0.1 \$/MWh (K_g = 0.1 \$/MWh), while marginal unit 15 should not increase its bid price. Furthermore, Figure 6 illustrates the precise adjustments needed for the marginal units in GenCo 3 to attain maximum profitability. According to the

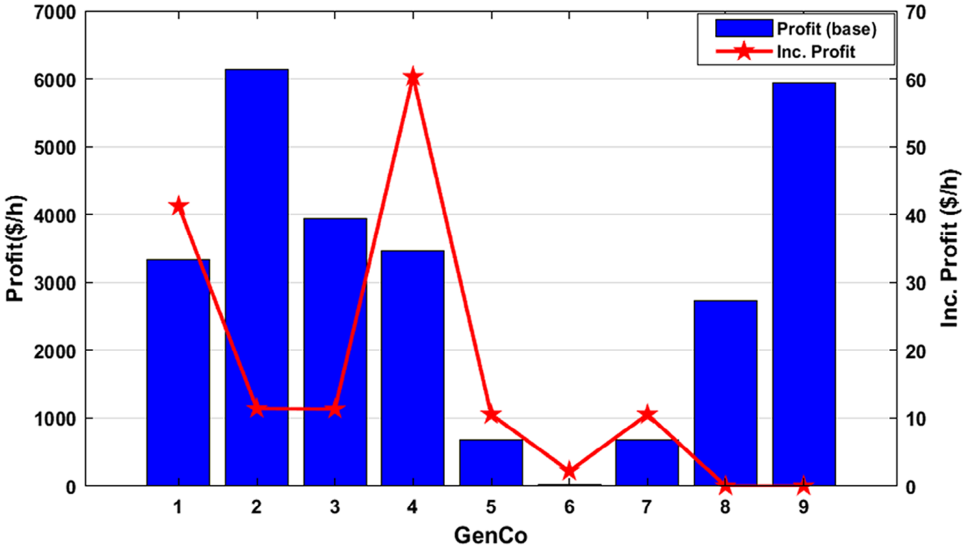

FIGURE 4 Profit of generation companies (GenCos) in the base case and its incremental profit by gradient vector.

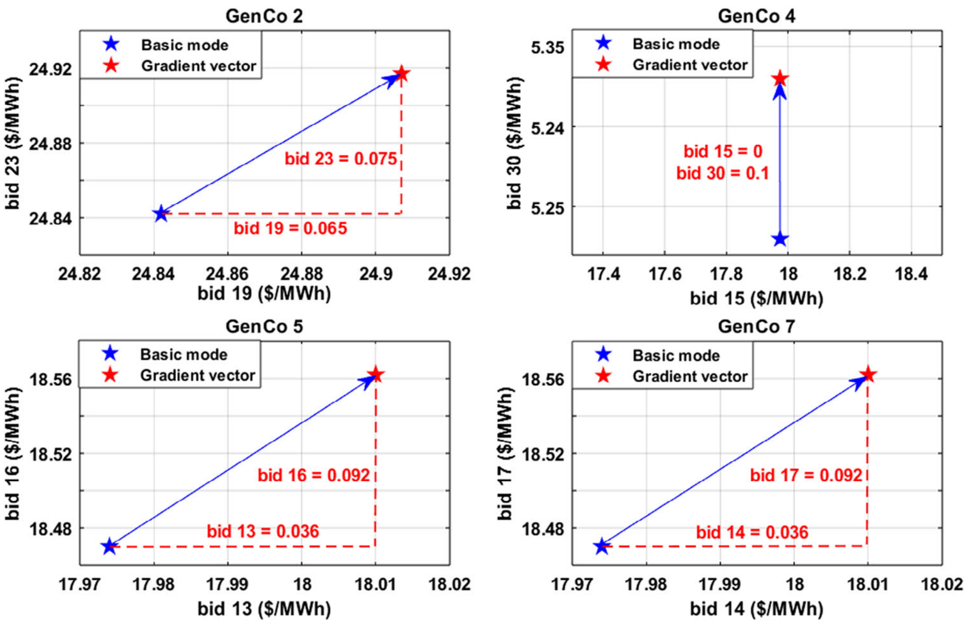

FIGURE 5 Optimal bid direction by gradient vector with $K_g = 0.1$. GenCo, generation company.

gradient vector method, GenCo 3′s three marginal units (18, 20, and 24) should adjust their bid prices by 0.076, 0.042, and 0.047 \$/MWh, respectively, to secure the highest profits with a step increment of 0.1 \$/MWh. In the next section, the accuracy of the gradient vector method (proposed method) will be validated by comparing its results with those obtained from the simulation method.

4.3 | Comparison of gradient vector with simulation method

In this section, the gradient vector method is compared with the simulation method to prove the correctness of the proposed method. The results of the simulation method for GenCos 2, 4, and 5, each housing two marginal units, are shown in Figure 7 with different steps (K_g = 0.1, 0.15, and 0.2 \$/MWh). In this figure, the two horizontal axes represent the bid prices of the marginal units within the respective GenCos, while the vertical axis quantifies the profit obtained from the different values of the bid prices of the units. For example, the highest profit obtained for GenCo 2 from the simulation method with a step of 0.1 \$/MWh is equal to 11.41 \$/h, which is the same value obtained from the gradient method; similar results apply to GenCos 4 and 5.

In addition, the profit from the increase in other bid prices (K_g = 0.15 and 0.2 \$/MWh) from the simulation method is the maximum possible profit for this GenCo. A significant

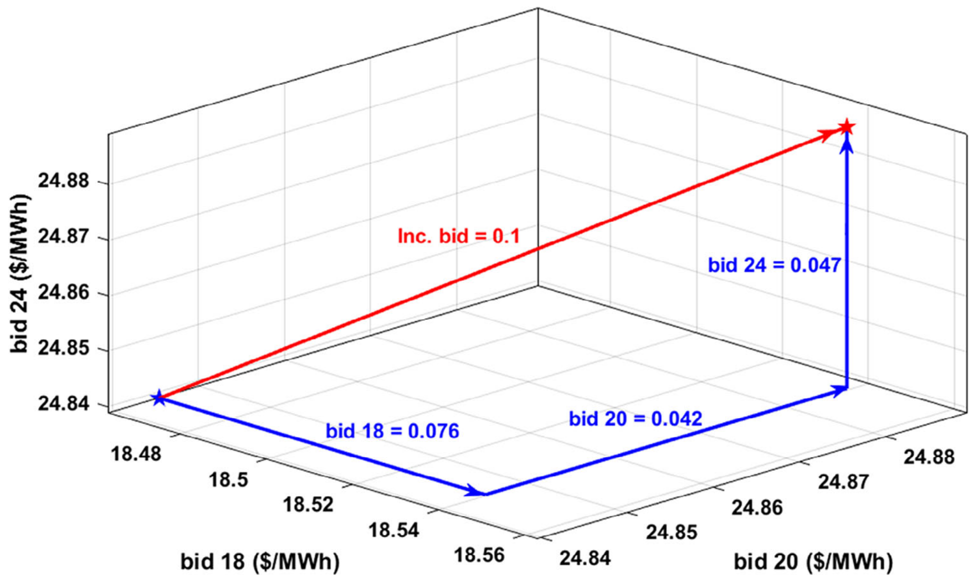

FIGURE 6 Optimal bid direction by gradient vector for GenCo 3 ($K_g = 0.1$ \$/MWh). GenCo, generation company.

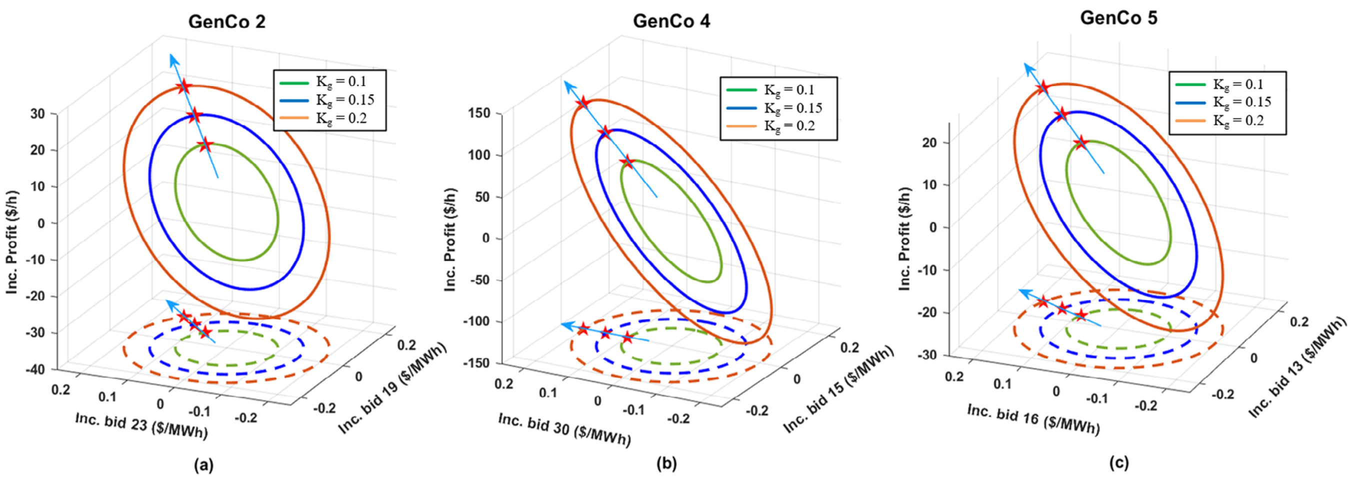

FIGURE 7 Profit changes obtained for GenCos 2, 4, and 5 from the simulation method. GenCo, generation company.

advantage of the gradient vector method over the simulation approach is its efficiency in computation. While the simulation method requires numerous iterations to refine the results, the gradient method necessitates only a single execution.

On the other hand, GenCo 3 has three marginal units. Therefore, the consideration of bid price adjustments for these units can be visualized as a sphere with a radius of K_g. Figure 8 shows the profit obtained from different values of the bid price of the units with different steps of the simulation method. Notably, the maximum profit achieved through the simulation method at a step increment of 0.1 \$/MWh is 11.32 \$/h. In order to achieve this profit, units 18, 20, and 24 are required to adjust their bid prices to 0.076, 0.042, and 0.047 \$/MWh, respectively, aligning precisely with the results derived from the gradient vector method. In addition, Figure 8 also presents the profits associated with higher step increments of 0.15 and 0.2 \$/MWh, and their maximum profits obtained at these increments match those obtained from the gradient vector method.

5 | CONCLUSION

This paper introduces a pioneering method that leverages the gradient vector to optimize the bid prices of generation companies (GenCos) for maximum profitability with specified price adjustments. By comparing the outcomes of this novel approach with those derived from traditional simulation methods, the accuracy and effectiveness of the proposed method are validated. The key advantages and findings of this research include:

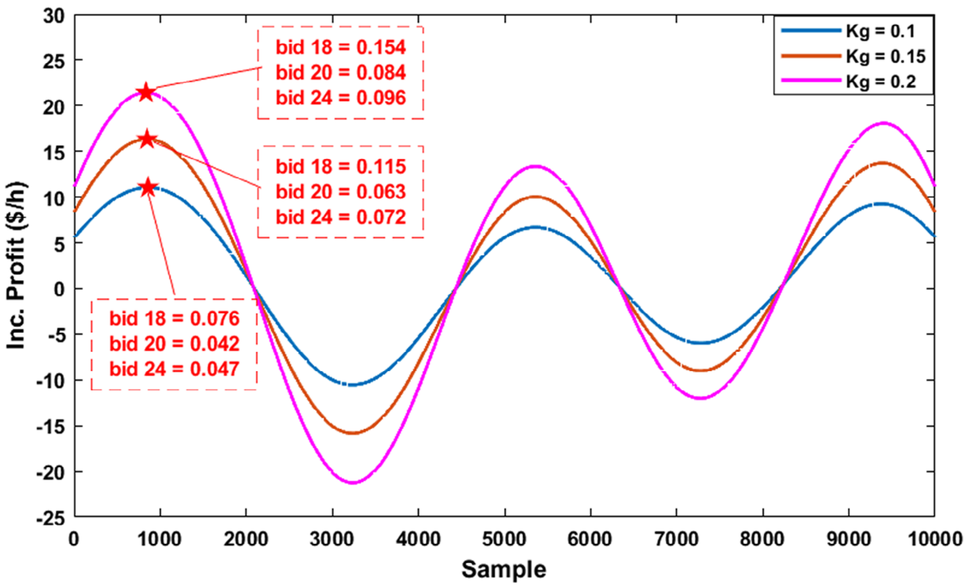

FIGURE 8 Profit changes obtained for GenCo 3 from the simulation method. GenCo, generation company.

- Contrary to the simulation method, which may require multiple iterations, the market-clearing program needs to be executed only once to identify the optimal direction for bid price changes of each GenCo's unit.
- The profit adjustments for each GenCo, attributable to changes in the optimal bid direction of their marginal units, have been meticulously calculated. Notably, the highest and lowest profit changes, with a step increment of 0.1 $/MWh, were observed for GenCo 4 and GenCo 6, with the values of 60.28 and 2.20 $/h, respectively.
- The method demonstrates the capability to accurately determine optimal bid price changes for each GenCo across varying steps (K_g).

The proposed method's applicability extends beyond the confines of the 24-bus network used for this study, suggesting potential for implementation in larger networks. Future research could explore the method's scalability and effectiveness in broader contexts, aiming to refine and adapt the approach for enhanced profit optimization in the evolving electricity market landscape.

AUTHOR CONTRIBUTIONS

Mohammad Ebrahim Hajiabadi: Substantial contributions to the conception or design of the paper; or the acquisition; analysis; or interpretation of data for the paper. **Mahdi Samadi**: Revising the paper critically for important intellectual content; final approval for publishing the paper. **Mohammad Hassan Nikkhah**: Revising the paper critically for important intellectual content. **Hossein Lotfi**: The important role for drafting the paper. **Li Li**: Revising the paper critically for important intellectual content.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data will be made available on request.

ORCID

Mohammad Ebrahim Hajiabadi https://orcid.org/0000-0002-7035-4125
Mahdi Samadi https://orcid.org/0000-0003-4987-5951
Mohammad Hassan Nikkhah https://orcid.org/0000-0001-8675-7191
Hossein Lotfi https://orcid.org/0000-0001-9514-7352

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