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Research Article

Optimal Location and Capacity of Distributed Generators in Expanding Load Distribution in Smart Cities

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ABSTRACT

The efficacy of a smart city relies on robust infrastructure, particularly a reliable electric power distribution system. As urban centers transition from fossil fuel vehicles to electric vehicles and experience economic growth, strategies are required to foster cleaner environments. The rapid increase in feeder loads can lead to overloading, resulting in degraded electricity quality, including voltage drops and significant power losses. Limited power supply from substations exacerbates the challenge of meeting feeder demands. Integrating distributed generators (DGs) powered by renewable energy sources offers a viable solution to these issues. Maintaining optimal power supply conditions for consumers is essential, even amid fluctuating loads. Real-time monitoring of electricity quality on each feeder is critical for evaluating operational status and determining the need for additional power injection. Voltage drop calculations can be effectively performed using feeder current data alone, simplifying assessments compared to traditional measurement and power flow methods that require detailed load data. This facilitates the identification of optimal DG locations and capacities, focusing on minimizing losses. The method's accuracy has been validated through simulations involving seven feeder nodes and applied to the IEEE 21-node feeder, expanded to 26 nodes. The implementation of five public EV charging stations demonstrates the method's practicality. Without DG power injection post-SUPB-EV expansion, voltage drops increased from 3.260% to 5.323%, and losses rose from 2.41 to 1.47. To maintain normal feeder operation, power injections of 300.7 kVA, 186.8 kVA, and 173.4 kVA are required at nodes 4, 5, and 6, respectively.

Keywords: smart city, feeder current approach, green power, public EV battery charging station, voltage drop, optimal DG location and capacity

INTRODUCTION

One key to the success of a smart city is having sufficient electricity infrastructure, particularly using modern technology infrastructure based on sustainable practices [1]. To prevent smart cities from failing, the significant rise in energy demand must be accompanied by effective smart energy planning [2]. Specifically, constant monitoring of electric power is necessary to enable utilization of green energy sources, in line with the goal of creating a sustainable city. It's essential for the electricity supplied to consumers to be reliable and for the quality of electricity to be maintained, with particular attention to ensuring that voltage drop does not exceed standards. The increase in feeder load due to the growing number of electric vehicles and battery charging stations in smart cities will lead to sharp increases in power losses. Monitoring voltage drop at each feeder is therefore necessary to maintain normal feeder operations. In cases of overloading, optimal power injection from Distributed Generation (DG) must be implemented, utilizing green power sources such as solar, wind, and fuel cells to ensure a clean city.

The process of calculating conventional stress drops and losses in reinforcement has been thoroughly explained in [3,4]. However, the measurement method is expensive due to the need for equipment at each load point. The power flow method provides accurate calculations and can be used to validate other methods. On the downside, this method requires data for each node in the feeder and involves iterative adjustments. It also has long computing times, making it unsuitable for real-time applications. Maintaining feeder performance necessitates that the voltage drop along the network stays within the normal operating conditions, which are between 3-5% [5]. However, the feeder can temporarily operate under emergency conditions, with the voltage drops allowed being 5% for normal operation and 10% for emergency operation based on [6].

Several methods for measuring voltage drop have been published [7-10]. The use of operator data in estimating voltage drops has been successfully studied by [7]. The methodology developed involves evaluation and parameters in determining voltage drops in electric power networks. An increase in voltage drop will lead to increased losses. Therefore, accurate calculation of the voltage drop on the feeder is essential. The use of ETAP software to determine the voltage drop has been utilized by [8]. Real-time determination of voltage drop requires a method that works quickly and is cost-effective. In this context, [9] has succeeded in developing a method for calculating the voltage drop at each feeder node using a feeder current injection approach. Procedures for evaluating low voltage drops in distribution networks using benchmark test methodology have been proposed by [10]. Efficient operation of the feeder under normal conditions entails keeping losses small (<2%). Calculation of feeder losses has been studied by [11,12]. Reducing losses at low cost can be achieved by injecting DG power into feeders that experience overload (high voltage drop). An iterative power flow procedure for optimizing losses has been successfully presented by [11]. Voltage regulation in radial distribution networks to minimize losses through reactive power injection and DG was proposed by [12]. Savings on feeder losses can be achieved through optimal capacitor bank placement, as studied by [13].

The optimal placement and size of DG power injection can help to normalize the work of overloaded feeders, as discussed in studies [14-17]. The presence of DG can reduce losses [14] by reducing the current flow in the feeder segments. Using DG to address feeder quality issues due to load growth offers various advantages. Researchers [15] have highlighted the benefits, especially in normalizing DG operations during emergencies caused by overloaded feeders. The presence of DG significantly improves reliability and electricity quality, including reducing voltage drops and losses. However, to maximize the benefits, it is crucial to determine the optimal location and size of DG [16]. Feeders, which are power lines with medium to low voltage at the end, experience significant losses. Several efforts have been made to minimize losses, including capacitor placement [13] and DG placement. To minimize losses, it is essential to optimize the placement of DG. Researchers have successfully used Particle Swarm Optimization (PSO) to determine the optimal location of DG [17].

In the modern era, city development is driving the move towards smart cities. These cities heavily rely on modern technology to ensure the efficient and effective functioning of all infrastructure. The electricity distribution system is a vital infrastructure supporting smart cities. Given the focus on green cities, efforts are underway to transition fossil/oil-fueled vehicles to electric vehicles (EVs). The increasing use of EVs requires the development of public EV battery charging stations. As a result, the electric power distribution feeder load will increase in tandem with the growth of SUPB-EV. It is crucial to control the growth of SUPB-EVs to prevent potential collapse of the electricity distribution system supporting the smart city. Such an occurrence could disrupt various activities, particularly in the business sector, resulting in significant financial losses. This paper presents a method to efficiently maintain the quality of electricity distribution. The approach involves calculating voltage drop using a feeder current method to significantly reduce data processing. The voltage drop value will determine whether the feeder is operating normally or is under heavy load. For feeders experiencing heavy load, power injection must be conducted to restore normal conditions. In the context of smart cities, power injection should be sourced from green sources such as solar and wind, with optimal locations and capacities determined using the proposed method. The feasibility of the proposed method is validated against the power flow method to ensure its accuracy and applicability.

OBJECTIVES

The distribution system network consists of medium voltage feeders and low voltage feeders. The quality of the distribution system's power supply is determined by the voltage drop in the medium voltage network, where the medium voltage security must be maintained within its operational limits. The voltage level at the consumer end must be kept within its minimum and maximum limits, for example, V ±5% or a voltage drop of 5%.

With the economic growth and improved welfare of society, the expansion of loads will increase, leading to more heavily loaded feeders (indicated by high voltage drop, exceeding the security limit). The effects of this voltage drop are increased network losses and poor voltage quality. These heavily loaded feeders need to be addressed. One of the suggested options in this article is to inject power through Distributed Generators (DGs). For efficient feeder operation, the location and capacity of DGs must be optimized.

The issue of expanding distribution loads for smart city areas has received attention from experts in various fields of study. The demand for a clean city by reducing the use of fossil fuels has received serious attention from decision-makers (city council). As a result of this policy, there's an increase in the use of electric vehicles, so public electric vehicle battery charging stations must be provided in various locations.

In the context of a smart city, distribution loads will increase rapidly, considering that the load of a single public electric vehicle battery charging station is from 20 kW to 100 kW. The expansion of this load must be identified as soon as possible, so that the operational conditions of the feeders can be known and any heavily loaded feeders can be promptly addressed by injecting power from green DGs to maintain a clean city.

The graph in Figure1 illustrates the reduction in voltage drop and losses resulting from DG power injection, explaining the optimal capacity problem of DG. The voltage drop decreases in a linear function while losses decrease in a nonlinear. An overload occurs when the voltage drop exceeds the maximum limit (ΔV_{max}). The voltage drop limit must be smaller than ΔV_{max}, ensuring an optimal voltage drop (ΔV_{opt}), for safety tolerance.

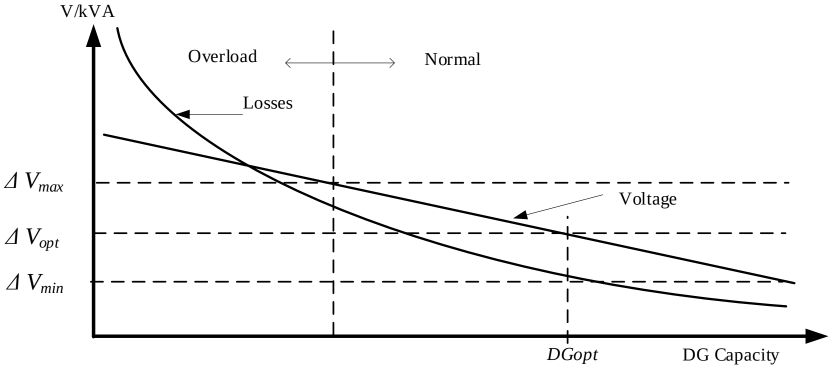

Figure 1. *Optimal DG capacity problem*

The placement of the Distributed Generation (DG) impacts losses. Optimal DG placement is crucial as it can maximize loss savings, as depicted in Figure 2. Generally, when DG is optimally located, the current flow in the feeder segment decreases. The optimal DG location can be determined by projecting the loss saving curve from the maximum point, yielding the optimal point location (L_{opt}). The illustration indicates that placing DG on the supply side does not affect losses (no loss savings), while locating DG at the end of the feeder will not achieve optimal loss savings.

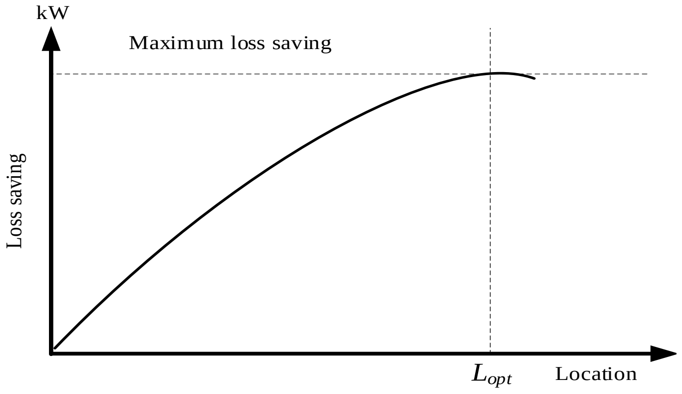

Figure 2. *Optimal DG location*

METHODS

A. Optimal Drop Voltage Calculation

Calculating the stress drop across a feeder can be easily done using measurement techniques. However, a feeder consists of several nodes, and determining the voltage drop at each node requires a large number of measuring instruments. In a distribution system with many feeders, this measurement technique is not economical. Another method for calculating the voltage at each node in the feeder is through power flow calculation. However, this method requires accurate data for each node. To find out the load on each node, measurements need to be taken. While power flow methods such as Newton, Gauss Seidel, and fast decoupled methods can work well, they are inefficient when applied to determine voltage drop at feeder nodes, especially for real-time purposes where the data changes constantly. Additionally, the power flow method will require a long computing time because it works through an iterative process to obtain calculation results.

This paper utilizes the Feder current approach technique developed by [9]. The voltage drop at a node k is expressed in (1). In this equation, there is only a single variable, namely the feeder injection current (I_F), assuming the other parameters are constant.

$$V_{D\text{-}k}=IZ_m\sum_{j=1}^{k\text{-}1}\sum_{i=j+1}^{n}\left(1+c(i\text{-}1)\right) \tag{1}$$

Where V_{D-k} represents the voltage drop at node k, I_F is the incoming feeder current, $Z_{j,j+1}$ is the impedance of segment j, j+1, and n is the number of nodes, and c is the current density factor. If the segment impedance is uniform (Z_m), then (1) can be simplified.

$$V_{D\text{-}k}=IZ_m\sum_{j=1}^{k\text{-}1}\sum_{i=j+1}^{n}\left(1+c(i\text{-}1)\right) \tag{2}$$

If the total impedance of the feeder is Z_t, then

$$Z_m=\frac{Z_t}{n} \tag{3}$$

The voltage drop at the end of the feeder can be derived from (2), namely for k=n and obtained (4).

$$V_{D\text{-}n}=s_v Z_F I_F \tag{4}$$

In this case, V_{D-n} represents the voltage drop at the end node, and s_v is the load point for the voltage drop. Z_F is the total impedance of the feeder. I_F is the supply current injected into the feeder. Suppose the DG capacity is S_{DG}, then the DG current can be defined by (5).

$$I_{DG}=-\frac{\sum_{i=1}^{n}S_{DG}}{\sqrt{3}V} \tag{5}$$

Furthermore, it is assumed that the power factors are identical to each other. Then, the incoming feeder current will be reduced and represented by (6).

$$I_F^*=I_F-I_{DG} \tag{6}$$

From (4), (5), and (6), it is obtained (7).

$$V_{D-n}=-s_v Z_F\left(I_F-\frac{S_{DG}}{\sqrt{3}\,V}\right) \tag{7}$$

To decrease the voltage-drop, we can reduce equation (7) to the DG power.

$$\Delta V_{DG}^{t} = -\frac{1}{\sqrt{3}\ V} \Delta S_{DG}^{t} s_v Z_{Tm} \qquad (8)$$

Or,

$$\Delta S_{DG}^{t} = -\frac{\sqrt{3}\ V}{s_v Z_{Tm}} \Delta V_{DG}^{t} \qquad (9)$$

As a result, the change in DG power is positive because the voltage drop is decreasing. Once we have the DG power change value, we can update the DG power for the next iteration will be defined (10).

$$S_{DG}^{t+1} = S_{DG}^{t} + \mu \Delta V_{DG}^{t} \qquad (10)$$

Where μ represents the iteration speed variable, it will decrease and reach zero when convergence is achieved by (11).

$$\mu = \frac{V_s + \Delta V_t}{V_s} \qquad (11)$$

Optimal conditions occur when the voltage drop reaches the optimal value at step t+1, denoted as $\Delta V_{t+1} = \Delta V_{opt}$.

B. Determine for Optimal Location of DG

The amount of loss reduction achieved by a Grid Distribution (GD) system depends on the location where the GD is placed. Losses will be minimized if the current in all feeder segments is reduced by the GD current. This occurs when the GD is placed at the node with the largest voltage drop. For instance, if the voltage drop is greatest at the end node, then the GD should be placed at that end node. However, if the voltage drop is highest in the lateral feeder at node k, then the GD should be placed at node k.

C. Optimal Loss Saving

The medium voltage feeder comprises a main feeder and a lateral feeder. Losses on the main feeder are the total of losses in each feeder segment and can be formulated in (12).

$$PR_{M} = \sum_{j=1}^{n-1} \left| \sum_{i=j+1}^{n} I_{i} \right|^{2} R_{j,j+1} \qquad (12)$$

Where PRM represents the main fedeer losses. $R_{j,j+1}$ denotes the resistance of the feeder segment from node j to node j+1. I_i stands for the lateral current at node i. Then, the constant c is substituted into (12) which results in (13).

$$PR_{M} = \sum_{j=1}^{n-1} \left| \sum_{i=j+1}^{n} I_{F}(1+c(i-1)) \right|^{2} R_{j,j+1} \qquad (13)$$

So that the size of the feeder segment is identical to the resistance R, then (13) becomes (14).

$$PR_{M} = I_{F}^{2} R \sum_{j=1}^{n-1} \left| \sum_{i=j+1}^{n} (1+c(i-1)) \right|^{2} \qquad (14)$$

Next, equation (13) is simplified to equation (15).

$$PR_{M} = s_{loss} I_{F}^{2} R_{F} \qquad (15)$$

The term s_{loss} represents a parameter indicating the load loss point, while R_F denotes the total resistance of the main fedeer. Lateral feeder losses can be determined using the provided formula by calculating the incoming current to the lateral feeder and its total resistance.

D. Calculation of Main and Lateral Feeder Currents

For instance, if the total load of a feeder is S_F with a power factor of f_{dF} and a voltage of V_F, then the total current entering the feeder is represented by (16).

$$I_F = \frac{S_F}{\sqrt{3}\, V_F} \qquad (16)$$

Feeder serves several distribution substations (GD) of different sizes. For example, the number of GDs with capacity S_{Di} for a number of k_i and j represents the variety of capacities so that the current in each GD is based on the total current formulated in equation (17).

$$I_{Di} = \frac{k_i S_{Di}}{\sum_{i=1}^{j} k_i S_{Di}} I_T \qquad (17)$$

For every feeder branch that has a GD of m_i, the current of the i branch in equation (17) can be determined using equation (18).

$$I_{Li} = \sum_{i=1}^{mi} I_{Di} \qquad (18)$$

E. Validation Method

Feeder serves a number of distribution substations (GD) of varying sizes. For example, the number of these distribution substations can vary. This method has been validated with a 7-node, 20 kV feeder as shown in Figure 3. The validation was performed using the power flow method, which is known for its accuracy. Table 1 displays the results of calculations using these two methods. The error rate of the proposed method is very low, both before and after DG injection, at just two digits in percentage units (refer to columns 4 and 7 in Table 1). The largest voltage drop, at node 7, is 5.323%. To reduce the voltage drop to 4%, a DG power of 1032.5 kVA is required. The node voltage conditions after DG injection are presented in columns 5 and 6. Besides reducing the voltage drop at each node, DG power injection also lowers the feeder current from 150 A to 112.7 A and decreases losses from 2.41% to 1.47%.

The reduction in voltage drop depends on the decrease in current in the feeder segment, which is heavily impacted by the placement of the DG at the feeder node. The closer the DG is placed to the supply substation, the smaller the current drop in the feeder segment, resulting in a smaller voltage drop.

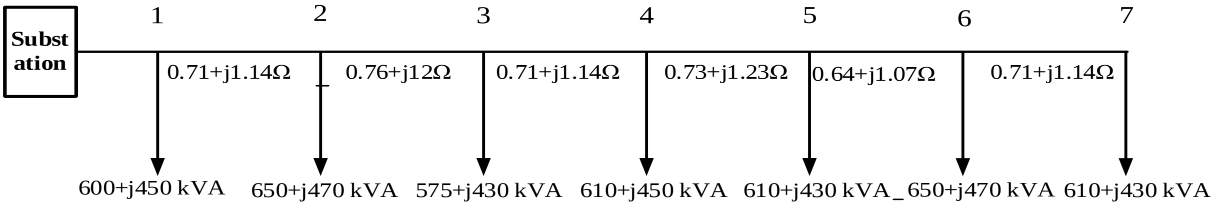

Figure 3. *Seven nodes feeder*

Table 1. Comparative Validation Result Of Two Methods

Node	Voltage Drop (%)					
	Without DG			With DG (1032.5 kVA)		
	OPF Method	Proposed Method	Error (%)	OPF Method	Proposed Method	Error (%)
1	2	3	4	5	6	7
1	0	0	0	0	0	0

2	1.494	1.499	0.005	1.120	1.126	0.006
3	2.796	2.806	0.010	2.099	2.108	0.009
4	3.798	3.807	0.009	2.849	2.860	0.011
5	4.587	4.608	0.021	3.440	3.462	0.022
6	5.056	5.079	0.023	3.790	3.816	0.026
7	5.301	5.323	0.022	4	4	0
Losses(%)	2.36	2.41	-	1.43	1.47	-

Table 2 illustrates how the placement of DG affects its ability to decrease the voltage at node 7 to 4%. DG can be placed at nodes 7, 6, and 5, and in those locations, it successfully reduces the voltage drop to 4%. However, at nodes 1 to 4, DG placement does not achieve the desired voltage reduction at node 7. When DG is placed at node 1, its high capacity does not have an impact on the voltage drop because the current from DG does not reduce the current in the line. The optimal location for DG placement, determined by minimizing DG capacity, is node 7, where the largest voltage drop occurs (5,323 5). At this node, a DG with a power capacity of 1032.5 kVA is recommended.

Table 2. Validation Effect of DG Placement

Location of DG	Optimal Capacity of DG (kVA)	Feeder Current (A)	Voltage Drop at N7 (%)
N7	1032.5	112.7	4.00
N6	1462.2	107,7	4.00
N5	2196.3	86.5	4.00

RESULTS

A. Implementation of the Proposed Method in Program

This section describes the algorithm for solving the optimal gradient descent problem on a feeder, based on the method outlined in section II. The following steps detail the procedures for solving the optimal gradient descent problem.

1. Input feeder data (impedance and GD capacity)
2. Set the maximum voltage drop limit value
3. Categorize the feeder as:
    - Light load (Green): $Vd_{max} \leq 95$ %
    - Heavy load (Yellow): $Vd_{max} \leq 95$ %
    - Overload (Red): $95\% < Vd_{max} \leq 100\%$
4. based on the maximum voltage drop limit
5. Determine the values of the constants c, s_v, and s_{loss}
6. Input main feeder current inflow.
7. Calculate the inflow of all lateral feeders.
8. Calculate the voltage drop before DG injection.
9. Identify the node with the largest voltage drop (such as in node k).
10. If the feeder is not categorized as overload, proceed to step 14.
11. Select the DG location at node k.
12. Determine the change in voltage drop ΔV_D^t.
13. Update DG capacity
14. Check voltage drop. If $V_{D-k} > V_{d-max}$, return to step 11. If not, proceed to step 14.
15. Calculate main feeder losses.

16. Calculate the losses of all lateral feeders.
17. Print the results.
18. Finished.

B. Case Study

a) Existing Conditions

To support the proposed method described earlier, numerical studies were conducted on an IEEE 21 node feeder. The load data can be found in Table 3, and the feeder inflow is 110 A to serve the load. The results of the voltage drop calculation using the proposed method are illustrated in Figure 4. The most significant voltage drop occurs at node N43, amounting to 3,260% or 81.15% of the standard (4%). Based on this maximum voltage drop, the existing feeder is categorized as normally loaded (green) according to Table 4. The existing condition feeder can still handle loads up to 128.2 A with a maximum voltage drop of 3.8% (yellow). This calculation does not require additional feeder.

Table 3. Transformer Capacity

No	Type	Capacity (kVA)
1	• (dot)	360
2	X(cross)	240
3	V(vie)	180

Table 4. Feeder Load Category

Load Feeder	Voltage Drop Standard	Remark	Indication
Light Load	<95%	Posible load expansion	Green
Heavy Load	95-100%	Consider power injection for load expansion	Yellow
Overload	>100%	DG power injection must be carried out	Red

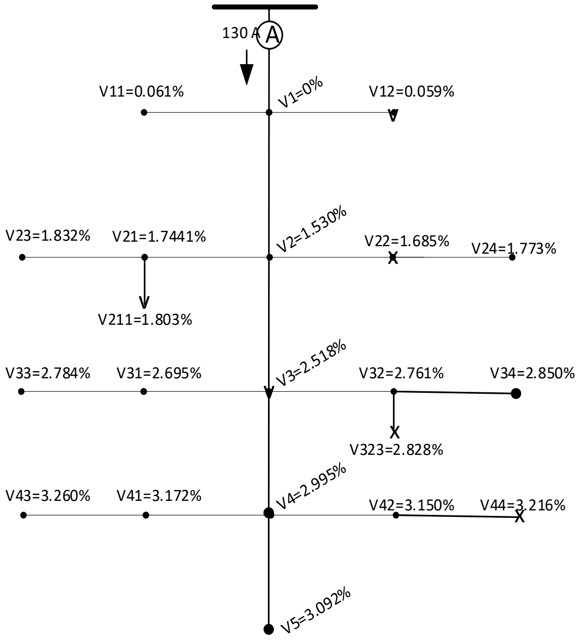

Figure 4. *Existing condition based on IEEE 21 nodes feeder*

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b) *Load Expantion*

Expansion will be carried out in two stages, detailed in Figure 5.

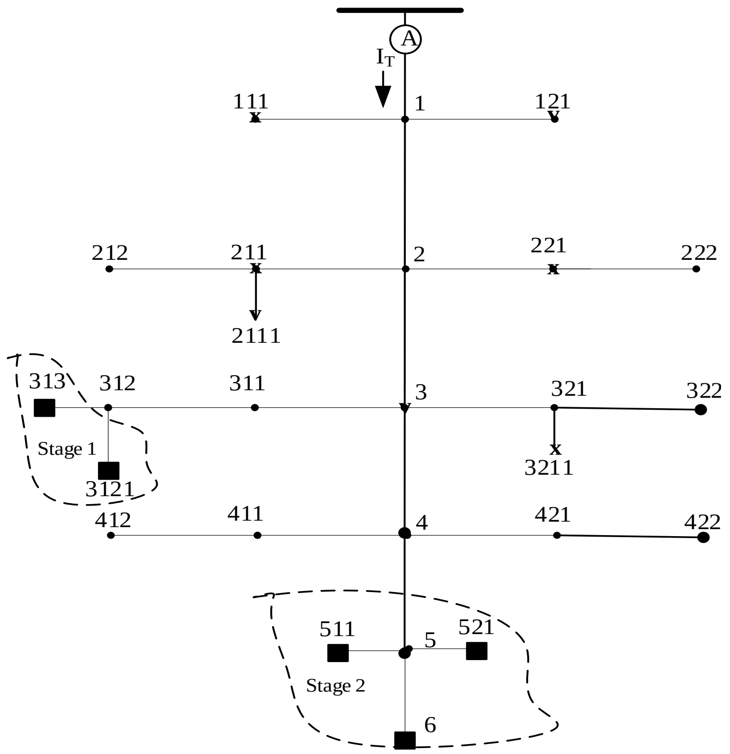

Figure 5. *Feeder IEEE 21 node after stages 1 and 2*

In Stage 1, two EV charging stations will be established at nodes N313 and N3121. Stage 3 will see the development of three general EV stations at nodes N511, N521, and N6. Each station will be powered by a DG with a capacity of 225 kVA. The feeder data is outlined in Table 5. It's estimated that the increase in feeder current will be 10 A for each additional EV public station.

Before load expansion, the feeder operated at light load conditions, showing a maximum voltage drop of 3.26% (classified in the green category). After the first stage of expansion, the feeder enters a heavy loading condition, resulting in a voltage drop of 3.87% (classified in the yellow category). In the second stage of expansion, the feeder becomes overloaded, with a voltage drop exceeding 4%. Ultimately, at the end of stage 2, the voltage drop increases to 5.276%.

Table 5. Feeder Data For EV Station

Node i	Node j	R(Ω)	X(Ω)
312	313	0.75	0.50
312	3121	0.85	0.60
5	6	1.25	1.15
5	511	0.60	0.40
5	521	0.75	0.50

Note: EV station capacity = 225 kVA with ■ symbols

c) *Solusion and Results*

The results of the calculations for adding an EV station are shown in Table 6. Without distributed generation (DG), the maximum voltage increased to 5.276% at node 6 with a current of 160 A, while previously the maximum voltage drop occurred at node 412 by 3260% with a load of 110 A. To reduce the maximum voltage drop to 4%, power injection is required at Nodes 4, 5, and 6. After the stage 2 expansion, the results are shown in Figure 6, where in order to achieve a maximum voltage drop of 4%, the feeder current needs to be reduced to 131.21 A.

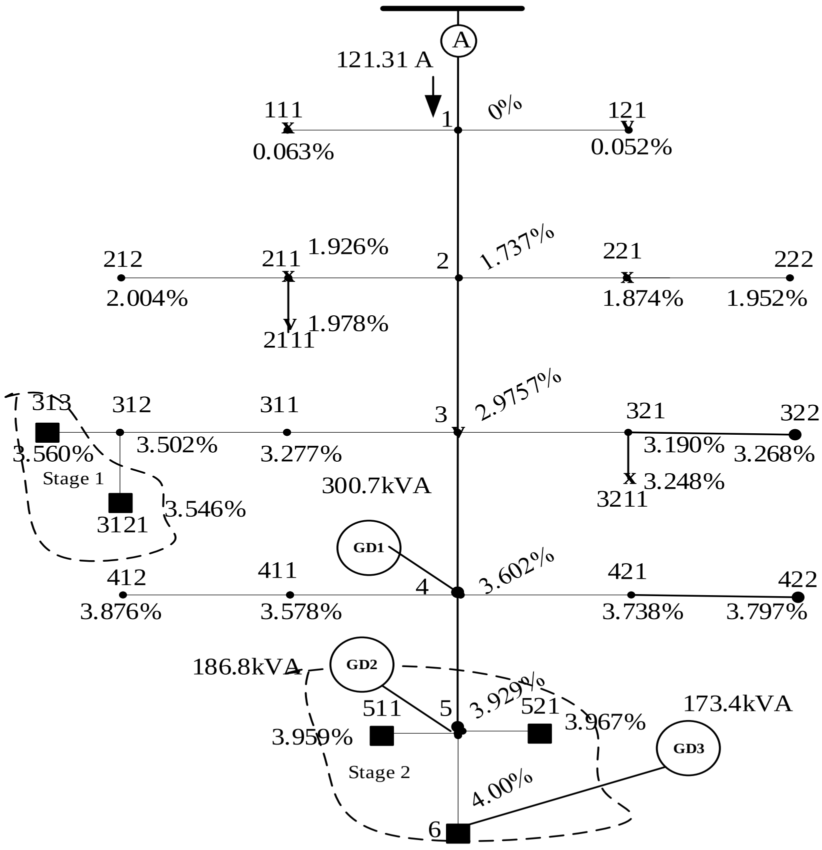

Figure 6. *Feeder IEEE 21 node voltage drop after stages 1 and 2*

Table 6. Feeder Condition VS DG Expansion Capacity

Item	Install capacity of GD (kVA)	Without DG			With DG			
		Voltage drop max. (%)	Node with drop voltage max.	Feeder indication in color	Voltage drop max. (%)	Feeder indication in color	Injective power of DG (kVA)	DG location
Existing	4500,0	3.26	N19	Green	3.26	Green	0	-
Stage1:								
1. N313	4725	3.56	N19	Green	3.56	Green	0	-
2. N3121	4950	3.87	N19	Yellow	3.87	Yellow	0	-
Stage 2:								
1. N511	5175	4.27	N6	Red	4.00	Yellow	300.7	N4
2. N521	5400	4.77	N6	Red	4.00	Yellow	186.8	N5
3. N6	5625	5.28	N6	Red	4.00	Yellow	173.4	N6

DISCUSSION

Electricity is a crucial factor in the development of smart cities, especially as we anticipate the increasing use of electric vehicles. This will require a sufficient number of public EV charging stations, as well as meeting the growing demand for other electricity usage. As the demand for electricity grows, it is important to develop an efficient electricity distribution system that can effectively support the use of clean energy. The electricity distribution system must be able to operate smoothly despite the increasing demand. Therefore, it is necessary to monitor the load conditions of the feeders. This paper proposes monitoring the feeder loading based on the largest voltage drop, categorizing them into three groups: 1. Light load feeders (green category, Loading <95%): These feeders can still accommodate more load. 2. Heavy load feeders (yellow, load between 95-100%): Additional power injection is needed when these are overloaded. 3. Overload feeders (red, load >100%): These feeders require power injection. In the context of smart cities, the focus is on seeking clean generation sources such as solar, wind, and fuel cells for this power injection.

The method described in this paper has been validated for determining the voltage drop across all feeder nodes using the power flow method for the 7-node feeder (see Fig. 3). The results obtained from this method closely align with those of the power flow method. By employing the feeder inflow approach, the voltage drop calculation can be carried out rapidly. The location of the distributed generation (DG) is determined by identifying the node with the highest voltage drop to maximize the reduction in feeder current. Table 2 validates that Node 7 exhibits the largest voltage drop and is the most optimal for minimizing the DG power injection capacity. The required DG power capacity to reduce the voltage drop at Node 7 from 5.323% to 4.00% is 1032.5 kVA.

Additionally, simulation results for the IEEE 21-node feeder are provided for both existing and expansion conditions to assess feeder mitigation due to electric vehicle (EV) load expansion. In the existing condition, the feeder experiences a light load (green), with Node 412 having the largest voltage drop of 3,260% (81.5% loading) and a feeder current of 110 A.

Stage 1 of the expansion was equipped with two SUPB-EVs, while stage 2 was equipped with three SUPB-EVs (General Battery Charging Station=GBCS-EV). It was assumed that each SUPB-EB would have an increased feeder current of 10 A. The complete calculation results are shown in Table 6, where the addition of one SUPB-EV feeder still falls within the green category. The feeders are in the yellow category after the completion of stage 1 expansion. In stage 2 expansion, if no power is injected, the category becomes red, with the largest voltage drop at the end of stage 2 being 5.276% at node 6.

DG power injection of 300.7 kVA was carried out at node 4 to prepare for the first SUPB-EV expansion in stage 2. For the second SUPB-EV expansion, a DG power of 186.8 kVA was required at node 5, and for the third SUPB-EV expansion, a DG power of 173.4 kVA was needed. At the end of the SUPB-EV expansion, the feeder current drops to 121.31 A. At the end of stage 1 expansion, the feeder condition is yellow. If no further expansion is injected, the feeder condition will become red. Mitigation of the voltage drop with each expansion of SUPB-EV, both without DG and with DG, is shown in Fig. 7. The voltage drop increases more sharply with each addition of SUPB-EV, as shown by the dotted black line curve. The voltage drop is maintained at 4.00% with DG power injection starting from the 3rd to 5th SUPB-EV expansion, as indicated by the black line curve.

The feeder needs power injection in three stages at nodes 4, 5, and 6 to bring the voltage drop down to a maximum of 4.00%. After the power injection, the feeder's condition is shown in Fig. 6, with a total DG power injection of 660.9 kVA. Due to this power injection, losses decreased by 1.18% from 2.86% at the end of stage 2. Fig. 7. indicates that the voltage drop is maintained at 4%, keeping losses below 2%.

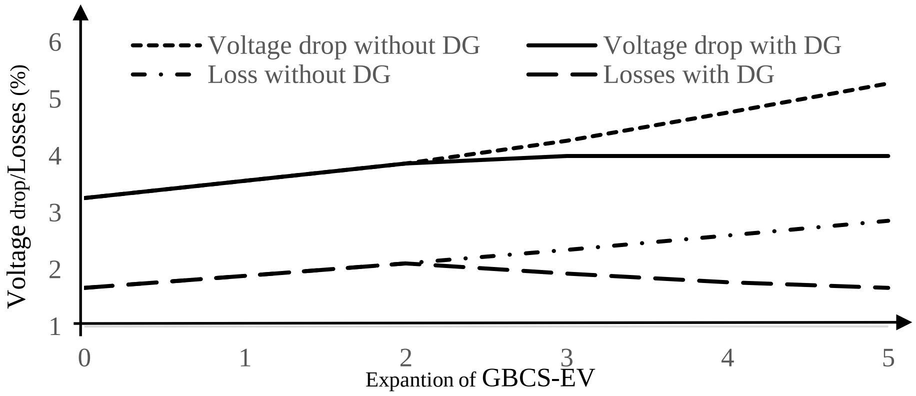

Figure 7. *Voltage drop and losses curve without DG vs with DC*

CONCLUSION

The method for calculating voltage drop based on feeder inflow and determining the best location and capacity for distributed generation (DG) has been developed with a clear mathematical approach. This method can work quickly as it only needs feeder current data and is suitable for real-time applications. The proposed method has been validated with the power flow method and has shown high accuracy results (double-digit error rate or 0.01%). Simulation results on the 21-node IEEE feeder, which was expanded to 26 nodes due to SUPB-EV expansion, demonstrate that this method can monitor any SUPB-EV expansion by displaying load categories in different colors (lightweight=green, heavy-yellow, and more=red). The expansion of the SUPB-EV without power injection will lead to a sharp increase in voltage drop (Fig. 7) due to the increase in feeder inflow. Injection of DG power at the optimal location and capacity reduces the voltage drop to 4.00% because the feeder input current decreases, from 150 A to 121.31 A at the end of stage 2 expansion. By maintaining a voltage drop of 4%, losses do not exceed 2%. Even at the end of stage 2, losses fell from 2.86% to 1.68%.

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