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Research Article

Distributed Generation Approach with Helping of Charging Stations

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ABSTRACT

This study addresses the optimization difficulties created by the combination of distributed generation (DG) and charging stations (CS), with the key difference that charging stations not only permit electric vehicle charging but also actively contribute to power supply. Using Convex Optimization (CVX) methods, the study formulates and solves optimization issues for coordinating and controlling DG units, taking into account charging stations' dual roles as power suppliers. The findings indicate that EVs can significantly contribute to grid stability, but challenges such as battery degradation and the need for advanced battery management systems (BMS) must be addressed to optimize these benefits. Simulation results show a potential improvement in grid stability the promise and the practical considerations of this innovative approach.

Keywords: *Distributed Generation, Electric Vehicle Charging Stations, Convex Optimization, Energy Management, Power System Optimization*

Şarj İstasyonlarının Yardımıyla Dağıtık Üretim Yaklaşımı

ÖZ

Bu makale, dağıtık enerji üretimi (DG) ve şarj istasyonlarının entegrasyonundan kaynaklanan optimizasyon zorluklarına odaklanmaktadır. Özel bir nokta ise şarj istasyonlarının yalnızca elektrikli araç şarjını kolaylaştırmakla kalmayıp aynı zamanda aktif bir şekilde enerji tedarik etmeleridir. Convex Optimization (CVX) yöntemlerini kullanarak, çalışma, şarj istasyonlarını enerji tedarikçisi olarak dikkate alarak DG birimlerini koordine etmek ve kontrol etmek için optimizasyon problemlerini formüle etmekte ve çözmektedir. Bu yaklaşımın amacı, şebeke istikrarını artırmak ve enerji dağıtımını optimize etmektir. Bulgular, EV'lerin şebeke istikrarına önemli ölçüde katkıda bulunabileceğini, ancak bu faydaları optimize etmek için pilin bozulması ve gelişmiş pil yönetim sistemlerine (BMS) duyulan ihtiyaç gibi zorlukların ele alınması gerektiğini gösteriyor. Simülasyon sonuçları, şebeke istikrarında potansiyel bir iyileşme olduğunu, bu yenilikçi yaklaşımın vaadini ve pratik hususlarını göstermektedir.

Anahtar Kelimeler: *Dağıtık Üretim, Elektrikli Araç Şarj İstasyonları, Dışbükey Optimizasyon, Enerji Yönetimi, Güç Sistemi Optimizasyonu*

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I. INTRODUCTION

The development of Electric Vehicles (EVs) is a turning point in the automotive industry, demonstrating a key transition towards a more sustainable and environmentally sensitive paradigm of transportation. The move from internal combustion engines to electric power has become a key component of international efforts to reduce environmental impact, pushed by growing concerns about air quality and climate change [1-2]. The development of electric vehicles (EVs) has progressed at an impressive rate due to developments in battery technology, increased energy efficiency, and growing interest in environmentally friendly transportation options. This change represents a major turning point in the history of mobility and opens the door to a future where personal transportation is more sustainable and cleaner [2-3].

The benefits of electric vehicles (EVs) go beyond environmental factors same as other sources [4] to include practical and economic aspects [6-7]. Electric vehicles (EVs) are a desirable option for fleet operators and individual consumers alike due to their lower maintenance costs, less reliance on oil, and lower operating costs. In addition, EVs' developing infrastructure, which includes a growing network of charging stations, makes it easier for them to integrate seamlessly into daily life [7-8].

The role that electric vehicles (EVs) can play as flexible mobile energy storage has received a lot of attention lately, especially when it comes to power grid management—especially when those power grids are dependent on renewable energy sources. Furthermore, bidirectional energy flow and two-way communication between EVs and the grid are made possible by the vehicle-to-grid (V2G) technology [8-9]. As noted in [10], in recent years, concepts like vehicle-to-home (V2H), vehicle-to-vehicle (V2V), and vehicle-to-grid (V2G) have become more and more appealing, with the potential to become a reality in the near future due to the charging/discharging capabilities of EVs and the energy-efficient requirements of power grids.

Prior studies [11-12-13] have demonstrated the potential of V2G in enhancing grid resilience and efficiency. Additionally, convex optimization has been widely applied in energy management systems for its ability to provide global optimal solutions under various constraints [12]. These references underline the relevance and innovative nature of combining V2G and convex optimization in this study. The ever-growing landscape of distributed generation and the widespread adoption of electric vehicles introduce a novel dimension where charging stations not only facilitate charging but also actively contribute to the power grid. This paper delves into the challenges and opportunities presented by this dual role of charging stations. Employing Convex Optimization methods [14], the study seeks to optimize the coordination and control of distributed generation units, taking into account the unique characteristic of charging stations as active power suppliers. The introduction outlines the motivation for this research, highlights the significance of addressing the dual-role charging stations, and presents the current state of the field.

In this article, the emphasis is placed on the V2G (Vehicle-to-Grid) capability of electric vehicles as a form of distributed generation (DG). Unlike traditional DG methods which include renewable sources like solar and wind, this study specifically explores the potential of electric vehicles to supply power back to the grid. This dual functionality of EVs not only supports the energy infrastructure but also contributes to grid stability and efficiency. The primary focus of this paper is to analyze both the technical and economic impacts of integrating V2G with distributed generation systems. Simulation results will distinctly address the technical aspects, such as power distribution and grid stability, and the economic aspects, including cost evaluation. For instance, the technical impact is evaluated through parameters like voltage stability and load balancing, while the economic impact is quantified using specific cost metrics and savings.

The paper's organization is as follows: in Section II explanation of the background of distributed generation and definition of convex optimization problem and the integration of proposed approach. In

Section III, focuses on presenting case studies and the simulation results. Conclusions are given in Section IV.

II. PRELIMINARIES

A. OPPORTUNITIES AND OBSTACLES OF ELECTRIC VEHICLES AS DISTRIBUTED ENERGY SUPPLIER

EVs have emerged as dynamic assets capable of enhancing grid stability by serving as flexible mobile energy storage units, mitigating strain during peak demand periods and emergencies. Their integration holds promise in supporting the balance between energy supply and demand, especially crucial in the context of intermittent renewable energy sources, thus contributing to a more resilient and adaptable grid infrastructure. Economically, EV owners stand to gain from participating in vehicle-to-grid (V2G) programs, tapping into additional revenue streams through the sale of excess energy back to the grid [15-16]. Simultaneously, utility companies can leverage the existing EV fleet to optimize resource allocation, thereby potentially saving on the costs associated with building new power plants or storage systems. Beyond economic advantages, the environmental impact of integrating EVs into the energy ecosystem cannot be overstated, with reduced reliance on fossil fuels leading to lower greenhouse gas emissions and fostering a more sustainable energy paradigm.

However, alongside these opportunities, a set of formidable obstacles must be addressed to unlock the full potential of EVs in this capacity. Battery degradation emerges as a significant concern, with frequent charging and discharging cycles accelerating wear and potentially reducing overall battery lifespan [17-18] is addressing the impact of vehicle-to-grid (V2G) on battery degradation and degradation is a critical concern for the successful implementation of V2G deployment This not only presents a challenge for maintaining EV fleets but also raises questions about the long-term viability of V2G participation. Technological and infrastructure limitations further complicate matters, as current grid infrastructure may not be adequately equipped to handle the bidirectional flow of energy between EVs and the grid. Overcoming these challenges requires substantial investment in infrastructure upgrades and the development of advanced battery management systems to ensure optimal performance and longevity. Additionally, economic and policy considerations play a crucial role in determining the feasibility of integrating EVs into the energy ecosystem. Economic viability hinges on factors such as electricity prices, incentives, and the cost of battery replacement, necessitating a clear and supportive policy framework to incentivize widespread adoption.

B. DISTRIBUTED GENERATION

Distributed generation refers to the generation of electricity from various small-scale energy sources located near the end-users, reducing the need for centralized power plants [22-23]. This approach aims to enhance energy efficiency, reliability, and sustainability. Mathematical equations play a crucial role in modeling and optimizing distributed generation systems. These equations encompass diverse parameters such as power output, efficiency, and cost factors, allowing engineers and researchers to formulate models that optimize the deployment and operation of distributed generation technologies. By employing mathematical equations, stakeholders can analyze the economic viability, environmental impact, and overall performance of distributed generation systems, fostering advancements in the integration of renewable energy sources into decentralized power networks [19-20]. In a distributed generation system, a quadratic cost function might be expressed as:

$$C(q) = aq^2 + bq + c \tag{1}$$

Where, $\mathrm{C(q)}$ is the total cost as a function of the quantity q, which could represent the installed capacity or power output of the distributed generation system. $\mathrm{a, b}$, and c are coefficients that depend on various factors such as initial invesment costs, variable costs, and fixed costs. The quadratic term $\mathrm{aq^2}$ signifies that the cost is proportional to the square of the quantity, suggesting economies or diseconomies of scale. The linear term bq captures additional costs that may increase linearly with the quantity, and the constant term c represents fixed costs that do not depend on the quantity.

C. CONVEX OPTİMİZATİON

Convex optimization is chosen for its robust ability to handle complex energy management problems while ensuring global optimality and computational efficiency. In the literature, convex optimization has been recommended for its tractability and effectiveness in distributed energy resource management [21]. By leveraging these properties, this study aims to optimize the coordination of DG units with V2G capabilities effectively.

Convex optimization is a mathematical discipline focused on the minimization or maximization of convex functions, subject to linear equality and inequality constraints. A convex function is one whose domain is a convex set, and it satisfies the property that the line segment connecting any two points on its graph lies above the graph itself. The general form of a convex optimization problem is given by:

$$\begin{array}{ll} \text{minimize} & f(x) \\ \text{subject to} & g_i(x) \leq 0, \quad i = 1, \dots, m \\ & h_j(x) = 0, \quad j = 1, \dots, p, \end{array} \tag{2}$$

where x is the optimization variable, f(x) is the objective are the function, $g_i(x)$’s are the inequality constraints, and $h_j(x)$’s are optimization problems the equality constraints. Convex optimization problems have widespread applications in various fields, including machine learning, signal processing, and control systems.

The CVX method provides a convenient and expressive way to formulate and solve convex optimization problems in MATLAB. The CVX package allows users to specify optimization problems using a natural and readable syntax. For instance, the objective and constraints of a convex optimization problem can be expressed concisely in CVX as:
Consider the subsequent optimization presented in its standard format:

$$\begin{array}{ll} \text{minimize} & f_0(x) \\ \text{subject to} & f_i(x) \leq 0, \quad i = 1, \dots, m \\ & h_i(x) = 0, \quad i = 1, \dots, p \end{array} \tag{3}$$

Convex optimization offers numerous advantages, making it a powerful tool for solving a wide range of optimization problems. One key advantage lies in the mathematical tractability of convex functions, ensuring that a local minimum is also a global minimum, simplifying the optimization process. Convex optimization problems are well-structured, allowing for efficient algorithms that guarantee convergence to the optimal solution. Additionally, the duality theory associated with convex optimization enables the derivation of strong theoretical guarantees, such as optimality conditions and bounds on the optimality gap.

When compared to non-convex optimization methods, convex optimization stands out in terms of global optimality guarantees. In non-convex optimization, finding a global minimum is challenging due to the presence of multiple local minima. Convex optimization, on the other hand, provides assurance that the solution obtained is globally optimal, eliminating concerns about getting trapped in suboptimal solutions. Convex optimization methods, illustrated by ule CVX package in MATLAB, also excel in terms of ease of implementation and readability. The clear syntax of CVX enables users to articulate difficult optimization issues in a comprehensible manner. Convex optimization attracts to researchers and practitioners in domains such as machine learning, finance, and engineering due to its simple nature of use and ability to solve a wide range of convex problems.

In summary, the advantages of convex optimization, including mathematical tractability, efficient algorithms, global optimality guarantees, and user-friendly interfaces like CVX, position it as a preferred approach for addressing optimization challenges in diverse applications.

III. CASE STUDIES

Distributed generation sources based on renewable energy can be integrated into the modern distribution system, and the percentage used has been continually increasing. After utilizing different approaches for each aggregator, we developed distributed generation dispatch approach with the help of vehicle charging station. We assumed that there is one slack bus, and 3 charging stations are capable supply power during one day which is 1440 minutes. Each charging station are considered a supply bus. To achieve the best outcome for the objective function, we employ CVX, a MATLAB®-based software (R2018b). The simulations were carried out on a Windows-based computer featuring a 2.8 GHz Intel Core-i5 processor and 16 GB of RAM. Our case studies are developed by following criteria's:

Total power that is supplied in each time period must equal the demand:

$$\sum_{i=1}^{n} P_i\,(t) = d_t\ , \mathrm{t} = 1, \dots ,1440 \tag{4}$$

Fach bus has a minimum and maximum allowed output power:

$$P_i^{min} \leq P_{i,t} \leq P_{\mathrm{i}}^{max}\ , \mathrm{t} = 1, \dots ,1440 \tag{5}$$

We assume that cost functions are quadratic:

$$\phi_{\mathbf{i}}(u) = \delta + \alpha_{\mathbf{i}} u + \beta_{\mathbf{i}} u^2 \tag{6}$$

$\delta =$ cost coefficients of the ith bus
$\alpha_{\mathbf{i}} =$ cost coefficients of the ith bus
$\beta_{\mathbf{i}} =$ cost coefficients of the ith bus
u= amount of power

Using equation 6, we developed our objective function which is given in equation 7 by considering equations 4-5 and 6.

$$\mathrm{C} = \sum_{\mathrm{i}=1}^{\mathrm{n}} \sum_{\mathrm{t}=1}^{\mathrm{T}} \phi_{\mathrm{i}}\left(\mathrm{p}_{\mathrm{i,t}}\right) \tag{7}$$

$$\begin{array}{ll} \text{minimize} & \sum_{\mathrm{t}=1}^{\mathrm{T}} \left(\phi_{\mathrm{i}}(\mathrm{p}_{\mathrm{i,t}})\right) \\ \text{subject to} & \mathrm{P}_{\mathrm{i}}^{\mathrm{min}} \leq \mathrm{p}_{\mathrm{i,t}} \leq \mathrm{P}_{\mathrm{i}}^{\mathrm{max}}, \mathrm{t} = 1, \dots, \mathrm{T} \\ & \sum_{i=1}^{n} P_i\,(t) = d_t\ ,\ \mathrm{t} = 1, \dots, \mathrm{T} \end{array} \tag{8}$$

We assume that slack bus is main bus that cover the demand, it has lowest cost coefficients. The bus demand is given in Figure 1. In Case I we are observing if slack bus is not able to meet the total demand, we can see that charging stations become active regarding to cost coefficient. In this case charging station 4 is not active and other supply are not exceeding their maximum supply limit. Coefficients of cost function are given Table 1.

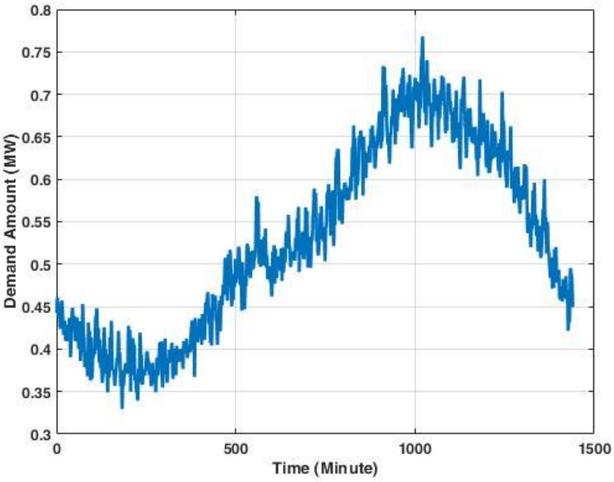

Figure 1. *Power demand during a day*

Table 1. *Parameters of cost function for Case I*

	δ	α_i	β_i	**Pmax**	**Pmin**
Slack Bus	3	0,1	0,1	0,6	0
Charging Station-1	0,5	0,4	0,1	0,1	0
Charging Station-2	0,5	0,5	0,1	0,1	0
Charging Station-3	0,5	0,6	0,1	0,1	0

After utilizing proposed algorithm, power supply and cost are calculated in Figure 2. In Case I, where the slack bus is unable to meet total demand, charging stations with lower cost coefficients are activated, then total demand is covered. However, total cost of power is increased around %100 percent by using different charging stations.

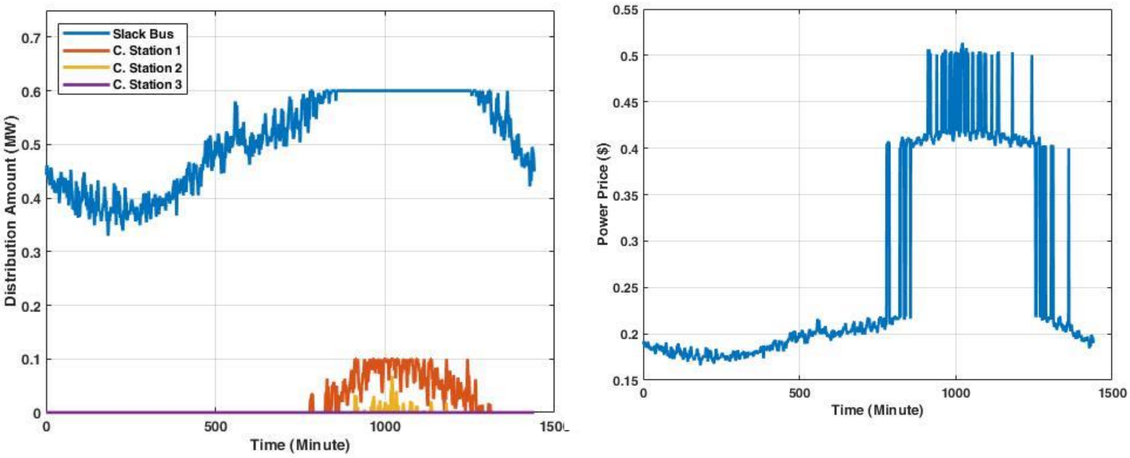

Figure 2. (a) *Power distribution amount.* ***(b)*** *Power price after distribution.*

In case II, we assume that slack bus is not able to cover the demand for a certain time and all charging stations have to power during emergency. In this case, we decrease slack bus Pmax amount from 0.6 mw to 0.5 mw and other parameters remain same which is given Table 2.

Table 2. *Parameters of cost function for Case II*

	δ	α_i	β_i	**Pmax**	**Pmin**
Slack Bus	3	0,1	0,1	0,5	0
Charging Station-1	0,5	0,4	0,1	0,1	0
Charging Station-2	0,5	0,5	0,1	0,1	0
Charging Station-3	0,5	0,6	0,1	0,1	0

After utilizing proposed algorithm, power supply and cost are calculated in Figure 3. In Case II, where the slack bus is unable to meet total demand, charging stations with lower cost coefficients are activated, then total demand is covered. However, total cost of power is increased more than case I, because this time charging station 3 is also active and it has biggest cost efficient.

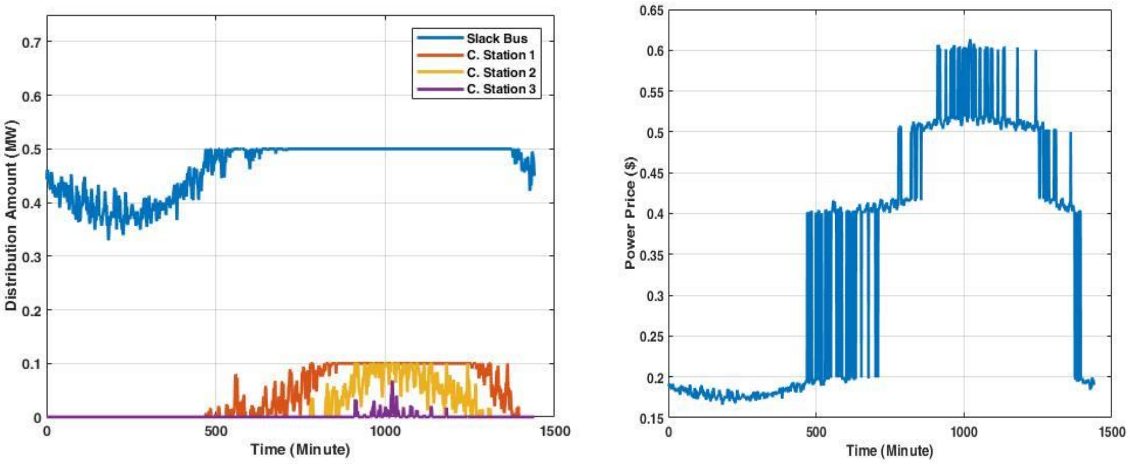

Figure 3. (a) *Power distribution amount.* ***(b)*** *Power price after distribution.*

IV. CONCLUSION

In conclusion, this paper presents a distributed generation approach that effectively integrates charging stations as active power suppliers. Utilizing Convex Optimization methods, the study successfully addresses the optimization challenges associated with the coordination and control of distributed generation in the presence of charging stations with a dual role. As electric vehicle adoption continues to rise, the proposed approach provides a foundation for resilient and efficient power infrastructure accommodating the dual functionality of charging stations. This study finds that V2G integration via convex optimization significantly enhances grid stability enhancement and optimal energy distribution. Future research could explore the integration of other optimization techniques and real-time data analytics to further improve system efficiency and resilience. Additionally, expanding the scope to include renewable energy sources alongside V2G could provide comprehensive solutions for sustainable energy management.

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