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Research Article

Linear Approach for Determining Optimal DG in Feeder Due to Increased Electric Vehicle Load

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ABSTRACT

In the era of artificial intelligence, power distribution is increasingly oriented toward green energy. Advances in various fields, particularly transportation, have played a crucial role in driving economic growth through the mobility of goods and people. However, the transportation sector has long been a major contributor to air pollution due to its reliance on fossil fuels. As a solution to this environmental issue, automotive experts have developed electric vehicles (EVs) to replace conventional vehicles. The rapid growth of EVs, especially in large cities, has impacted power distribution expansion to meet battery charging demands. Many EV charging stations are connected to existing feeders, leading to system overload in power distribution networks. One of the best solutions to address this issue is to inject power from Distributed Generator (DG)-based power plants, particularly those utilizing green energy sources. This paper presents an optimization method for optimal DG to restore overloaded feeders to normal operating conditions. Testing on an extended IEEE 21-node distribution system, expanded to 28 nodes, reveals that after connecting three EV charging stations, the voltage drop increased from 3.891% (existing condition) to 5.01%. The optimization results indicate that placing a DG at node 6 with a capacity of 642.2 kVA can reduce the voltage drop to 4.0%. If the DG with the same capacity is placed outside node 6, the voltage drop will be higher. For example, placing it at node 5 results in a voltage drop of 4.42%.

Keywords: Power Distribution,Green Energy,Electric Vehicles,Optimal DG,Voltage Drop.

INTRODUCTION

The rapid advancement of electric vehicle (EV) technology is driven by rising oil prices and the environmental impact of conventional vehicles. As a result, EV-based transportation has become a preferred choice in modern society. However, the increasing adoption of EVs significantly impacts the existing power distribution network. The connection of EV charging stations to distribution feeders can lead to overload conditions, characterized by voltage drops exceeding permissible limits. This issue can be mitigated by injecting power from distributed generation (DG) units rather than expanding the feeder network.

The analysis of how the increasing adoption of EVs impacts investments in the power distribution network is presented by [1]. Using a novel model, this study finds that large-scale EV adoption could increase the need for new grid infrastructure and raise the average network cost by up to 84% compared to current conditions. Study [2] employs a multi-agent-based simulation to evaluate the impact of EV adoption on the power distribution network and national CO_2 emission targets. The findings indicate that the existing residential distribution network cannot accommodate the rising EV load, with an estimated overload occurring by 2031 when EV penetration reaches 67% within the system.

An exploration of coordination between transmission and distribution networks to accommodate a higher penetration of EVs and photovoltaic (PV) systems is presented in [3]. The authors emphasize the importance of utilizing existing assets and flexibility to integrate EVs and PVs without exceeding operational constraints at both transmission and distribution levels.

Voltage drop due to distribution line resistance and impedance, along with solutions such as reactive power compensation and voltage control, has been comprehensively discussed in [4]. Meanwhile, [5] highlights the Voltage

Quality Controller technology as an advanced solution to mitigate voltage drops in modern grids using a smart grid-based approach. Both books provide valuable insights into the causes, effects, and technical solutions for improving voltage quality in power distribution systems.

The impact of DG on voltage variations within distribution networks is examined in [6], where the authors identify worst-case scenarios and propose mitigation strategies to maintain voltage stability. Study [7] focuses on optimizing distribution system configuration to reduce power losses. While not directly addressing DG, the reconfiguration concepts discussed are relevant for determining the optimal DG placement to enhance network efficiency. A quantitative assessment method for evaluating the technical benefits of DG, including power quality improvement and distribution system efficiency, is developed in [8]. Meanwhile, aspects of DG planning and evaluation, including optimal DG placement strategies to minimize power losses and enhance distribution network stability, are the focus of [9].

The discussion on business models for EV adoption and charging infrastructure in Brazil is provided by [10,11]. This research highlights key challenges such as infrastructure costs, regulatory barriers, and grid integration. Additionally, identified opportunities include government incentives, advancements in battery technology, and potential collaboration between the public and private sectors. The study also examines how various business models can enhance EV adoption by considering economic factors and sustainable energy policies, categorizing EV charging models in Table I

Tabel 1: Duration of EV charging time

Power (kW)	Current type	Category	Time (minutes)
11	AC	Semi-fast	240
22	AC	Semi-fast	120
43	AC	fast	60
50	DC	Ultra-fast	50
150	DC	Ultra-fast	16

The calculation and monitoring of voltage drop in distribution feeders have been studied in [11], [12], [13], [14], [15]. The method for calculating voltage drop and designing optimal distribution feeders in urban areas to improve power system efficiency and reliability is successfully presented in [11]. A voltage drop monitoring method on the load side of medium-voltage feeders, using a real-time measurement-based approach to enhance voltage quality, is discussed in [12]. An analysis of voltage drop in medium-voltage distribution networks—considering feeder currents at the substation transformer to optimize distribution system performance—is examined in [13] . Meanwhile, [14] proposes a parametric model for evaluating and predicting voltage drop in distribution networks, which can be used for more accurate power system planning and operation. The estimation method for technical losses in primary feeder conductors of the distribution system is discussed in [15]. This approach considers network parameters such as conductor impedance and load distribution to improve the accuracy of power loss calculations. The study provides insights into factors affecting distribution system efficiency and offers methods that can assist in power network planning and optimization to minimize energy losses.

The study on EN 50160 standards [16] defines voltage characteristics in public distribution systems across Europe. This standard includes power quality parameters such as nominal voltage levels, voltage variations, frequency, flicker, harmonics, and other voltage disturbance phenomena. The study provides an in-depth understanding of the voltage quality limits that electricity providers must meet to ensure energy supply reliability and protect customers' electrical equipment.

The study on optimal DG capacity is successfully implemented in [17]. The proposed method uses a feeder current-based approach to determine voltage drop. The optimal DG capacity is defined such that the maximum voltage drop does not exceed the allowable limit. Adjustments in DG power injection are used to regulate voltage drop reduction until it reaches the permissible threshold.

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The following three references discuss different approaches to the placement and sizing of Distributed Generation (DG) in distribution networks. Reference [18] proposed a multi-objective approach based on Particle Swarm Optimization (PSO) to optimize power losses, system reliability, and operational constraints, demonstrating improved distribution efficiency. Refrence [19] applied Grey Wolf Optimization (GWO) to the IEEE 33-bus system and a real 59-bus system, achieving significant reductions in power loss and improved voltage profiles. Meanwhile, [20] focused on DC distribution networks and developed a stochastic Mixed-Integer Linear Programming (MILP) model to account for uncertainties in load demand and renewable energy supply. These three studies offer important contributions to effective and sustainable DG planning, although their implementation requires detailed load data at each node, resulting in long computation times.

In the current era, the growth of electric vehicles (EVs) has become a reality, especially in major cities. Charging an EV requires power ranging from 11 kW to 150 kW, as shown in Table 1. On the other hand, existing feeders were originally designed to serve conventional loads, with loading levels already approaching their maximum capacity (between 70% and 90%) of approximately 10 MVA. If additional loads exceed the feeder's capacity, the feeder network must be expanded. While technically feasible, feeder network expansion requires significant investment. A cost-effective alternative to address this issue is injecting power into the feeder to reduce voltage drop back to its normal level. In addition, online monitoring of feeder loading must use a fast calculation method

This paper is an extension of [18], which previously studied DG capacity optimization. The current study further develops this work by determining the optimal DG location using a linear current-based approach on distribution feeders. From this linear model, the voltage drop is calculated as a function of feeder distance, enabling a rapid evaluation of voltage drop along the feeder

OBJECTIVES

A feeder experiencing load expansion from EV charging stations may become overloaded, indicated by a voltage drop exceeding its maximum limit, as shown in Figure 1. This voltage drop is used to evaluate the feeder, ensuring its operation remains normal (i.e., the voltage drop stays within permissible limits). The reduction of voltage drop is achieved by injecting power from a Distributed Generation (DG) source.

This optimization helps maintain voltage levels within acceptable limits while preventing excessive losses. Proper DG placement also enhances the overall efficiency and reliability of the power distribution system. As a result, the integration of DG supports a more sustainable and stable electrical network.

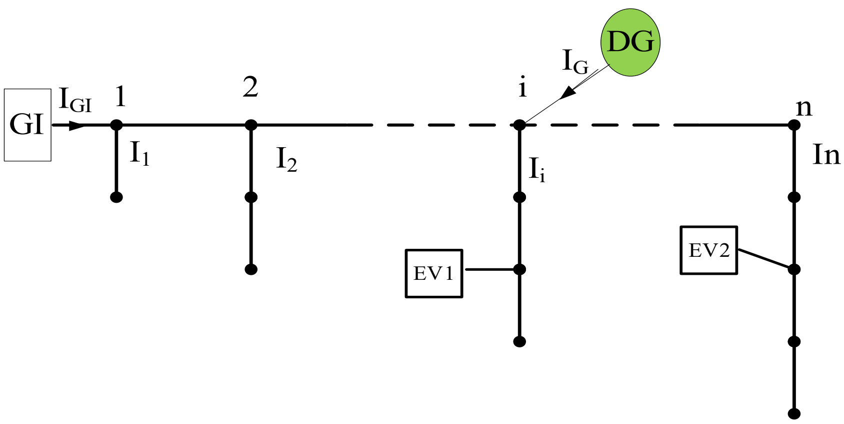

Figure 1: Current versus distance in feeder

This simplification allows for more efficient calculations in determining the optimal DG placement. A linearized current flow model helps predict voltage drops more accurately across the feeder. With this approach, the required DG capacity can be minimized while maintaining voltage stability. Ultimately, this method enhances the efficiency and reliability of the power distribution.

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METHODS

A. Optimal Capacity of DG

The current flowing in the feeder consists of the aggregate of the existing load current, the EV station load current, and the injected DG current. According to [18], the current in the feeder after expansion is influenced by these three components. The expansion of EV stations increases the total feeder current, leading to a higher voltage drop. To mitigate this, DG injection helps compensate for the additional load. Proper sizing and placement of the DG ensure that the feeder operates within acceptable voltage limits.

$$I = I_T + I_{ev} - I_{DG} \qquad (1)$$

Where I is the total current flowing in the feeder, I_T is the total current in the feeder before expansion, I_{ev} is the total current from the expanded EV station load, and I_{GD} is the injection current from the DG. For a DG power of S_{DG} and feeder voltage V, then:

$$I_{DG} = \frac{S_{DG}}{\sqrt{3}\ \mathrm{V}} \qquad (2)$$

Then, the voltage drop is defined based on the lamp load, namely:

$$\Delta V_n = sZ_{Tm} I \qquad (3)$$

Where Z_{Tm} is the total impedance of the main feeder, s is the ratio of the lumped load distance to the feeder length, and I is the input current into the feeder.

After the feeder expansion with DG injection, the voltage drop based on (3) is recalculated to reflect the new current distribution. The DG helps reduce the voltage drop, ensuring that the feeder operates within acceptable limits.

$$\Delta V_n = sZ_{Tm}\left(I_T^* - \frac{S_{DG}}{\sqrt{3}\ \mathrm{V}} \right) \qquad (4)$$

where,

$$I_T^* = I_T - I_{ev} \qquad (5)$$

From (4), the change in voltage drop with respect to the change in DG power is obtained as follows:

$$\Delta(\Delta V_n) = -sZ_{Tm} \frac{1}{\sqrt{3}\ \mathrm{V}} \Delta S_{DG} \qquad (6)$$

Equation (6) states that an increase in power injection from the DG will reduce the voltage drop. The optimal DG capacity is achieved when the voltage drop decreases to its allowable limit. Suppose the limit is x%, and the voltage drop before DG power injection exceeds this limit by Δx, then the required DG capacity is:

$$S_{DG} = \frac{\sqrt{3}\ V}{sZ_{Tm}} x \qquad (7)$$

B. Optimal Location of DG

Generally, the feeder load is not uniform, which causes the current flowing along the feeder to be nonlinear, as shown in Figure 2. If the current flowing along the feeder is approximated as linear (dashed line), then the current as a function of feeder distance is simplified as follows:

$$I(x) = I_F - ax \qquad (8)$$

Journal of Information Systems Engineering and Management
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Research Article

Where $I(x)$ is the current as a function of the feeder distance x, and I_F represents the feeder current (i.e., the incoming current to the feeder). Meanwhile, a is a function of the feeder length L and the current at the end of the feeder I_N,

$$a = \frac{I_F - I_N}{L} \quad (9)$$

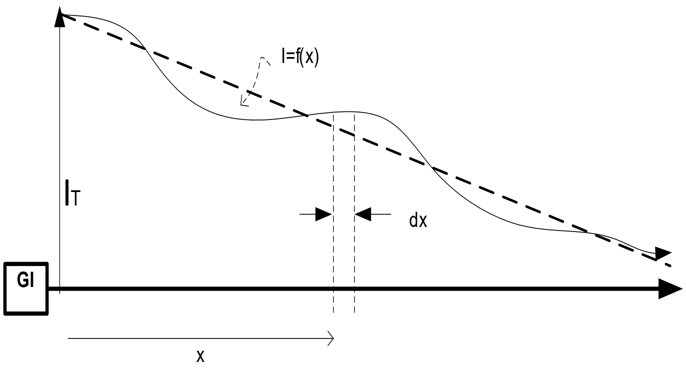

Figure 2: Current versus distance in feeder

Meanwhile, the impedance of the element dx is given by:

$$\partial Z = z\,\partial \mathrm{x} \quad (10)$$

Where z is the characteristic impedance of the feeder line. Subsequently, the voltage drop across this element is given by:

$$\partial V = \partial Z\, I(x) \quad (11)$$

Then, (1) and (3) are substituted into (4), resulting in a new expression for the voltage drop. This result simplifies the analysis of voltage variations along the feeder.

$$\partial V = z(I_F - ax)\partial \mathrm{x} \quad (12)$$

Solusi (12) is,

$$\Delta V(x) = z\left(\mathrm{I_F} x - \frac{1}{2} a x^2\right) \quad (13)$$

This equation represents the calculation of the voltage drop along the feeder. By substituting the value of x from (13), the voltage drop at the end of the line is obtained as follows:

$$\Delta V(n) = \left(\frac{I_F - I_N}{2}\right) zL \quad (14)$$

From Figure 2, the DG current enters at node i. Assuming its distance is x_i and its current is I_{DG}, the current flowing along the line is:

$$I'(x) = \begin{cases} I(x) - I_{DG},\ 0 \le \mathrm{x} < \mathrm{x_i} \\ \mathrm{I(x)}, \mathrm{x_i} \le x \le L \end{cases} \quad (15)$$

From (12), (14), and (15), the voltage drop after the DG current is injected into the feeder can be expressed as:

Journal of Information Systems Engineering and Management
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$$\Delta V(x) = z\left(I_F x_i - \frac{1}{2}a x_i^2\right) - z I_{DG} x_i + z\left(I(x_i)(x - x_i) - \frac{1}{2}a(x - x_i)^2\right) \quad (16)$$

The minimum voltage drop from (16) occurs when the following condition is met.

$$I(x_1) = I_{DG} \quad (17)$$

Thus, the optimal location of the DG is:

$$x_{op} = \frac{I'_T - I_{DG}}{a} \quad (18)$$

C. Research Algorithm

The algorithm developed in this study follows a series of sequential steps. First, the distribution network is modeled, including the topological configuration, load profile, and initial feeder current conditions. Next, a linear current model is applied to calculate the voltage drop at each node. The algorithm then evaluates several potential locations for optimal DG placement based on voltage drop criteria.

This research focuses on optimizing the placement of DG units in the main feeder to reduce voltage drop. To achieve this, a systematic algorithm is developed to evaluate various placement scenarios. The algorithm follows a series of structured steps to identify the optimal DG locations that improve voltage profiles along the feeder:

1. Collect feeder parameter data.
2. Measure the feeder input current (I_T) before expansion and the additional current due to EV load (I_{ev}).
3. Calculate the current at the end of the feeder (I_N).
4. Compute the linear parameter value (a).
5. Calculate the ratio of the lumped load distance to the feeder length (s).
6. Determine the voltage drop limit ($x\%$).
7. Compute the voltage drop (ΔV).
   - If $\Delta V < x\%$, the feeder can be expanded. Proceed to Step 8.
   - Otherwise, inject DG power and proceed to Step 10.
8. Expand the EV load and measure the feeder input current after expansion (I'_T).
9. Calculate the new voltage drop.
   - If $\Delta V < x\%$, proceed to the next step.
10. Compute the optimal DG power (S_{DG}) and its corresponding current (I_{DG}).
11. Determine the optimal DG location ((x_{op}).
12. Obtain and analyze the results.
13. Finish.

D. Case Study

In this case study, an IEEE 21-node feeder [18] is extended to 27 nodes, with 7 additional nodes on the main feeder, as shown in Figure 3. This expansion is assumed to be driven by load growth and the potential presence of DG. Table 2 presents the transformer capacity data. The existing feeder load is assumed to be 140 A at a voltage of 20 kV.

Tabel 2: Capacity of Transformer

No.	Table Column Head		
	Type	Capacity (kVA)	EV Charging Station (kVA)
1	• (dot)	240	80
2	X(cross)	180	70
3	V(vie)	160	60

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Figure 3 shows that the EV station loads are placed on the lateral feeder, with EV1, EV2, and EV3 located at Nodes 2, 34, and 43, respectively. Meanwhile, the optimal DG reduces the voltage drop to 4% after these EV loads, totaling 1500 kVA, are connected.

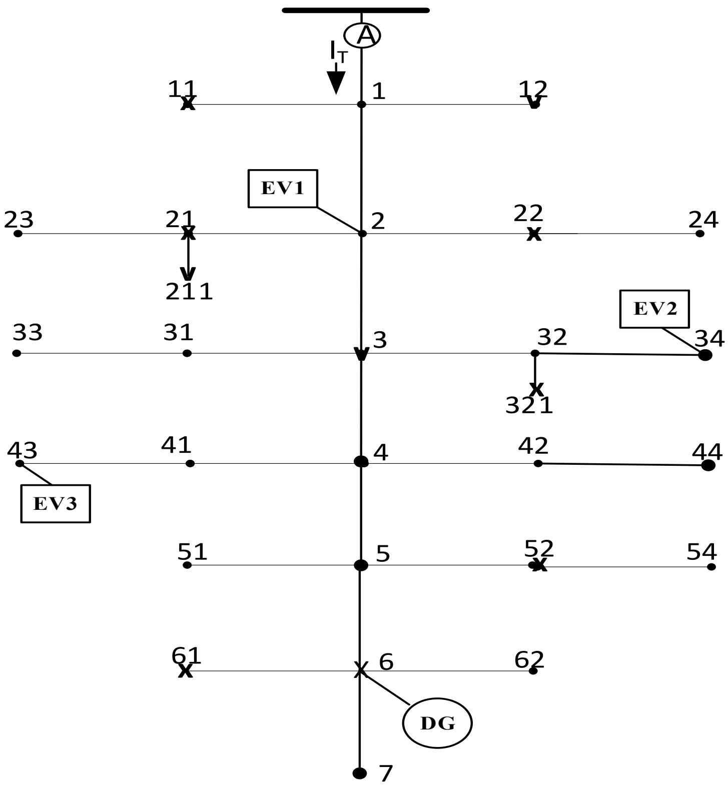

Figure 3: Feeder IEEE 21 nodes diperluas jadi 28 nodes

The calculation results are presented in Table 3. Under existing conditions, the feeder operates normally with a voltage drop of 3.981% (< 4.0%). After connecting three EV stations, the voltage drop increases to 5.01%, exceeding the upper limit of 4.0%. The optimal DG placement is at Node 6, with a capacity of 642.2 kVA. Once the DG is connected, the feeder returns to normal operating conditions. It is important to note that these calculations are based on peak load conditions. If the load is below peak levels, the voltage drop will be less than 4.0%.

Tabel 3: Voltage drop secanario DG 240 kVA

Item	I_T (A)	S_{ev}(kVA)	S_{DG}(kVA)	Location	ΔV (%)
Existing	140	-	-	-	3.981
+EV	180	1500	-	-	5.01
+DG	161.44	-	642.2	N6	4.00

RESULTS

The determination of the optimal DG placement in a heavily loaded feeder—resulting from the expansion of EV charging stations that caused the voltage drop to exceed the maximum limit of 4.0%—has been presented in this paper. The optimal capacity and location of the DG have been mathematically derived and clearly demonstrated.

By optimally designing the DG, its required capacity can be minimized. Since DG power sources are typically clean but limited in capacity—such as photovoltaic panels—optimizing DG capacity is essential for promoting green power distribution.

Calculation results for the feeder case in Figure 3 show that, after the addition of three EV charging stations, the voltage drop increased from 3.981% to 5.01%. The voltage returned to acceptable levels (4.0%) when a DG with a capacity of 642.2 kVA was installed at Node 6. If the same DG capacity is installed at any node other than Node 6, the voltage drop exceeds 4.0%. For instance, placing the DG at Node 5 results in a voltage drop of 4.42%, while at Node 7, it results in 4.04%.

These results demonstrate that the feeder expansion from 21 nodes to 27 nodes can be successfully accommodated without requiring significant modifications to the existing network structure. As a result, the original configuration can be maintained, minimizing the need for reconstruction and preserving overall system efficiency

DISCUSSION

The proposed method for optimizing DG, including both its location and capacity, is presented in this paper. While the optimal DG capacity has been studied by [17], this study focuses on determining the optimal DG location using a linear approach to the current flow in the feeder, allowing the optimal DG placement to be derived mathematically.

This method has been tested on the IEEE 21-node feeder, expanded to 28 nodes, as shown in Figure 3. The calculation results indicate that the optimal DG location is at Node 6 with a capacity of 642.2 kVA (Table 3).

If the DG is placed outside Node 6, the voltage drop will exceed 4.0%. For example, placing it at Node 5 results in a voltage drop of 4.42%. To reduce the voltage drop to 4.0%, the DG capacity must be increased to 1107.2 kVA—an increase of 465 kVA from 642.2 kVA. Similarly, placing the DG at Node 7 results in a voltage drop of 4.04%.

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